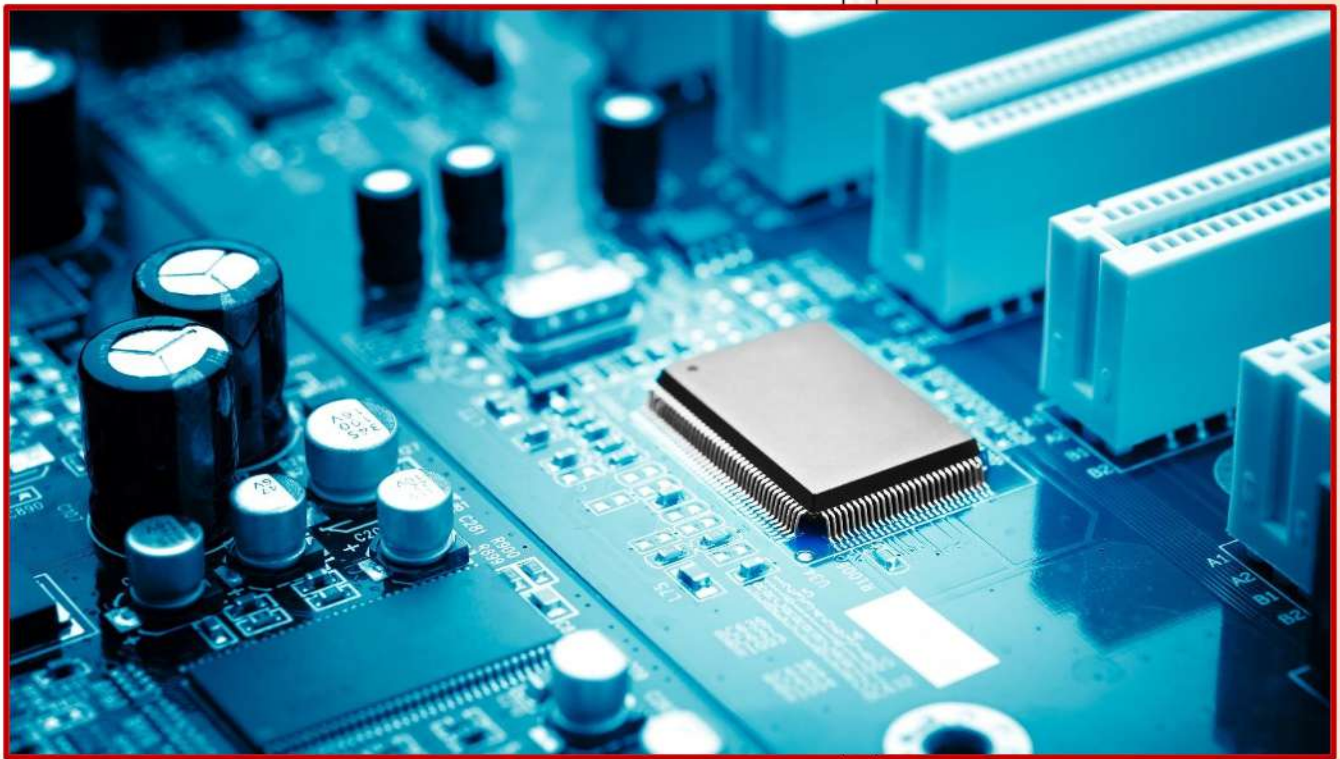
SHA-SHIB GROUP OF INSTITUTIONS

Training Notes

# Module 04- Electronic Fundamentals



SHA-SHIB GROUP

EMPOWERING KNOWLEDGE THROUGH VISION

FOREWORD

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- The information in this book is for study/ training purposes only and no revision service will be provided to the holder.

- While carrying out a procedure/ work on aircraft/ aircraft equipment you must always refer to the relevant Aircraft Maintenance Manual or Equipment Manufacturer's Handbook.

- For health and safety in the workplace you should follow the regulations/ Guidelines as specified by the Equipment Manufacturer, your company, National Safety Authorities and National Governments.

## Knowledge Levels – Category A, B1, B2, B3 and C Aircraft Maintenance Licence

Basic knowledge for categories A, B1, B2 and B3 are indicated by the allocation of knowledge levels indicators (1, 2 or 3) against each application subject. Category C applicants must meet either the category B1 or the category B2 basic knowledge levels.
The knowledge level indicators are defined as follows:

### LEVEL 1

- A familiarization with the principal elements of the subject.

Objectives: The applicant should be familiar with the basic elements of the subject.

- The applicant should be able to give a simple description of the whole subject, using common words and examples.
- The applicant should be able to use typical terms.

### LEVEL 2

- A general knowledge of the theoretical and practical aspects of the subject.
- An ability to apply that knowledge.

Objectives: The applicant should be able to understand the theoretical fundamentals of the subject.

- The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
- The applicant should be able to use mathematical formulae in conjunction with physical laws describing the subject.
- The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
- The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

### LEVEL 3

- A detailed knowledge of the theoretical and practical aspects of the subject.
- A capacity to combine and apply the separate elements of knowledge in a logical and comprehensive manner.

Objectives: The applicant should know the theory of the subject and interrelationships with other subjects.

- The applicant should be able to give a detailed description of the subject using theoretical fundamentals and specific examples.
- The applicant should understand and be able to use mathematical formulae related to the subject.
- The applicant should be able to read, understand and prepare sketches, simple drawings and schematics describing the subject.
- The applicant should be able to apply his knowledge in a practical manner using manufacturer's instructions.
- The applicant should be able to interpret results from various sources and measurements and apply corrective action where appropriate.

# -: DGCA MODULARISATION :-

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**CAR – 66 ISSUE II R 2**

## (LICENSING OF AIRCRAFT MAINTENANCE ENGINEERS)

## DIRECTORATE GENERAL OF CIVIL AVIATION

**TECHNICAL CENTRE, OPP SAFDURJUNG AIRPORT, NEW DELHI**

| Modules | Subject | A or B1 Aero plane with | | A or B1 Helicopter with | | B2 |
|---|---|---|---|---|---|---|
| | | Turbine Engine (s) | Piston Engine (s) | Turbine Engine (s) | Piston Engine (s) | Avionics |
| 1 | Not Applicable | | | | | |
| 2 | Not Applicable | | | | | |
| 3 | ELECTRICAL FUNDAMENTALS | X | X | X | X | X |
| 4 | ELECTRONIC FUNDAMENTALS | X | X | X | X | X |
| 5 | DIGITAL TECHNIQUES ELECTRONIC INSTRUMENT SYSTEMS | X | X | X | X | X |
| 6 | MATERIALS AND HARDWARE | X | X | X | X | X |
| 7A | MAINTENANCE PRACTICES | X | X | X | X | X |
| 7B | MAINTENANCE PRACTICES | | | | | |
| 8 | BASIC AERODYNAMICS | X | X | X | X | X |
| 9A | HUMAN FACTORS | X | X | X | X | X |
| 9B | HUMAN FACTORS | | | | | |
| 10 | AVIATION LEGISLATION | X | X | X | X | X |
| 11A | TURBINE AEROPLANE AERODYNAMICS, STRUCTURES AND SYSTEMS | X | | | | |
| 11B | PISTON AEROPLANE AERODYNAMICS, STRUCTURES AND SYSTEMS | | X | | | |
| 11C | PISTON AEROPLANE AERODYNAMICS, STRUCTURES AND SYSTEMS | | | | | |
| 12 | HELICOPTER AERODYNAMICS, STRUCTURES AND SYSTEMS | | | X | X | |
| 13 | AIRCRAFT AERODYNAMICS, STRUCTURES AND SYSTEMS | | | | | X |
| 14 | PROPULSION | | | | | X |
| 15 | GAS TURBINE ENGINE | X | | X | | |
| 16 | PISTON ENGINE | | X | | X | |
| 17A | PROPELLER | X | X | | | |
| 17B | PROPELLER | | | | | |

| TRAINING NOTES<br>MODULE: 4 | | | |
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| SUBJECT NAME: ELECTRONIC FUNDAMENTALS | | | |
| UNIT NO. | OBJECTIVE | LEVEL | |
| | | B1 | B2 |
| 4.1 | **4.1 Semiconductors**<br>4.1.1 Diodes<br>Diode symbols;<br>Diode characteristics and properties;<br>Diodes in series and parallel;<br>Main characteristics and use of silicon-controlled rectifiers (thyristors), light emitting diode, photo conductive diode, varistor, rectifier diodes;<br>Functional testing of diodes.<br>Materials, electron configuration, electrical properties;<br>P and N type materials: effects of impurities on conduction, majority and minority characters;<br>PN junction in a semiconductor, development of a potential across a PN junction in unbiased, forward biased and reverse biased conditions;<br>Operation and function of diodes in the following circuits: clippers, clampers, full and half wave rectifiers, bridge rectifiers, voltage doublers and triplers;<br>Detailed operation and characteristics of the following devices: silicon controlled rectifier (thyristor), light emitting diode, Shottky diode, photo conductive diode, varactor diode, varistor, rectifier diodes, Zener diode.<br>***4.1.2 Transistors***<br>*(a)* Transistor symbols;<br>Component description and orientation;<br>Transistor characteristics and properties.<br>(b)Construction and operation of PNP and NPN transistors;<br>Base, collector and emitter configurations;<br>Testing of transistors.<br>Basic appreciation of other transistor types and their uses.<br>Application of transistors: classes of amplifier (A, B, C);<br>Simple circuits including: bias, decoupling, feedback and stabilisation;<br>Multistage circuit principles: cascades, push-pull, oscillators, multivibrators, flip-flop circuits.<br>***4.1.3 Integrated Circuits***<br>(a) Description and operation of logic circuits and linear circuits/operational amplifiers.<br>(b) Description and operation of logic circuits and linear circuits;<br>Introduction to operation and function of an operational amplifier used as: integrator, differentiator, voltage follower, comparator;<br>Operation and amplifier stages connecting methods: resistive capacitive, inductive (transformer), inductive resistive (IR), direct;<br>Advantages and disadvantages of positive and negative feedback. | 2 | 2 |
| 4.2 | **4.2 Printed Circuit Boards**<br>Description and use of printed circuit boards. | 1 | 2 |
| 4.3 | **4.3 Servomechanisms**<br>(a) Understanding of the following terms: Open and closed loop systems, feedback, follow up, analogue transducers; | 1 | - |

| | | | |
|---|---|---|---|
| | Principles of operation and use of the following synchro system components/features: resolvers, differential, control and torque, transformers, inductance and capacitance transmitters.<br>(b) Understanding of the following terms: Open and closed loop, follow up, servomechanism, analogue, transducer, null, damping, feedback, deadband;<br>Construction operation and use of the following synchro system components: resolvers, differential, control and torque, E and I transformers, inductance transmitters, capacitance transmitters, synchronous transmitters;<br>Servomechanism defects, reversal of synchro leads, hunting. | | |

Module 04: Enabling Objectives and Certification Statement

## Certification Statement

These Study Notes comply with the syllabus of DGCA, CAR – 66 (Appendix I) and the associated Knowledge Levels as specified.

# REVISION LOG

| Sr. No. | Issue / Revision No. | Issue / Revision Date | Pages Revised | Signature |
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# UNIT 1: SEMICONDUCTORS

## 1.1. DIODES

Semiconductor technology is present in almost every area of modern day technology and as such semiconductor theory is a very important element of electronics.

One of the fundamental structures within semiconductor technology is the PN junction. It is the fundamental building block of semiconductor diodes and transistors and a number of other electronic components.

The semiconductor diode has the valuable property that electrons only flow in one direction across it and as a result it acts as a rectifier. As it has two electrodes it receives its name - diode. In view of this, it is one of the most fundamental structures in semiconductor technology. Large numbers of diodes are manufactured each year, and of course the semiconductor diode is the basis of many other devices apart from diodes. The bipolar junction transistor, junction FET and many more all rely on the PN junction for their operation. This makes the semiconductor PN junction diode one of the key enablers in today's electronics technology.

## PN JUNCTION

In its basic form a semiconductor diode is formed from a piece of silicon by making one end P type and the other end N type. This means that both ends have different characteristics. One end has an excess of electrons whilst the other has an excess of holes. Where the two areas meet the electrons fill the holes and there areno free holes or electrons. This means that there are no available charge carries in this region. In view of the fact that this area is depleted of charge carriers it is known as the depletion region.

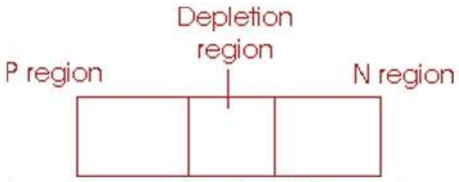
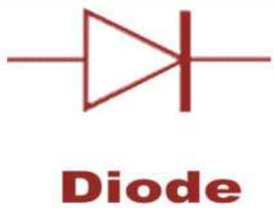



Fig 1.1: The semiconductor diode PN junction with no bias applied

## DIODE SYMBOLS




Even though the depletion region is very thin, often only few thousandths of a millimeter, current cannot flow in the normal way. Different effects are noticed dependent upon the way in which the voltage is applied to the junction. If the voltage is applied such that the P type area becomes positive and the N type becomes negative, holes are attracted towards the negative voltage and are assisted to jump across the depletion layer. Similarly electrons move towards the positive voltage and jump the depletion layer. Even though the holes and electrons are moving in opposite directions, they carry opposite charges and as a result they represent a current flow in the same direction.

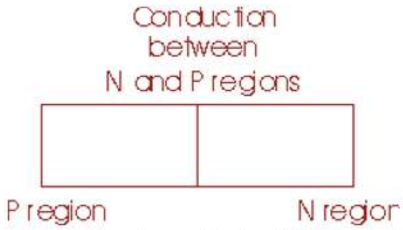



Fig 1.2(a): The semiconductor diode PN junction with forward bias

If the voltage is applied to the semiconductor diode in the opposite senses no current flows. The reason for this is that the holes are attracted towards the negative potential that is applied to the P type region. Similarly the electrons are attracted towards the positive potential which is applied to the N type region. In other words the holes and electrons are attracted away from the junction itself and the depletion region increases in width. Accordingly no current flows.

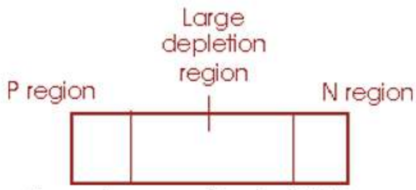



Fig 1.2(b):The semiconductor diode PN junction with reverse bias

## PN JUNCTION CHARACTERISTICS

The PN junction is not an ideal rectifier diode having infinite resistance in the reverse direction and no resistance in the forward direction.

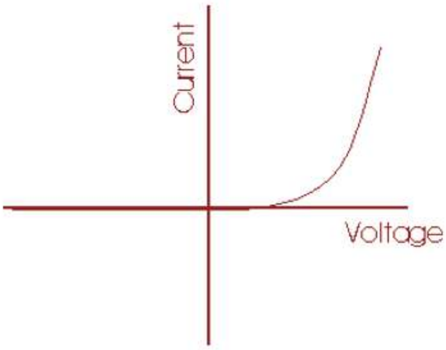



Fig 1.3:The characteristic of a diode PN junction

In the forward direction (forward biased) it can be seen that very little current flows until a certain voltage has been reached. This represents the work that is required to enable the charge carriers to cross the depletion layer. This voltage varies from one type of semiconductor to another. For germanium it is around 0.2 or 0.3 volts and for silicon it is about 0.6 volts. In fact it is possible to measure a voltage of about 0.6 volts across most small current diodes when they are forward biased. Power rectifier diodes normally have a larger voltage across them but this is partly due to the fact that there is some resistance in the silicon, and partly due to the fact that higher currents are flowing and they are operating further up the curve.

From the diagram it can be seen that a small amount of current flows in the reverse direction (reverse biased). It has been exaggerated to show it on the diagram, and in normal circumstances it is very much smaller than the forward current. Typically it may be a Pico amps or micro amps at the most. However it is worse at higher temperatures and it is also found that germanium is not as good as silicon.

These reverse current results from what are called minority carriers. These are a very small number of electrons found in a P typeregion or holes in an N type region. Early semiconductors has relatively high levels of minority carriers, but now that the manufacture of semiconductor materials is very much better the number of minority carriers is much reduced as are the levels of reverse currents.

## 1.2. DIODE CHARACTERISTICS AND PROPERTIES

- Forward Characteristics
- Reverse Characteristics

### FORWARD CHARACTERISTICS

When a diode is connected in a Forward Bias condition, a negative voltage is applied to the N-type material and a positive voltage is applied to the P-type material. If this external voltage becomes greater than the value of the potential barrier, approx. 0.7 volts for silicon and 0.3 volts for germanium, the potential barriers opposition will be overcome and current will start to flow.

This is because the negative voltage pushes or repels electrons towards the junction giving them the energy to cross over and combine with the holes being pushed in the opposite direction towards the junction by the positive voltage. This results in a characteristics curve of zero current flowing up to this voltage point, called the "knee" on the static curves and then a high current flow through the diode with little increase in the external voltage.

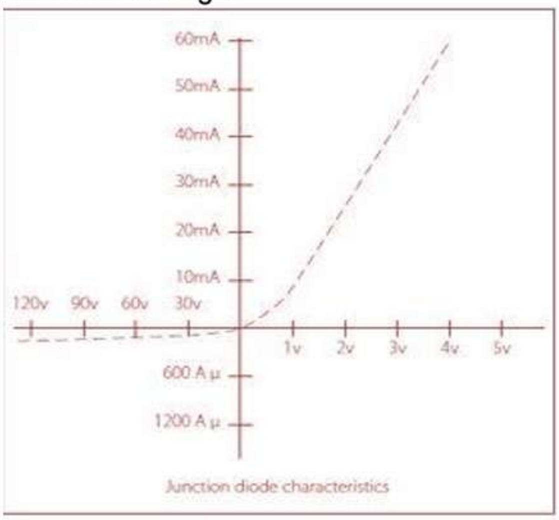



Fig1.4

The application of a forward biasing voltage on the junction diode results in the depletion layer becoming very thin and narrow which represents a low impedance path through the junction thereby allowing high currents to flow. The point at which this sudden increase in current takes place is represented on the static I-V characteristics curve above as the "knee" point.

This condition represents the low resistance path through the PN junction allowing very large currents to flow through the diode with only a small increase in bias voltage. The actual potential difference across the junction or diode is kept constant by the action of the depletion layer at approximately 0.3v for germanium and approximately 0.7v for silicon junction diodes.

Since the diode can conduct "infinite" current above this knee point as it effectively becomes a short circuit, therefore resistors are used in series with the diode to limit its current flow. Exceeding its maximum forward current specification causes the device to dissipate more power in the form of heat than it was designed for resulting in a very quick failure of the device.

## REVERSE CHARACTERISTICS

When a diode is connected in a Reverse Bias condition, a positive voltage is applied to the N-type material and a negative voltage is applied to the P-type material.

The positive voltage applied to the N-type material attracts electrons towards the positive electrode and away from the junction, while the holes in the P-type end are also attracted away from the junction towards the negative electrode.

The net result is that the depletion layer grows wider due to a lack of electrons and holes and presents a high impedance path, almost an insulator. The result is that a high potential barrier is created thus preventing current from flowing through the semiconductor material.

A high resistance value to the PN junction and practically zero current flows through the junction diode with an increase in bias voltage. However, a very small leakage current does flow through the junction which can be measured in micro-amperes, (μA ).

One final point, if the reverse bias voltage Vr applied to the diode is increased to a sufficiently high enough value, it will cause the diode's PN junction to overheat and fail due to the avalanche effect around the junction. This may cause the diode to become shorted and will result in the flow of maximum circuit current, and this shown as a step downward slope in the reverse static characteristics curve below.

## 1.3. DIODES IN SERIES AND PARALLEL

Connecting diodes in series increases the reverse blocking capabilities of the diodes. Each diode must carry the same leakage current, and have the same blocking voltage. However, in reality even two diodes of the same part number will not have the same characteristics due to tolerances in the production process. This gives rise to problems when diodes are connected in series, since the blocking voltages will differ slightly.

In the forward-biased condition, both diodes conduct the same amount of current and the forward voltage drop for each diode would be almost equal. In the reversed-biased condition, however, where each diode has to carry the same leakage current, the blocking voltage would differ significantly.

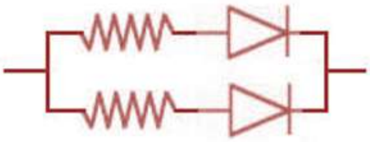


Fig 1.5

In PN Junction Diodessince the current flowing across a PN junction isproportional to its cross-sectional area, two identical PN junctions connected in parallel act effectively as a single PN junction with twice the cross-sectional area, hence twice .

## 1.4. SILICON CONTROL RECTIFIER

It is a tri-junction PNPN device having three external connections: anode (A), cathode (C) and gate (G) as shown in Fig 1.6

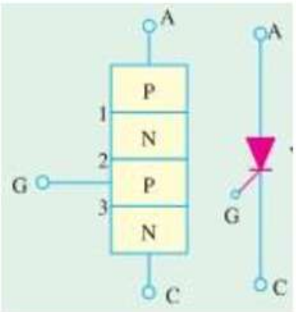



Fig 1.6

A silicon-controlled rectifier is a four-layer solid statecurrent controlling device. SCRs are unidirectional devices i.e. can conduct current only in one direction as opposed to TRIACs which are bidirectional i.e. current can flow through them in either direction. SCRs can be triggered normally only by currents going into the gate as opposed to TRIACs which can be triggered normally by either a positive or a negative current applied to its gate electrode.

The Silicon Control Rectifier (SCR) consists of four layers of semiconductors, which form NPNP or PNP structures. It has three junctions, labelledJ1, J2, and J3 and three terminals. The anode terminal of an SCR is connected to the P-Type material of a

PNPN structure and the cathode terminal is connected to the N-Type layer, while the gate of the Silicon Control Rectifier SCR is connected to the P-Type material nearest to the cathode.

An SCR consists of four layers of alternating P and N type semiconductor materials. Silicon is used as the intrinsic semiconductor, to which the proper dopants are added. The junctions are either diffused or alloyed. The planar construction is used for low power SCRs (and all the junctions are diffused). The mesa type construction is used for high power SCRs. In this case, junction J2 is obtained by the diffusion method and then the outer two layers are alloyed to it, since the PNPN pellet is required to handle large currents. It is properly braced with tungsten or molybdenum plates to provide greater mechanical strength. One of these plates is hard soldered to a copper stud, which is threaded for attachment of heat sink. The doping of PNPN will depend on the application of SCR, since its characteristics are similar to those of the thyratron. Today, the term thyristor applies to the larger family of multilayer devices that exhibit bistable state-change behaviour that is, switching either ON or OFF.

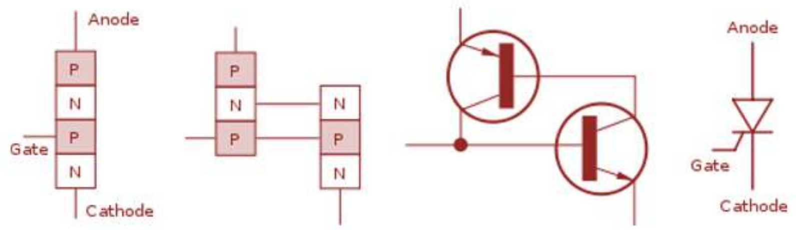



Fig 1.7

## MAIN CHARACTERISTICS OF SILICON CONTROLLED RECTIFIER

### BIASING

With the polarity of V as shown in Fig 1.8 (a), the junctions J1 and J3 become forward-biased whereas J2 is reverse-biased. Hence, no current (except leakage current) can flow through the SCR. In Fig 1.8 (b), polarity of V has been reversed. It is seen that, now, junctions J1 and J3 become reverse-biased and only J2 is forward-biased. Again, there is no flow of current through the SCR.

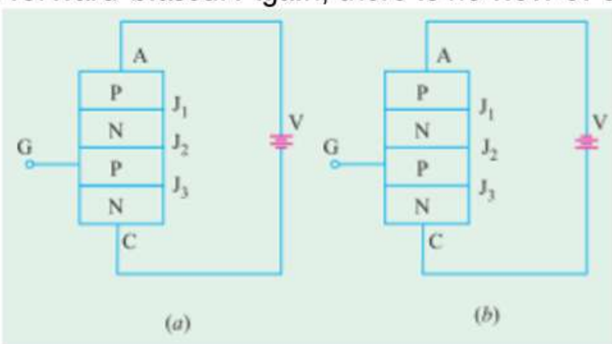



Fig 1.8 (a) Fig 1.8 (b)

### Operation

In Fig 1.8 (a) current flow is blocked due to reverse-biased junction J2. However, when anode voltage is increased, a certain critical value called forward breakover voltage VBO is reached when J2 breaks down and SCR switches suddenly to a highly conducting state. Under this condition, SCR offers very little forward resistance (0.01 Ω – 1.0 Ω) so that voltage across it drops to a low value

(about 1 V) as shown in Fig 1.9 and current is limited only by the power supply and the load resistance. Current keeps flowing indefinitely until the circuit is opened briefly.
With supply connection as in Fig 1.8 (b) the current through the SCR is blocked by the two reversebiased junctions J1 and J3. When V is increased, a stage comes when Zener breakdown occurs which may destroy the SCR (Fig 1.9). Hence, it is seen that SCR is a unidirectional device unlike triac which is bi-directional.

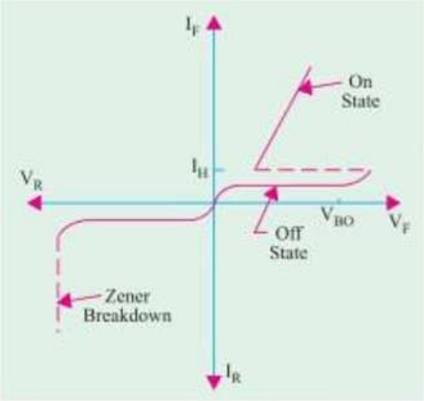



Fig 1.9

Uses of SCR

Main application of an SCR is as a power control device. It has been shown above that when SCR is OFF, its current is negligible and when it is ON, its voltage is negligible. Consequently, it never dissipates any appreciable amount of power even when controlling substantial amounts of load power. For example, one SCR requires only 150 mA to control a load current of 2500 A. Other common areas of its application include.

1. Relay controls
2. Regulated power supplies
3. Static switches
4. Motor controls
5. Inverters,
6. Battery chargers,
7. Heater controls,
8. Phase control.

## 1.5. LIGHT EMITTING DIODE

A light-emitting diode (LED) is forward-biased P-N junction which emits visible light when energised.As discussed earlier, charge carrier recombination takes place when electrons from the N-side cross the junction and recombine with the holes on the P-side.
Now, electrons are in the higher conduction band on the N-side whereas holes are in the lower valence band on the P-side. During recombination, some of the energy difference is given up in the form of heat and light (i.e. photons).For Si and Ge junctions, greater percentage of this energy is given up in the form of heat so that the amount emitted as light is insignificant. But in the case of other semiconductor materials like gallium arsenide (GaAs), gallium phosphide (GaP) and gallium-arsenide-phosphide (GaAsP), a greater percentage of energy released during recombination is given out in the form of light. If the semiconductor material is translucent, light is emitted and the junction

becomes a light source i.e. a light-emitting diode (LED) as shown schematically in Fig 1.10 (a) The colour of the emitted light depends on the type of material used as given below.

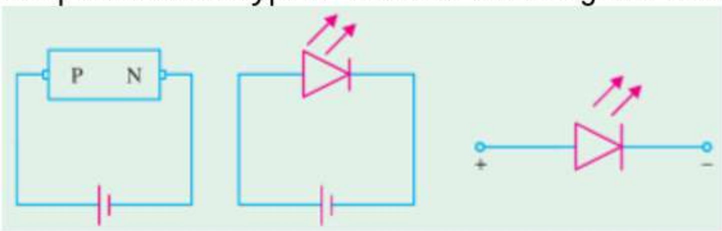



Fig 1.10(a)

1. GaAs — infrared radiation (invisible).
2. GaP — red or green light.
3. GaAsP — red or yellow (amber) light.

LEDs that emit blue light are also available but red is the most common. LEDs emit no light when reverse-biased. In fact, operating LEDs in reverse direction will quickly destroy them. Fig 1.10 shows a picture of LEDs that emits different colours of light.

The LED consists of a chip of semiconducting material doped with impurities to create a p-n junction. As in other diodes, current flows easily from the p-side, or anode, to the n-side, or cathode, but not in the reverse direction. Charge-carriers electrons and holes

flow into the junction from electrodes with different voltages. When an electron meets a hole, it falls into a lower energy level and releases energy in the form of a photon. as shown in Fig 1.10 (b)

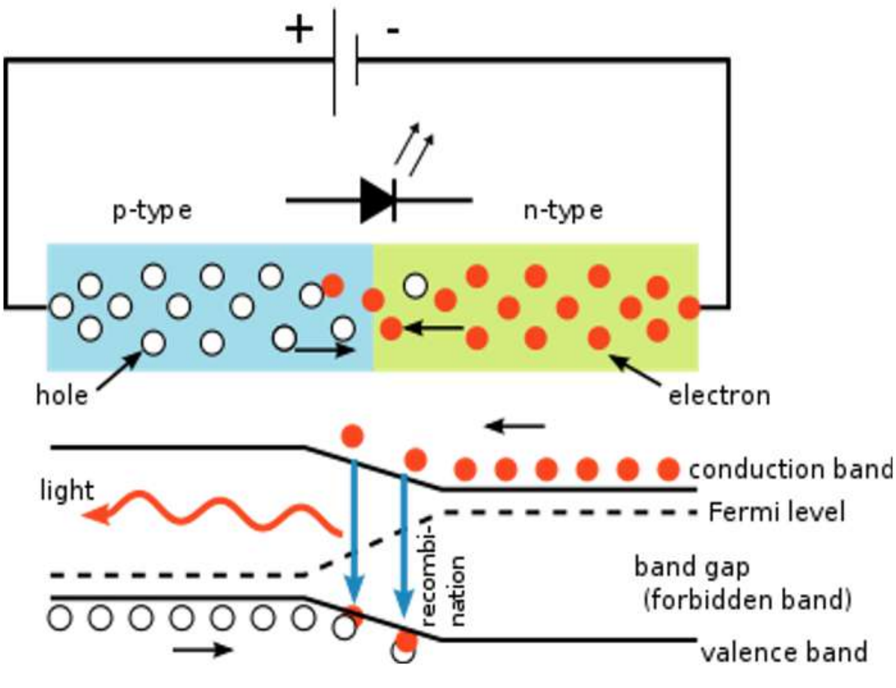



Fig 1.10(b)

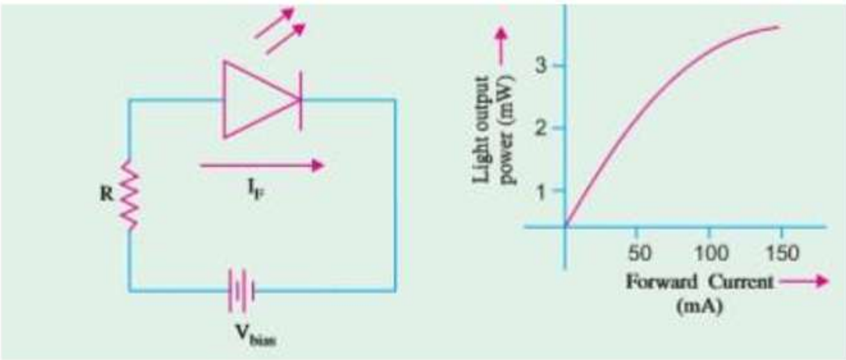



Fig 1.11

## Working of LED

The forward voltage across an LED is considerably greater than for a silicon PN junction diode. Typically the maximum forward voltage for LED is between 1.2 V and 3.2 V depending on the device. Reverse breakdown voltage for an LED is of the order of 3 V to 10 V. Fig 1.11 shows a simple circuit to illustrate the working of an LED. The LED emits light in response to a sufficient forward current. The amount of power output translated into light is directly proportional to the forward current as shown in Fig 1.11 It is evident from this figure that greater the forward current, the greater the light output.

## 1.8. PHOTO CONDUCTIVE DIODE


Fig 1.12:Symbol for PHOTODIODE

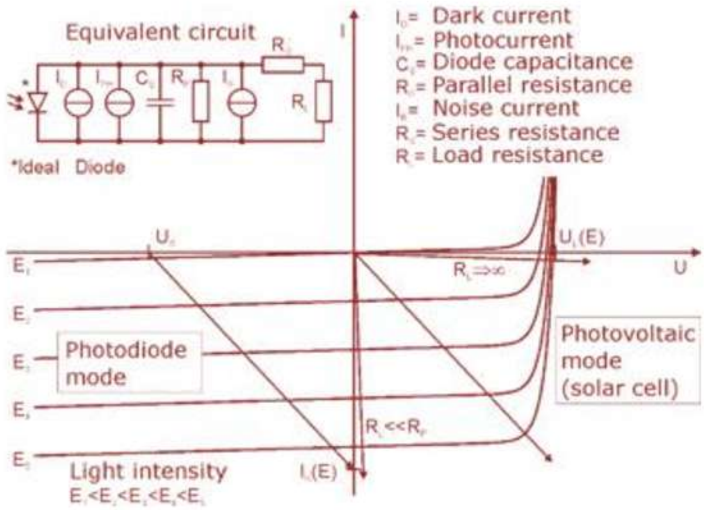



Fig 1.13 : I-V characteristic of a photodiode.

A photodiode is a semiconductor device that converts light into current. The current is generated when photons are absorbed in the photodiode. A small amount of current is also produced when no light is present. Photodiodes may contain optical filters, built-in lenses, and may have large or small surface areas. Photodiodes usually have a slower response time as its surface area increases. The common, traditional solar cell used to generate electric solar power is a large area photodiode.

Photodiodes are similar to regular semiconductor diodes except that they may be either exposed (to detect vacuum UV or X-rays) or packaged with a window or optical fiber connection to allow light to reach the sensitive part of the device. Many diodes designed for use specifically as a photodiode use a PIN junction rather than a p-n junction, to increase the speed of response. A photodiode is designed to operate in reverse bias.

A photodiode is a p-n junction or PIN structure. When a photon of sufficient energy strikes the diode, it creates an electron-hole pair. This mechanism is also known as the inner photoelectric effect. If the absorption occurs in the junction's depletion region, or one diffusion length away from it, these carriers are swept from the junction by the built-in electric field of the depletion region. Thus holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced. The total current through the photodiode is the sum of the dark current (current that is generated in the absence of light) and the photocurrent, so the dark current must be minimized to maximize the sensitivity of the device.

## 1.7. VARISTOR

A varistor is an electronic component with a non-linear current–voltage characteristic, and is therefore also known as a voltage-dependent resistor (VDR). The response curve of a varistor is similar to a diode. In contrast to a diode however, it has the same characteristic for both directions of traversing current. At low voltage it has a high electrical resistance which decreases as the voltage is raised.

Varistors are used as control or compensation elements in circuits either to provide optimal operating conditions or to protect against excessive transient voltages. When used as protection devices, they shunt the current created by the excessive voltage away from sensitive components when triggered.

A varistor remains non-conductive as a shunt-mode device during normal operation when the voltage across it remains well below its "clamping voltage", thus varistors are typically used for suppressing line voltage surges. However, a varistor may not be able to successfully limit a very large surge from an event like a lightning strike where the energy involved is many orders of magnitude greater than it can handle. In general, the primary case of Varistor breakdown is localized heating caused as an effect of thermal runaway.

## RECTIFIER DIODES

### Crystal Diode as a Rectifier

Fig 1.14 illustrates the rectifying action of a crystal diode. The a.c. input voltage to be rectified, the diode and load RL are connected in series. The d.c. output is obtained across the load as explained in the following discussion. During the positive half-cycle of a.c. input voltage, the arrowhead becomes positive w.r.t. bar. Therefore, diode is forward biased and conducts current in the circuit. The result is that positive half-cycle of input voltage appears across RL as shown. However, during the negative half-cycle of input a.c. voltage, the diode becomes reverse biased because now the arrowhead is negative w.r.t. bar. Therefore, diode does not conduct and no voltage appears across load RL. The result is that output consists of positive half-cycles of input a.c. voltage while the negative half-cycles are suppressed. In this way, crystal diode has been able to do rectification i.e. change a.c. into d.c. It may be seen that output across RL is pulsating d.c.

It is interesting to see that behavior of diode is like a switch. When the diode is forward biased, it behaves like a closed switch and connects the a.c. supply to the load RL. However, when the diode is reverse biased, it behaves like an open switch and disconnects the a.c. supply from the load RL. This switching action of diode permits only the positive half-cycles of input a.c. voltage to appear across RL.

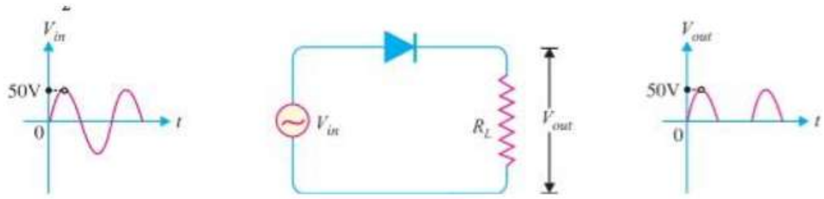



Fig. 1.14

## Functional Testing Silicon Diodes (Not LED Or Zener)

To test a silicon diode such as a 1N4001 all you need is an ohm-meter. If you are using an analog VOM type meter, set the meter to one of the lower ohms scales, say 0- 2K, and measure the resistance of the diode both ways. If you get zero both ways, the diode is shorted. If you get INFINITY both ways, the diode is open. If you get INFINITY one way but some reading the other way (the value is not important) then the diode is good.
If you use a digital multi-meter (DMM), then there should be a special setting on the Ohms range for testing diodes. Often the setting is marked with a diode symbol:

Measure the diode resistance both ways. One way the meter should indicate an open circuit. The other way you should get a reading (often a reading around 600). That indicates the diode is good. If you measure an open circuit both ways, the diode is open. If you measure low resistance both ways, the diode is shorted.

## Testing Diodes in Circuit

The procedures described above assume the diode under test is not part of any circuit. If you are trying to test a diode that is on a circuit board or otherwise connected to other components, then you should disconnect one end of the diode. On a circuit board you can unsolder one end of the diode and lift it off the board. Make sure that you first disconnect all power going to the circuit before you disconnect the diode. After disconnecting one end,proceed as described above.

Materials, electron configuration, electrical properties

The electrical conduction properties of different elements and compounds can be explained in terms of the electrons having energies in the valence and conduction bands. The electrons lying in the lower energy bands, which are normally filled, play no part in the conduction process.

Insulators - Stated simply, insulators are those materials in which valence electrons arebound very tightly to their parent atoms, thus requiring very large electric field to remove them from the

attraction of their nuclei. In other words, insulators have no free charge carriers available with them under normal conditions.

In terms of energy bands, it means that insulators

1. have a full valence band
2. have an empty conduction band
3. have a large energy gap (of several eV) between them
4. at ordinary temperatures, the probability of electrons from full valence band gaining sufficient energy so as to surmount energy gap and thus become available for conduction in the conduction band, is slight.

This is shown in Fig 1.15 (a) For conduction to take place, electrons must be given sufficient energy to jump from the valence band to the conduction band. Increase in temperature enables some electrons to go to the conduction band which fact accounts for the negative resistance-temperature coefficient of insulators.

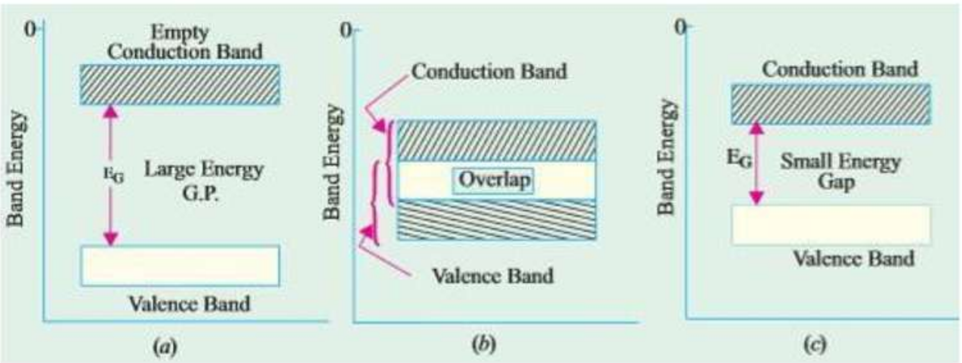



Fig 1.15 (a) Fig 1.15 (b) Fig 1.15 (c)

Conductors - Put in a simple way, conducting materials are those in which plenty of free electrons are available for electric conduction.

In terms of energy bands, it means that electrical conductors are those which have overlapping valence and conduction bands as shown in Fig 1.15 (b)

In fact, there is no physical distinction between the two bands. Hence, the availability of a large number of conduction electrons.

Another point worth noting is that in the absence of forbidden energy gap in good conductors, there is no structure to establish holes. The total current in such conductors is simply a flow of electrons. It is exactly for this reason that the existence of holes was not discovered until semi-conductors were studied thoroughly.

## Semiconductors

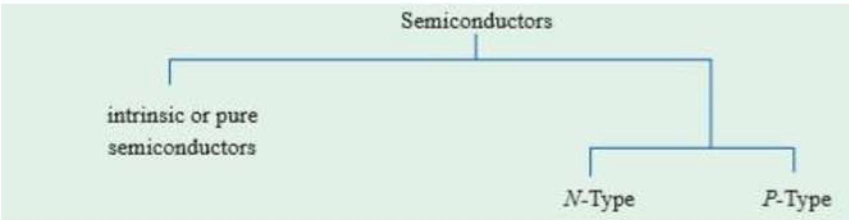
A semiconductor material is one whose electrical properties lie in between those of insulators and good conductors. Examples are: germanium and silicon.

In terms of energy bands, semiconductors can be defined as those materials which have almost an empty conduction band and almost filled valence band with a very narrow energy gap (of the order of 1 eV) separating the two.

At $0^{o}K$, there are no electrons in the conduction band and the valence band is completely filled. However, with increase in temperature, width of the forbidden energy bands is decreased so that some of the electrons are liberated into the conduction band. In other words, conductivity of semiconductors increases with temperature.

Types of Semiconductors

Semiconductors can be classified as shown below :




Intrinsic Semiconductors

An intrinsic semiconductor is one which is made of the semiconductor material in its extremely pure form. Common examples of such semiconductors are : pure germanium and silicon which have forbidden energy gaps of 0.72 eV and 1.1 eV respectively

Extrinsic Semiconductors

Those intrinsic semiconductors to which some suitable impurity or doping agent or dopant has been added in extremely small amounts (about 1 part in 108) are called extrinsic semiconductors.

The usual doping agents are :

1. pentavalent atoms having five valence electrons (arsenic, antimony, phosphorus)
2. trivalent atoms having three valence electrons (gallium, indium, aluminium, boron).

Pentavalent doping atom is known as donor atom because it donates or contributes one electron to the conduction band of pure germanium. The trivalent atom, on the other hand, is called acceptor atom because it accepts one electron from the germanium atom.

Depending on the type of doping material used, extrinsic semiconductors can be sub-divided into two classes:

(i) N-type semiconductors and
(ii) P-type semiconductors

## N-type Extrinsic Semiconductor.

This type of semiconductor is obtained when a pentavalent material like antimonty (Sb) is added to pure germanium crystal. As shown in Fig 1.16 (a) each antimony atom forms covalent bonds with the surrounding four germanium atoms with the help of four of its five electrons. The fifth electron is superfluous and is loosely bound to the antimony atom. Hence, it can be easily excited from the valence band to the conduction band by the application of electric field or increase in thermal energy. Thus, practically every antimony atom introduced into the germanium lattice, contributes one conduction electron into the germanium lattice without creating a positive hole. Antimony is called donor impurity and makes the pure germanium an N-type (N for negative) extrinsic semi-conductor. As an aid to memory, the student should associate the N in donor with N in the N-type material and N in Negative charge carrier.

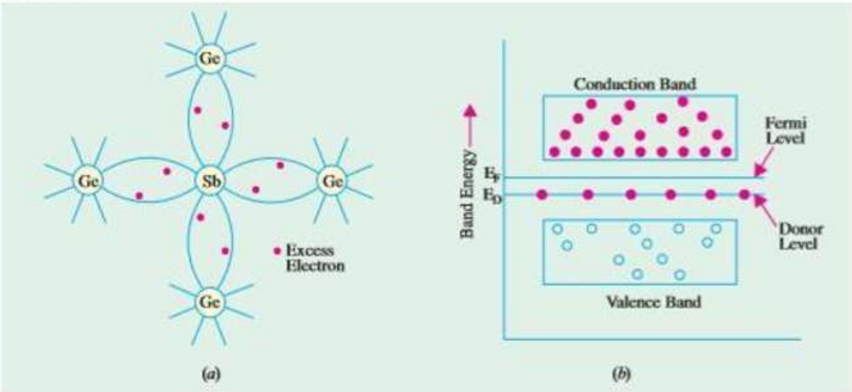



Fig 1.16(a)          Fig 1.16(b)

It may be noted that by giving away its one valence electron, the donor atom becomes a positivelycharged ion. But it cannot take part in conduction because it is firmly fixed or tied into the crystal lattice. It will be seen that apart from electrons and holes intrinsically available in germanium, the addition of antimony greatly increases the number of conduction electrons. Hence, concentration of electrons in the conduction band is increased and exceeds the concentration of holes in the valence band. Because of this, Fermi level shifts upwards towards the bottom of the conduction band as shown in Fig 1.16 (b) because the number of charge carriers has become more in conduction band than in valence band.

It is seen from the above description that in N-type semiconductors, electrons are the majority carriers while holes constitute the minority carriers. Hence, N-type semiconductor conducts principally by electrons in the nearly empty conduction band and the process is called 'excess' conduction.

## P-type Extrinsic Semiconductor

This type of semiconductor is obtained when traces of a trivalent like boron (B) are added to a pure germanium crystal.

In this case, the three valence electrons of boron atom form covalent bonds with four surrounding germanium atoms but one bond is left incomplete and gives rise to a hole as shown in Fig 1.17(a).

Thus, boron which is called an acceptor impurity causes as many positive holes in a germanium crystal as there are boron atoms thereby producing a P-type (P for positive) extrinsic semiconductor. As an aid to memory, the student should associate the P in acceptor with P in P-type material and P with Positive charge carrier.

In this type of semiconductor, conduction is by the movement of holes in the valence band. Accordingly, holes form the majority carriers whereas electrons constitute minority carriers. The process of conduction is called 'deficit' conduction.

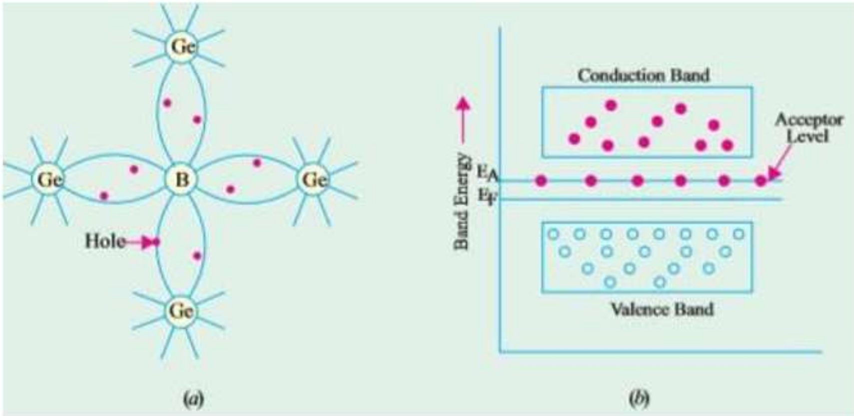



Fig 1.17(a)        Fig 1.17(b)

Since concentration of holes in the valence band is more than the concentration of electrons in the conduction band, Fermi level shifts nearer to the valence band Fig 1.17 (b). The acceptor level lies immediately above the Fermi level. Conduction is by means of hole movement at the top of valence band, acceptor level readily accepting electrons from the valence band.

Again, it may be noted that even though P-type semiconductor
r has excess of holes for conduction purposes, on the whole it is electrically neutral for the same reasons as given above.

## P-N Junction in Semiconductor

It is possible to manufacture a single piece of a semiconductor material half of which is doped by P-type impurity and the other half by N-type impurity as shown in Fig 1.18 The plane dividing the two zones is called junction.

Theoretically, junction plane is assumed to lie where the density of donors and acceptors is equal. The P-N junction is fundamental to the operation of diodes, transistors and other solid-state devices. Let us see if anything unusual happens at the junction. It is found that following three phenomena take place :

1. A thin depletion layer or region (also called space-charge region or transition region) is established on both sides of the junction and is so called because it is depleted of free charge carriers. Its thickness is about 10−6 m.
2. A barrier potential or junction potential is developed across the junction.
3. The presence of depletion layer gives rise to junction and diffusion capacitances

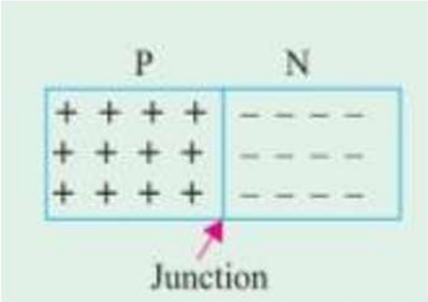



Fig 1.18

Development of a potential across a PN junction in unbiased, forward biased and reverse biased conditions

Even though depletion layer is cleared of charge carriers, it has oppositely-charged fixed rows of ions on its two sides. Because of this charge separation, an electric potential difference VB is established across the junction even when the junction is externally isolated Fig1.19 It is known as junction or barrier potential. It stops further flow of carriers across the junction unless supplied by energy from an external source. At room temperature of 300⁰K, VB is about 0.3 V for Ge and 0.7 V for Si.

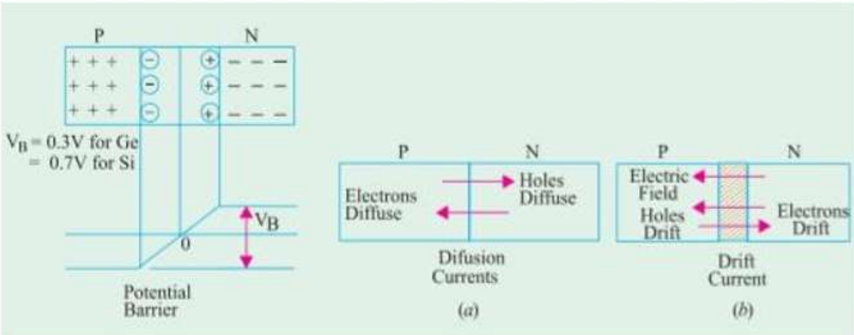



Fig 1.19

1. As soon as P-N junction is formed, free electrons and holes start diffusing across the junction and recombining.
2. Their recombination leads to the appearance of a depletion layer across the junction which contains no mobile carriers but only immobile ions.
3. These immobile ions set up a barrier potential and hence an electric field which sets up drift current that is equal and opposite to the diffusion current when final equilibrium is reached.

## Forward Biased P-N Junction

Suppose, positive battery terminal is connected to P-region of a semiconductor and the negative battery terminal to the N-region as shown in Fig 1.20 (a) In that case the junction is said to be biased in the forward direction because it permits easy flow of current across the junction.

As soon as battery connection is made, holes are repelled by the positive battery terminal and electrons by the negative battery terminal with the result that both the electrons and the holes are driven towards the junction where they recombine. This en masse movement of electrons to the left and that of holes to the right of the junction constitutes a large current flow through the semiconductor. Obviously, the junction offers low resistance in the forward direction.

## Forward Biased V/I Characteristic

A typical V/I characteristic for a forward biased P-N junction is shown in Fig 1.20 It is seen that forward current rises exponentially with the applied forward voltage. However, at ordinary room temperature, a p.d. of about 0.3 V is required before a reasonable amount of forward current starts flowing in a germanium junction. This voltage is known as threshold voltage (Vth) or cut-in voltage or knee voltage VK. It is practically the same as barrier voltage VB. Its value for silicon junction is about 0.7 volt. For V < Vth, current flow is negligible. But as applied voltage increases beyond the threshold value, the forward current increases sharply. If forward voltage is increased beyond a certain safe value, it will produce an extremely large current which may destroy the junction due to overheating. Ge devices can stand junction temperatures around 100ºC whereas Si units can function upto 175ºC.

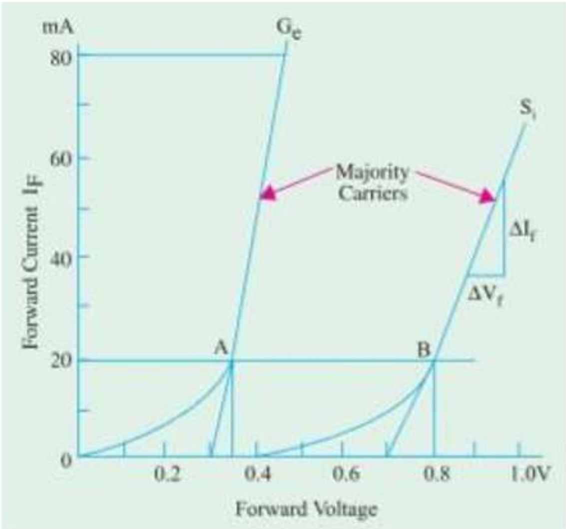



Fig 1.20

## Reverse Biased P-N Junction

When battery connections to the semiconductor are made as shown in Fig 1.21 (a) the junction is said to reverse-biased. In this case, holes are attracted by the negative battery terminal and electrons by the positive terminal so that both holes and electrons move away from the junction and away from each other. Since there is no electron-hole combination, no current flows and the junction offers high resistance.

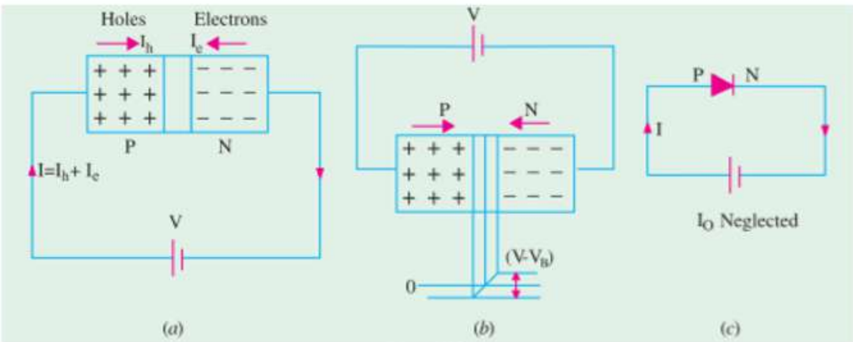



Fig 1.22(a) Fig 1.22(b) Fig 1.22(c)

Incidentally, it may be noted that under reverse bias condition, width of depletion layer is increased because of increased barrier potential.

Although, in this case, there is practically no current due to majority carriers, yet there is a small amount of current (a few µA only) due to the flow of minority carriers across the junction.Due to thermal energy, there are always generated some holes in the N-type region and some electrons in the P-type region of the semiconductor. The battery drives these minority carriers across the junction thereby producing a small current called reverse current or reverse saturation current I0 or IS.

## Reverse V/I Characteristic

As said earlier, the reverse saturation current is also referred to as leakage current of the P-N junction. Fig 1.23 shows V/I characteristics of a reverse-biased P-N junction. It is seen that as reverse voltage is increased from zero, the reverse current quickly rises to its maximum or saturation value. Keeping temperature constant as the reverse voltage is increased, Io is found to increase only slightly. This slight increase is due to the impurities on the surface of the semiconductor which behaves as a resistor and hence obeys Ohm's law. This gives rise to a very small current called surface leakage current.

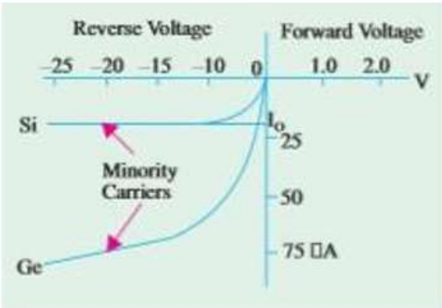



Fig 1.23

## Diode parameters

While discussing the diode circuits, the reader will generally come across the following terms :

(i) Maximum Forward current

It is the current flowing through a forward biased diode. Every diode has a maximum value of forward current which it can safely carry. If this value is exceeded, the diode may be destroyed due to excessive heat. For this reason, the manufacturers' data sheet specifies the maximum forward current that a diode can handle safely.

(ii) Peak inverse voltage

It is the maximum reverse voltage that a diode can withstand without destroying the junction. If the reverse voltage across a diode exceeds this value, the reverse current increases sharply and breaks down the junction due to excessive heat. Peak inverse voltage is extremely important when diode is used as a rectifier. In rectifier service, it has to be ensured that reverse voltage across the diode does not exceed its PIV during the negative half-cycle of input a.c. voltage. As a matter of fact, PIV consideration is generally the deciding factor in diode rectifier circuits. The peak inverse voltage may be between 10V and 10 kV depending upon the type of diode.

(iii) Reverse current or leakage current

It is the current that flows through a reverse biased diode. This current is due to the minority carriers. Under normal operating voltages, the reverse current is quite small. Its value is extremely small (< 1μ A) for silicon diodes but it is appreciable (j 100 μA) for germanium diodes.

(iv) Maximum power dissipation

It is the maximum power that can be dissipated at the junction without damaging it. The power dissipated at the junction is equal to the product of junction current and the voltage across the junction. This is a very important consideration and is invariably specified by the manufacturer in the data sheet.

Every pn junction has limiting values of maximum forward current, peak inverse voltage and maximum power rating. The pn junction will give satisfactory performance if it is operated within these limiting values. However, if these values are exceeded, the pn junction may be destroyed due to excessive heat.

## Operation and function of diodes in Clippers and Clampers

These are diode waveshaping circuits i.e. circuits meant to control the shape of the voltage and current waveforms to suit various purposes. Each performs the waveshaping function indicated by itsname. The output of the clipping circuit appears as if a portion of the input signal were clipped off. But clamper circuits simply clams(i.e. lift up or down) the input signal to a different dc level.

### Clippers

A clipping circuit requires a minimum of two components i.e. a diode and a resistor. Often, dc battery is also used to fix the clipping level. The input waveform can be clipped at different levels by simply changing the battery voltage and by interchanging the position of various elements. We will use an ideal diode which acts like a closed switch when forward-biased and as an open switch when reverse-biased. Such circuit are used in radars and digital computers etc. when it is desired to remove signal voltages above or below a specified voltage level. Another application is in radio receivers for communication circuits where noise pulses that rise well above the signal amplitude are clipped down to the desired level.

When positive half-cycle of the signal voltage is applied to the clipper i.e. when A is positive with respect to B, the diode D is reverse-biased. Hence, it acts as an open switch. Consequently, the entire input voltage appears across it.

During the negative half-cycle of the signal voltage when circuit terminal B becomes positive with respect to A, the diode is forward-biased. Hence, it acts like a closed switch (or short) across which no voltage is dropped. Hence, the waveshape of V0 is as shown in Fig 1.28 It is seen that the negative portion of the signal voltage has been removed. Hence, such a circuit is called a negative clipper.

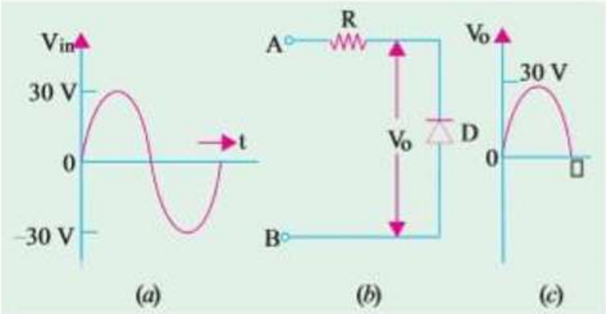



Fig 1.28

When Diode and Resistor are Interchanged

In this case, the circuit becomes as shown in Fig.1.29 Now, the output voltage V0 is that which is dropped across R. During the positive half-cycle of the signal voltage, D acts as an open switch. Hence, all applied voltage drops across D and none across R. So, there is no output signal voltage. During the negative input halfcycle, terminal B is positive and so it is forward-biases B which acts as a short. Hence, there is no voltage drop across D. Consequently, all the applied signal voltage drops across R and none across D. As a result, the negative half-cycle of the input signal is allowed to pass through the clipper circuit. Obviously, now the circuit acts as a positive clipper.

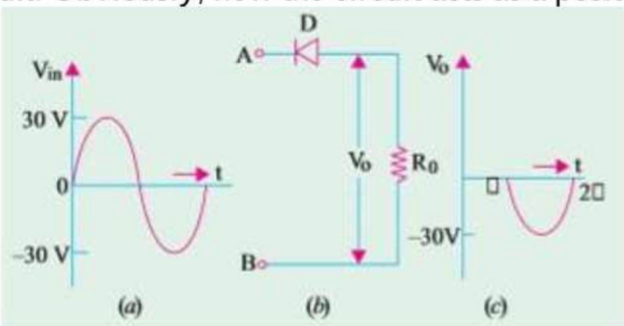



Fig.1.29

## Clampers

To put it simply, clamping is the process of introducing a dc level into an ac signal. Clampers are also sometimes known as dc restorers. By way of illustration, consider the signal shown in Fig. 1.30(a) It is a sine wave with equal positive and negative swings of ± 5 V about 0 V. Hence, its average value over one cycle is zero (it has no dc level).

In Fig 1.30(b) the signal waveform has been lifted up so as to just touch the horizontal axis. It is now said to have acquired a dc level of 5 V. This output wave-form is said to be positively clamped at 0 V. Fig1.30 (c) shows an output waveform which is negatively clamped at 0 V.

A circuit capable of accepting the input signal shown in Fig 1.30 (a) and delivering the output shown in Fig 1.30 (b) or (c) is called a clamper. Such a circuit has a minimum requirement of three elements.

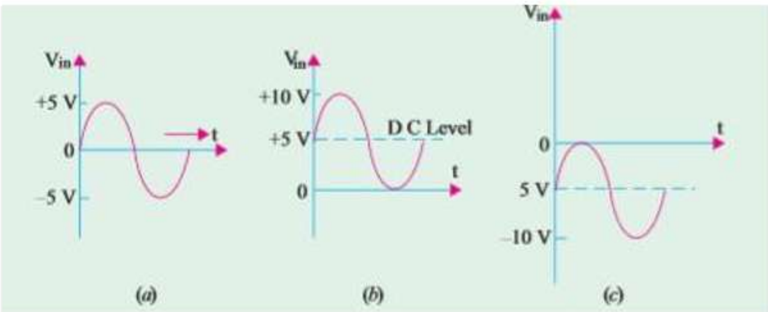


Fig1.30(a) Fig1.30(a) Fig1.30(a)

## Voltage doublers and triplers

With a diode, we can build a rectifier to produce a d.c voltage that is nearly equal to the peak value of input a.c voltage. We can also use diodes and capacitors to build a circuit that will provide a d.c output that is multiple of the peak input a.c. voltage. Such a circuit is called a voltage multiplier. For example, a voltage doubler will provide a d.c output that is twice the peak input a.c voltage, a voltage tripler will provide a d.c output that is three times the peak input a.c voltage and so on.

## Half-Wave Voltage Doubler

A half-wave voltage doubler consists of two diodes and two capacitors connected in a manner as shown in Fig 1.31 It will be shown that if the peak input a.c. voltage is VS(pk), the d.c. output voltage will be 2 VS (pk) provided the diodes are ideal (this assumption is fairly reasonable). The basic idea in a voltage multiplier is to charge each capacitor to the peak input a.c. voltage and to arrange the capacitors so that their stored voltages will add.

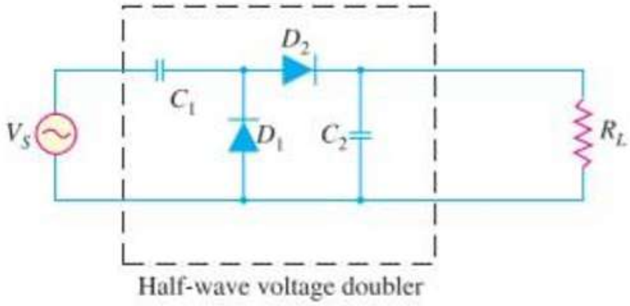



Fig 1.31

For reasons associated with economics of generation and transmission, the electric power available is usually an a.c supply. The supply voltage varies sinu-soidally and has a frequency of 50 Hz. It is used for lighting, heating and electric motors. But there are many applications (e.g. electronic circuits) where d.c supply is needed. When such a d.c supply is required, the mains a.c. supply is rectified by using crystal diodes. The following two rectifier circuits can be used :

(i) Half-wave rectifier
(ii) Full-wave rectifier

## Half-Wave Rectifier

In half-wave rectification, the rectifier conducts current only during the positive half-cycles of input a.c. supply. Thenegative half-cycles of a.c. supply are suppressed i.e. during negative half-cycles, no current is conducted and hence no voltage appears across the load. Therefore, current always flows in one direction (i.e. d.c.) through the load though after every half-cycle as shown in Fig 1.32(a)

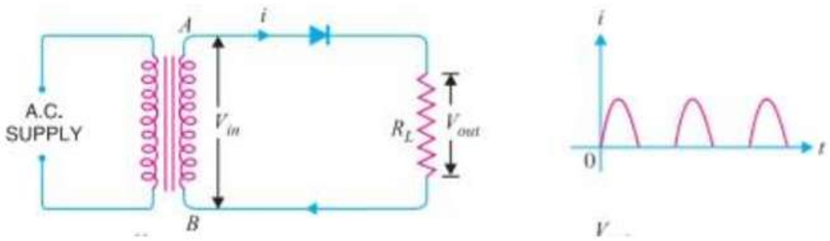



Fig 1.32(a)

## Full-Wave Rectifier

In full-wave rectification, current flows through the load in the same direction for both half-cycles of input a.c voltage. This can be achieved with two diodes working alternately. For the positive halfcycle of input voltage, one diode supplies current to the load and for the negative half-cycle, the other diode does so ; current being always in the same direction through the load. Therefore, a full-wave rectifier utilizes both half-cycles of input a.c voltage to produce the d.c output . The following two circuits are commonly used for full-wave rectification.

(i) Centre-tap full-wave rectifier
(ii) Full-wave bridge rectifier

## Centre-Tap Full-Wave Rectifier

The circuit employs two diodes D1 and D2 as shown below. A centre tapped secondary winding AB is used with two diodes connected so that each uses one half-cycle of input a.c voltage. In other words, diode D1 utilizes the a.c voltage appearing across the upper half (OA) of secondary winding for rectification while diode D2 uses the lower half winding OB.

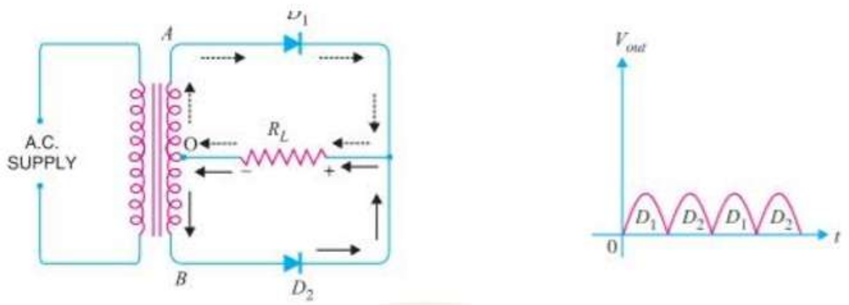



Fig 1.32 (b)

## Full-Wave Bridge Rectifier

The need for a centre tapped power transformer is eliminated in the bridge rectifier. It contains four diodes D1, D2, D3 and D4 connected to form bridge as shown in Fig 1.32 (c) The a.c. supply to be rectified is applied to the diagonally opposite ends of the bridge through the transformer. Between other two ends of the bridge, the load resistance RL is connected.

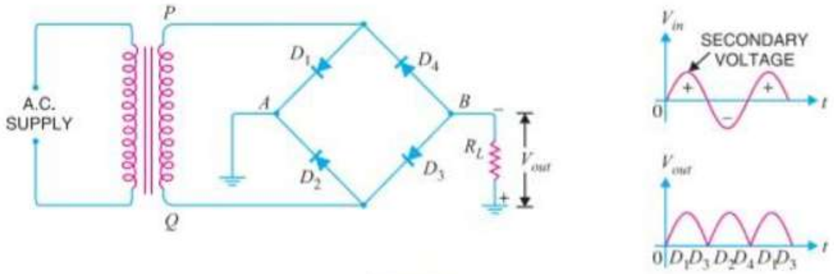



Fig 1.32 (c)

## Schottky Diode

It is also called Schottky barrier diode or hot-carrier diode. It is mainly used as a rectifier at signal frequencies exceeding 300 MHz.

It has more uniform junction region and is more rugged than PIN diode − its main rival.

### (a) Construction –

It is a metal-semiconductor junction diode with no depletion layer. It uses a metal (like gold, silver, platinum, tungsten etc.) on the side of the junction and usually an Ntype doped silicon semiconductor on the other side. The diode and its schematic symbol are shown in Fig 1.33

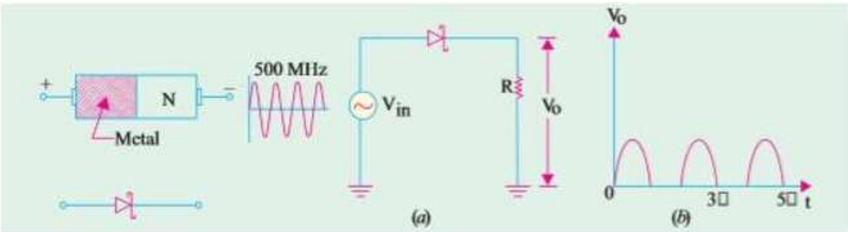



Fig 1.33 Fig 1.34 (a) Fig 1.34(b)

### (b) Operation

When the diode is unbiased, electrons on the N-side have lower energy levels than electrons in the metal. Hence, they cannot surmount the junction barrier (called Schottky barrier) for going over to the metal.

When the diode is forward-biased, conduction electrons on N-side gain enough energy to cross the junction and enter the metal. Since these electrons plunge into the metal with very large energy, they are commonly called 'hot-carriers'. That is why this diode is often referred to as hot-carrier diode.

### (c) Applications

This diode possesses two unique features as compared to an ordinary P-N junction diode :

1. it is a unipolar device because it has electrons as majority carriers on both sides of the junction. An ordinary P-N junction diode is a bipolar device because it has both electrons and holes as majority carriers;
2. since no holes are available in metal, there is no depletion layer or stored charges to worry about. Hence, Schottky diode can switch OFF faster than a bipolar diode.
Because of these qualities, Schottky diode can easily rectify signals of frequencies exceeding 300 MHz. As shown in Fig 1.34(b), it can produce an almost perfect half-wave rectified output.
The present maximum current rating of the device is about 100A. It is commonly used in switching power supplies that operate at frequencies of 20 GHz. Another big advantage of this diode is its low noise figure which is extremely important in communication receivers and radar units etc.
It is also used in clipping and clamping circuits, computer gating, mixing and detecting networks used is communication systems.

## Varactor Diode

The varactor diode is a semiconductor, voltage-dependent variable capacitor alternatively known as varicap or voltacap or voltage-variable capacitor (VVC) diode. Basically, it is just a reverse-biased junction diode whose mode of operation depends on its transition capacitance (CT).Reverse-biased junctions behave like capacitors whose capacitance is ∝ 1/VRn where n varies from 1/3 to 1/2. As reverse voltage VR is increased, depletion layer widens thereby decreasing the junction capacitance. Hence, we can change diode capacitance by simply changing VR. Silicon diodes which are optimized for this variable capacitance effect are called varactors.
The picture, schematic symbol and a simple equivalent circuit for a varactor are shown in Fig 1.35

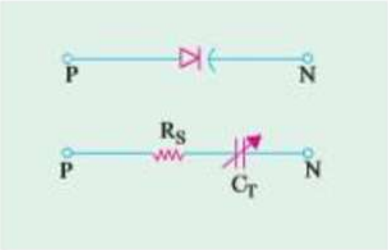



Fig 1.35

Applications Since the junction capacitance of a varactor is in the pF range, it is suitable for use in highfrequency circuits. Its main applications are as
1. automatic frequency control device
2. FM modulator
3. adjustable band-pass filter
4. Parametric amplifier.

## Zener Diode

It has already been discussed that when the reverse bias on a crystal diode is increased, a critical voltage, called breakdown voltage is reached where the reverse current increases sharply to a high value. The breakdown region is the knee of the reverse characteristic as shown in Fig 1.37.The satisfactory explanation of this breakdown of the junction was first given by the American scientist C.

Zener.Therefore, the breakdown voltage is sometimes called zener voltage and the sudden increase in current is known as zener current.

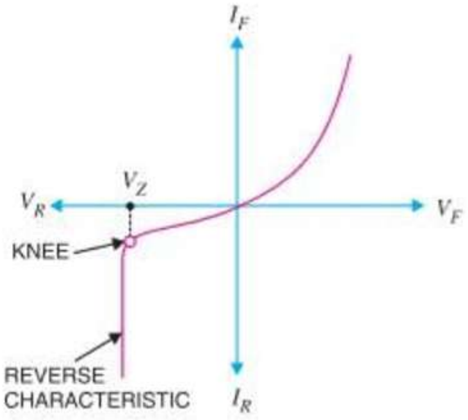



Fig 1.37

The breakdown or zener voltage depends upon the amount of doping. If the diode is heavily doped, depletion layer will be thin and consequently the breakdown of the junction will occur at a lower reverse voltage. On the other hand, a lightly doped diode has a higher breakdown voltage. When an ordinary crystal diode is properly doped so that it has a sharp breakdown voltage, it is calleda zener diode.

A properly doped crystal diode which has a sharp breakdown voltage is known as a zener diode.

Fig 1.38 shows the symbol of a zener diode. It may be seen that it is just like an ordinary diode except that the bar is turned into z-shape.

Fig 1.38

The following points may be noted about the zener diode:

(i) A zener diode is like an ordinary diode except that it is properly doped so as to have a sharp breakdown voltage.

(ii) A zener diode is always reverse connected i.e. it is always reverse biased.

(iii) A zener diode has sharp breakdown voltage, called zener voltage VZ.

(iv) When forward biased, its characteristics are just those of ordinary diode.

(v) The zener diode is not immediately burnt just because it has entered the *breakdown region. As long as the external circuit connected to the diode limits the diode current to less than burn out value, the diode will not burn out

## SUMMARY

Even though the basic semiconductor diode may appear to have limited applications, it finds uses in a great variety of applications. Specialized versions of the diode are used for particular applications. The light emitting diode (LED) and photodiode are but two examples. However the PN junction is also the basis of the bipolar junction transistor, and the junction FET. There are also many other examples of its use. As a result many billions of the semiconductor diodes are manufactured each year, and it is the most fundamental structure to today's semiconductor electronics scene.

In electronics, a diode is a two-terminal electronic component with asymmetric conductance; it has low (ideally zero) resistance to current in one direction, and high (ideally infinite) resistance in the other. A semiconductor diode, the most common type today, is a crystalline piece of semiconductor material with a p–n junction connected to two electrical terminals. A vacuum tube diode has two electrodes, a plate (anode) and a heated cathode. Semiconductor diodes were the first semiconductor electronic devices today, most diodes are made of silicon, but other semiconductors such as selenium or germanium are sometimes used.

The most common function of a diode is to allow an electric current to pass in one direction called the diode's forward direction, while blocking current in the opposite direction called the reverse direction. This unidirectional behavior is called rectification, and is used to convert alternating current to direct current, including extraction of modulation from radio signals in radio receivers—these diodes are forms of rectifiers.

However, diodes can have more complicated behavior than this simple on–off action, due to their nonlinear current-voltage characteristics. Semiconductor diodes begin conducting electricity only if a certain threshold voltage or cut-in voltage is present in the forward direction (a state in which the diode is said to be forward-biased). The voltage drop across a forward-biased diode varies only a little with the current, and is a function of temperature; this effect can be used as a temperature sensor or voltage reference.

Semiconductor diodes' current–voltage characteristic can be tailored by varying the semiconductor materials and doping, introducing impurities into the materials. These techniques are used to create special-purpose diodes that perform many different functions. For example, diodes are used to regulate voltage (Zener diodes), to protect circuits from high voltage surges (avalanche diodes), to electronically tune radio and TV receivers (varactor diodes), to generate radio frequency oscillations (tunnel diodes, Gunn diodes, IMPATT diodes), and to produce light (light emitting diodes). Tunnel, Gunn and IMPATT diodes exhibit negative resistance, which is useful in microwave applications.

## 4.1.2: Transistors

When a third doped element is added to a crystal diode in such a way that two pn junctions are formed, the resulting device is known as a transistor. The transistor—an entirely new type of electronic device—is capable of achieving amplification of weak signals in a fashion comparable and often superior to that realised by vacuum tubes. Transistors are far smaller than vacuum tubes, have no filament and hence need no heating power and may be operated in any position. They are mechanically strong, have practically unlimited life and can do some jobs better than vacuum tubes.

### Transistor

A transistor consists of two pn junctions formed by *sandwiching either p-type or n-type semiconductor between a pair of opposite types. Accordingly ; there are two types of transistors, namely;

(i) n-p-n transistor
(ii) p-n-p transistor

An n-p-n transistor is composed of two n-type semiconductors separated by a thin section of ptype as shown in Fig 2.1(a) However, a p-n-p transistor is formed by two p-sections separated by a thin section of n-type as shown in Fig 2.1 (b)

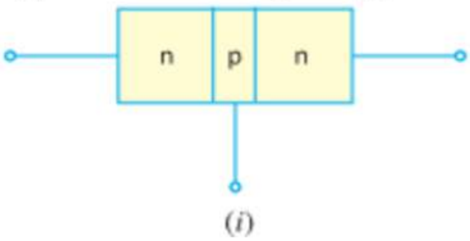



Fig 2.1(a)

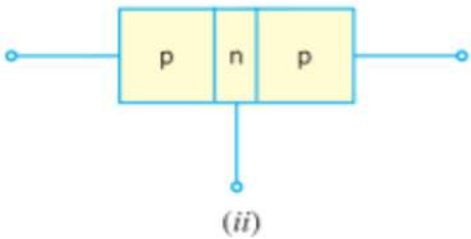



Fig 2.1(b)

In each type of transistor, the following points may be noted :

(i) These are two pn junctions. Therefore, a transistor may be regarded as a combination of two diodes connected back to back.
(ii) There are three terminals, one taken from each type of semiconductor.
(iii) The middle section is a very thin layer. This is the most important factor in the function of a transistor.

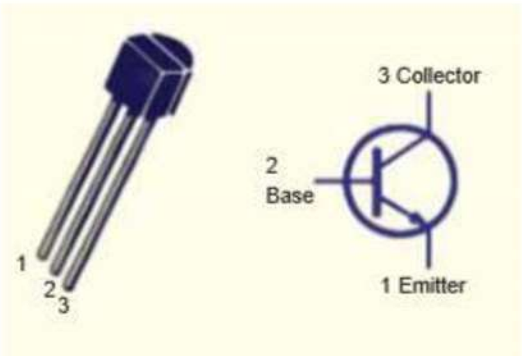



Fig. 2.2

A transistor is a three-terminal semiconductor device that can perform two functions that are fundamental to the design of electronic circuits: amplification and switching. Put simply, amplification consists of magnifying a signal by transferring energy to it from an external source, whereas a transistor switch is a device for controlling a relatively large current between or voltage across two terminals by means of a small control current or voltage applied at a third terminal.

Origin of the name "Transistor". When new devices are invented, scientists often try to devise a name that will appropriately describe the device. A transistor has two pn junctions. As discussed later, one junction is forward biased and the other is reverse biased. The forward biased junction has a low resistance path whereas a reverse biased junction has a high resistance path. The weak signal is introduced in the low resistance circuit and output is taken from the high resistance circuit. Therefore, a transistor transfers a signal from a low resistance to high resistance. The prefix 'trans' means the signal transfer property of the device while 'istor' classifies it as a solid element in the same general family with resistors.

A transistor (pnp or npn) has three sections of doped semiconductors. The section on one side is the emitter and the section on the opposite side is the collector. The middle section is called the base and forms two junctions between the emitter and collector.

### (i) Emitter

The section on one side that supplies charge carriers (electrons or holes) is called the emitter. The emitter is always forward biased w.r.t. base so that it can supply a large number of *majority carriers. In Fig 2.3(a), the emitter (p-type) of pnp transistor is forward biased and supplies hole charges to its junction with the base. Similarly, in Fig 2.3 (b), the emitter (n-type) of npn transistor has a forward bias and supplies free electrons to its junction with the base.

### (ii) Collector

The section on the other side that collects the charges is called the collector. The collector is always reverse biased. Its function is to remove charges from its junction with the base. In Fig 2.3 (a), the collector (p-type) of pnp transistor has a reverse bias and receives hole charges that flow in the output circuit. Similarly, in Fig. 2.3 (b), the collector (n-type) of npn transistor has reverse bias and receives electrons.

### (iii) Base

The middle section which forms two pn-junctions between the emitter and collector is called the base. The base-emitter junction is forward biased, allowing low resistance for the emitter circuit. The base-collector junction is reverse biased and provides high resistance in the collector circuit.

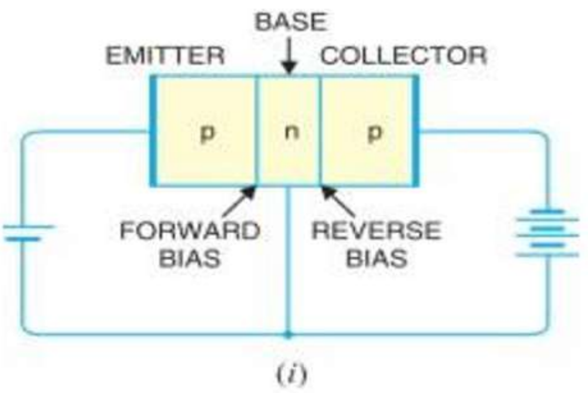



Fig 2.3(a)

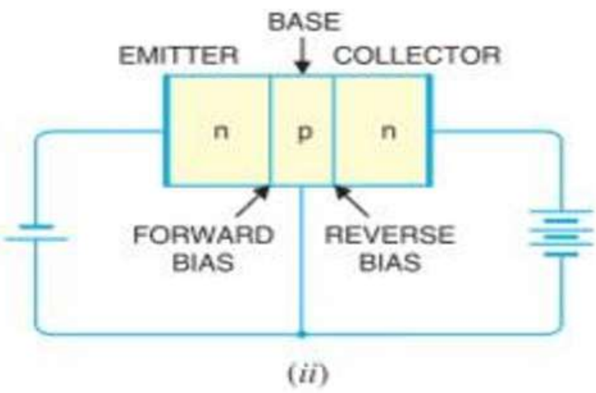



Fig 2.3(b)

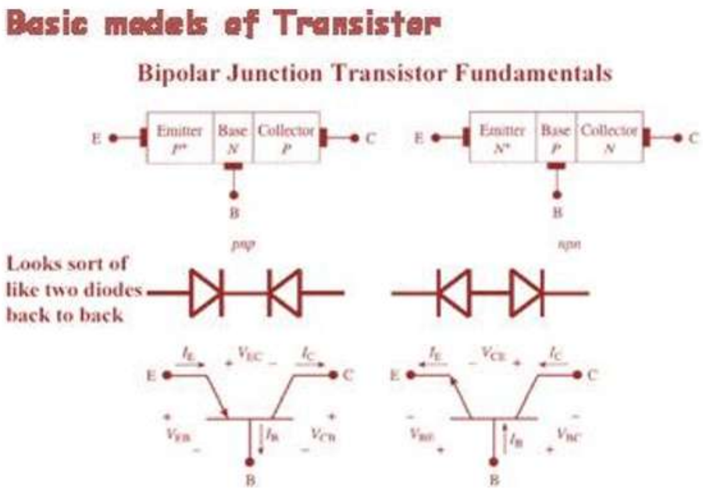



Fig 2.4

There are two main types of transistors: Field-Effect Transistors and Bipolar Junction Transistors. The origin of the term “transistor” will be clear once you understand BJTs.

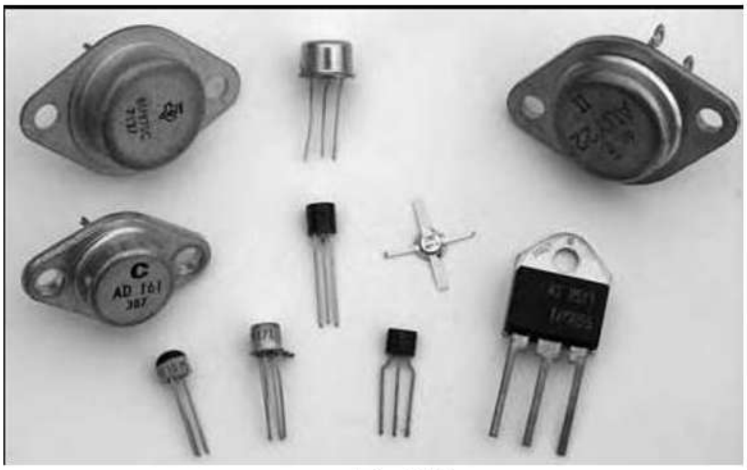



Fig 2.5

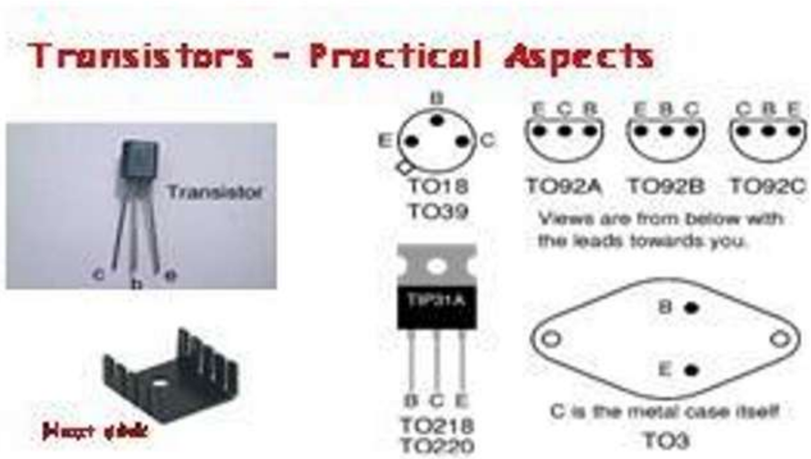



Fig 2.6

## Transistor Symbols

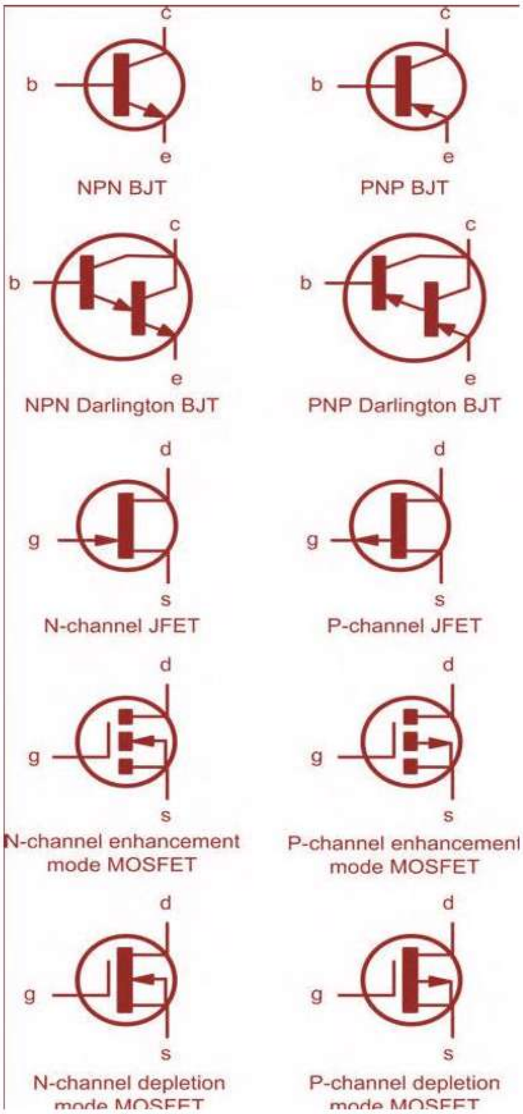



Fig 2.7:Transistor symbols

## Transistor classification

Transistors fall into two main classes (bipolar and field effect). They are also classified according to the semiconductor material employed (Si or Ge) and to their field of application (e.g. general purpose, switching, high frequency, etc.)

## 2.3. Bipolar Junction Transistor

A BJT is formed by joining three sections of semiconductor material, each with a different doping concentration. The three sections can be either a thin n region sandwiched between p+ and p layers, or a p region between n and n+ layers, where the superscript plus indicates more heavily doped material. The resulting BJTs are called pnp and npn transistors, respectively; we discuss only the latter in this document. Figure 12 illustrates the approximate construction, symbols and nomenclature for the two types of BJTs.

## 2.4. Transistor Characteristic and properties

### a. CHARACTERISTIC AND PROPERTIES

The characteristics of a BJT are usually presented in the form of a set of graphs relating voltage and current present at the transistors terminals. Figure 2.8show a typical input characteristic (IB plotted against VBE) for an NPN BJT operating in common-emitter mode. In this mode, the input current is applied to the base and the output current appears in the collector (the emitter is effectively common to both the input and output circuits).

The input characteristic shows that very little base current flows until the base–emitter voltage VBE exceeds 0.6 V. Thereafter, the base current increases rapidly (this characteristic bears a close resemblance to the forward part of the characteristic for a Si diode). Fig 2.9 shows a typical set of output (collector) characteristics (IC plotted against VCE) for an NPN bipolar transistor. Each curve corresponds to a different value of base current. Note the "knee" in the characteristic below VCE =2 V. Also note that the curves are quite flat. For this reason (i.e. since the collector current does not change very much as the collector– emitter voltage changes) we often refer to this as a constant current characteristic. Figure 2.10 shows a typical transfer characteristic for an NPN BJT. Here IC is plotted against IB for a small-signal general-purpose transistor. The slope of this curve (i.e. the ratio of IC to IB) is the common-emitter current gain of the transistor.

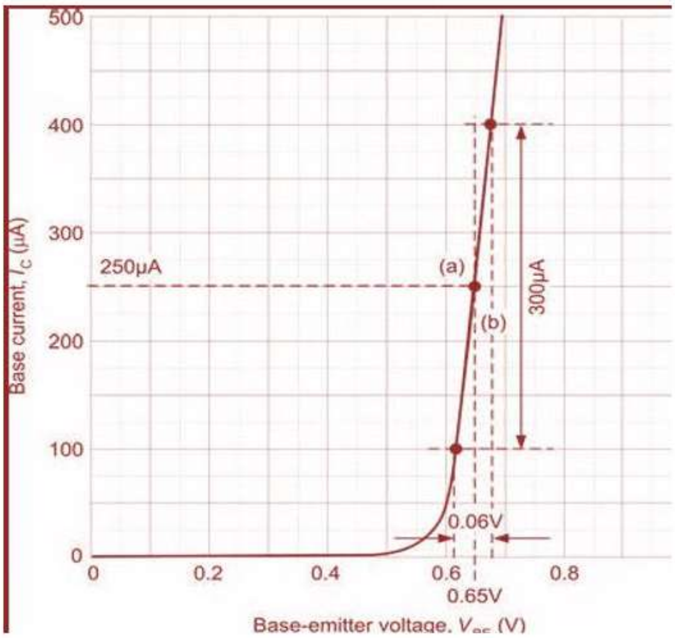



Fig. 2.8 : Input Characteristic for an NPN BJTFig. 2.9 : Output characteristic for an NPN BJT

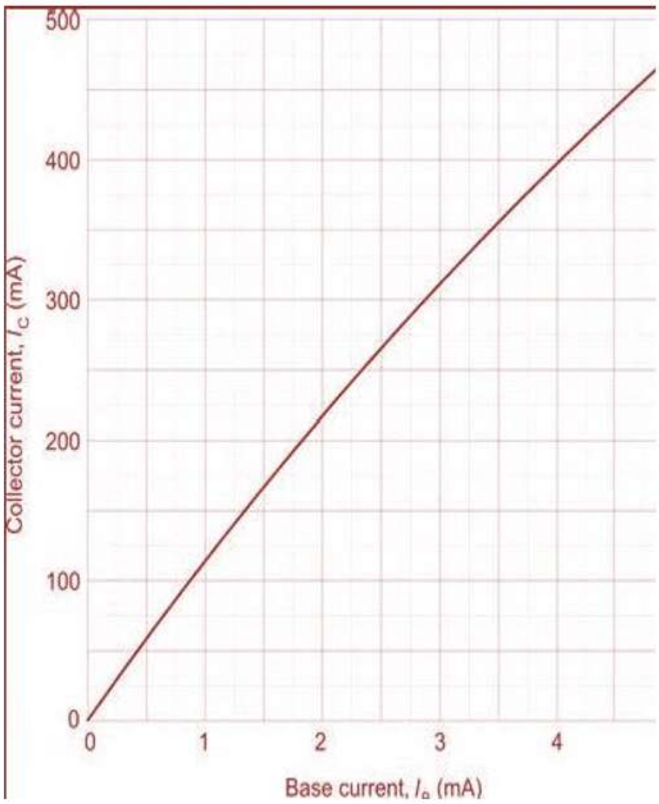



Fig.2.10 :Transfer characteristic

## b. TRANSISTOR PARAMETER

The transistor characteristics that we met in the previous section provide us with some useful information that can help us to model the behavior of a transistor. In particular, we can use the three characteristic graphs to determine the following parameters:

- INPUT RESISTANCE (FROM THE INPUT CHARACTERISTIC)

  Static (or DC) input resistance= VBE/IB (from corresponding points on the graph)

  Dynamic (or AC) input resistance= VBE/_IB (from the slope of the graph)

  (Note that _VBE means "change of VBE" and IB means "change of IB")

- OUTPUT RESISTANCE (FROM THE OUTPUT CHARACTERISTIC)

  Static (or DC) output resistance= VCEIC (from corresponding points on the graph)

Dynamic (or AC) output resistance= VCE/IC (from the slope of the graph)

(Note that _VCE means "change of VCE" and IC means "change of IC")

- CURRENT GAIN (FROM THE TRANSFER CHARACTERISTIC)

Static (or DC) current gain=IC/IB (from corresponding points on the graph)

Dynamic (or AC) current gain=IC/IB (from the slope of the graph)

## 2.5. CONSTRUCTION OF NPN AND PNP TRANSISTOR

Conventional bipolar junction transistors (BJT) generally comprise NPN or PNP junctions of either silicon (Si) or germanium (Ge) material. The junctions are produced in a single slice of silicon by diffusing impurities through a photographically reduced mask. Silicon transistors are superior when compared with germanium transistors in the vast majority of applications (particularly at high temperatures) and thus germanium devices are very rarely encountered in modern electronic equipment. The construction of typical NPN and PNP BJT are shown in Figs 2.11 and 2.22. In order to conduct the heat away from the junction (important in medium and high-power applications) the collector is often connected to the metal case of the transistor. The symbols and simplified junction models for NPN and PNP transistors are shown in Fig. 2.13. It is important to note that the base region (P-type material in the case of an NPN transistor or N-type material in the case of a PNP transistor) is extremely narrow.

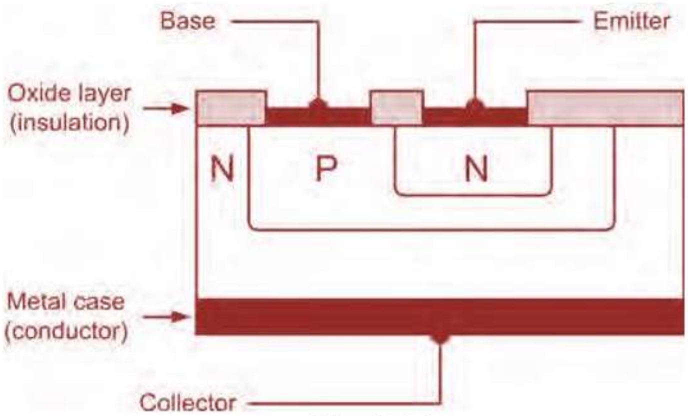
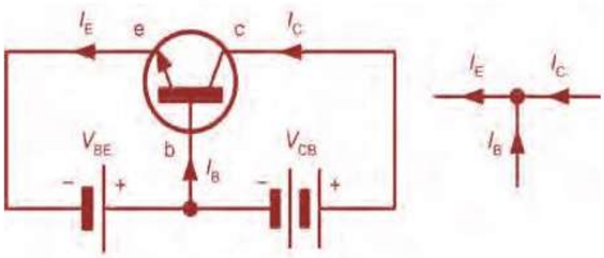
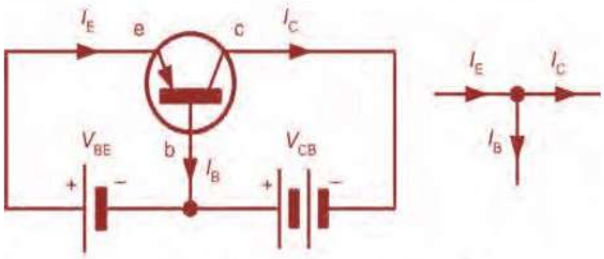



Fig. 2.11

Fig. 2.12




(a) NPN bipolar junction transistor (BJT)




(b) PNP bipolar junction transistor (BJT)

## 2.6. OPERATION OF NPN AND PNP TRANSISTORS

Operation of a pnptransistor is analogous to that of a npntransistor except that the role of charge carries reversed. In NPNtransistors, electron flow is dominant while pnptransistors rely mostly on the flow of "holes" Therefore, to zeroth order, npnand pnptransistors behave similarly except the sign of current and voltages are reversed. i.e., pnp = -npn. In practice, npntransistors are much more popular than pnptransistors because electrons move faster in a semiconductor. As a result, annpntransistor has a faster response time compared to a pnptransistor. The operation of the npnBJT may be explained by considering the transistor as consisting of two back-to-back pnjunctions. The base-emitter (BE) junction acts very much as a diode when it is forward-biased; thus, one can picture the corresponding flow of hole and electron currents from base to emitter when the collector is open and the BE junction is forward-biased, as depicted in Figure 18. Some of the electron-hole pairs in the base will recombine; the remaining charge carriers will give rise to a net flow of current from base to emitter. It is also important to observe that the base is much narrower than the emitter section of the transistor

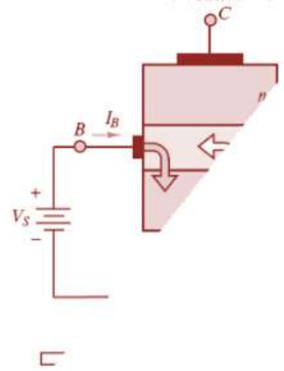



Fig. 2.14

Imagine, now, reverse-biasing the base-collector (BC) junction. In this case, an interesting phenomenon takes place: the electrons "emitted" by the emitter with the BE junction forward-biased reach the very narrow base region, and after a few are lost to recombination in the base, most of these electrons are "collected" by the collector. Figure 19 illustrates how the reverse bias across the BC junction is in such a direction as to sweep the electrons from the emitter into the collector. This phenomenon can take place because the base region is kept particularly narrow. Since the base is narrow, there is a high probability that the electrons will have gathered enough momentum from the electric field to cross the reverse-biased collector-base junction and make it into the collector. The result is that there is a net flow of current from collector to emitter (opposite in direction to the flow of electrons), in addition to the hole current from base to emitter. The electron current flowing into the collector through the base is substantially larger than that which flows into the base from the external circuit.

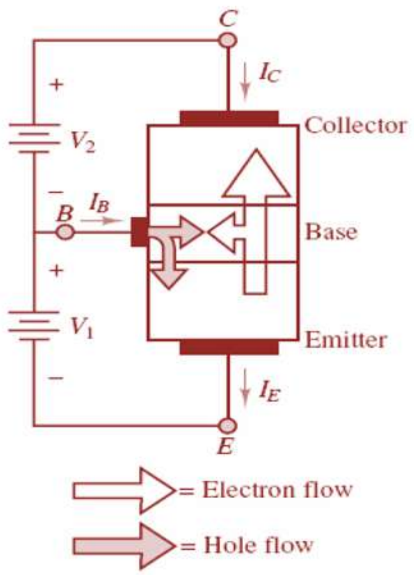



Fig 2.15

One can see from figure Fig. 2.16 that if KCL is to be satisfied, we must have:

$I_E = I_B + I_C$

The most important property of the BJT is that the small base current controls the much larger collector current.

$IC = \beta I_B$

Here b is a current amplification factor dependent on the physical properties of the BJT. Typical values of b range from 20 to 200. Note that b is not a parameter you want to design your circuit around. In other words, you want to make your BJT circuit amplify independent of b, we will learn how later. The number of independent variables required to uniquely define the operation of the transistor may be determined by applying KVL and KCL to the circuit of Fig 2.16. Two voltages and two currents are sufficient to specify the operation of the device. Note that since the BJT is a three-terminal device, it will not be sufficient to deal with a single i–v characteristic; two such characteristics are required to explain the operation of this device. One of these characteristics relates the base current, iBto the base-emitter voltage vBE; the other relates the collector current iCto the collector-emitter voltage vCE. The latter characteristic actually consists of a family of curves. To determine these I-V characteristics, consider the I-V curves of Fig 2.17 and 2.18, using the circuit notation of Figure, the collector is open and the BE junction is shown to be very similar to a diode. The ideal current source IBB injects a base current, which causes the junction to be forward-biased. By varying IBB, one can obtain the open-collector BE junction I-V curve shown in the figure.

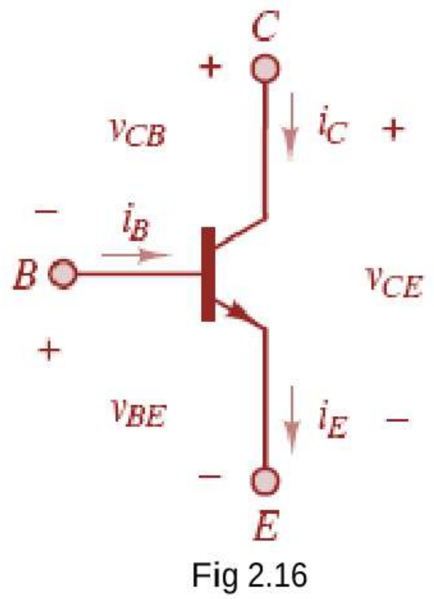



Fig 2.16

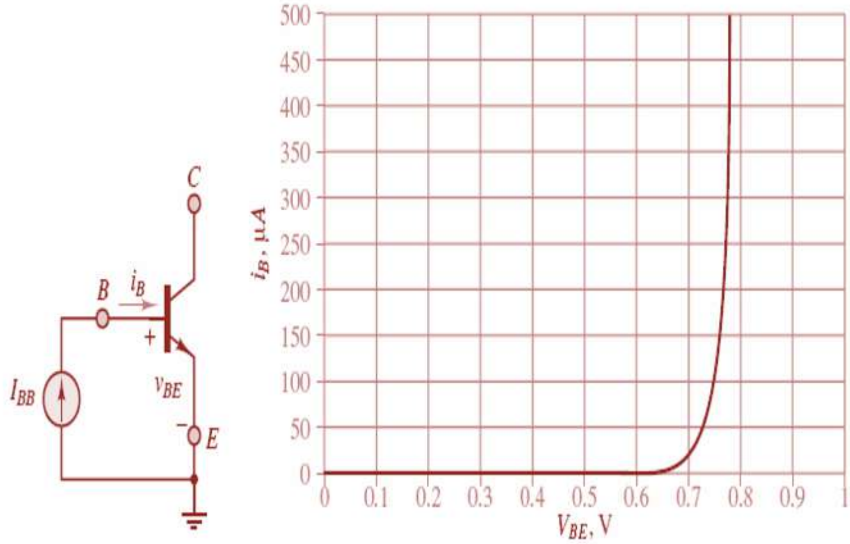



Fig.2.17

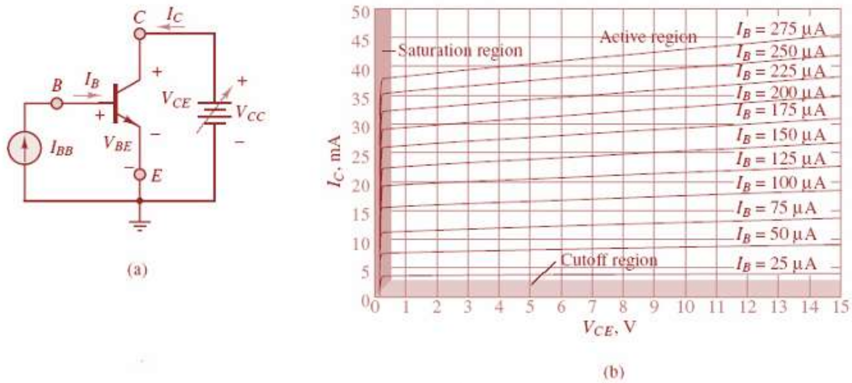



Fig 2.18

If a voltage source were now to be connected to the collector circuit, the voltage vCE and, therefore, the collector current iC could be varied, in addition to the base current iB. The resulting circuit is depicted in Figure (a). By varying both the base current and the collector-emitter voltage, one could then generate a plot of the device collector characteristic. This is also shown in Figure (b). Note that this figure depicts not just a single iC-vCE curve, but an entire family, since for each value of the base current iB, an iCvCE curve can be generated. We identify three operating regions in the collector characteristic:

- The cutoff region where both junctions are reverse-biased, the base current is very small, essentially no collector current flows and the transistor is off.

- The saturation region, in which both junctions are forward biased.

- The active linear region, in which the transistor can act as a linear amplifier where the BE junction is forward-biased and the CB junction is reverse-biased.

## 2.7. TRANSISTOR OPERATING CONFIGURATIONS

(BASE,COLLECTOR AND EMITTER CONFIGURATIONS)

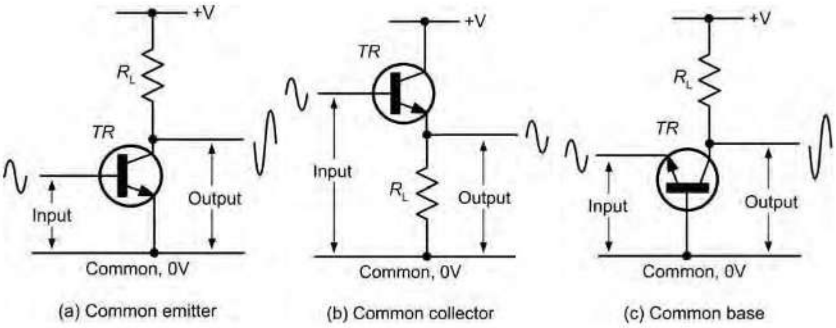



Fig. 2.19 transistor configuration

Three basic circuit arrangements are used for transistor amplifiers and these are based on the three circuit configurations that we met earlier (i.e. they depend upon which one of the three transistor connections is made common to both the input and the output). In the case of bipolar transistors, the configurations are known as common emitter, common collector (or emitter follower) and common base. Where field effect transistors are used, the corresponding configurations are common source, common drain (or source follower) and common gate. These basic circuit configurations depicted in Fig 2.19 exhibit quite different performance characteristics, as shown in the table below.

| Parameter | Common Emitter | Common Collector | Common Base |
|---|---|---|---|
| Voltage gain | medium/high (40) | unity (1) | high (200) |
| Current gain | high (200) | high (200) | unity (1) |
| Power gain | very high (8000) | high (200) | high (200) |
| Input resistance | medium (2.5 k Ω) | high (100 k Ω) | low (200 Ω) |
| Output resistance | medium/high (20 k Ω ) | low (100 Ω ) | high (100 k |
| Phase shift | 180° | 0° | 0° |

A requirement of most amplifiers is that the output signal should be a faithful copy of the input signal or be somewhat larger in amplitude. Other types of amplifier are 'non-linear', in which case their input and output waveforms will not necessarily be similar. In practice, the degree of linearity provided by an amplifier can be affected by a number of factors including the amount of bias applied and the amplitude of the input signal. It is also worth noting that a linear amplifier will become non-linear when the applied input signal exceeds a threshold value. Beyond this value the amplifier is said to be overdriven and the output will become increasingly distorted if the input signal is further increased. The optimum value of bias for linear (Class A) amplifiers is that value which ensures that the active devices are operated at the mid-point of their characteristics. In practice, this means that a static value of collector current will flow even when there is no signal present. Furthermore, the collector current will flow throughout the complete cycle of an input signal (i.e. conduction will take place over an angle of 360 °). At no stage should the transistor be saturated (VCE _ 0 V or VDS _ 0 V) nor should it be cut-off (VCE _ VCC or VDS _ VDD). In order to ensure that a static value of collector current flows in a transistor, a small bias current must be applied to the base of the transistor. This current is usually derived from the same voltage rail that supplies the collector circuit via one or more resistors of appropriate value.

## CURRENT GAIN

In general terms, current gain is the ratio of output current to input current. When a transistor is operating in common emitter mode the input current appears at the base and the output current at the collector. Thus, for this mode of operation the current gain will simply be the ratio of collector current, IC, to base current, IB. We use the symbol hFE to represent the static value of current gain when a transistor is connected in common emitter mode. Thus:

$$H(FE) = IC / IB$$

Typical values of common emitter current gain vary from about 40 to 200.

## 2.8. TESTING OF TRANSISTOR

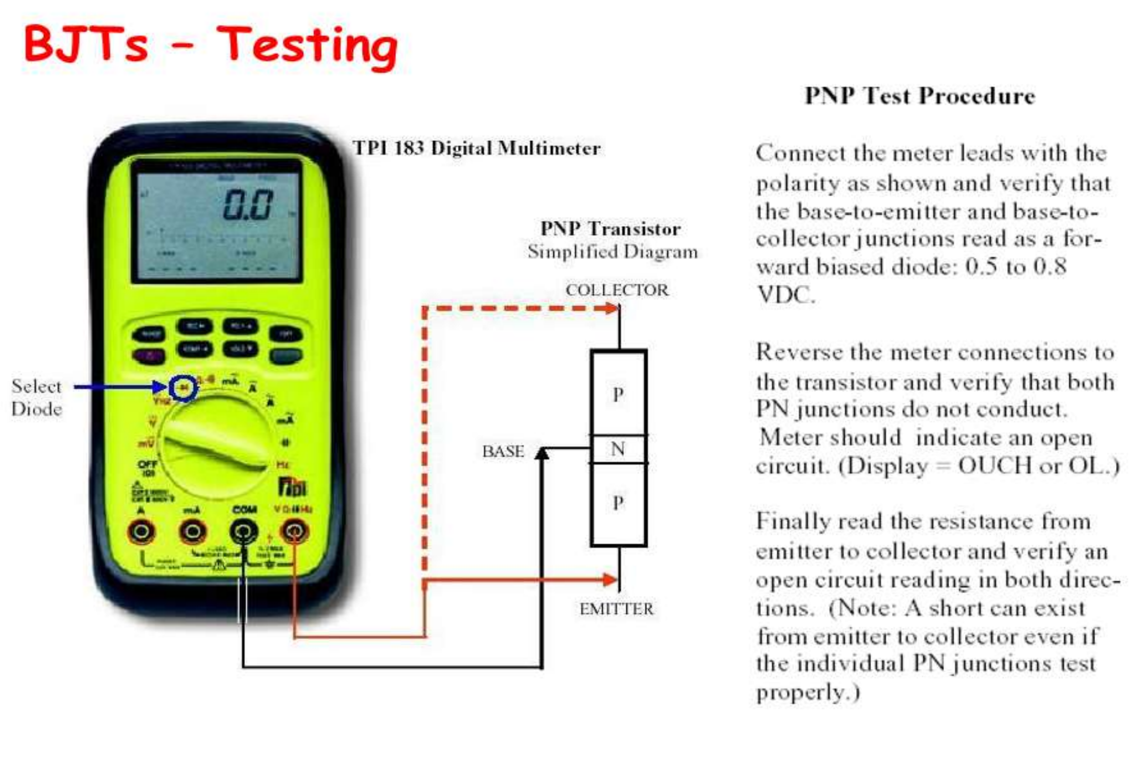



Fig 2.20

# BJTs – Testing

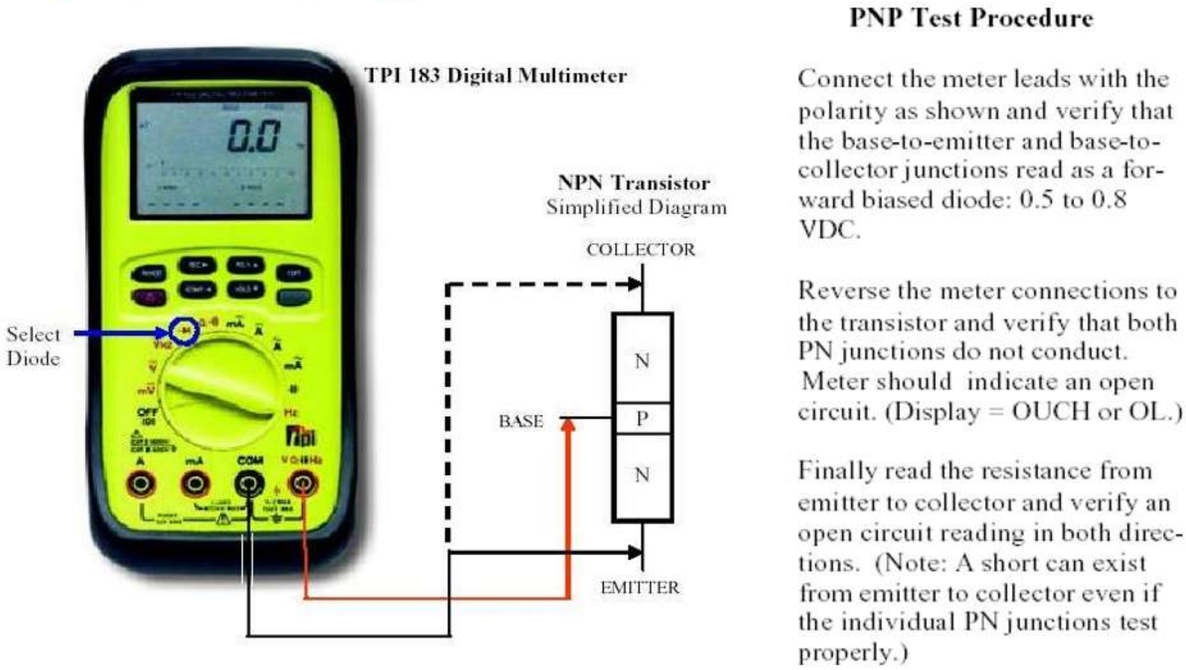



Fig. 2.21

BASIC APPRECIATION OF OTHER TRANSISTOR TYPES AND THEIR USES

## 2.9. Field Effect Transistor

FETs are available in two basic forms: junction gate and insulated gate. The gate–source junction of a junction gate field effect transistor (JFET) is effectively a reverse-biased P–N junction. The gate connection of an insulated gate field effect transistor (IGFET), on the other hand, is insulated from the channel and charge is capacitive coupled to the channel. To keep things simple, we will consider only JFET devices. Figure 6.58 shows the basic construction of an N-channel JFET. FETs comprise a channel of P- or N-type material surrounded by material of the opposite polarity. The ends of the channel (in which conduction takes place) form electrodes known as the source and drain. The effective width of the channel (in which conduction takes place) is controlled by a charge placed on the third (gate) electrode. The effective resistance between the source and drain is thus determined by the voltage present at the gate.

JFETs offer a very much higher input resistance when compared with bipolar transistors. For example, the input resistance of a bipolar transistor operating in common-emitter mode is usually around 2.5 k_. A JFET transistor operating in equivalent common-source mode would typically exhibit an input resistance of 100M_! This feature makes JFET devices ideal for use in applications where a very high-input resistance is desirable. As with bipolar transistors, the characteristics of an FET are often presented in the form of a set of graphs relating voltage and current present at the transistors terminals. The three connections on a JFET are referred to as the gate, source and drain. Inside a JFET there is a resistive connection between the source and drain and a normally reverse-biased junction between the gate and source. In a JFET, the effective resistance between the source and drain is determined by the voltage that appears between the gate and source.

| BJT | FET |
|---|---|
| Collector | Drain |
| Base | Gate |
| Emitter | Source |
| N/A | Body |

Fig. 25

NOTE : FET Transistors switch by voltage rather than by current

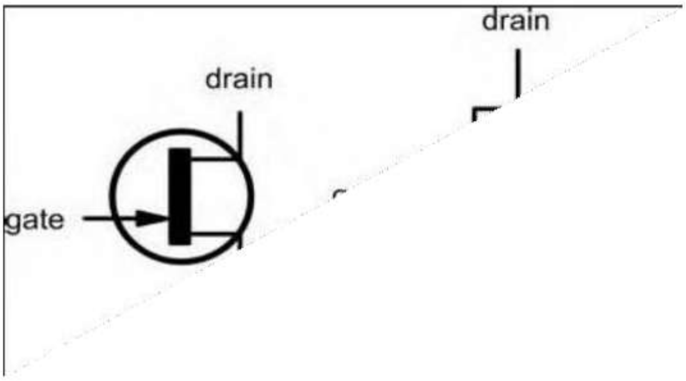



Fig 2.22

- FET (FIELD EFFECT TRANSISTORS) TYPE
  - MOSFET (Metal Oxide Semiconductor Field Effect Transistor)
  - JFET (Junction Field Effect Transistor)
  - MESFET
  - HEMT
  - MODFET

NOTE: Most common are the n-type MOSFET or JFET

# FET Transistors – Circuit Symbols

- In practice the body and source leads are almost always connected
- Most packages have these leads already connected

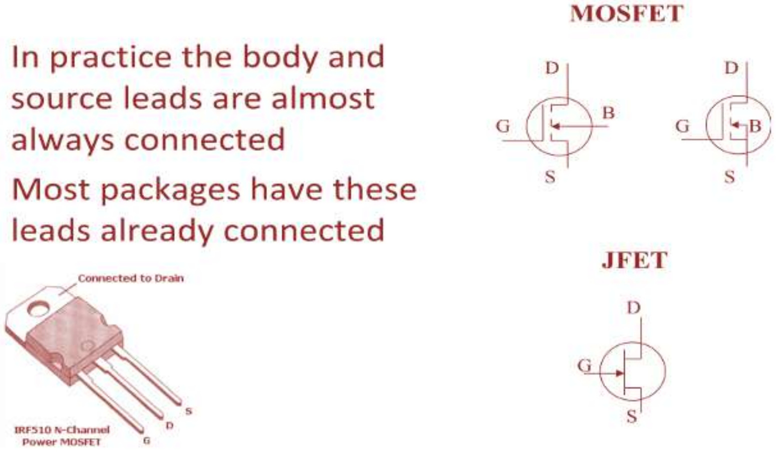



Fig 2.23

# FET Transistors – How it works

- The "Field Effect"
- The resulting field at the plate causes electrons to gather
- As an electron bridge forms current is allowed to flow

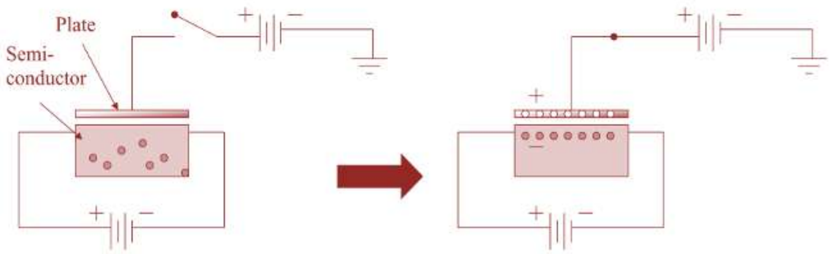



Fig 2.24

# FET Transistors

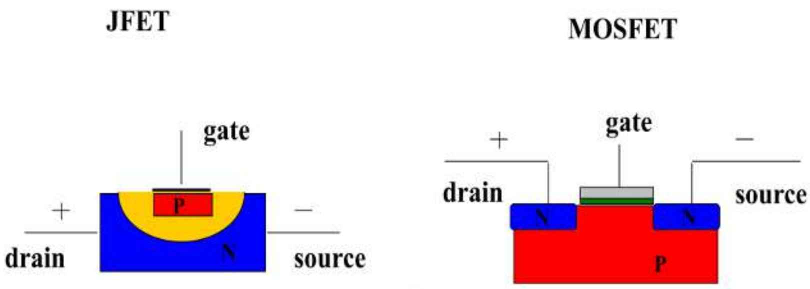



Fig 2.25

## 3. POWER TRANSISTORS

- Additional material for current handling and heat dissipation
- Can handle high current and voltage
- Functionally the same as normal transistors


Fig. : 2.26

## TRANSISTOR USES

- Switching
- Amplification
- Variable Resistor

# UNIT 3

## Application of transistors: classes of amplifier (A, B, C)

### 3.1. CLASS A AMPLIFIERS

- In a class A amplifier, the transistor conducts for the full cycle of the input signal (360°)
  - used in low-power applications
- The transistor is operated in the active region, between saturation and cutoff
  - saturation is when both junctions are forward biased
  - the transistor is in cutoff when $I_B = 0$
- The load line is drawn on the collector curves between saturation and cutoff

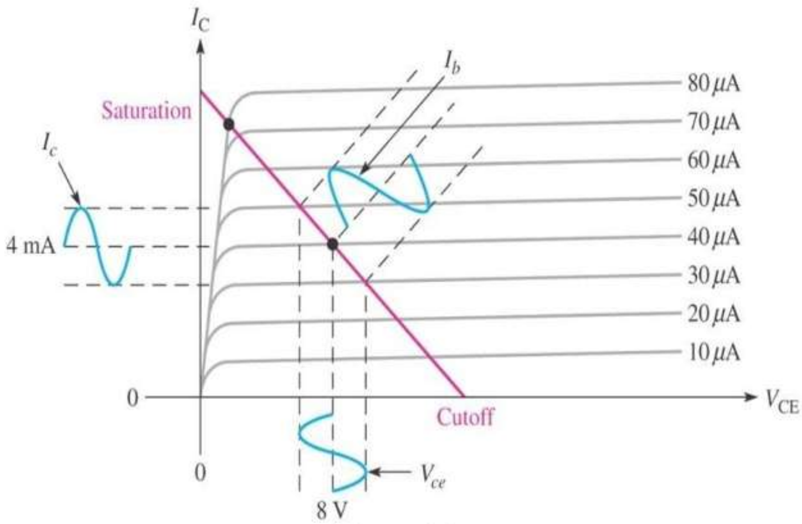



Fig. : 3.1

- Three biasing mode for class A amplifiers
  - common-emitter (CE) amplifier: capacitors are used for coupling ac without disturbing dc levels

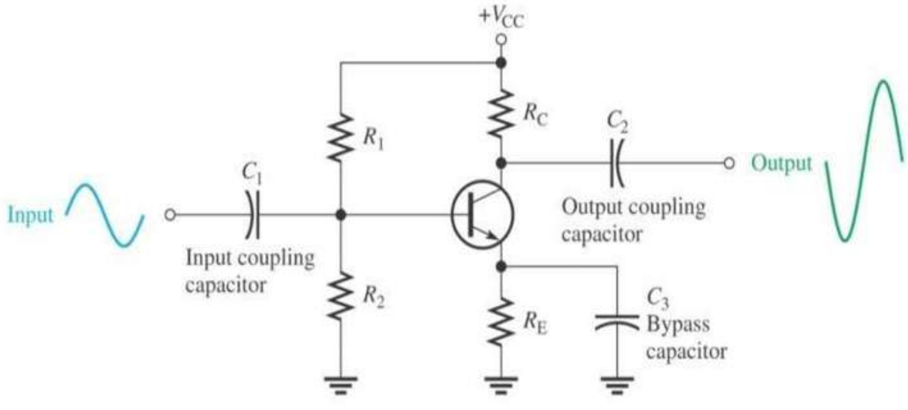



Fig 3.2

- common-collector (CC) amplifier: voltage gain is approximately 1, but current gain is greater than 1

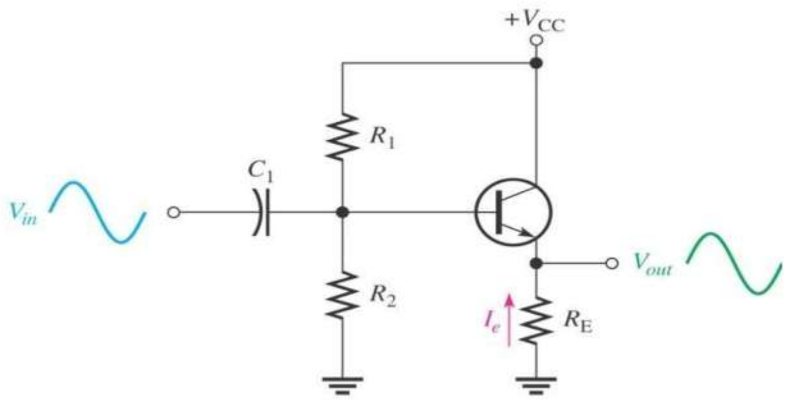



Fig 3.3

- Common-base (CB) amplifier:

  - ✓ the base is the grounded (common) terminal
  - ✓ the input signal is applied to the emitter
  - ✓ output signal is taken off the collector
  - ✓ output is in-phase with the input
  - ✓ voltage gain is greater than 1
  - ✓ current gain is always less than 1

Such type of amplifier is required to drive large resistive loads such as a loudspeaker or to drive a motor in a robot and for these types of applications where high switching currents are needed Power Amplifiers are required.

## CLASS A AMPLIFIER AND ITS APPLICATIONS:

- The most commonly used type of power amplifier configuration is the Class A Amplifier. The Class A amplifier is the most common and simplest form of power amplifier that uses the switching transistor in the standard common emitter circuit configuration as seen previously. The transistor is always biased "ON" so that it conducts during one complete cycle of the input signal waveform producing minimum distortion and maximum amplitude to the output.

- This means then that the Class A Amplifier configuration is the ideal operating mode, because there can be no crossover or switch-off distortion to the output waveform even during the negative half of the cycle. Class A power amplifier output stages may use a single power transistor or pairs of transistors connected together to share the high load current. Consider the Class Aamplifier circuit below.

## SINGLE STAGE AMPLIFIER CIRCUIT

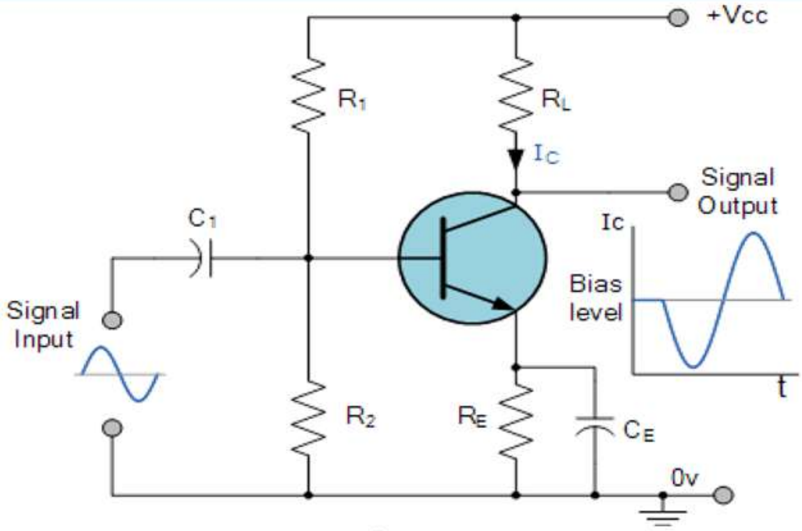



Fig 3.4

- This is the simplest type of Class A power amplifier circuit. It uses a single-ended transistor for its output stage with the resistive load connected directly to the Collector terminal. When the transistor switches "ON" it sinks the output current through the Collector resulting in an inevitable voltage drop across the Emitter resistance thereby limiting the negative output capability.
- The efficiency of this type of circuit is very low (less than 30%) and delivers small power outputs for a large drain on the DC power supply. A Class A amplifier stage passes the same load current even when no input signal is applied so large heat sinks are needed for the output transistors.
- However, another simple way to increase the current handling capacity of the circuit while at the same time obtain a greater power gain is to replace the single output transistor with a Darlington Transistor. These types of devices are basically two transistors within a single package, one small "pilot" transistor and another larger "switching" transistor. The big advantage of these

devices are that the input impedance is suitably large while the output impedance is relatively low, thereby reducing the power loss and therefore the heat within the switching device.

## DARLINGTON TRANSISTOR CONFIGURATIONS

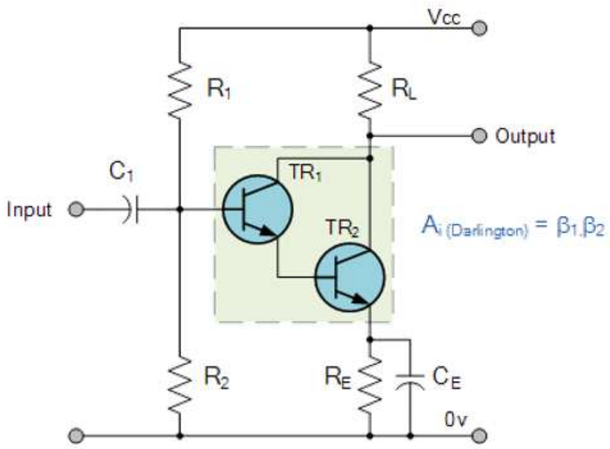


Fig 3.5

- The overall current gain Beta (β) or hfe value of a Darlington device is the product of the two individual gains of the transistors multiplied together and very high β values along with high Collector currents are possible compared to a single transistor circuit.
- To improve the full power efficiency of the Class A amplifier it is possible to design the circuit with a transformer connected directly in the Collector circuit to form a circuit called a Transformer Coupled Amplifier. The transformer improves the efficiency of the amplifier by matching the impedance of the load with that of the amplifiers output using the turns ratio ( n ) of the transformer and an example of this is given below.

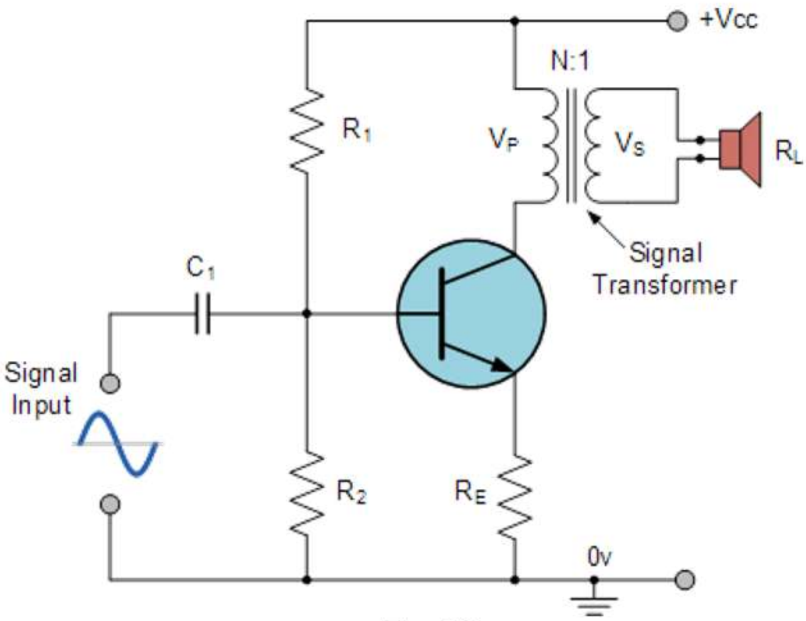


Fig 3.6

- As the Collector current, Ice is reduced to below the quiescent Q-point set up by the base bias voltage, due to variations in the base current, the magnetic flux in the transformer core collapses causing an induced emf in the transformer primary windings. This causes an instantaneous collector voltage to rise to a value of twice the supply voltage 2Vcc giving a maximum collector current of twice Ic when the Collector voltage is at its minimum.

- An output transformer improves the efficiency of the amplifier by matching the impedance of the load with that of the amplifiers output impedance. By using an output or signal transformer with a suitable turns ratio, class-A amplifier efficiencies reaching 40% are possible with most commercially available Class-A type power amplifiers being of this type of configuration.

- However, the transformer is an inductive device due to its windings and core so the use of inductive components in amplifier switching circuits is best avoided as any back emf's generated may damage the transistor without adequate protection.

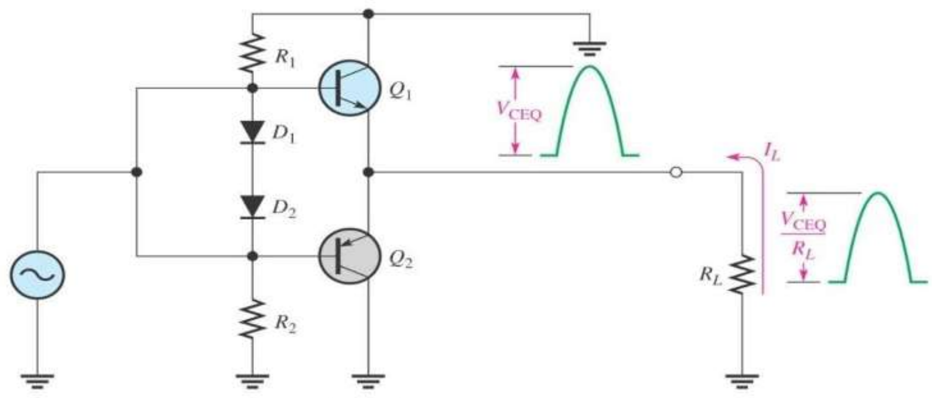
- Also another big disadvantage of this type of transformer coupled class A amplifier circuit is the additional cost and size of the audio transformer required.

- The type of "Class" or classification that an amplifier is given really depends upon the conduction angle, the portion of the 360° of the input waveform cycle, in which the transistor is conducting. In the Class A amplifier the conduction angle is a full 360° or 100% of the input signal while in other amplifier classes the transistor conducts during a lesser conduction angle.

## 3.2. BJT CLASS B AMPLIFIERS AND APPLICATIONS

- When an amplifier is biased such that it operates in the linear region for 180° of the input cycle and is in cutoff for 180°, it is a class B amplifier

  - A class B amplifier is more efficient than a class A
  - In order to get a linear reproduction of the input waveform, the class B amplifier is configured in a push-pull arrangement
  - The transistors in a class B amplifier must be biased above cutoff to eliminate crossover distortion



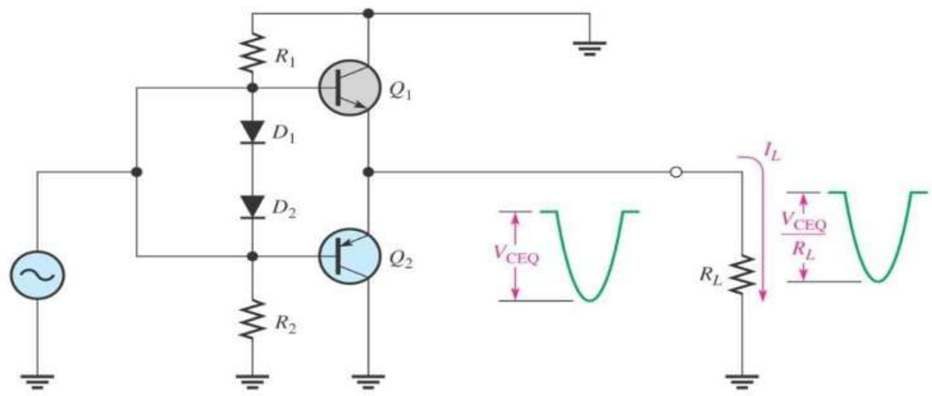




Fig 3.7

## THE CLASS B AMPLIFIER

Push-pull amplifiers use two "complementary" or matching transistors, one being an NPN-type and the other being a PNP-type with both power transistors receiving the same input signal together that is equal in magnitude, but in opposite phase to each other. This results in one transistor only amplifying one half or 180° of the input waveform cycle while the other transistor amplifies the other half or remaining 180° of the input waveform cycle with the resulting "two-halves" being put back together again at the output terminal.

Then the conduction angle for this type of amplifier circuit is only 180° or 50% of the input signal. This pushing and pulling effect of the alternating half cycles by the transistors gives this type of circuit its amusing "push-pull" name, but are more generally known as the Class B Amplifier as shown below.

## 3.3. CLASS B PUSH-PULL TRANSFORMER AMPLIFIER CIRCUIT

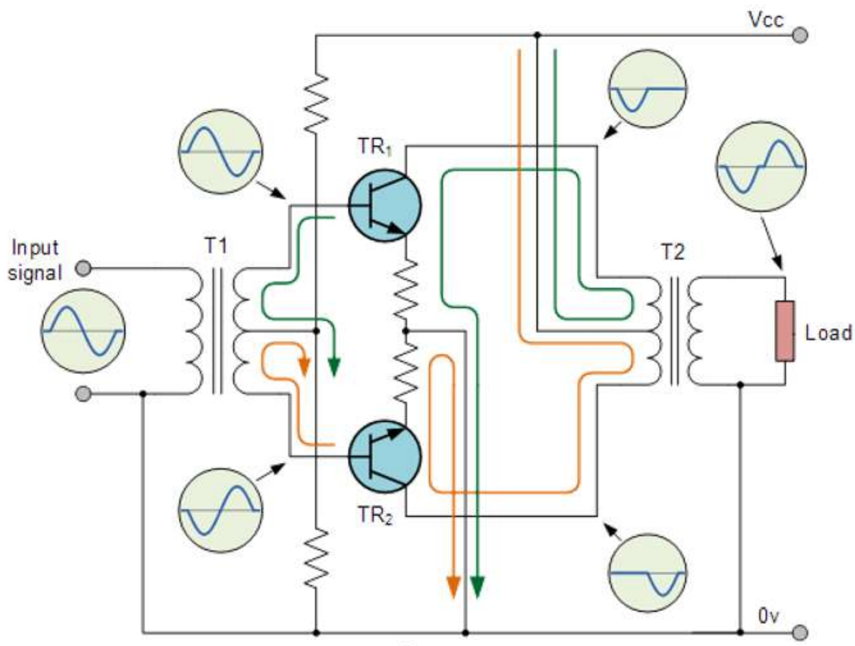



Fig 3.8

The circuit above shows a standard **Class B Amplifier** circuit that uses a balanced center-tappedinput transformer, which splits the incoming waveform signal into two equal halves and which are 180° out of phase with each other. Another centre-tapped transformer on the output is used to recombine the two signals providing the increased power to the load. The transistors used for this type of transformer push-pull amplifier circuit are both NPN transistors with their emitter terminals connected together.

Here, the load current is shared between the two power transistor devices as it decreases in one device and increases in the other throughout the signal cycle reducing the output voltage and current to zero. The result is that both halves of the output waveform now swing from zero to twice the quiescent current thereby reducing dissipation. This has the effect of almost doubling the efficiency of the amplifier to around 70%.

Assuming that no input signal is present, and then each transistor carries the normal quiescent collector current, the value of which is determined by the base bias which is at the cut-off point. If the transformer is accurately centre tapped, then the two collector currents will flow in opposite directions (ideal condition) and there will be no magnetization of the transformer core, thus minimizing the possibility of distortion.

When an input signal is present across the secondary of the driver transformer T1, the transistor base inputs are in "anti-phase" to each other as shown, thus if TR1 base goes positive driving the transistor into heavy conduction, its collector current will increase but at the same time the base current of TR2 will go negative further into cut-off and the collector current of this transistor decreases by an equal amount and vice versa. Hence negative halves are amplified by one transistor and positive halves by the other transistor giving this push-pull effect.

Unlike the DC condition, these AC currentsare ADDITIVE resulting in the two output half-cycles being combined to reform the sine-wave in the output transformers primary winding which then appears across the load.
Class B Amplifier operation has zero DC bias as the transistors are biased at the cut-off, so each transistor only conducts when the input signal is greater than the base-emitter voltage. Therefore, at zero input there is zero output and no power is being consumed. This then means that the actual Q-point of a Class B amplifier is on the Vce part of the load line as shown below.

## CLASS B OUTPUT CHARACTERISTICS CURVES

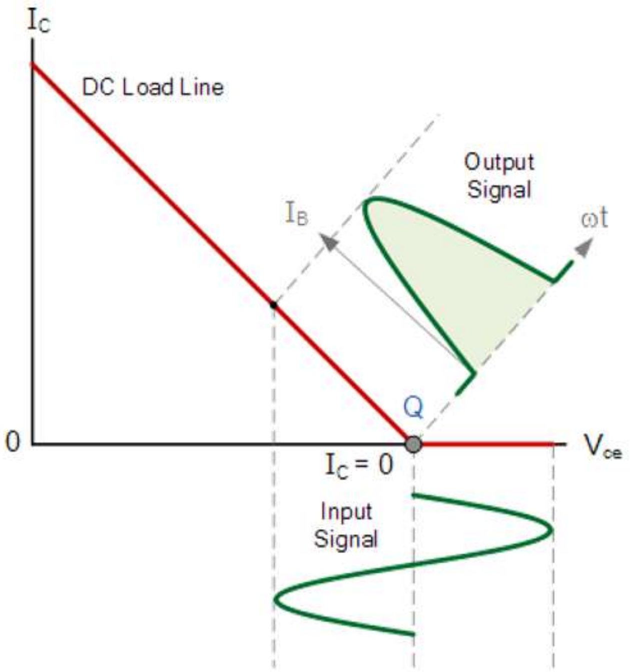



Fig 3.9

The Class B Amplifier has the big advantage over their Class A amplifier cousins in that no current flows through the transistors when they are in their quiescent state (ie, with no input signal), therefore no power is dissipated in the output transistors or transformer when there is no signal present unlike Class A amplifier stages that require significant base bias thereby dissipating lots of heat – even with no input signal present.

So the overall conversion efficiency ( η ) of the amplifier is greater than that of the equivalent Class A with efficiencies reaching as high as 70% possible resulting in nearly all modern types of push-pull amplifiers operated in this Class B mode.

## 3.4. TRANSFORMERLESS CLASS B PUSH-PULL AMPLIFIER

One of the main disadvantages of the Class B amplifier circuit above is that it uses balanced centre-tapped transformers in its design, making it expensive to construct. However, there is another type of Class B amplifier called a Complementary-Symmetry Class B Amplifier that does not use transformers in its design therefore, it is transformer less using instead complementary or matching pairs of power transistors.

As transformers are not needed this makes the amplifier circuit much smaller for the same amount of output, also there are no stray magnetic effects or transformer distortion to effect the quality of the output signal. An example of a "transformer less" Class B amplifier circuit is given below.

### CLASS B TRANSFORMERLESS OUTPUT STAGE

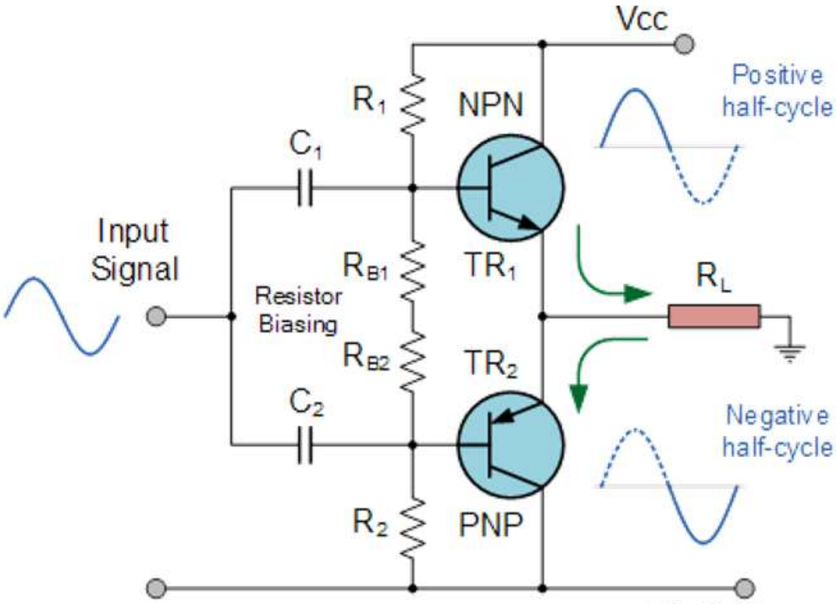



Fig 3.10

The Class B amplifier circuit above uses complimentary transistors for each half of the waveform and while Class B amplifiers have a much high gain than the Class A types, one of the maindisadvantages of class B type push-pull amplifiers is that they suffer from an effect known commonly as Crossover Distortion.
This means that the part of the output waveform which falls below this 0.7 volt window will not be reproduced accurately as the transition between the two transistors (when they are switching over from one transistor to the other), the transistors do not stop or start conducting exactly at the zero crossover point even if they are specially matched pairs.
The output transistors for each half of the waveform (positive and negative) will each have a 0.7 volt area in which they are not conducting. The result is that both transistors are turned "OFF" at exactly the same time.

A simple way to eliminate crossover distortion in a Class B amplifier is to add two small voltage sources to the circuit to bias both the transistors at a point slightly above their cut-off point. This then would give us what is commonly called an Class AB Amplifier circuit. However, it is impractical to add additional voltage sources to the amplifier circuit so PN-junctions are used to provide the additional bias in the form of silicon diodes.

## 3.5. BJT CLASS AB AMPLIFIERS

- In the Class AB operation, the transistor current flows for more than 50 percent but less than 100 percent of the input signal.
- Unlike the Class A amplifier, the output signal is distorted. A portion of the output circuit appears to be truncated.
- This is due to the lack of current through the transistor during this point of operation.
- When the emitter in this case becomes positive enough, the transistor cannot conduct because the base to emitter junction is no longer forward biased.
- The input signal going positive beyond this point will not produce any further output and the output will remain level.

### THE CLASS AB AMPLIFIER OPERATION:

We know that we need the base-emitter voltage to be greater than 0.7v for a silicon bipolar transistor to start conducting, so if we were to replace the two voltage divider biasing resistors connected to the base terminals of the transistors with two silicon Diodes, the biasing voltage applied to the transistors would now be equal to the forward voltage drop of the diode. These two diodes are generally called Biasing Diodes or Compensating Diodes and are chosen to match the characteristics of the matching transistors. The circuit below shows diode biasing.

### CLASS AB AMPLIFIER

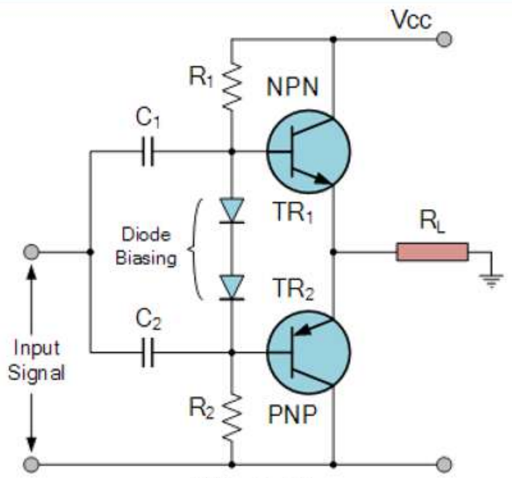



Fig 3.11

The Class AB Amplifier circuit is a compromise between the Class A and the Class B configurations. This very small diode biasing voltage causes both transistors to slightly conduct even when no input signal is present. An input signal waveform will cause the transistors to operate as normal in their active region thereby eliminating any crossover distortion present in pure Class B amplifier designs.

A small collector current will flow when there is no input signal but it is much less than that for the Class A amplifier configuration. This means then that the transistor will be “ON” for more than half a cycle of the waveform but much less than a full cycle giving a conduction angle of between 180 to $360^o$ or 50 to 100% of the input signal depending upon the amount of additional biasing used. The amount of diode biasing voltage present at the base terminal of the transistor can be increased in multiples by adding additional diodes in series.

Class B amplifiers are greatly preferred over Class A designs for high-power applications such as audio power amplifiers and PA systems. Like the Class-A Amplifier circuit, one way to greatly boost the current gain ( $A_i$ ) of a Class B push-pull amplifier is to use Darlington transistors pairs instead of single transistors in its output circuitry.

## 3.6. BJT CLASS C AMPLIFIERS

- In Class C operations, transistor current flows for less than 50 percent of the input signal.
- This class of operation is the most efficient. Because the transistor does not conduct except during a small portion of the input signal, this is the most efficient class of amplifier.
- The distortion of the Class C amplifier is greater (poor fidelity) than the Class A, AB, and B amplifiers because a small portion of the input signal is reproduced on the output.
- Class C amplifiers are used when the output signal is used for only small portions of time.

## CLASS C AMPLIFIER

- The Class C Amplifier design has the greatest efficiency but the poorest linearity of the classes of amplifiers mentioned here. The previous classes, A, B and AB are considered linear amplifiers, as the output signals amplitude and phase are linearly related to the input signals amplitude and phase.

- However, the class C amplifier is heavily biased so that the output current is zero for more than one half of an input sinusoidal signal cycle with the transistor idling at its cut-off point. In other words, the conduction angle for the transistor is significantly less than 180 degrees, and is generally around the 90 degrees area.

- While this form of transistor biasing gives a much improved efficiency of around 80% to the amplifier, it introduces a very heavy distortion of the output signal. Therefore, class C amplifiers are not suitable for use as audio amplifiers.

## CLASS C AMPLIFIER

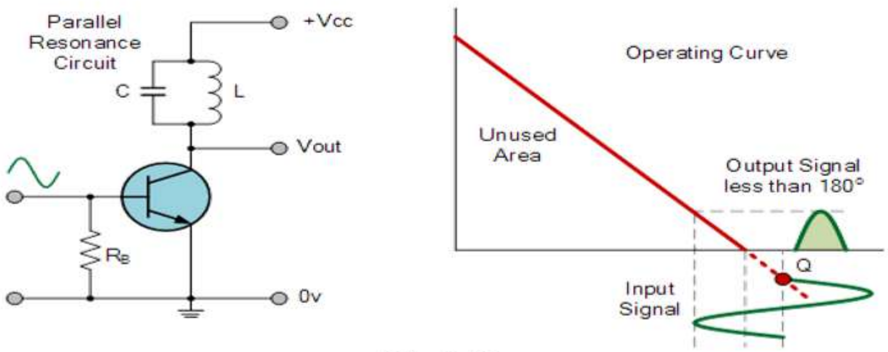



Fig 3.12

- Due to its heavy audio distortion, class C amplifiers are commonly used in high frequency sine wave oscillators and certain types of radio frequency amplifiers, where the pulses of current produced at the amplifiers output can be converted to complete sine waves of a particular frequency by the use of LC resonant circuits in its collector circuit.
- Amplifier Classes Summary
- Then we have seen that the quiescent DC operating point (Q-point) of an amplifier determines the amplifier classification. By setting the position of the Q-point at half way on the load line of the amplifiers characteristics curve, the amplifier will operate as a class A amplifier. By moving the Q-point lower down the load line changes the amplifier into a class AB, B or C amplifier.
- Then the class of operation of the amplifier with regards to its DC operating point can be given as:

## AMPLIFIER CLASSES AND EFFICIENCY

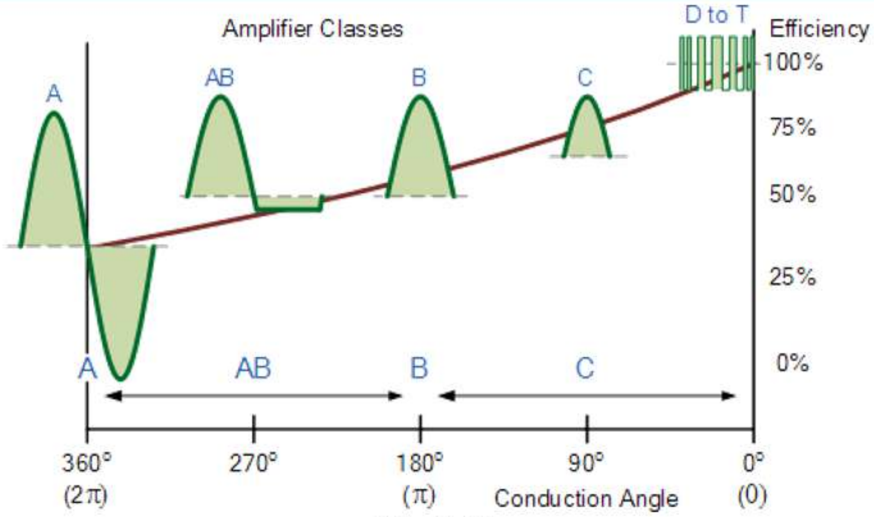



Fig 3.13

As well as audio amplifiers there is a number of highefficiency Amplifier Classes relating to switching amplifierdesigns that use different switching techniques to reduce power loss and increase efficiency. Some amplifier class designs listed below use RLC resonators or multiple power-supply voltages to reduce power loss, or are digital DSP (digital signal processing) type amplifiers which use pulse width modulation (PWM) switching techniques.

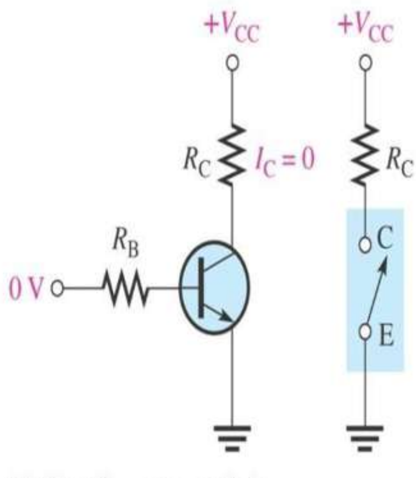
| Class of Operation | Bias Point | Conduction Angle | Efficiency | Application |
|---|---|---|---|---|
| A | Mid Point | 360 | 5-40 | Linear audio amplifier |
| AB | Projected Cutoff | 210 | 20-40 | Push pull audio amplifier |
| B | At Cutoff | 180 | 40-70 | Push pull audio amplifier |
| C | Beyond Cutoff | 120 | 70-90 | RF power amplifier |

## 3.7. THE BJT AS A SWITCH

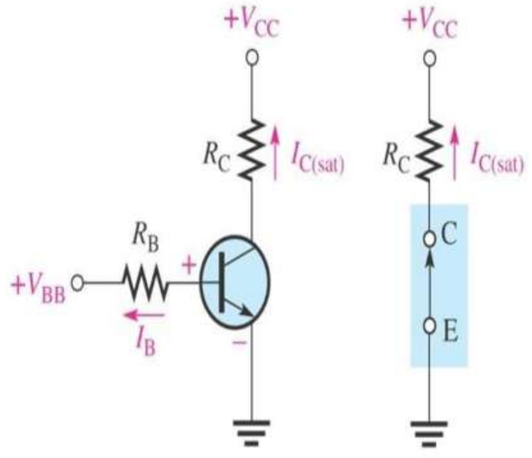
- When used as an electronic switch, a transistor normally is operated alternately in cutoff and saturation

  – A transistor is in cutoff when the base-emitter junction is not forward-biased. $V_{CE}$ is approximately equal to $V_{CC}$.

  – When the base-emitter junction is forward-biased and there is enough base current to produce a maximum collector current, the transistor is saturated.




(a) Cutoff — open switch



(b) Saturation — closed switch

Fig 3.14

## 4.1. BIASING

A bipolar junction transistor, (BJT) is very versatile. It can be used in many ways, as an amplifier, a switch or an oscillator and many other uses too. Before an input signal is applied its operating conditions need to be set. This is achieved with a suitable bias circuit, some of which I will describe. A bias circuit allows the operating conditions of a transistor to be defined, so that it will operate over a pre-determined range. This is normally achieved by applying a small fixed dc voltage to the input terminals of a transistor.

### SIMPLE BIAS CIRCUIT:

The simplest bias circuit is shown below. It consists only of a fixed bias resistor and load resistor. The BJT is operating in common emitter mode. The dc current gain or beta, $h_{FE}$ is the ratio of dc collector current divided by dc base current. The BJT is a BC107A. The values of Rb and Rc can be determined by either mathematical approach or by using the output characteristic curves for the BC107A.

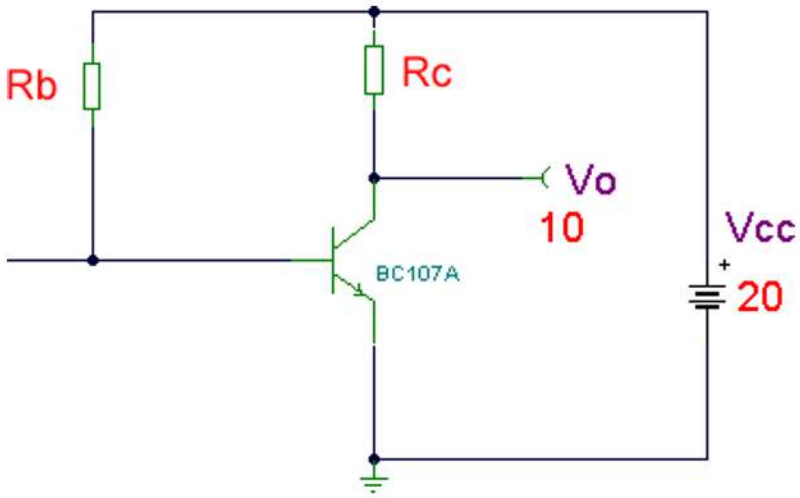



Fig 3.15

### QUIESCENT POINT (Q-POINT)

The point Vo in the diagram above is where the output signal would be taken. For simplicity, the input signal and coupling capacitors have been omitted. For minimum distortion and clipping it is desirable to bias this point to half the supply voltage, 10 volts dc in this case. This is also known as the quiescent point. The ac output signal would then be superimposed on the dc bias voltage. The Q-point is sometimes indicated on the output characteristics curves for a transistor amplifier. The quiescent point also refers to the dc conditions (bias conditions) of a circuit without an input signal.

### Q-POINT VALUE

I have mentioned that setting the Q-point to half the supply voltage is a good idea. It gives a circuit the highest margin for overload. However, any amplifier will clip if the input amplitude exceeds the limit for which the circuit was designed. However, there are certain cases when it is not necessary to bias a stage to half the supply voltage. Examples would be an RF amplifier design where the input signal is in microvolts or mill volts. If the stage had a gain of 200 then the output (assuming a 2mV peak input) would only need to swing up and down 400mV about the Q-point. Hence a stage with a supply voltage of 12 volts could have its Q-point set at 10 volts or even 2 volts without problems. Another example would be a microphone stage where similar low level input signals are involved.

OUTPUT CHARACTERISTIC CURVE FOR A BC107A

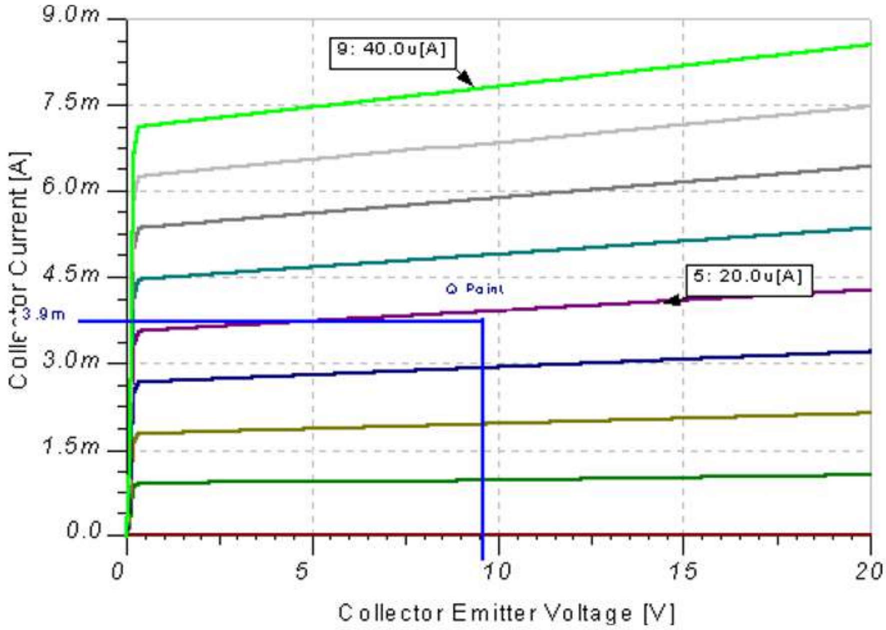



Fig 3.16

## BIAS DESIGN

The collector voltage Vc for the simple bias design is 10 volt. The dc current gain, $h_{FE}$ for the BC107A is obtained from the manufacturer's data sheets and varies between devices. A typical beta is around 290. Taking a base current of 20uA and reading values direct from the output curves, the collector current, for a collector emitter voltage of 10 volts is around 3.9mA. As $h_{FE}$= Ic / Ib then a BC107A must have a beta of at least 3.9mA / 20uA = 195 to work with this circuit. Also, the base emitter voltage, Vbe is typically 0.6v. Knowing the above data and using ohm's law , values for Rb and Rc can be determined:

Rb = Vcc - Vbe / Ib = (20-0.6) / 20u = 970k use (1M)
Rc = Vc / Ic = 10 / 3.9m = 2.56K use (2.7K)

## 4.2. SIMPLE CIRCUIT: STABILIZATION AND FEEDBACK

- Feedback is the coupling of an amplifier's output to its input.

- Positive, or regenerative feedback has the tendency of making an amplifier circuit unstable, so that it produces oscillations (AC). The frequency of these oscillations is largely determined by the components in the feedback network.

- Negative, or degenerative feedback has the tendency of making an amplifier circuit more stable, so that its output changes less for a given input signal than without feedback. This reduces the gain of the amplifier, but has the advantage of decreasing distortion and increasing bandwidth (the range of frequencies the amplifier can handle).

- Negative feedback may be introduced into a common-emitter circuit by coupling collector to base, or by inserting a resistor between emitter and ground.

- An emitter-to-ground "feedback" resistor is usually found in common-emitter circuits as a preventative measureagainst thermal runaway.

- Negative feedback also has the advantage of making amplifier voltage gain more dependent on resistor values and less dependent on the transistor's characteristics.

- Common-collector amplifiers have much negative feedback, due to the placement of the load resistor between emitter and ground. This feedback accounts for the extremely stable voltage gain of the amplifier, as well as its immunity against thermal runaway.

- Voltage gain for a common-emitter circuit may be re-established without sacrificing immunity to thermal runaway, by connecting a bypass capacitor in parallel with the emitter "feedback resistor."

- If the voltage gain of an amplifier is arbitrarily high (tens of thousands, or greater), and negative feedback is used to reduce the gain to reasonable levels, it will be found that the gain will approximately equal $R_{feedback}/R_{in}$. Changes in transistor β or other internal component values will have little effect on voltage gain with feedback in operation, resulting in an amplifier that is stable and easy to design.

## FEEDBACK

If some percentage of an amplifier's output signal is connected to the input, so that the amplifier amplifies part of its own output signal, we have what is known as feedback. Feedback comes in twovarieties: positive (also called regenerative), and negative (also called degenerative). Positive feedback reinforces the direction of an amplifier's output voltage change, while negative feedback does just the opposite.

A familiar example of feedback happens in public-address ("PA") systems where someone holds the microphone too close to a speaker: a high-pitched "whine" or "howl" ensues, becausethe audio amplifier system is detecting and amplifying its own noise. Specifically, this is an example of positive or regenerative feedback, as any sound detected by the microphone is amplified and turned into a louder sound by the speaker, which is then detected by the microphone again, and so on . . . the result being a noise of steadily increasing volume until the system becomes "saturated" and cannot produce any more volume.

One might wonder what possible benefit feedback is to an amplifier circuit, given such an annoying example as PA system "howl." If we introduce positive, or regenerative, feedback into an amplifier circuit, it has the tendency of creating and sustaining oscillations, the frequency of which determined by the values of components handling the feedback signal from output to input. This is one way to make an oscillator circuit to produce AC from a DC power supply. Oscillators are very useful circuits, and so feedback has a definite, practical application for us. See "Phase shift oscillator" , Ch 9 for a practical application of positive feedback.

Negative feedback, on the other hand, has a "dampening" effect on an amplifier: if the output signal happens to increase in magnitude, the feedback signal introduces a decreasing influence into the input of the amplifier, thus opposing the change in output signal. While positive feedback drives an amplifier circuit toward a point of instability (oscillations), negative feedback drives it the opposite direction: toward a point of stability.

An amplifier circuit equipped with some amount of negative feedback is not only more stable, but it distorts the input waveform less and is generally capable of amplifying a wider range of frequencies. The tradeoff for these advantages (there just has to be a disadvantage to negative feedback, right?) is decreased gain. If a portion of an amplifier's output signal is "fed back" to the input to oppose any changes in the output, it will require a greater input signal amplitude to drive the amplifier's output to the same amplitude as before. This constitutes a decreased gain. However, the advantages of stability, lower distortion, and greater bandwidth are worth the tradeoff in reduced gain for many applications.

Let's examine a simple amplifier circuit and see how we might introduce negative feedback into it, starting with Figure below.

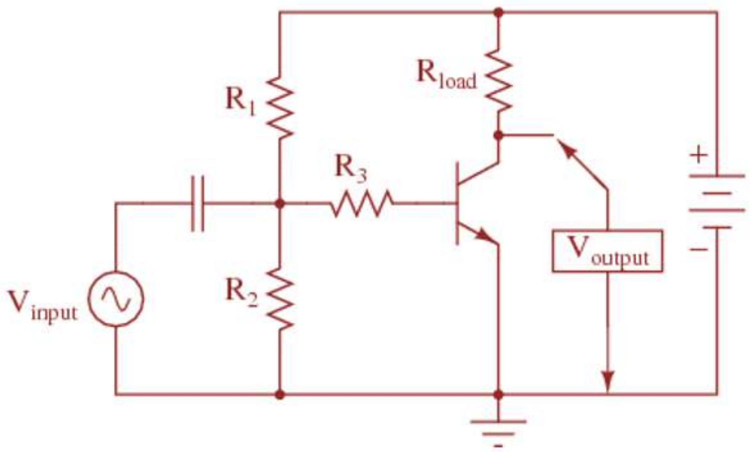



Fig 4.1

## COMMONEMITTER AMPLIFIER WITHOUT FEEDBACK

The amplifier configuration shown here is a common-emitter, with a resistor bias network formed by $R_1$ and $R_2$. The capacitor couples $V_{input}$to the amplifier so that the signal source doesn't have a DC voltage imposed on it by the $R_1/R_2$ divider network. Resistor $R_3$ serves the purpose of controlling voltage gain. We could omit it for maximum voltage gain, but since base resistors like this are common in common-emitter amplifier circuits, we'll keep it in this schematic.

Like all common-emitter amplifiers, this one inverts the input signal as it is amplified. In other words, a positive-going input voltage causes the output voltage to decrease, or move toward negative, and vice versa. The oscilloscope waveforms are shown in Figure below.

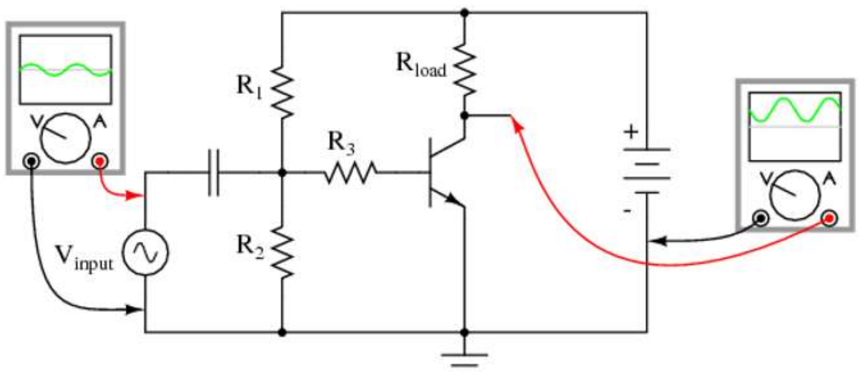



Fig 4.2

Common-emitter amplifier, no feedback, with reference waveforms for comparison.

Because the output is an inverted, or mirror-image, reproduction of the input signal, any connection between the output (collector) wire and the input (base) wire of the transistor in Figure below will result in negative feedback.

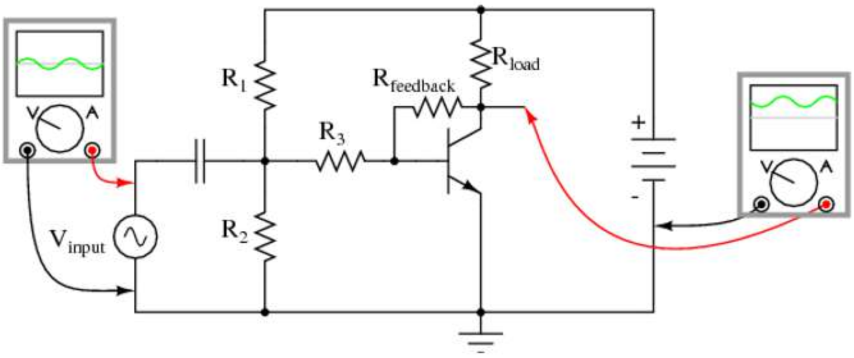



Fig 4.3

Negative feedback, collector feedback, decreases the output signal.

The resistances of $R_1$, $R_2$, $R_3$, and $R_{feedback}$ function together as a signal-mixing network so that the voltage seen at the base of the transistor (with respect to ground) is a weighted average of the input voltage and the feedback voltage, resulting in signal of reduced amplitude going into the transistor. So, the amplifier circuit in Figure above will have reduced voltage gain, but improved linearity (reduced distortion) and increased bandwidth.
A resistor connecting collector to base is not the only way to introduce negative feedback into this amplifier circuit, though. Another method, although more difficult to understand at first, involves the placement of a resistor between the transistor's emitter terminal and circuit ground in Figure below.

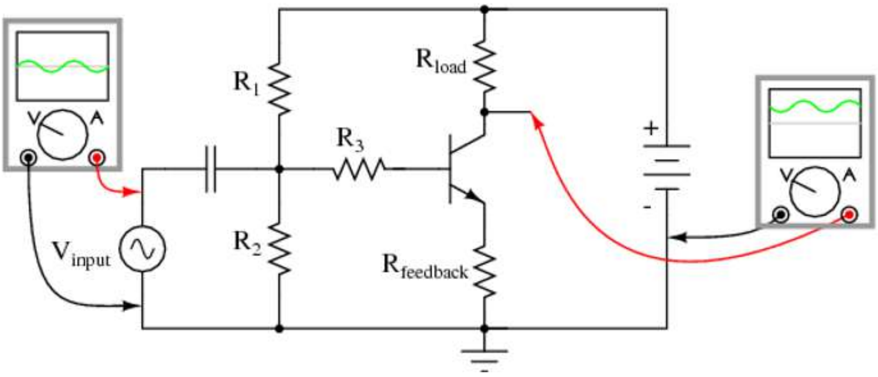



Fig 4.4

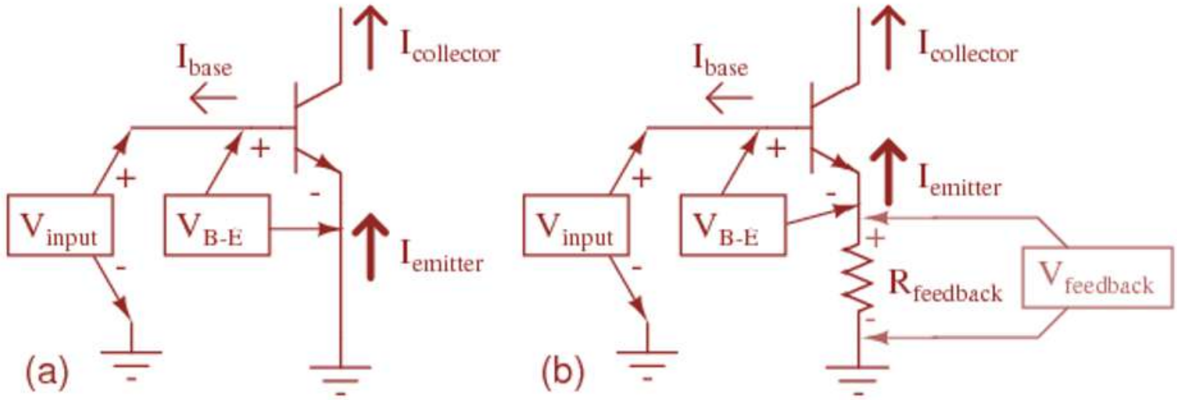
Emitter feedback: A different method of introducing negative feedback into a circuit.

This new feedback resistor drops voltage proportional to the emitter current through the transistor, and it does so in such a way as to oppose the input signal's influence on the base-emitter junction of the transistor. Let's take a closer look at the emitter-base junction and see what difference this new resistor makes in Figure below.

With no feedback resistor connecting the emitter to ground in Figure below (a) , whatever level of input signal ($V_{input}$) makes it through the coupling capacitor and $R_1/R_2/R_3$ resistor network will be impressed directly across the base-emitter junction as the transistor's input voltage ($V_{B-E}$). In other words, with no feedback resistor, $V_{B-E}$ equals $V_{input}$. Therefore, if $V_{input}$ increases by 100 mV, then $V_{B-}$

$_E$ increases by 100 mV: a change in one is the same as a change in the other, since the two voltages are equal to each other.

Now let's consider the effects of inserting a resistor ($R_{feedback}$) between the transistor's emitter lead and ground in Figure below (b)




(a) No feedback vs (b) emitter feedback. A waveform at the collector is inverted with respect to the base. At (b) the emitter waveform is in-phase (emitter follower) with base, out of phase with collector. Therefore, the emitter signal subtracts from the collector output signal

Fig 4.5

Note how the voltage dropped across $R_{feedback}$ adds with $V_{B-E}$ to equal $V_{input}$. With $R_{feedback}$ in the $V_{input}$ -- $V_{B-E}$ loop, $V_{B-E}$ will no longer be equal to $V_{input}$. We know that $R_{feedback}$ will drop a voltage proportional to emitter current, which is in turn controlled by the base current, which is in turn controlled by the voltage dropped across the base-emitter junction of the transistor ($V_{B-E}$). Thus, if $V_{input}$ were to increase in a positive direction, it would increase $V_{B-E}$, causing more base current, causing more collector (load) current, causing more emitter current, and causing more feedback voltage to be dropped across $R_{feedback}$. This increase of voltage drop across the feedback resistor, though, subtracts from $V_{input}$ to reduce the $V_{B-E}$, so that the actual voltage increase for $V_{B-E}$ will be less than the voltage increase of $V_{input}$. No longer will a 100 mV increase in $V_{input}$ result in a full 100 mV increase for $V_{B-E}$, because the two voltages are not equal to each other.

Consequently, the input voltage has less control over the transistor than before, and the voltage gain for the amplifier is reduced: just what we expected from negative feedback.

In practical common-emitter circuits, negative feedback isn't just a luxury; it's a necessity for stable operation. In a perfect world, we could build and operate a common-emitter transistor amplifier with no negative feedback, and have the full amplitude of $V_{input}$ impressed across the transistor's base-emitter junction. This would give us a large voltage gain.Unfortunately, though, the relationship between base-emitter voltage and base-emitter current changes with temperature, as predicted by the "diode equation." As the transistor heats up, there will be less of a forward voltage drop across the base-emitter junction for any given current. This causes a problem for us, as the $R_1/R_2$ voltage divider network is designed to provide the correct quiescent current through the base of the transistor so that it will operate in whatever class of operation we desire (in this example, I've shown the amplifier working in class-A mode). If the transistor's voltage/current relationship changes with temperature, the amount of DC bias voltage necessary for the desired class of operation will change. A hot transistor will draw more bias current for the same amount of bias voltage, making it heat up even more, drawing even more bias current. The result, if unchecked, is called thermal runaway. Common-collector amplifiers, (Figure below) however, do not suffer from thermal runaway. Why is this? The answer has everything to do with negative feedback.

## 4.3. SIMPLE CIRCUIT: COUPLING AND DECOUPLING

- Capacitive coupling acts like a high-pass filter on the input of an amplifier. This tends to make the amplifier's voltage gain decrease at lower signal frequencies. Capacitive-coupled amplifiers are all but unresponsive to DC input signals.

- Direct coupling with a series resistor instead of a series capacitor avoids the problem of frequency-dependent gain, but has the disadvantage of reducing amplifier gain for all signal frequencies by attenuating the input signal.

- Transformers and capacitors may be used to couple the output of an amplifier to a load, to eliminate DC voltage from getting to the load.

- Multi-stage amplifiers often make use of capacitive coupling between stages to eliminate problems with the bias from one stage affecting the bias of another.

To overcome the challenge of creating necessary DC bias voltage for an amplifier's input signal without resorting to the insertion of a battery in series with the AC signal source, we used a voltage divider connected across the DC power source. To make this work in conjunction with an AC input signal, we "coupled" the signal source to the divider through a capacitor, which acted as a high-pass filter. With that filtering in place, the low impedance of the AC signal source couldn't "short out" the DC voltage dropped across the bottom resistor of the voltage divider. A simple solution, but not without any disadvantages.

Most obvious is the fact that using a high-pass filter capacitor to couple the signal source to the amplifier means that the amplifier can only amplify AC signals. A steady, DC voltage applied to the input would be blocked by the coupling capacitor just as much as the voltage divider bias voltage is blocked from the input source. Furthermore, since capacitive reactance is frequency-dependent, lower-frequency AC signals will not be amplified as much as higher-frequency signals. Non-sinusoidal signals will tend to be distorted, as the capacitor responds differently to each of the signal's constituent harmonics. An extreme example of this would be a low-frequency square-wave signal in Figurebelow.

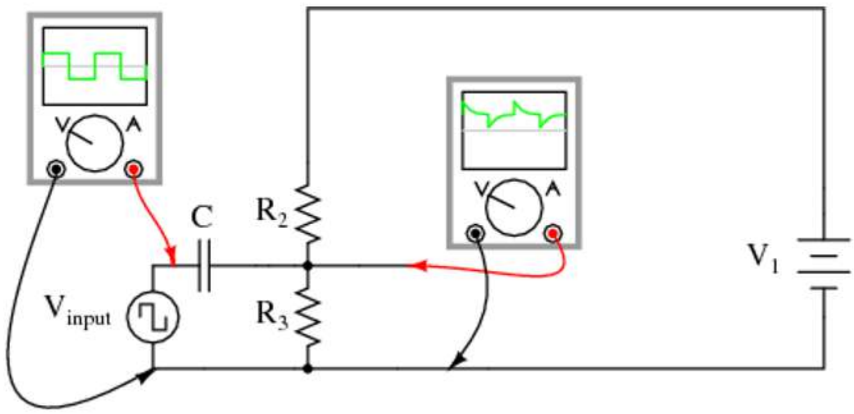



Fig 4.6

Capacitively coupled low frequency square-wave shows distortion.

Incidentally, this same problem occurs when oscilloscope inputs are set to the "AC coupling" mode as in Figure below. In this mode, a coupling capacitor is inserted in series with the measured voltage signal to eliminate any vertical offset of the displayed waveform due to DC voltage combined with the signal. This works fine when the AC component of the measured signal is of a fairly high frequency, and the capacitor offers little impedance to the signal. However, if the signal is of a low frequency, or contains considerable levels of harmonics over a wide frequency range, the oscilloscope's display of the waveform will not be accurate.

## 4.4. Push-pull

Fundamentally, a push-pull circuit uses a pair of effectively separate transistors operating 180O out of phase with one another. If good amplitude and phase balance is maintained between the signals in each half of the device, then an RF ground will exist at the midpoint. This approach leads to several advantages over single-ended designs:

- Input and Output Impedances Doubled
- Reduced Even Order Harmonics
- Increased Output Power
- Higher Bandwidths Possible
- Reduced Effect of Common Lead Inductance

Perhaps the most significant disadvantages are the need for differential RF excitation and the fact that excellent symmetry is required in both the matching circuit and the device itself.

A push pull amplifier is an amplifier which has an output stage that can drive a current in either direction through the load. The output stage of a typical push pull amplifier consists of two identical BJTs or MOSFETs one sourcing current through the load while the other one sinking the current from the load. Push pull amplifiers are superior over single ended amplifiers (using a single transistor at the output for driving the load) in terms of distortion and performance. A single ended amplifier, how well it may be designed will surely introduce some distortion due to the non-linearity of its dynamic transfer characteristics. Push pull amplifiers are commonly used in situations where low distortion, high efficiency and high output power are required. The basic operation of a push pull amplifier is as follows: The signal to be amplified is first split into two identical signals 180° out of phase. Generally this splitting is done using an input coupling transformer. The input coupling transformer is so arranged that one signal in applied to the input of one transistor and the other signal is applied to the input of the other transistor. Advantages of push pull amplifier are low distortion, absence of magnetic saturation in the coupling transformer core, and cancellation of power supply ripples which results in the absence of hum while the disadvantages are the need of two identical transistors and the requirement of bulky and costly coupling transformers.

## CLASS A PUSH PULL AMPLIFIER

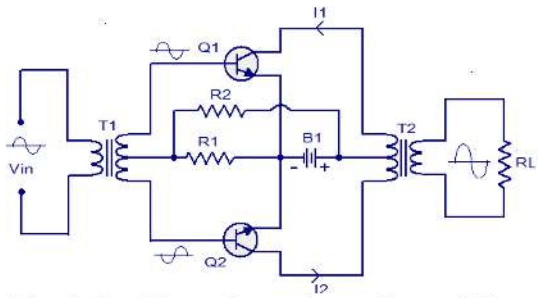



Fig 4.7 : Class A push pull amplifier

A push pull amplifier can be made in Class A, Class B, Class AB or Class C configurations. The circuit diagram of a typical Class A push pull amplifier is shown above. Q1 and Q2 is two identical transistor and their emitter terminals are connected together. R1 and R2 are meant for biasing the transistors. Collector terminals of the two transistors are connected to the respective ends of the primary of the output transformer T2. Power supply is connected between the centre tap of the T2 primary and the emitter junction of the Q1 and Q2. Base terminal of each transistor is connected to the respective ends of the secondary of the input coupling transformer T1. Input signal is applied to the primary of T1 and output load RL is connected across the secondary of T2.Quiescent current of Q2 and Q1 flows in opposite directions through the corresponding halves of the primary of T2 and as a result there will be no magnetic saturation. From the figure you can see the phase split signals being applied to the base of each transistor. When Q1 is driven positive using the first half of its input signal, the collector current of Q1 increases. At the same time Q2 is driven negative using the first half of its input signal and so the collector current of Q2 decreases. From the figure you can understand that the collector currents of Q1 and Q2 ie; I1 and I2 flow in the same direction trough the corresponding halves of the T2 primary. As a result an amplified version of the original input signal is induced in the T2 secondary. It is clear that the current through the T2 secondary is the difference between the two collector currents. Harmonics will be much less in the output due to cancellation and this is results in low distortion.

## CLASS B PUSH PULL AMPLIFIER

The Class B push pull amplifier is almost similar to the Class a push pull amplifier and the only difference is that there is no biasing resistors for a Class B push pull amplifier. This means that the two transistors are biased at the cut off point. The Class B configuration can provide better power output and has higher efficiency (up to 78.5%). Since the transistor is biased at the cut-off point, they consume no power during idle condition and this adds to the efficiency. The advantages of Class B push pull amplifiers are, ability to work in limited power supply conditions (due to the higher efficiency), absence of even harmonics in the output, simple circuitry when compared to the Class A configuration etc. The disadvantages are higher percentage of harmonic distortion when compared to the Class A; cancellation of power supply ripples is not as efficient as in Class A push pull amplifier and which results in the need of a well regulated power supply. The circuit diagram of a classic Class B push pull amplifier is shown in the diagram below.

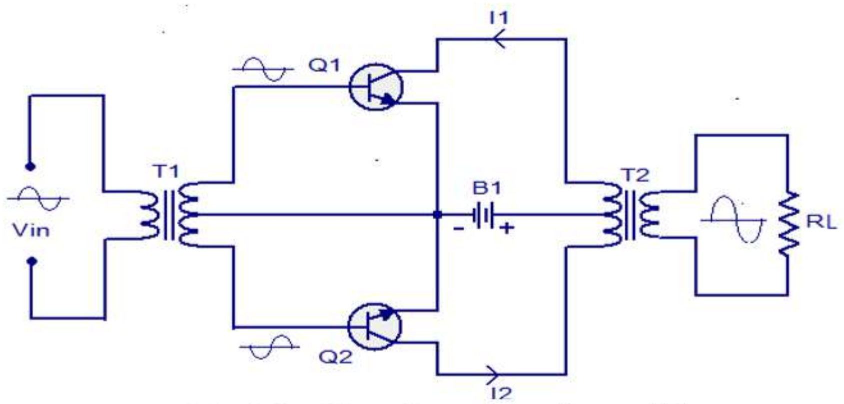



Fig 4.8 : Class B push pull amplifier

The circuit arrangement of the Class B push pull amplifier is similar to the Class A push pull amplifier except for the absence of the biasing resistors. T1 is the input coupling capacitor and the input signal is applied to its primary. Q1 and Q2 are two identical transistors and their emitter terminals are connected together. Centre tap of the input coupling transformer and the negative end of the voltage source is connected to the junction point of the emitter terminals. Positive end of the voltage source is connected to the centre tap of the output coupling transformer. Collector terminals of each transistor are connected to the respective ends of the primary of the output coupling transformer T2. Load RL is connected across the secondary of T2.

The input signal is converted into two similar but phase opposite signals by the input transformer T1. One out of these two signals is applied to the base of the upper transistor while the other one is applied to the base of the other transistor. You can understand this from the circuit diagram. When transistor Q1 is driven to the positive side using the positive half of its input signal, the reverse happens in the transistor Q2. That means when the collector current of Q1 is going in the increasing direction, the collector current of Q2 goes in the decreasing direction. Anyway the current flow through the respective halves of the primary of the T2 will be in same direction. Have a look at the figure for better understanding. This current flow through the T2 primary results in a wave form induced across its secondary. The wave form induced across the secondary is similar to the original input signal but amplified in terms of magnitude.

## CROSS OVER DISTORTION

Cross over distortion is a type of distortion commonly seen in Class B amplifier configurations? As we said earlier, the transistors are biased at cut off point in the Class B amplifier. We all know a Silicon transistor requires 0.7V and a Germanium diode requires 0.2V of voltage across its base emitter junction before entering in to conducting mode and this base emitter voltage is called cut in voltage. Germanium diodes are out of scope in amplifiers and we can talk about a Class B push pull amplifier based on Silicon transistors. Since the transistors are biased to cut off, the voltage across their base emitter junction remains zero during the zero input condition. The only source for the transistors to get the necessary cut in voltage is the input signal itself and the required cut in voltage will be looted from the input signal itself. As a result portion of the input wave form that is below 0.7V (cut in voltage) will be cancelled and so the corresponding portions will be absent in the output wave form too. Have a look at the figure below for better understanding.

## 4.5. CASCADES

CASCADE OPERATION

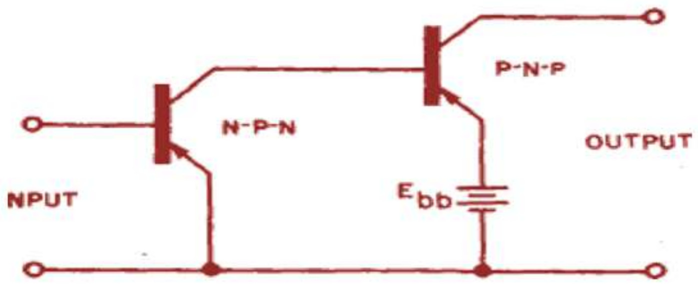



Fig 4.9 : A direct-coupled symmetrical cascade.

One type of symmetrical circuit that proves very practical is the cascaded arrangement illustrated in Fig. 74. This tandem circuit represents the simplest possible cascade, since the only components of the system are the transistors and the battery supply. The gain per stage is low compared to the maximum available gain because of the mismatch existing between the stages. However, the reduced number of components and the simplicity of the design often outweigh this disadvantage.

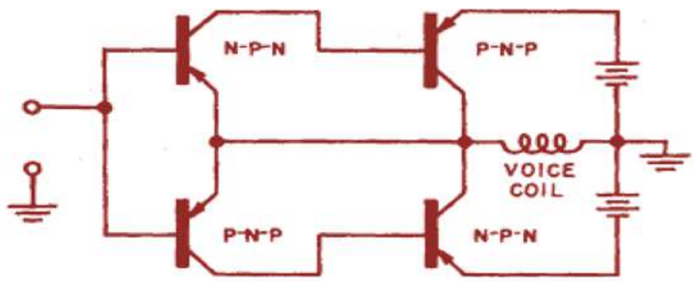



Fig 4.10 : Two-stage symmetrical push-pull amplifier

A circuit which incorporates the major features of both push-pull and cascaded symmetrical configurations is shown in Fig. 75. This arrangement can serve as a single-ended power amplifier to feed a low impedance speaker from a relatively high resistance source. The two transistors in the output

circuit are operated in the grounded emitter connection. Therefore, the phase of the input signal is reversed in going from base to collector. The base of the last stage is connected directly to the collector output circuit of the input stage. Since the signal also undergoes phase reversal in the first stage, the output of the transistors on each side of the load are in phase. The stability of this circuit is very high because it incorporates 100 percent degenerative feedback. The large amount of feedback keeps the distortion very low, and also allows the load to be very small. Since the circuit is in effect a two-stage Class B push-pull amplifier, the standby collector dissipation is negligible. The amplifier is capable of delivering a constant a-c output of about 400 milliwatts using transistors rated at 100 milliwatts. In intermittent short term operation, the same amplifier can deliver about a watt without damage to the transistors.

It is apparent that complementary-symmetry circuits offer considerable promise for further investigation. Their use in the field of high quality, low-cost portable audio systems is particularly attractive because the output can be fed directly into a voice coil, thus eliminating the expensive and often troublesome output transformer.

# UNIT 5 : OSCILLATOR

## 5.1. LC Oscillator Basics

### a. INTRODUCTION

Oscillators are used in many electronic circuits and systems providing the central "clock" signal that controls the sequential operation of the entire system. Oscillators convert a DC input (the supply voltage) into an AC output (the waveform), which can have a wide range of different wave shapes and frequencies that can be either complicated in nature or simple sine waves depending upon the application.

Oscillators are also used in many pieces of test equipment producing either sinusoidal sine waves, square, saw tooth or triangular shaped waveforms or just a train of pulses of a variable or constant width. LC Oscillators are commonly used in radio-frequency circuits because of their good phase noise characteristics and their ease of implementation.

An Oscillator is basically an Amplifier with "Positive Feedback", or regenerative feedback (in-phase) and one of the many problems in electronic circuit design is stopping amplifiers from oscillating while trying to get oscillators to oscillate.

Oscillators work because they overcome the losses of their feedback resonator circuit either in the form of a capacitor, inductor or both in the same circuit by applying DC energy at the required frequency into this resonator circuit. In other words, an oscillator is an amplifier which uses positive feedback that generates an output frequency without the use of an input signal. It is self sustaining.

Then an oscillator has a small signal feedback amplifier with an open-loop gain equal to or slightly greater than one for oscillations to start but to continue oscillations the average loop gain must return to unity. In addition to these reactive components, an amplifying device such as an Operational Amplifier or Bipolar Transistor is required. Unlike an amplifier there is no external AC input required to cause the Oscillator to work as the DC supply energy is converted by the oscillator into AC energy at the required frequency.

### Basic Oscillator Feedback Circuit

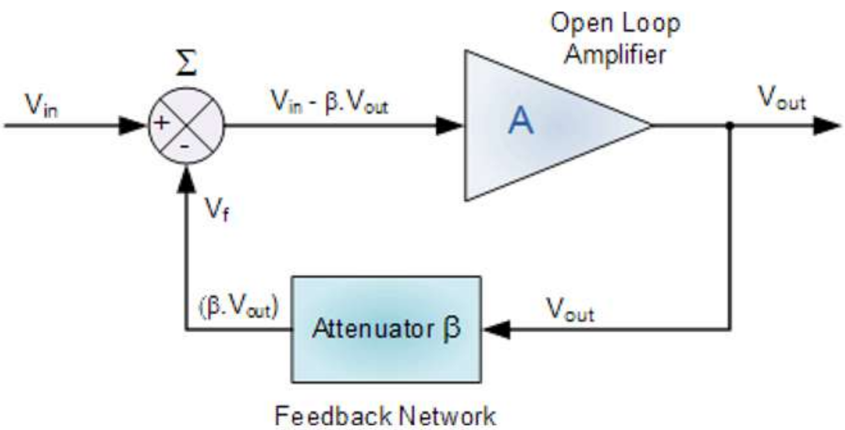



Fig 5.1 *Where: β is a feedback fraction.*

Oscillators are circuits that generate a continuous voltage output waveform at a required frequency with the values of the inductors, capacitors or resistors forming a frequency selective LC resonant tank circuit and feedback network. This feedback network is an attenuation network which has a gain of less than one ($\beta < 1$) and starts oscillations when $A\beta > 1$ which returns to unity ($A\beta = 1$) once oscillations commence.

The LC oscillators frequency is controlled using a tuned or resonant inductive/capacitive (LC) circuit with the resulting output frequency being known as the Oscillation Frequency. By making the oscillators feedback a reactive network the phase angle of the feedback will vary as a function of frequency and this is called Phase-shift.

There are basically types of Oscillators

## 1. SINUSOIDAL OSCILLATORS

These are known as Harmonic Oscillators and are generally a "LC Tuned-feedback" or "RC tuned-feedback" type Oscillator that generates a purely sinusoidal waveform which is of constant amplitude and frequency.

## 2. NON-SINUSOIDAL OSCILLATORS

These are known as Relaxation Oscillators and generate complex non-sinusoidal waveforms that changes very quickly from one condition of stability to another such as "Square-wave", "Triangular-wave" or "Sawtoothed-wave" type waveforms.

## SUMMARY

The basic conditions required for an LC oscillator resonant tank circuit are given as follows.

- For oscillations to exist an oscillator circuit MUST contain a reactive (frequency-dependant) component either an"Inductor", (L) or a "Capacitor", (C) as well as a DC power source.
- In a simple inductor-capacitor, LC circuit, oscillations become damped over time due to component and circuit losses.
- Voltage amplification is required to overcome these circuit losses and provide positive gain.
- The overall gain of the amplifier must be greater than one, unity.
- Oscillations can be maintained by feeding back some of the output voltage to the tuned circuit that is of the correct amplitude and in-phase, ($0^o$).
- Oscillations can only occur when the feedback is "Positive" (self-regeneration).
- The overall phase shift of the circuit must be zero or $360^o$ so that the output signal from the feedback network will be "in-phase" with the input signal.

## 5.2. THE COLPITTS OSCILLATOR

The Colpitts Oscillator, named after its inventor Edwin Colpitts is another type of LC oscillator design. In many ways, the Colpitts oscillator is the exact opposite of the Hartley Oscillator we looked at in the previous tutorial. Just like the Hartley oscillator, the tuned tank circuit consists of an LC resonance sub-circuit connected between the collector and the base of asingle stage transistor amplifier producing a sinusoidal output waveform.

The basic configuration of the Colpitts Oscillator resembles that of the Hartley Oscillator but the difference this time is that the centre tapping of the tank sub-circuit is now made at the junction of a "capacitive voltage divider" network instead of a tapped autotransformer type inductor as in the Hartley oscillator.

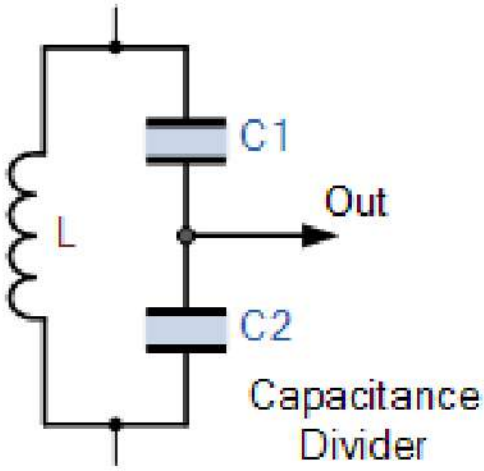



Fig 5.2: The Colpitts Oscillator

## TANK CIRCUIT

The Colpitts Oscillator uses a capacitor voltage divider as its feedback source. The two capacitors, C1 and C2 are placed across a common inductor, L as shown so that C1, C2 and L forms the tuned tank circuit the same as for the Hartley oscillator circuit.

The advantage of this type of tank circuit configuration is that with less self and mutual inductance in the tank circuit, frequency stability is improved along with a more simple design.

As with the Hartley oscillator, the Colpitts oscillator uses a single stage bipolar transistor amplifier as the gain element which produces a sinusoidal output. Consider the circuit below.

## Basic Colpitts Oscillator Circuit

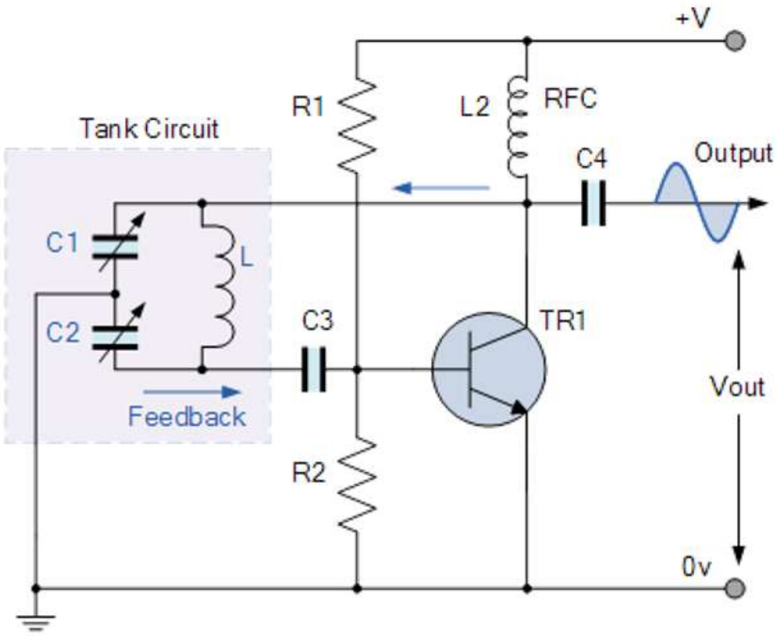



Fig 5.3

The transistor amplifiers emitter is connected to the junction of capacitors, C1 and C2 which are connected in series and act as a simple voltage divider. When the power supply is firstly applied, capacitors C1 and C2 charge up and then discharge through the coil L. The oscillations across the capacitors are applied to the base-emitter junction and appear in the amplified at the collector output.

The amount of feedback depends on the values of C1 and C2 with the smaller the values of C the greater will be the feedback.

The required external phase shift is obtained in a similar manner to that in the Hartley oscillator circuit with the required positive feedback obtained for sustained undamped oscillations. The amount of feedback is determined by the ratio of C1 and C2. These two capacitances are generally "ganged" together to provide a constant amount of feedback so that as one is adjusted the other automatically follows.

The frequency of oscillations for a Colpitts oscillator is determined by the resonant frequency of theLC tank circuit and is given as:

$$f_r = \frac{1}{2\pi\sqrt{LC_T}}$$

The configuration of the transistor amplifier is of a Common Emitter Amplifier with the output signal $180^o$ out of phase with regards to the input signal. The additional $180^o$ phase shift require for oscillation is achieved by the fact that the two capacitors are connected together in series but in parallel with the inductive coil resulting in overall phase shift of the circuit being zero or $360^o$.

Resistors, R1 and R2 provide the usual stabilizing DC bias for the transistor in the normal manner while the capacitor acts as a DC-blocking capacitors. The radio-frequency choke (RFC) is used to provide a high reactance (ideally open circuit) at the frequency of oscillation, ($f_r$) and a low resistance at DC.

## SUMMARY

Then to summarise, the Colpitts Oscillator consists of a parallel LC resonator tank circuit whose feedback is achieved by way of a capacitive divider. Like most oscillator circuits, theColpitts oscillator exists in several forms, with the most common form being the transistor circuit above.

The centre tapping of the tank sub-circuit is made at the junction of a "capacitive voltage divider" network to feed a fraction of the output signal back to the emitter of the transistor. The two capacitors in series produce a $180^o$ phase shift which is inverted by another $180^o$ to produce the required positive feedback. The oscillating frequency which is a purer sine-wave voltage is determined by the resonance frequency of the tank circuit.

## 5.3 THE HARTLEY OSCILLATOR

One of the main disadvantages of the basic LC Oscillator circuit we looked at in the previous tutorial is that they have no means of controlling the amplitude of the oscillations and also, it is difficult to tune the oscillator to the required frequency. If the cumulative electromagnetic coupling between L1 and L2 is too small there would be insufficient feedback and the oscillations would eventually die away to zero.

Likewise if the feedback was too strong the oscillations would continue to increase in amplitude until they were limited by the circuit conditions producing signal distortion. So it becomes very difficult to "tune" the oscillator.

However, it is possible to feed back exactly the right amount of voltage for constant amplitude oscillations. If we feed back more than is necessary the amplitude of the oscillations can be controlled by biasing the amplifier in such a way that if the oscillations increase in amplitude, the bias is increased and the gain of the amplifier is reduced.

If the amplitude of the oscillations decreases the bias decreases and the gain of the amplifier increases, thus increasing the feedback. In this way the amplitude of the oscillations are kept constant using a process known as Automatic Base Bias.

One big advantage of automatic base bias in a Voltage Controlled Oscillator, is that the oscillator can be made more efficient by providing a Class-B bias or even a Class-C bias condition of the transistor. This has the advantage that the collector current only flows during part of the oscillation cycle so the quiescent collector current is very small. Then this "self-tuning" base oscillator circuit forms one of the most common types of LC parallel resonant feedback oscillator configurations called the Hartley Oscillator circuit.

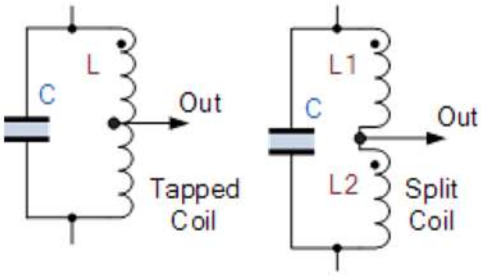



Fig 5.4. Hartley Oscillator Tank Circuit

In the Hartley Oscillator the tuned LC circuit is connected between the collector and the base of a transistor amplifier. As far as the oscillatory voltage is concerned, the emitter is connected to a tapping point on the tuned circuit coil.

The feedback part of the tuned LC tank circuit is taken from the centre tap of the inductor coil or even two separate coils in series which are in parallel with a variable capacitor, C as shown.

The Hartley circuit is often referred to as a split-inductance oscillator because coil L is centre-tapped. In effect, inductance L acts like two separate coils in very close proximity with the current flowing through coil section XY induces a signal into coil section YZ below.

An Hartley Oscillator circuit can be made from any configuration that uses either a single tapped coil (similar to an autotransformer) or a pair of series connected coils in parallel with a single capacitor as shown below.

## Basic Hartley Oscillator Design

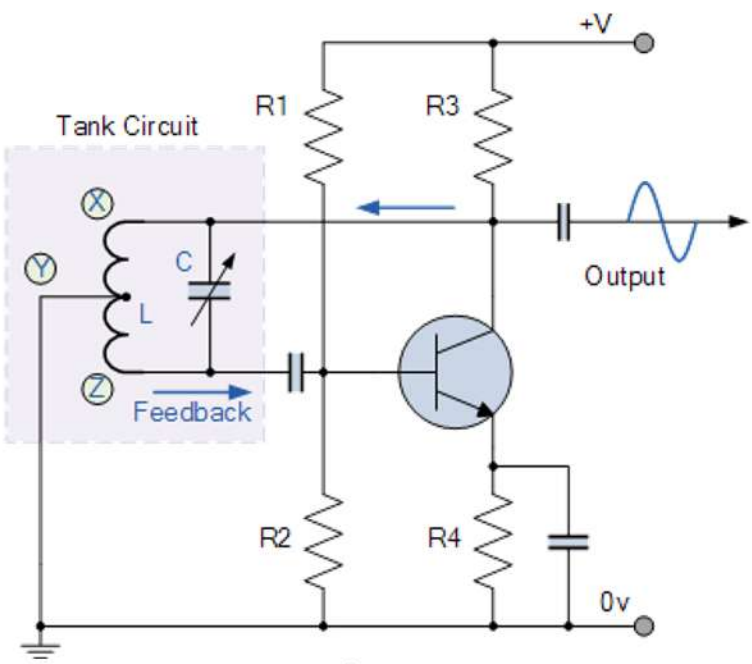



Fig 5.5

When the circuit is oscillating, the voltage at point X (collector), relative to point Y (emitter), is 180°out-of-phase with the voltage at point Z (base) relative to point Y. At the frequency of oscillation, the impedance of the Collector load is resistive and an increase in Base voltage causes a decrease in the Collector voltage. Then there is a 180° phase change in the voltage between the Base and Collector and this along with the original 180° phase shift in the feedback loop provides the correct phase relationship of positive feedback for oscillations to be maintained.

The amount of feedback depends upon the position of the "tapping point" of the inductor. If this is moved nearer to the collector the amount of feedback is increased, but the output taken between the Collector and earth is reduced and vice versa. Resistors, R1 and R2 provide the usual stabilizing DC bias for the transistor in the normal manner while the capacitors act as DC-blocking capacitors.

In this Hartley Oscillator circuit, the DC Collector current flows through part of the coil and for this reason the circuit is said to be "Series-fed" with the frequency of oscillation of the Hartley Oscillator being given as.

$$f = \frac{1}{2\pi\sqrt{L_T C}}$$

Where : $L_T = L_1 + L_2 + 2M$

NOTE: $L_T$ is the total cumulatively coupled inductance if two separate coils are used including their mutual inductance, M.

The frequency of oscillations can be adjusted by varying the "tuning" capacitor, C or by varying the position of the iron-dust core inside the coil (inductive tuning) giving an output over a wide range of frequencies making it very easy to tune. Also the Hartley Oscillator produces an output amplitude which is constant over the entire frequency range.

## SUMMARY

Then to summarise, the Hartley Oscillator consists of a parallel LC resonator tank circuit whose feedback is achieved by way of an inductive divider. Like most oscillator circuits, the Hartley oscillator exists in several forms, with the most common form being the transistor circuit above.

This Hartley Oscillator configuration has a tuned tank circuit with its resonant coil tapped to feed a fraction of the output signal back to the emitter of the transistor. Since the output of the transistors emitter is always "in-phase" with the output at the collector, this feedback signal is positive. The oscillating frequency which is a sine-wave voltage is determined by the resonance frequency of the tank circuit.

## 5.4. THE RC OSCILLATOR

In our series of tutorials about Amplifiers, we saw that a single stage amplifier will produce 180$^o$ of phase shift between its output and input signals when connected in a class-A type configuration. For an oscillator to sustain oscillations indefinitely, sufficient feedback of the correct phase, ie, "Positive Feedback" must be provided with the amplifier being used as one inverting stage to achieve this.

In an RC Oscillator circuit the input is shifted 180$^o$ through the amplifier stage and 180$^o$ again through a second inverting stage giving us "180$^o$ + 180$^o$ = 360$^o$" of phase shift which is effectively the same as 0$^o$ thereby giving us the required positive feedback. In other words, the phase shift of the feedback loop should be "0".

In a Resistance-Capacitance Oscillator or simply an RC Oscillator, we make use of the fact that a phase shift occurs between the input to a RC network and the output from the same network by using RC elements in the feedback branch, for example.

RC Phase-Shift Network

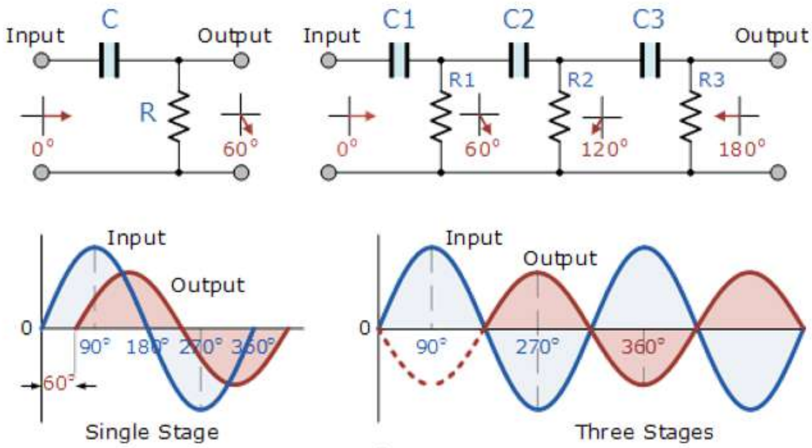



Fig 5.6

The circuit on the left shows a single Resistor-Capacitor Network whose output voltage "leads" the input voltage by some angle less than 90$^o$. An ideal single-pole RC circuit would produce a phase shift of exactly 90$^o$, and because 180$^o$ of phase shift is required for oscillation, at least two single-poles must be used in an RC oscillator design.

However in reality it is difficult to obtain exactly 90$^o$ of phase shift so more stages are used. The amount of actual phase shift in the circuit depends upon the values of the resistor and the capacitor, and the chosen frequency of oscillations with the phase angle ( Φ ) being given as:

RC Phase Angle

$$X_C = \frac{1}{2 \pi f C} \qquad R = R$$

$$Z = \sqrt{R^2 + (XC)^2}$$

$$\therefore \phi = \tan^{-1} \frac{X_C}{R}$$

## Basic RC Oscillator Circuit

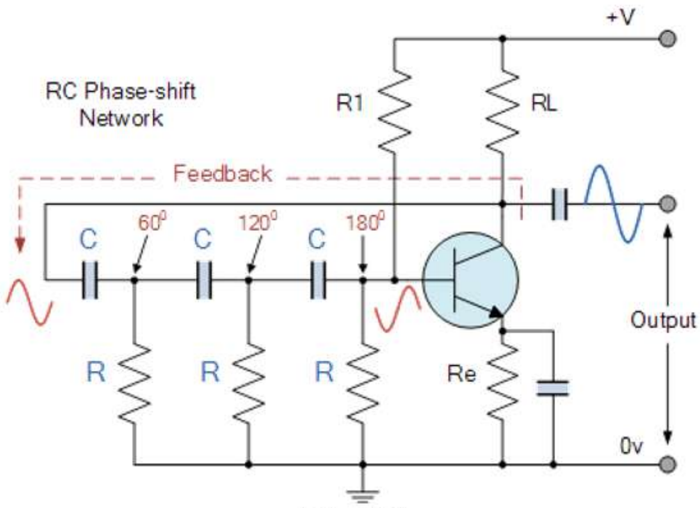



Fig 5.7

The basic RC Oscillator which is also known as a Phase-shift Oscillator, produces a sine wave output signal using regenerative feedback obtained from the resistor-capacitor combination. This regenerative feedback from the RC network is due to the ability of the capacitor to store an electric charge, (similar to the LC tank circuit).

This resistor-capacitor feedback network can be connected as shown above to produce a leading phase shift (phase advance network) or interchanged to produce a lagging phase shift (phase retard network) the outcome is still the same as the sine wave oscillations only occur at the frequency at which the overall phase-shift is $360^o$.

By varying one or more of the resistors or capacitors in the phase-shift network, the frequency can be varied and generally this is done by keeping the resistors the same and using a 3-ganged variable capacitor.

If all the resistors, R and the capacitors, C in the phase shift network are equal in value, then the frequency of oscillations produced by the RC oscillator is given as:

$$f_r = \frac{1}{2\pi RC\sqrt{2N}}$$

Where:
$f_r$ is the Output Frequency in Hertz

R is the Resistance in Ohms
C is the Capacitance in Farads
N is the number of RC stages. (N = 3)

Since the resistor-capacitor combination in the RC Oscillator circuit also acts as an attenuator producing an attenuation of -1/29th ( $V_o/V_i = \beta$ ) per stage, the gain of the amplifier must be sufficient to overcome the circuit losses. Therefore, in our three stage RC network above the amplifier gain must be greater than 29.

The loading effect of the amplifier on the feedback network has an effect on the frequency of oscillations and can cause the oscillator frequency to be up to 25% higher than calculated. Then the feedback network should be driven from a high impedance output source and fed into a low impedance load such as a common emitter transistor amplifier but better still is to use an Operational Amplifier as it satisfies these conditions perfectly.

## UNIT 6: MULTIVIBRATORS

Individual Sequential Logic circuits can be used to build more complex circuits such as Multivibrators, Counters, Shift Registers, Latches and Memories etc, but for these types of circuits to operate in a "sequential" way, they require the addition of a clock pulse or timing signal to cause them to change their state. Clock pulses are generally continuous square or rectangular shaped waveform that is produced by a single pulse generator circuit such as aMultivibrator.

A multivibrator circuit oscillates between a "HIGH" state and a "LOW" state producing a continuous output. Astablemultivibrators generally have an even 50% duty cycle, that is that 50% of the cycle time the output is "HIGH" and the remaining 50% of the cycle time the output is "OFF". In other words, the duty cycle for an actable timing pulse is 1:1.

Sequential Logic Circuits that use the clock signal for synchronization are dependent upon the frequency and clock pulse width to activate there switching action. Sequential circuits may also change their state on either the rising or falling edge, or both of the actual clock signals as we have seen previously with the basic flip-flop circuits. The following lists are terms associated with a timing pulse or waveform.

### ACTIVE HIGH

If the state change occurs from a "LOW" to a "HIGH" at the clock's pulse rising edge or during the clock width.

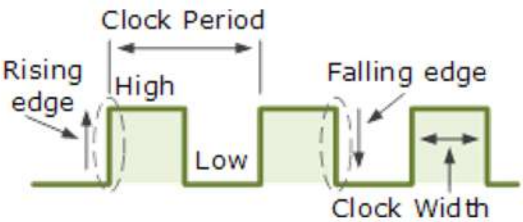



Fig 6.1 : Clock Signal Waveform

### ACTIVE LOW

If the state change occurs from a "HIGH" to a "LOW" at the clock's pulses falling edge.

### DUTY CYCLE

This is the ratio of the clock width to the clock period.

### CLOCK WIDTH

This is the time during which the value of the clock signal is equal to a logic "1", or HIGH.

### CLOCK PERIOD

This is the time between successive transitions in the same direction, i.e. between two rising or two falling edges.

## CLOCK FREQUENCY

The clock frequency is the reciprocal of the clock period, frequency = 1/clock period

Clock pulse generation circuits can be a combination of analogue and digital circuits that produce a continuous series of pulses (these are called astablemultivibrators) or a pulse of a specific duration (these are called monostable multivibrators). Combining two or more of multivibrators provides generation of a desired pattern of pulses (including pulse width, time between pulses and frequency of pulses).

There are basically three types of clock pulse generation circuits:

## 1. ASTABLE

A free-running multivibrator that has NO stable states but switches continuously between two states this action produces a train of square wave pulses at a fixed frequency.

## 2. MONOSTABLE

A one-shot multivibrator that has only ONE stable state and is triggered externally with it returning back to its first stable state.

## 3.BISTABLE

A flip-flop that has TWO stable states that produces a single pulse either positive or negative in value.

One way of producing a very simple clock signal is by the interconnection of logic gates. As NAND gates contains amplification, they can also be used to provide a clock signal or timing pulse with the aid of a single Capacitor and a single Resistor to provide the feedback and timing function.

These timing circuits are often used because of their simplicity and are also useful if a logic circuit is designed that has unused gates which can be utilised to create the monostable or actable oscillator. This simple type of RC Oscillator network is sometimes called a "Relaxation Oscillator".

## 6.1. ASTABLE MULTIVIBRATOR CIRCUITS

Astable Multivibrators are the most commonly used type of multivibrator circuit. An astable multivibrator is a free running oscillator that have no permanent "meta" or "steady" state but are continually changing their output from one state (LOW) to the other state (HIGH) and then back again. This continual switching action from "HIGH" to "LOW" and "LOW" to "HIGH" produces a continuous and stable square wave output that switches abruptly between the two logic levels making it ideal for timing and clock pulse applications.

As with the previous monostable multivibrator circuit above, the timing cycle is determined by the RC time constant of the resistor-capacitor, RC Network. Then the output frequency can be varied by changing the value(s) of the resistors and capacitor in the circuit.

## NAND Gate Astable Multivibrator

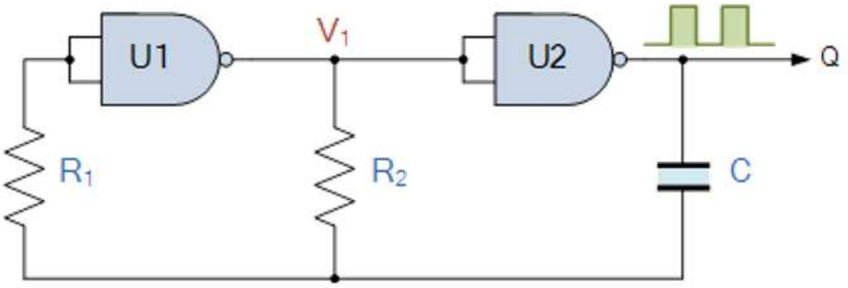



Fig 6.2

The astable multivibrator circuit uses two CMOS NOT gates such as the CD4069 or the 74HC04 hex inverter ICs, or as in our simple circuit below a pair of CMOS NAND such as the CD4011 or the 74LS132 and an RC timing network. The two NAND gates are connected as inverting NOT gates.

Suppose that initially the output from the NAND gate U2 is HIGH at logic level "1", then the input must therefore be LOW at logic level "0" (NAND gate principles) as will be the output from the first NAND gate U1. Capacitor, C is connected between the output of the second NAND gate U2 and its input via the timing resistor, $R_2$. The capacitor now charges up at a rate determined by the time constant of $R_2$ and C.

As the capacitor, C charges up, the junction between the resistor $R_2$ and the capacitor, C, which is also connected to the input of the NAND gate U1 via the stabilizing resistor, $R_2$ decreases until the lower threshold value of U1 is reached at which point U1 changes state and the output of U1 now becomes HIGH. This causes NAND gate U2 to also change state as its input has now changed from logic "0" to logic "1" resulting in the output of NAND gate U2 becoming LOW, logic level "0".

Capacitor C is now reverse biased and discharges itself through the input of NAND gate U1. Capacitor, C charges up again in the opposite direction determined by the time constant of both $R_2$and C as before until it reaches the upper threshold value of NAND gate U1. This causes U1 to change state and the cycle repeats itself over again.

Then, the time constant for a NAND gate Astable Multivibrator is given as T = 2.2RC in seconds with the output frequency given as f = 1/T.

FOR EXAMPLE

If the resistor $R_2 = 10k\Omega$ and the capacitor C = 45nF, the oscillation frequency of the circuit would be given as:

$$f = \frac{1}{T} = \frac{1}{2.2\,RC} = \frac{1}{2.2 \times 10\ k\Omega \times 45\,nF} = 1\ kHz$$

Then the output frequency is calculated as being 1kHz, which equates to a time constant of 1mS so the output waveform would look like:

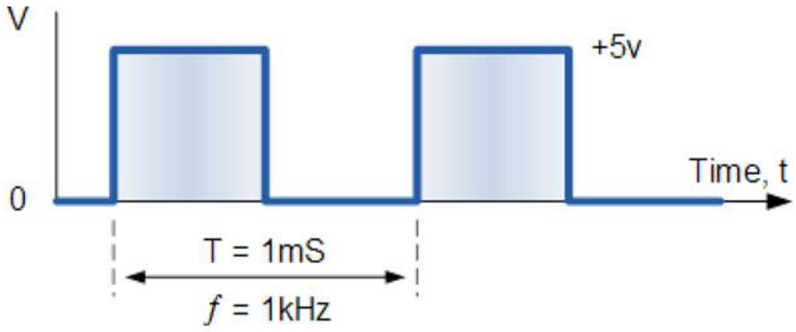



Fig 6.3

## 6.2. MONOSTABLE MULTIVIBRATOR CIRCUITS

Monostable Multivibrators or "one-shot" pulse generators are generally used to convert short sharp pulses into wider ones for timing applications. Monostable multivibrators generate a single output pulse, either "HIGH" or "LOW", when a suitable external trigger signal or pulse T is applied.

This trigger pulse signal initiates a timing cycle which causes the output of the monostable to change state at the start of the timing cycle, ( $t_1$ ) and remain in this second state until the end of the timing period, ( $t_2$ ) which is determined by the time constant of the timing capacitor, $C_T$ and the resistor, $R_T$. The monostable multivibrator now stays in this second timing state until the end of the RC time constant and automatically resets or returns itself back to its original (stable) state. Then, a monostable circuit has only one stable state. A more common name for this type of circuit is simply a "Flip-Flop" as it can be made from two cross-coupled NAND gates (or NOR gates) as we have seen previously. Consider the circuit below.

Simple NAND Gate Monostable Circuit

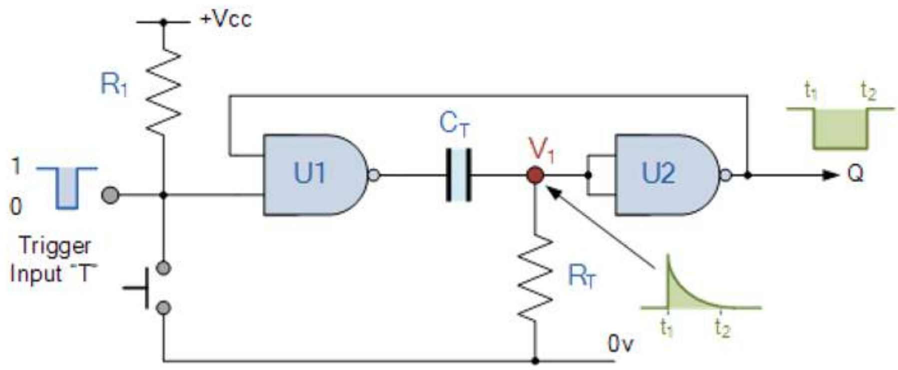



Fig 6.4

Suppose that initially the trigger input T is held HIGH at logic level "1" by the resistor $R_1$ so that the output from the first NAND gate U1 is LOW at logic level "0", (NAND gate principals). The timing resistor, $R_T$ is connected to a voltage level equal to logic level "0", which will cause the capacitor, $C_T$to be discharged. The output of U1 is LOW, timing capacitor $C_T$ is completely discharged therefore junction V1 is also equal to "0" resulting in the output from the second NAND gate U2, which is connected as an inverting NOT gate will therefore be HIGH.

The output from the second NAND gate, ( U2 ) is fed back to one input of U1 to provide the necessary positive feedback. Since the junctionV1 and the output of U1 are both at logic "0" no current flows in the capacitor $C_T$. This result in the circuit being Stable and it will remain in this state until the trigger input T changes.

If a negative pulse is now applied either externally or by the action of the push-button to the trigger input of the NAND gate the NAND gate U1, the output of U1 will go HIGH to logic "1" (NAND gate principles).

Since the voltage across the capacitor cannot change instantaneously (capacitor charging principals) this will cause the junction at V1 and also the input to U2 to also go HIGH, which in turn will make the output of the NAND gate U2 change LOW to logic "0" The circuit will now remain in this second state even if the trigger input pulse T is removed. This is known as the Meta-stable state.

The voltage across the capacitor will now increase as the capacitor $C_T$ starts to charge up from the output of U1 at a time constant determined by the resistor/capacitor combination. This charging process continues until the charging current is unable to hold the input of U2 and therefore junction V1 HIGH.

When this happens, the output of U2 switches HIGH again, logic "1", which in turn causes the output of U1 to go LOW and the capacitor discharges into the output of U1 under the influence of resistor $R_T$. The circuit has now switched back to its original stable state.

Thus for each negative going trigger pulse, the monostable multivibrator circuit produces a LOW going output pulse. The length of the output time period is determined by the capacitor/resistor combination (RC Network) and is given as the Time Constant T = 0.69RC of the circuit in seconds. Since the input impedance of the NAND gates is very high, large timing periods can be achieved.

As well as the NAND gate monostable type circuit above, it is also possible to build simple monostable timing circuits that start their timing sequence from the rising-edge of the trigger pulse using NOT gates, NAND gates and NOR gates connected as inverters as shown below.

NOT GATE MONOSTABLE MULTIVIBRATOR

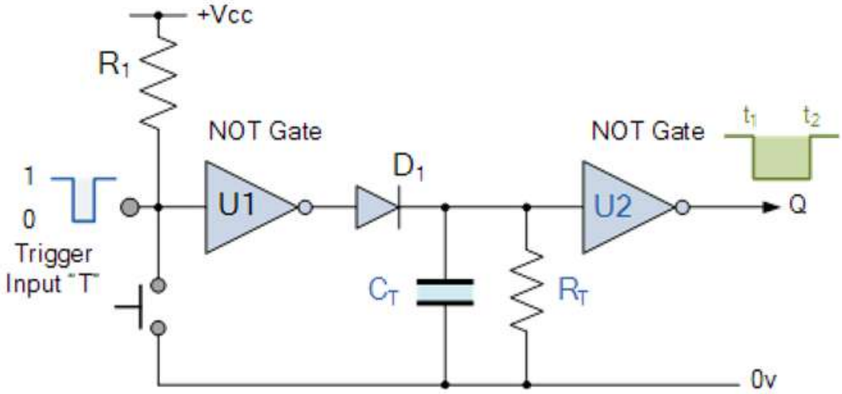



Fig 6.5

As with the NAND gate circuit above, initially the trigger input T is HIGH at a logic level "1" so that the output from the first NOT gateU1 is LOW at logic level "0". The timing resistor, $R_T$ and the capacitor, $C_T$ are connected together in parallel and also to the input of the second NOT gate U2. As the input to U2 is LOW at logic "0" its output at Q is HIGH at logic "1".

When a logic level "0" pulse is applied to the trigger input T of the first NOT gate it changes state and produces a logic level "1" output. The diode D1 passes this logic "1" voltage level to the RCtiming network. The voltage across the capacitor, $C_T$ increases rapidly to this new voltage level, which is also connected to the input of the second NOT gate. This in turn outputs a logic "0" at And the circuit stays in this Meta-stable state as long as the trigger input T applied to the circuit remains LOW.

When the trigger signal returns HIGH, the output from the first NOT gate goes LOW to logic "0" (NOT gate principals) and the fully charged capacitor, $C_T$ starts to discharge itself through the parallel resistor, $R_T$ connected across it. When the voltage across the capacitor drops below the lower threshold value of the input to the second NOT gate, its output switches back again producing a logic level "1" at Q. The diode D1 prevents the timing capacitor from discharging itself back through the first NOT gates output.

Then, the Time Constant for a NOT gate Monostable Multivibrator is given
as T = 0.8RC + Triggering seconds.

One main disadvantage of Monostable Multivibrators is that the time between the application of the next trigger pulse T has to be greater than the RC time constant of the circuit.

## 6.3. BISTABLE MULTIVIBRATOR CIRCUITS

The Bistable Multivibrators circuit is basically a SR flip-flop that we look at in the previous tutorials with the addition of an inverter or NOT gate to provide the necessary switching function. As with flip-flops, both states of a bistable multivibrator are stable, and the circuit will remain in either state indefinitely. This type of multivibrator circuit passes from one state to the other "only" when a suitable external trigger pulse T is applied and to go through a full "SET-RESET" cycle two triggering pulses are required. This type of circuit is also known as a "Bistable Latch", "Toggle Latch" or simply "T-latch".

## NAND Gate Bistable Multivibrator

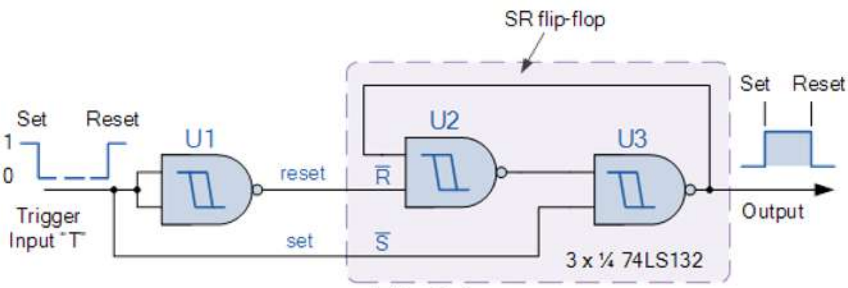



Fig 6.6

The simplest way to make a Bistable Latch is to connect together a pair of Schmitt NAND gates to form a SR latch as shown above. The two NAND gates, U2 and U3 form the bistable which is triggered by the input NAND gate, U1. This U1 NAND gate can be omitted and replaced by a single toggle switch to make a switch denounce circuit as seen previously in the SR Flip-flop tutorial.

When the input pulse goes "LOW" the bistable latches into its "SET" state, with its output at logic level "1", until the input goes "HIGH" causing the bistable to latch into its "RESET" state, with its output at logic level "0". The output of a bistable multivibrator will stay in this "RESET" state until another input pulse is applied and the whole sequence will start again.

Then a Bistable Latch or "Toggle Latch" is a two-state device in which both states either positive or negative, (logic "1" or logic "0") are stable.

Bistable Multivibrators have many applications such as frequency dividers, counters or as a storage device in computer memories but they are best used in circuits such as Latches andCounters.

# UNIT 7: FLIP FLOP

## 7.1. SR FLIP-FLOP

The SR flip-flop, also known as a SR Latch, can be considered as one of the most basic sequential logic circuit possible. This simple flip-flop is basically a one-bit memory bistable device that has two inputs, one which will "SET" the device (meaning the output = "1"), and is labelled S and another which will "RESET" the device (meaning the output = "0"), labelled R.

Then the SR description stands for "Set-Reset". The reset input resets the flip-flop back to its original state with an output Q that will be either at a logic level "1" or logic "0" depending upon this set/reset condition.

A basic NAND gate SR flip-flop circuit provides feedback from both of its outputs back to its opposing inputs and is commonly used in memory circuits to store a single data bit. Then the SR flip-flop actually has three inputs, Set, Reset and its current output Q relating to it's current state or history. The term "Flip-flop" relates to the actual operation of the device, as it can be "flipped" into one logic Set state or "flopped" back into the opposing logic Reset state.

## THE NAND GATE SR FLIP-FLOP

The simplest way to make any basic single bit set-reset SR flip-flop is to connect together a pair of cross-coupled 2-input NAND gates as shown, to form a Set-Reset Bistable also known as an active LOW SR NAND Gate Latch, so that there is feedback from each output to one of the other NANDgate inputs. This device consists of two inputs, one called the Set, S and the other called the Reset,R with two corresponding outputs Q and its inverse or complement Q (not-Q) as shown below.

## THE BASIC SR FLIP-FLOP

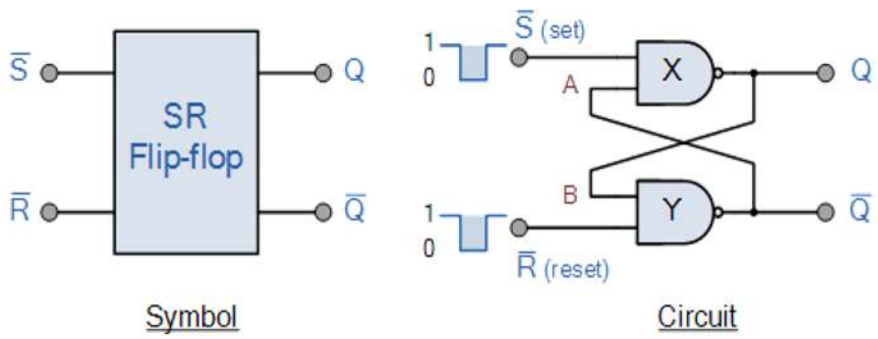



Fig 7.1

## THE SET STATE

Consider the circuit shown above. If the input R is at logic level "0" (R = 0) and input S is at logic level "1" (S = 1), the NAND gate Y has at least one of its inputs at logic "0" therefore, its output Q must be at a logic level "1" (NAND Gate principles). Output Q is also fed back to input "A" and so both inputs to NAND gate X are at logic level "1", and therefore its output Q must be at logic level "0".

Again NAND gate principals. If the reset input R changes state, and goes HIGH to logic "1" with remaining HIGH also at logic level "1", NAND gate Y inputs are now R = "1" and B = "0". Since one of its inputs is still at logic level "0" the output at Q still remains HIGH at logic level "1" and there is no change of state. Therefore, the flip-flop circuit is said to be "Latched" or "Set" with Q = "1" and Q = "0".

## RESET STATE

In this second stable state, Q is at logic level "0", (not Q = "0") its inverse output at Q is at logic level "1", (Q = "1"), and is given by R = "1" and S = "0". As gate X has one of its inputs at logic "0" its output Q must equal logic level "1" (again NAND gate principles). Output Q is fed back to input "B", so both inputs to NAND gate Y are at logic "1", therefore, Q = "0".

If the set input, S now changes state to logic "1" with input R remaining at logic "1", output Q still remains LOW at logic level "0" and there is no change of state. Therefore, the flip-flop circuits "Reset" state has also been latched and we can define this "set/reset" action in the following truth table.

### TRUTH TABLE FOR THIS SET-RESET FUNCTION

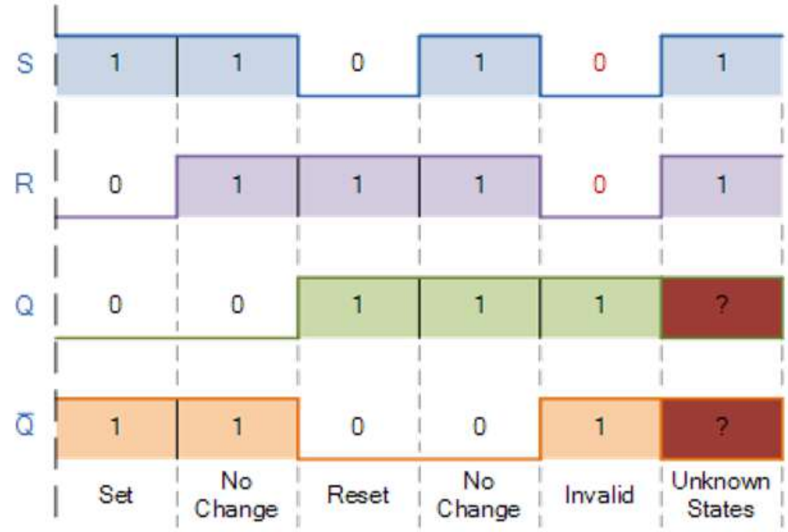
| State | S | R | Q | Q | Description |
|---|---|---|---|---|---|
| Set | 1 | 0 | 0 | 1 | Set Q » 1 |
| | 1 | 1 | 0 | 1 | No Change |
| Reset | 0 | 1 | 1 | 0 | Reset Q » 0 |
| | 1 | 1 | 1 | 0 | No Change |
| Invalid | 0 | 0 | 1 | 1 | Invalid Condition |

It can be seen that when both inputs S = "1" and R = "1" the outputs Q and Q can be at either logic level "1" or "0", depending upon the state of the inputs S or R BEFORE this input condition existed. Therefore the condition of S = R = "1" does not change the state of the outputs Q and Q.

However, the input state of S = "0" and R = "0" is an undesirable or invalid condition and must be avoided. The condition of S = R = "0" causes both outputs Q and Q to be HIGH together at logic level "1" when we would normally want Q to be the inverse of Q. The result is that the flip-flop loses control of Q and Q, and if the two inputs are now switched "HIGH" again after this condition to logic

"1", the flip-flop becomes unstable and switches to an unknown data state based upon the unbalance as shown in the following switching diagram.

## S-R FLIP-FLOP SWITCHING DIAGRAM

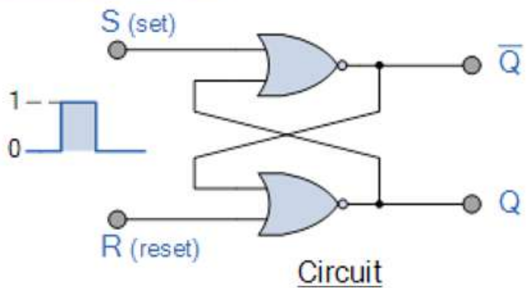



This unbalance can cause one of the outputs to switch faster than the other resulting in the flip-flop switching to one state or the other which may not be the required state and data corruption will exist. This unstable condition is generally known as its Meta-stable state.

Then, a bistable SR flip-flop or SR latch is activated or set by a logic "1" applied to its S input and deactivated or reset by a logic "1" applied to its R. The SR flip-flop is said to be in an "invalid" condition (Meta-stable) if both the set and reset inputs are activated simultaneously.

As well as using NAND gates, it is also possible to construct simple one-bit SR Flip-flops using two cross-coupled NOR gates connected in the same configuration. The circuit will work in a similar way to the NAND gate circuit above, except that the inputs are active HIGH and the invalid condition exists when both its inputs are at logic level "1", and this is shown below.

## THE NOR GATE SR FLIP-FLOP




Circuit

| S | R | Q | Q̄ |
|---|---|---|---|
| 0 | 0 | No change | |
| 0 | 1 | 0 | 1 |
| 1 | 0 | 1 | 0 |
| 1 | 1 | 0 | 0 (Invalid) |

Fig 7.2

## SWITCH DEBOUNCE CIRCUITS

Edge-triggered flip-flops require a nice clean signal transition, and one practical use of this type of set-reset circuit is as a latch used to help eliminate mechanical switch "bounce". As its name implies, switch bounce occurs when the contacts of any mechanically operated switch, push-button or keypad are operated and the internal switch contacts do not fully close cleanly, but bounce together first before closing (or opening) when the switch is pressed.

This gives rise to a series of individual pulses which can be as long as tens of milliseconds that an electronic system or circuit such as a digital counter may see as a series of logic pulses instead of one long single pulse and behave incorrectly. For example, during this bounce period the output voltage can fluctuate wildly and may register multiple input counts instead of one single count. Then set-reset SR Flip-flops or Bistable Latch circuits can be used to eliminate this kind of problem and this is demonstrated below.

## SR FLIP FLOP SWITCH DEBOUNCE CIRCUIT

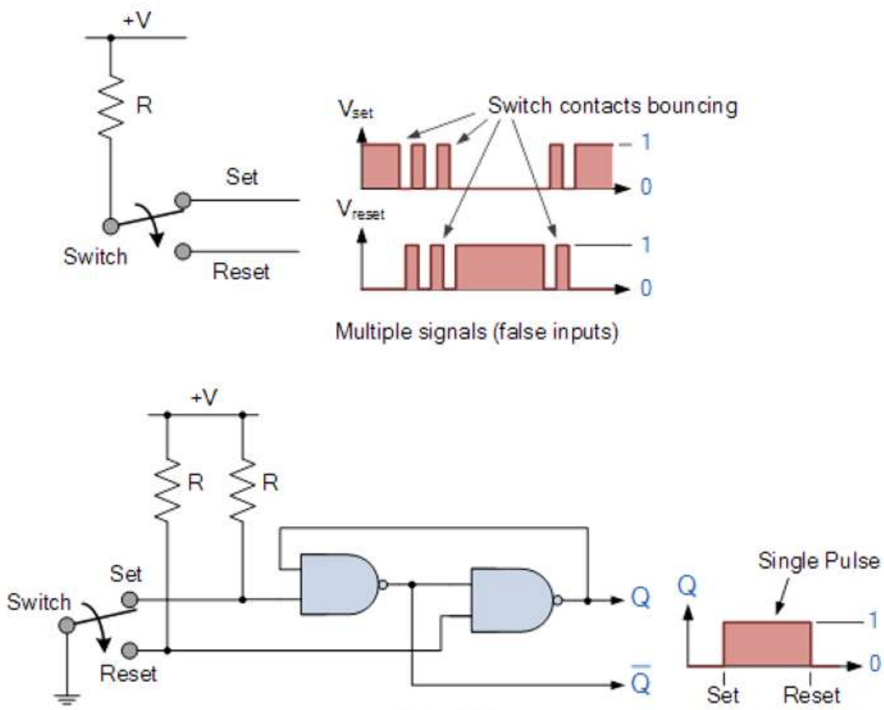



Fig 7.3

Depending upon the current state of the output, if the set or reset buttons are depressed the output will change over in the manner described above and any additional unwanted inputs (bounces) from the mechanical action of the switch will have no effect on the output at Q.

When the other button is pressed, the very first contact will cause the latch to change state, but any additional mechanical switch bounces will also have no effect. The SR flip-flop can then be RESET automatically after a short period of time, for example 0.5 seconds, so as to register any additional and intentional repeat inputs from the same switch contacts, such as multiple inputs from a keyboards "RETURN" key.

Commonly available IC's specifically made to overcome the problem of switch bounce are the MAX6816, single input, MAX6817, dual input and the MAX6818 octal input switch debouncer IC's. These chips contain the necessary flip-flop circuitry to provide clean interfacing of mechanical switches to digital systems.

Set-Reset bistable latches can also be used as Monostable (one-shot) pulse generators to generate a single output pulse, either high or low, of some specified width or time period for timing or control purposes. The 74LS279 is a Quad SR Bistable Latch IC, which contains four individual NAND type bistable's within a single chip enabling switch debounce or monostable/actable clock circuits to be easily constructed.

## 7.2 THE JK FLIP FLOP

From the previous tutorial we now know that the basic gated SR NAND flip flop suffers from two basic problems: number one, the S = 0 and R = 0 condition (S = R = 0) must always be avoided, and number two, if S or R change state while the enable input is high the correct latching action may not occur. Then to overcome these two fundamental design problems with the SR flip-flop design, the JK flip Flop was developed.

This simple JK flip Flop is the most widely used of all the flip-flop designs and is considered to be a universal flip-flop circuit. The sequential operation of the JK flip flop is exactly the same as for the previous SR flip-flop with the same "Set" and "Reset" inputs. The difference this time is that the "JK flip flop" has no invalid or forbidden input states of the SR Latch even when S and R are both at logic "1".

The JK flip flop is basically a gated SR Flip-flop with the addition of a clock input circuitry that prevents the illegal or invalid output condition that can occur when both inputs S and R are equal to logic level "1". Due to this additional clocked input, a JK flip-flop has four possible input combinations, "logic 1", "logic 0", "no change" and "toggle". The symbol for a JK flip flop is similar to that of an SR Bistable Latch as seen in the previous tutorial except for the addition of a clock input.

## THE BASIC JK FLIP-FLOP

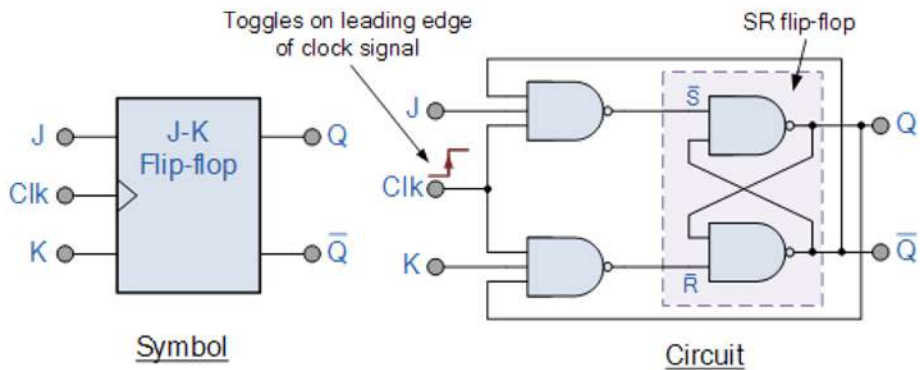



Fig 7.4

Both the S and the R inputs of the previous SR bistable have now been replaced by two inputs called the J and K inputs, respectively after its inventor Jack Kilby. Then this equates to: J = S andK = R. The two 2-input AND gates of the gated SR bistable have now been replaced by two 3-input NANDgates with the third input of each gate connected to the outputs at Q and Q. This cross coupling of the SR flip-flop allows the previously invalid condition of S = "1" and R = "1" state to be used to produce a "toggle action" as the two inputs are now interlocked.

If the circuit is now "SET" the J input is inhibited by the "0" status of Q through the lower NAND gate. If the circuit is "RESET" the K input is inhibited by the "0" status of Q through the upper NAND gate. As Q and Q are always different we can use them to control the input. When both inputs J and K are equal to logic "1", the JK flip flop toggles as shown in the following truth table.

THE TRUTH TABLE FOR THE JK FUNCTION

| | Input | | Output | | Description |
|---|---|---|---|---|---|
| | J | K | Q | Q | |
| Same as for the SR Latch | 0 | 0 | 0 | 0 | Memory No Change |
| | 0 | 0 | 0 | 1 | |
| | 0 | 1 | 1 | 0 | Reset Q » 0 |
| | 0 | 1 | 0 | 1 | |
| | 1 | 0 | 0 | 1 | Set Q » 1 |
| | 1 | 0 | 1 | 0 | |
| Toggle Action | 1 | 1 | 0 | 1 | Toggle |
| | 1 | 1 | 1 | 0 | |

Then the JK flip-flop is basically an SR flip flop with feedback which enables only one of its two input terminals, either SET or RESET to be active at any one time thereby eliminating the invalid condition seen previously in the SR flip flop circuit. Also when both the J and the K inputs are at logic level "1" at the same time, and the clock input is pulsed either "HIGH", the circuit will "toggle" from its SET state to a RESET state, or visa-versa. This results in the JK flip flop acting more like a T-type toggle flip-flop when both terminals are "HIGH".

Although this circuit is an improvement on the clocked SR flip-flop it still suffers from timing problems called "race" if the output Q changes state before the timing pulse of the clock input has time to go "OFF". To avoid this the timing pulse period (T) must be kept as short as possible (high frequency). As this is sometimes not possible with modern TTL IC's the much improved Master-Slave JK Flip-flop was developed.

The master-slave flip-flop eliminates all the timing problems by using two SR flip-flops connected together in a seriesconfiguration. One flip-flop acts as the "Master" circuit, which triggers on the leading edge of the clock pulse while the other acts as the "Slave" circuit, which triggers on the falling edge of the clock pulse. This results in the two sections, the master section and the slave section being enabled during opposite half-cycles of the clock signal.

The TTL 74LS73 is a Dual JK flip-flop IC, which contains two individual JK type bistable's within a single chip enabling single or master-slave toggle flip-flops to be made. Other JK flip flop IC's include the 74LS107 Dual JK flip-flop with clear, the 74LS109 Dual positive-edge triggered JK flip flop and the 74LS112 Dual negative-edge triggered flip-flop with both preset and clear inputs.

DUAL JK FLIP-FLOP 74LS73

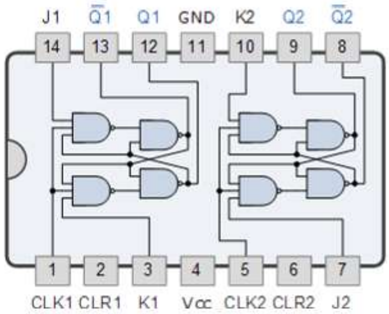



Fig 7.5

## THE MASTER-SLAVE JK FLIP-FLOP

The Master-Slave Flip-Flop is basically two gated SR flip-flops connected together in a series configuration with the slave having an inverted clock pulse. The outputs from Q and Q from the "Slave" flip-flop are fed back to the inputs of the "Master" with the outputs of the "Master" flip flop being connected to the two inputs of the "Slave" flip flop. This feedback configuration from the slave's output to the master's input gives the characteristic toggle of the JK flip flop as shown below.

### The Master-Slave Jk Flip Flop

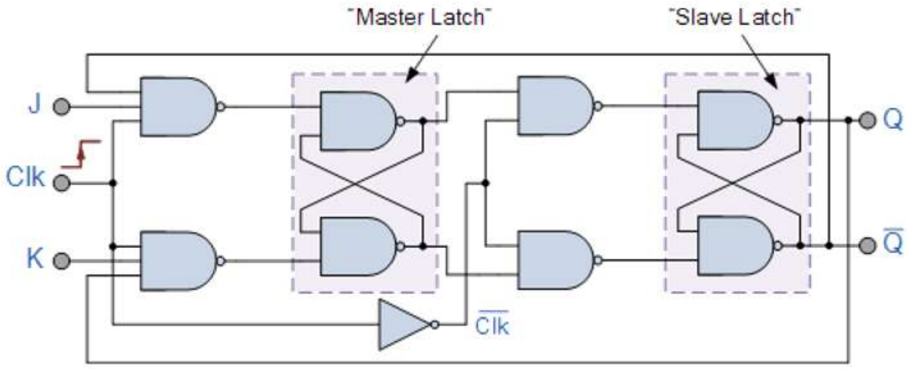



Fig 7.6

The input signals J and K are connected to the gated "master" SR flip flop which "locks" the input condition while the clock (Clk) input is "HIGH" at logic level "1". As the clock input of the "slave" flip flop is the inverse (complement) of the "master" clock input, the "slave" SR flip flop does not toggle. The outputs from the "master" flip flop are only "seen" by the gated "slave" flip flop when the clock input goes "LOW" to logic level "0".

When the clock is “LOW”, the outputs from the “master” flip flop are latched and any additional changes to its inputs are ignored. The gated “slave” flip flop now responds to the state of its inputs passed over by the “master” section.

Then on the “Low-to-High” transition of the clock pulse the inputs of the “master” flip flop are fed through to the gated inputs of the “slave” flip flop and on the “High-to-Low” transition the same inputs are reflected on the output of the “slave” making this type of flip flop edge or pulse-triggered.

Then, the circuit accepts input data when the clock signal is “HIGH”, and passes the data to the output on the falling-edge of the clock signal. In other words, the **Master-Slave JK Flip flop** is a “Synchronous”device as it only passes data with the timing of the clock signal.

# UNIT 8 : INTEGRATED CIRCUITS

## 8.1. INTRODUCTION OF ICS

Integrated circuits (ICs) are a keystone of modern electronics. They are the heart and brains of most circuits. They are the ubiquitous little black “chips” you find on just about every circuit board. Unless you’re some kind of crazy, analog electronics wizard, you’re likely to have at least one IC in every electronics project you build, so it’s important to understand them, inside and out.


**Fig 8.1 :Integrated circuits are the little black “chips”, found all over embedded electronics.**

An IC is a collection of electronic components – resistors, transistors, capacitors etc. – all stuffed into a tiny chip, and connected together to achieve a common goal. They come in all sorts of flavors: single-circuit logic gates, op amps, 555 timers, voltage regulators, motor controllers, microcontrollers, microprocessors, FPGAs…the list just goes on-and-on.

## INSIDE THE IC

When we think integrated circuits, little black chips are what come to mind. But what’s inside that black box?

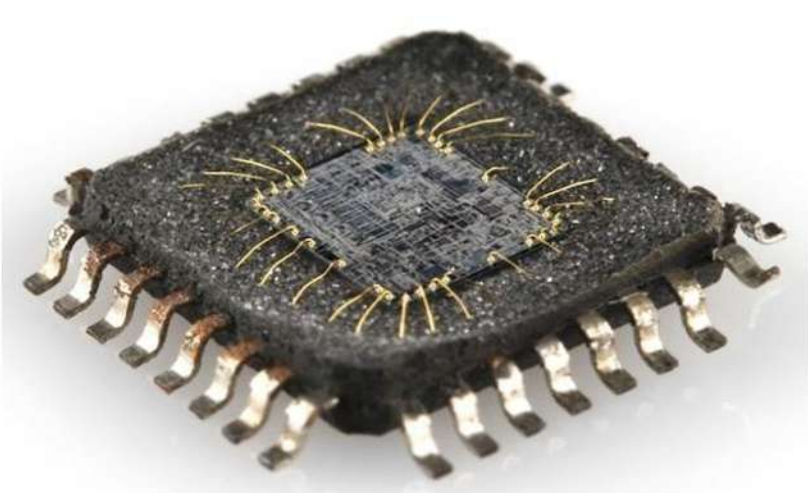


Fig 8.2 :The guts of an integrated circuit, visible after removing the top.

The real “meat” to an IC is a complex layering of semiconductor wafers, copper, and other materials, which interconnect to form transistors, resistors or other components in a circuit. The cut and formed combination of these wafers is called a die.

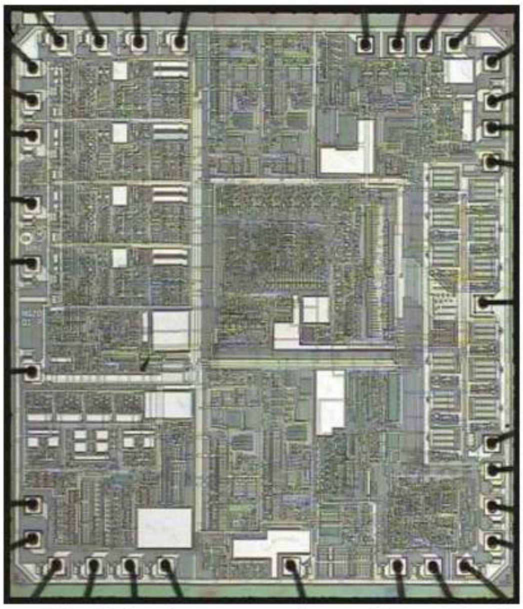


Fig 8.3 :An overview of an IC die.

While the IC itself is tiny, the wafers of semiconductor and layers of copper it consists of are incredibly thin. The connections between the layers are very intricate. Here’s a zoomed in section of the die above:

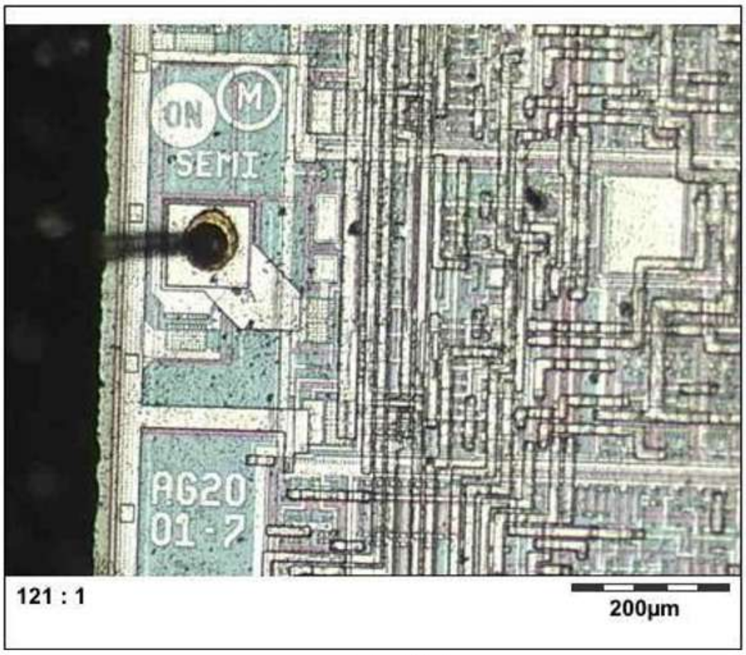



Fig 8.4

An IC die is the circuit in its smallest possible form, too small to solder or connect to. To make our job of connecting to the IC easier, we package the die. The IC package turns the delicate, tiny die, into the black chip we're all familiar with.

## 8.2. INTEGRATED CIRCUIT CLASSIFICATION

Considerable cost savings can be made by manufacturing all of the components required for a particular circuit function on one small slice of semiconductor material (usually Si). The resulting integrated circuit may contain as few as 10 or more than 100,000 active devices (transistors and diodes). With the exception of a few specialized applications (such as amplification at high-power levels) integrated circuits have largely rendered conventional circuits (i.e. those based on discrete components) obsolete. Integrated circuits can be divided into two general classes, linear (analogue) and digital. Typical examples of linear integrated circuits are operational amplifiers whereas typical examples of digital integrated are logic gates. A number of devices bridge the gap between the analogue and digital world. Such devices include analogue to digital converters (ADCs), digital to analogue converters (DACs) and timers. Table and Figure 76 outline the main types of integrated circuit.

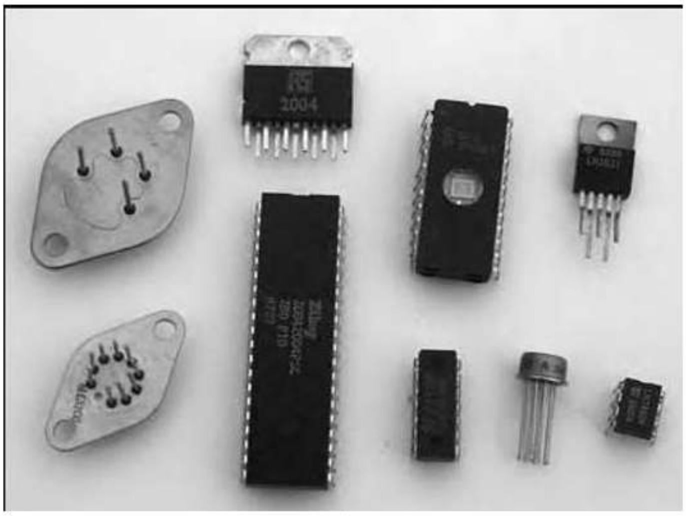


Fig 8.5

Integrated circuits combine the functions of many individual components into a single small package. Integrated circuits can be divided into three main categories: digital, linear and hybrid.

## 8.3. DESCRIPTION AND OPERATION OF LOGIC CIRCUITS

Digital integrated circuits have numerous applications quite apart from their obvious use in computing. Digital signals exist only in discrete steps or levels; intermediate states are disallowed. Conventional electronic logic is based on two binary states, commonly referred to as logic 0 (low) and logic 1 (high). A comparison between digital and analogue signals is shown in Fig 8.6. The relative size of a digital integrated circuit (in terms of the number of active devices that it contains) is often referred to as its scale of integration and the following terminology is commonly used:

| Scale of Abbreviation | Number of Integration | logic Gates* |
|---|---|---|
| Small | SSI | 1-10 |
| Medium | MSI | 10-100 |
| Large | LSI | 100-1000 |
| Very large | VLSI | 1000-10000 |
| Super large | SLSI | 10000-100000 |

## BUFFERS

Buffers do not affect the logical state of a digital signal (i.e. a logic 1 input results in a logic 1 output whereas a logic 0 input results in a logic output). Buffers are normally used to provide extra current drive at the output but can also be used to regularize the logic levels present at an interface.

## DIGITAL

Logic gates Digital integrated circuits that provide logic functions, such as AND, OR, NAND and NOR. Microprocessors Digital integrated circuits that are capable of executing a sequence of programmed instructions. Microprocessors are able to store digital data whilst it is being processed and to carry out a variety of operations on the data, including comparison, addition and subtraction.Memory devices Integrated circuits that are used to store digital information.

## ANALOGUE

Operational amplifiers Integrated circuits that are designed primarily for linear operation and which form the fundamental building blocks of a wide variety of linear circuits, such as amplifiers, filters and oscillators. Low-noise amplifiers Linear integrated circuits that are designed so that they introduce very little noise which may otherwise degrade low-level signals. Voltage regulators Linear integrated circuits that are designed to maintain a constant output voltage in circumstances when the input voltage or the load current changes over a wide range.

## HYBRID (COMBINED DIGITAL AND ANALOGUE)

Timers Integrated circuits that are designed primarily for generating signals that have an accurately defined time interval, such as that which could be used to provide a delay or determine the time between pulses. Timers generally comprise several operational amplifiers together with one or more bistable devices. ADCs Integrated circuits that are used to convert a signal in analogue form to one in digital form. A typical application would be where temperature is sensed using a thermistor to generate an analogue signal.

This signal is then converted to an equivalent digital signal using an ADC and then sent to a microprocessor for processing. DACs Integrated circuits that are used to convert a signal in digital form to one in analogue form. A typical application would be where the speed of a DC motor is to be controlled from the output of a microprocessor. The digital signal from the microprocessor is converted to an analogue signal by means of a DAC. The output of the DAC is then further amplified before applying it to the field winding of a DC motor.

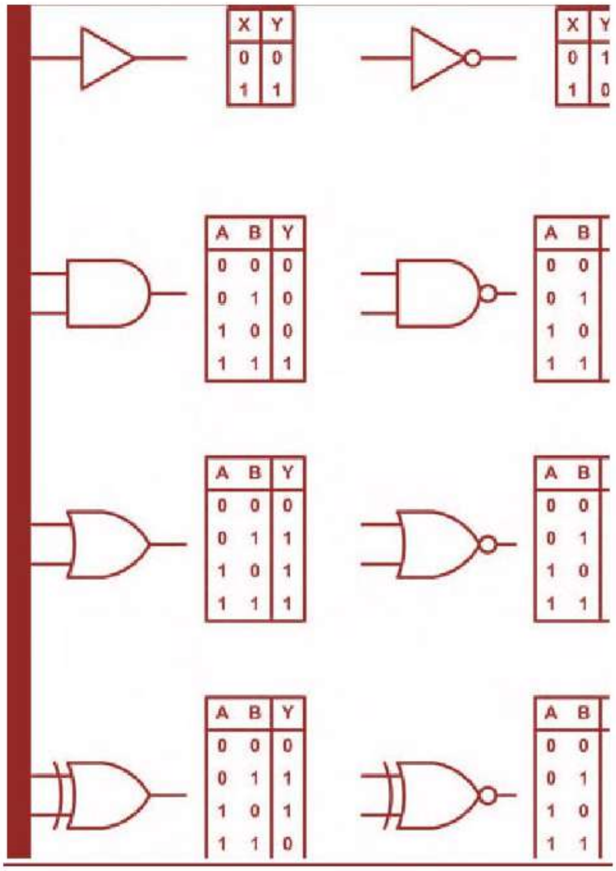



Fig 8.7

## INVERTERS

Inverters are used to complement the logical state (i.e. a logic 1 input results in a logic 0 output and vice versa). Inverters also provide extra current drive and, like buffers, are used in interfacing applications where they provide a means of regularizing logic levels present at the input or output of a digital system.

## AND GATES

AND gates will only produce a logic 1 output when all inputs are simultaneously at logic 1. Any other input combination results in a logic 0 output.

## OR GATES

ORgates will produce a logic 1 output whenever any one or more inputs are at logic 1. Putting this in another way, an OR gate will only produce a logic 0 output whenever all of its inputs are simultaneously at logic 0.

## NAND GATES

NAND gates will only produce a logic 0 output when all inputs are simultaneously at logic 1. Any other input combination will produce a logic 1 output. A NAND gate, therefore, is nothing more than an AND gate with its output inverted! The circle shown at the output denotes this inversion. NOR gates NOR gates will only produce a logic 1 output when all inputs are simultaneously at logic 0. Any other input combination will produce a logic 0 output. A NOR gate, therefore, is simply an OR gate with its output inverted. A circle is again used to indicate inversion.

## EXCLUSIVE-OR GATES

Exclusive-OR gates will produce a logic 1 output whenever either one of the inputs is at logic 1 and the other is at logic 0. Exclusive-OR gates produce a logic 0 output whenever both inputs have the same logical state (i.e. when both are at logic 0 or at logic 1).

## MONOSTABLES

A logic device which has only one stable output state is known as a monostable. The output of such a device is initially at logic 0 (low) until an appropriate level change occurs at its trigger input. This level change can be from 0 to 1 (positive edge trigger) or 1 to 0 (negative edge trigger) depending upon the particular monostable device or configuration. Upon receipt of a valid trigger pulse the output of the monostable changes state to logic 1.Then, after atime interval determined by external C–R timing components, the output reverts to logic 0. The device then awaits the arrival of the next trigger. A typical application for a monostable device is in stretching a pulse of very short duration.

## BISTABLES

The output of a bistable has two stable states (logic 0 or 1) and once set, the output of the device will remain at a particular logic level for an indefinite period until reset. A bistable thus constitutes a simple form of memory cell as it will remain in its latched state (whether set or reset) until commanded to change its state (or until the supply is disconnected). Various forms of bistable are available including R–S, D-type and J–K types.

## LOGIC FAMILY

Digital integrated circuit devices are often classified according to the semiconductor technology which a device belongs being largely instrumental in determining its operational characteristics (such as power consumption, speed and immunity to noise). The two basic logic families are complementarymetal oxide semiconductor (CMOS) and transistor–transistor logic (TTL). Each of these families is then further subdivided. Representative circuits of a two-input AND gate in both technologies is shown in Figure 79.
The most common family of TTL logic devices is known as the 74 series. Devices from this family are coded with the prefix number 74

## 8.4. LOGIC CIRCUIT CHARACTERISTICS

Logic levels are simply the range of voltages used to represent the logic states 0 and 1. The logic levels for CMOS differ markedly from those associated with TTL. In particular, CMOS logic levels are relative to the supply voltage used whilst the logic levels associated with TTL devices tend to be absolute. The following table usually applies:

| | CMOS | TTL |
|---|---|---|
| Logic 1 | >2/3 VDD | >2V |
| Logic 0 | <1/3 VDD | <0.8V |
| Indeterminate | between 1/3 VDD 2/3 VDD | between and 2/3 VDD 0.8 and 2V |

NOTE:VDD is the positive supply associated with CMOS devices.

The noise margin is an important feature of any logic device. Noise margin is a measure of the ability of the device to reject noise; the larger the noise margin, the better is its ability to perform in an environment in which noise is present. Noise margin is defined as the difference between the minimum values of high-state output and high-state input voltage and the maximum values of low-state output and low-state input voltage. Hence:

Noise Margin = VOH(MIN) –VIH(MIN)

OR

Noise Margin = VOL(MAX) –VIL(MAX)

Where VOH n(MIN) is the minimum value of highstate (logic 1) output voltage, VIH(MIN) is the minimum value of high-state (logic 1) input voltage, VOL(MAX) is the maximum value of lowstate (logic 0) output voltage and VIL(MIN) is the minimum value of low-state (logic 0) input voltage. The noise margin for standard 7400-series TTL is typically 400mV whilst that for CMOS is 1/3 VDD as shown in Figure.

## THE IDEAL AMPLIFIER

In amplifier modules 1 to 5 voltage and power amplifiers are described in some detail so that the circuit elements that go into making an amplifier can be understood. Each of these circuit elements, such as negative and positive feedback, impedance, linearity, gain and efficiency are used with the aim of improving the amplifier's performance towards the goal of making the ideal amplifier. The bad news is that the ideal amplifier does not exist, but the good news is that the op amp does!

The ideal amplifier should:

- Have an infinitely wide bandwidth.
- Have an infinitely high gain available that can be easily controlled.
- Be ideally linear, with no distortion.
- Generate no noise (have an infinitely high signal to noise ratio).
- Be easily convertible to perform different amplifier functions.
- Be cheap

All of the above is what the op-amp does, or at least comes pretty close to.

## EARLY OP AMPS

Amplifiers with gain controlled by negative feedback were first thought of in the 1930s as a way of creating amplifiers for the telephone system that could have a controllable and reliable gain, but became operational amplifiers when they were adopted by designers of analogue computers, because of their ability to perform accurate mathematical operations, such as adding, subtracting, integration and differentiation.

OP AMP ICS

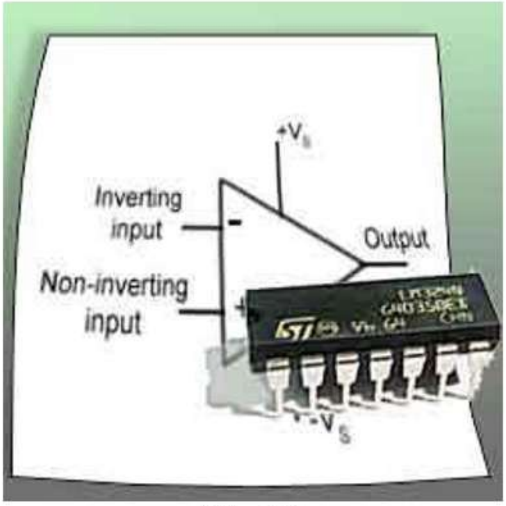



Fig 8.8

Operational amplifiers can still be built from discrete components but with the introduction of silicon planar technologies and integrated circuits their performance has improved and both size and cost have reduced dramatically. Although computing, for which op amps were originally designed, has practically all moved from analogue circuitry to digital electronics, the op amp has become so useful in so many circuits that deal with real (analogue) quantities such as sound, light, heat and motion, that the op amp is now a widely varied and indispensable part of electronics equipment.

This module will discuss the basic properties of op amps and comparators, and how their integrated circuit versions can be manipulated to make simple circuits that provide so many vital functions in electronics.

## 8.5. IC PACKAGES

The package is what encapsulates the integrated circuit die and splays it out into a device we can more easily connect to. Each outer connection on the die is connected via a tiny piece of gold wire to a pad or pin on the package. Pins are the silver, extruding terminals on an IC, which go on to connect to other parts of a circuit. These are of utmost importance to us, because they're what will go on to connect to the rest of the components and wires in a circuit.

There are many different types of packages, each of which has unique dimensions, mounting-types, and/or pin-counts.

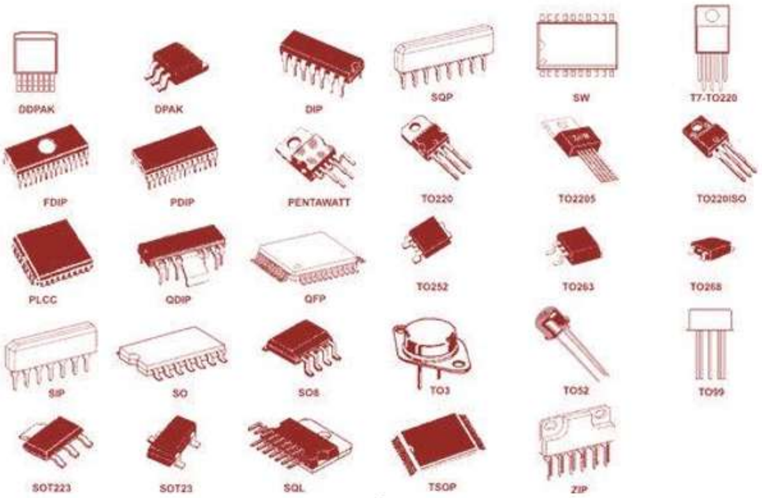


Fig 8.9

## POLARITY MARKING AND PIN NUMBERING

All ICs are polarized, and every pin is unique in terms of both location and function. This means the package has to have some way to convey which pin is which. Most ICs will use either a notch or a dot to indicate which pin is the first pin. (Sometimes both, sometimes one or the other.)


Fig 8.10

Once you know where the first pin is, the remaining pin numbers increase sequentially as you move counter-clockwise around the chip.


Fig 8.11

## MOUNTING STYLE

One of the main distinguishing package type characteristics is the way they mount to a circuit board. All packages fall into one of two mounting types: through-hole (PTH) or surface-mount (SMD or SMT). Through-hole packages are generally bigger, and much easier to work with. They're designed to be stuck through one side of a board and soldered to the other side.

Surface-mount packages range in size from small to minuscule. They are all designed to sit on one side of a circuit board and be soldered to the surface. The pins of a SMD package either extrude out the side, perpendicular to the chip, or are sometimes arranged in a matrix on the bottom of the chip. ICs in this form factor are not very "hand-assembly-friendly." They usually require specialtools to aid in the process.

## DIP (DUAL IN-LINE PACKAGES)

DIP, short for dual in-line package, is the most common through-hole IC package you'll encounter. These little chips have two parallel rows of pins extending perpendicularly out of a rectangular, black, plastic housing.

Fig 8.12

The 28-pin ATmega328 is one of the more popular DIP-packaged microcontrollers (thanks, Arduino!).
Each of the pins on a DIP IC are spaced by 0.1" (2.54mm), which is a standard spacing and perfect for fitting intobreadboards and other prototyping boards. The overall dimensions of a DIP package depend on its pin count, which may be anywhere from four to 64.

The area between each row of pins is perfectly spaced to allow DIP ICs to straddle the center area of a breadboard. This provides each of the pins its own row in the board, and it makes sure they don't short to each other.

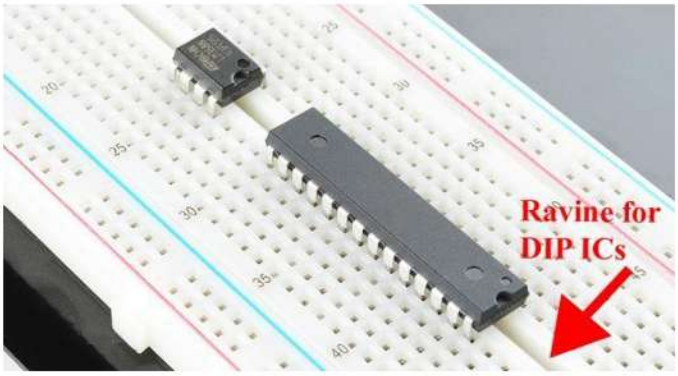



Fig 8.13

Aside from being used in breadboards, DIP ICs can also be soldered into PCBs. They're inserted into one side of the board and soldered into place on the other side. Sometimes, instead of soldering directly to the IC, it's a good idea tosocket the chip. Using sockets allows for a DIP IC to be removed and swapped out, if it happens to "let its blue smoke out."

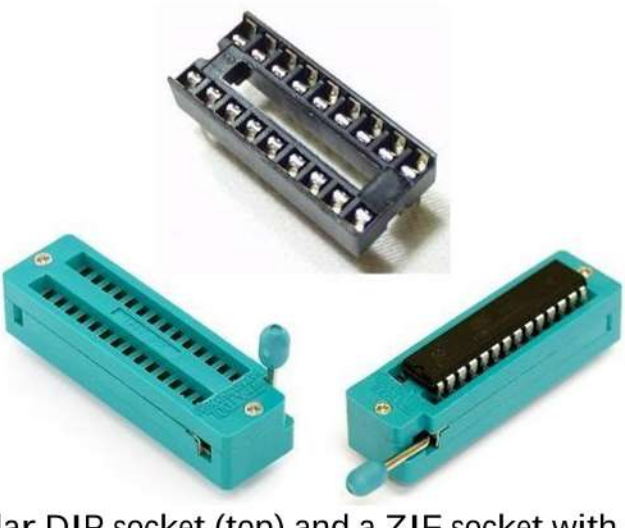


Fig 8.14 A regular DIP socket (top) and a ZIF socket with and without an IC.

## SURFACE-MOUNT (SMD/SMT) PACKAGES

There is a huge variety of surface-mount package types these days. In order to work with surface-mount packaged ICs, you usually need a custom printed circuit board (PCB) made for them, which has a matching pattern of copper on which they're soldered.

Here are a few of the more common SMD package types out there, ranging in hand-solderability from “doable” to “doable, but only with special tools” to “doable only with very special, usually automated tools”.

## SMALL-OUTLINE (SOP)

Small-outline IC (SOIC) packages are the surface-mount cousin of the DIP. It’s what you’d get if you bent all the pins on a DIP outward, and shrunk it down to size. With a steady hand, and a close eye, these packages are among the easiest SMD parts to hand solder. On SOIC packages, each pin is usually spaced by about 0.05" (1.27mm) from the

The SSOP (shrink small-outline package) is an even smaller version of SOIC packages. Other, similar IC packages include TSOP (thin small-outline package) and TSSOP (thin-shrink small-outline package).

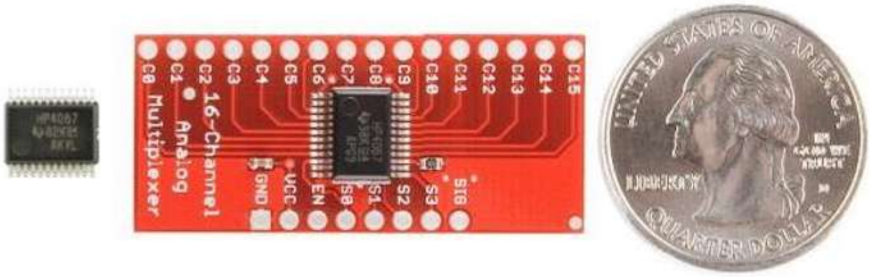



Fig 8.15 : A 16-Channel Multiplexer (CD74HC4067) in a 24-pin SSOP package. Mounted on a board in the middle (quarter added for size-comparison).

A lot of the more simple, single-task-oriented ICs like the MAX232 or multiplexers come in SOIC or SSOP forms.

## QUAD FLAT PACKAGES

Splaying IC pins out in all four directions gets you something that might look like a quad flat package (QFP). QFP ICs might have anywhere from eight pins per side (32 total) to upwards of seventy (300+ total). The pins on a QFP IC are usually spaced by anywhere from 0.4mm to 1mm. Smaller variants of the standard QFP package include thin (TQFP), very thin (VQFP), and low-profile (LQFP) packages.

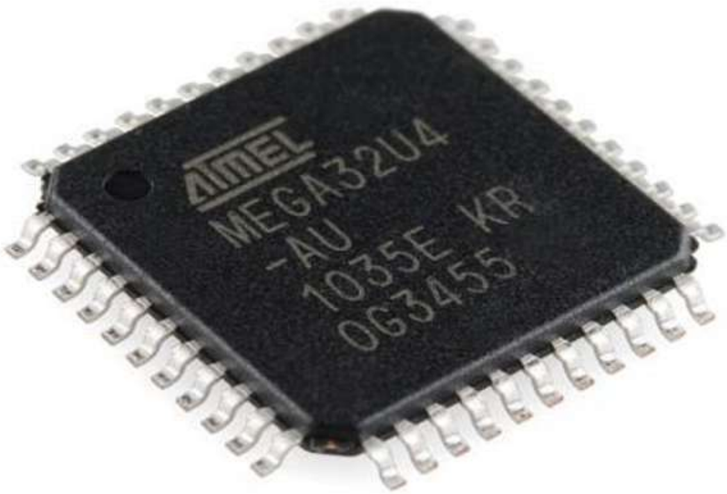



Fig 8.16 : The ATmega32U4 in a 44-pin (11 on each side) TQFP package.

If you sanded the legs off a QFP IC, you get something that might look like a quad-flat no-leads (QFN) package. The connections on QFN packages are tiny, exposed pads on the bottom corner edges of the IC. Sometimes they wrap around, and are exposed on both the side and bottom, other packages only expose the pad on the bottom of the chip.

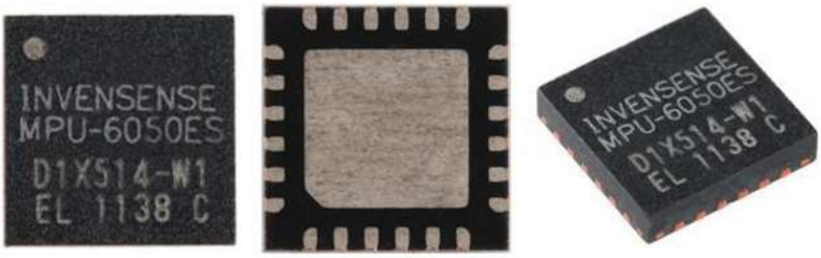



Fig 8.17 :The multitalented MPU-6050 IMU sensor comes in a relatively tiny QFN package, with 24 total pins hiding on the bottom edge of the IC.

Thin (TQFN), very thin (VQFN), and micro-lead (MLF) packages are smaller variations of the standard QFN package. There are even dual no-lead (DFN) and thin-dual no-lead (TDFN) packages, which have pins on just two of the sides.

Many microprocessors, sensors, and other modern ICs come in QFP or QFN packages. The popular ATmega328microcontroller is offered in both a TQFP package and a QFN-type (MLF) form, while a tiny accelerometer/gyroscope like the MPU-6050 comes in a miniscule QFN form.

## BALL GRID ARRAYS

Finally, for really advanced ICs, there are ball grid array (BGA) packages. These are amazingly intricate little packages where little balls of solder are arranged in a 2-D grid on the bottom of the IC. Sometimes the solder balls are attached directly to the die!

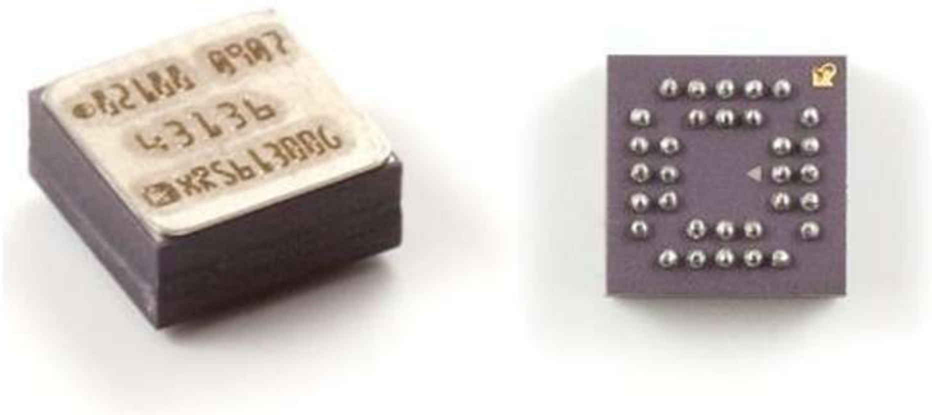


Fig 8.18

BGA packages are usually reserved for advanced microprocessors, like those on the pc Duino or Raspberry Pi.

If you can hand solder a BGA-packaged IC, consider yourself a master solderer. Usually, to put these packages onto a PCB requires an automated procedure involving pick-and-place machines and reflow ovens.

## COMMON ICS

Integrated circuits are prevalent in so many forms across electronics, it's hard to cover everything. Here are a few of the more common ICs you might encounter in educational electronics.

Logic Gates, Timers, Shift Registers, Etc.

Logic gates, the building blocks of much more ICs themselves, can be packaged into their own integrated circuit. Some logic gate ICs might contain a handful of gates in one package, like this quad-input AND gate:

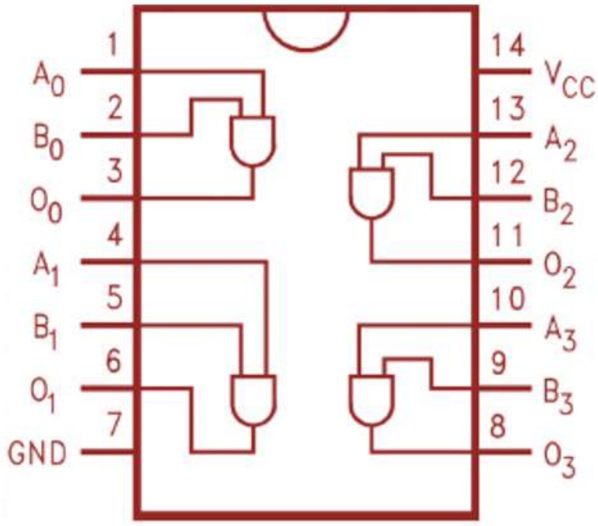



Fig 8.19

Logic gates can be connected inside an IC to create timers, counters, latches, shift registers, and other basic logic circuitry. Most of these simple circuits can be found in DIP packages, as well as SOIC and SSOP.

Microcontrollers, Microprocessors, FPGAs, Etc.

Microcontrollers, microprocessors, and FPGAs, all packing thousands, millions, even billions of transistors into a tiny chip, are all integrated circuits. These components exist in a wide range in functionality, complexity, and size; from an 8-bit microcontroller like the ATmega328 in an Arduino, to a complex 64-bit, multi-core microprocessor organizing activity in your computer.

These components are usually the largest IC in a circuit. Simple microcontrollers can be found in packages ranging from DIP to QFN/QFP, with pin counts lying somewhere between eight and a hundred. As these components grow in complexity, the package gets equally complex. FPGAs and complex microprocessors can have upwards of a thousand pins and are only available in advanced packages like QFN, LGA, or BGA.

## SENSORS

Modern digital sensors, like temperature sensors, accelerometers, and gyroscopes all come packed into an integrated circuit.

These ICs are usually smaller than the microcontrollers, or other ICs on a circuit board, with pin counts in the three to twenty ranges. DIP sensor ICs are becoming a rarity, as modern components are usually found in QFP, QFN, even BGA packages.

# UNIT 9: OPERATIONAL AMPLIFIER BASICS

As well as resistors and capacitors, Operational Amplifiers, or Op-amps as they are more commonly called, are one of the basic building blocks of Analogue Electronic Circuits. Operational amplifiers are linear devices that have all the properties required for nearly ideal DC amplification and are therefore used extensively in signal conditioning, filtering or to perform mathematical operations such as add, subtract, integration and differentiation.

An Operational Amplifier is basically a three-terminal device which consists of two high impedance inputs, one called the Inverting Input, marked with a negative or "minus" sign, ( - ) and the other one called the Non-inverting Input, marked with a positive or "plus" sign ( + ).

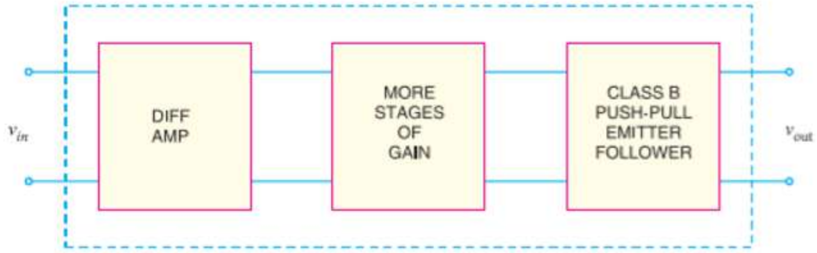
The third terminal represents the Operational Amplifiers output port which can both sink and source either a voltage or a current. In a linear operational amplifier, the output signal is the amplification factor, known as the amplifiers gain ( A ) multiplied by the value of the input signal and depending on the nature of these input and output signals, there can be four different classifications of operational amplifier gain.

- Voltage – Voltage "in" and Voltage "out"
- Current – Current "in" and Current "out"
- Trans-conductance – Voltage "in" and Current "out"
- Trans- resistance – Current "in" and Voltage "out"

Since most of the circuits dealing with operational amplifiers are voltage amplifiers, we will limit the tutorials in this section to voltage amplifiers only, (Vin and Vout).

## OPERATIONAL AMPLIFIER GENERAL CONDITIONS

Fig shows the block diagram of an operational amplifier. Note that OP-Amp is a multistage amplifier. The three stages are : differential amplifier input stage followed by a high-gain CE amplifier and finally the output stage. The key electronic circuit in an OP-Amp is the differential amplifier. A differential amplifier (DA) can accept two input signals and amplifies the difference between these two input signals.



Block diagram of OP-Amp

The following points may be noted about operational amplifiers (OP-Amps) :

(i) The input stage of an OP-Amp is a differential amplifier (DA) and the output stage is typically a class B push-pull emitter follower.

(ii) The internal stages of an OP-Amp are direct-coupled i.e., no coupling capacitors are used. The direct coupling allows the OP-Amp to amplify d.c. as well as a.c. signals.

(iii) An OP-Amp has very high input impedance (ideally infinite) and very low output impedance (ideally zero). The effect of high input impedance is that the amplifier will draw a very small current (ideally zero) from the signal source. The effect of very low output impedance is that the amplifier will provide a constant output voltage independent of current drawn from the source.

(iv) An OP-Amp has very high *open-loop voltage gain (ideally infinite); typically more than 200,000.

(v) The OP-Amps are almost always operated with negative feedback. It is because the openloop voltage gain of these amplifiers is very high and we can sacrifice the gain to achieve the advantages of negative feedback including large bandwidth (BW) and gain stability

The Two Basic Operational Amplifier Circuits

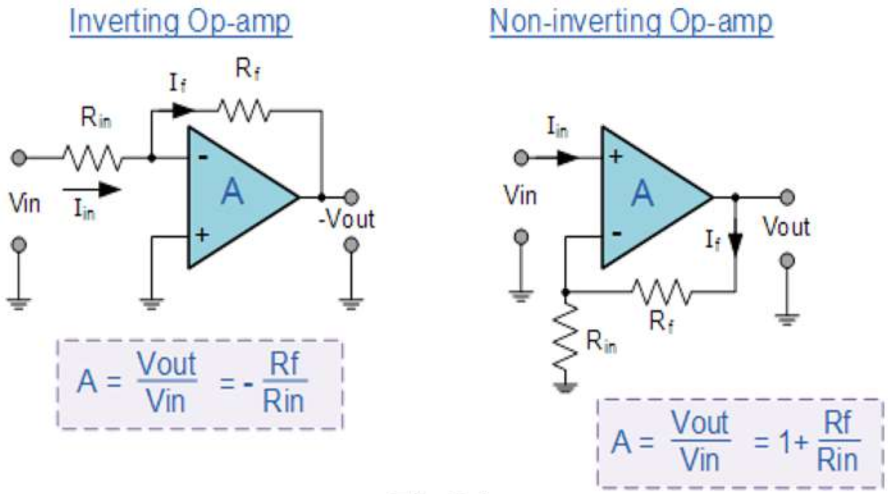



Fig 9.1

- For negative feedback, were the feed-back voltage is in "anti-phase" to the input the overall gain of the amplifier is reduced.

- For positive feedback, were the feed-back voltage is in "Phase" with the input the overall gain of the amplifier is increased.

- By connecting the output directly back to the negative input terminal, 100% feedback is achieved resulting in a Voltage Follower (buffer) circuit with a constant gain of 1 (Unity).

- Changing the fixed feedback resistor ( R*f* ) for a Potentiometer, the circuit will have Adjustable Gain.

## OPERATIONAL AMPLIFIER GAIN

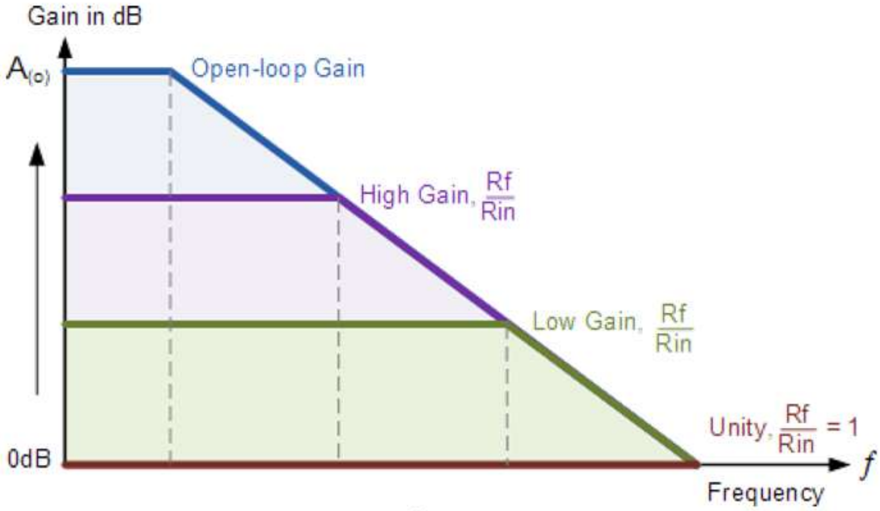
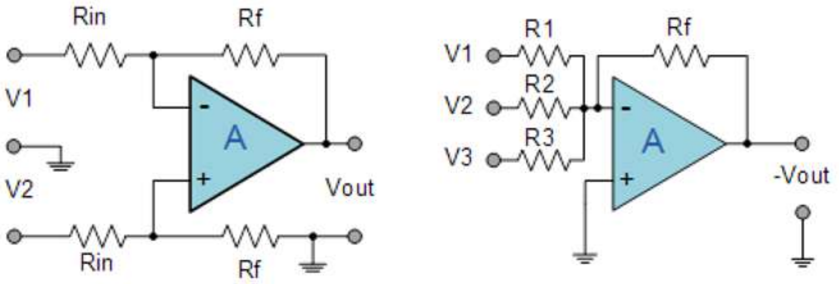



Fig 9.2

- The Open-loop gain called the Gain Bandwidth Product, or (GBP) can be very high and is a measure of how good an amplifier is.
- Very high GBP makes an operational amplifier circuit unstable as a micro volt input signal causes the output voltage to swing into saturation.
- By the use of a suitable feedback resistor, ( R*f* ) the overall gain of the amplifier can be accurately controlled.

## DIFFERENTIAL AND SUMMING AMPLIFIERS




$$V_{out} = \frac{R_f}{R_{in}}(V2 - V1)$$

$$V_{out} = -\left(\frac{R_f}{R1}V1 + \frac{R_f}{R2}V2 + \frac{R_f}{R3}V3\right)$$

Fig 9.3

- By adding more input resistors to either the inverting or non-inverting inputs Voltage Adders or Summers can be made.

- Voltage follower op-amps can be added to the inputs of Differential amplifiers to produce high impedance Instrumentation amplifiers.

The Differential Amplifier produces an output that is proportional to the difference between the 2 input voltages.

The amplified output signal of an Operational Amplifier is the difference between the two signals being applied to the two inputs. In other words the output signal is a differential signal between the two inputs and the input stage of an Operational Amplifier is in fact a differential amplifier.

## OP-AMP INTEGRATORS AND DIFFERENTIATORS

A circuit that performs the mathematical integration of input signal is called an integrator. The output of an integrator is proportional to the area of the input waveform over a period of time. A circuit that performs the mathematical differentiation of input signal is called a differentiator. The output of a differentiator is proportional to the rate of change of its input signal. Note that the two operations are opposite.

### Integrator

An integrator is a circuit that performs integration of the input signal. The most popular application of an integrator is to produce a ramp output voltage (i.e. a linearly increasing or decreasing voltage). Fig.9.4 shows the circuit of an OP-amp integrator. It consists of an OP-amp, input resistor R and feedback capacitor C. Note that the feedback component is a capacitor instead of a resistor. As we shall see, when a signal is applied to the input of this circuit, the output-signal waveform will be the integration of input-signal waveform.

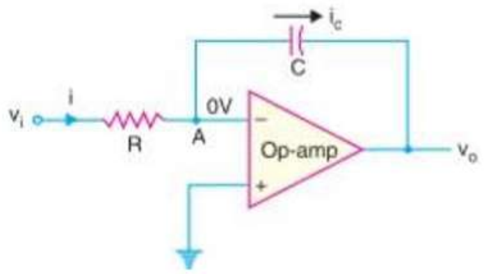



Fig 9.4

For example, if the input to the integrator is a square wave, the output will be a triangular wave as shown in Fig 9.5

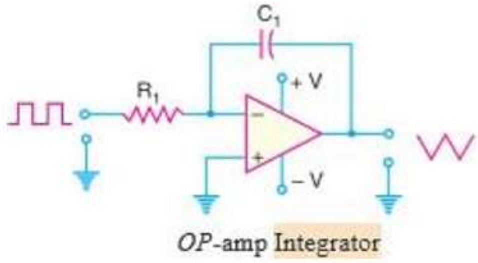



Fig 9.5

The output voltage of integrator is given by

$$v_o = -\frac{1}{RC}\int_0^t v_i\,dt$$

## Differentiator

A differentiator is a circuit that performs differentiation of the input signal. In other words, a differentiator produces an output voltage that is proportional to the rate of change of the input voltage. Its important application is to produce a rectangular output from a ramp input. Fig 9.6 shows the circuit of OP-amp as differentiator. It consists of an OP-amp, an input capacitor C and feedback resistor R. Note how the placement of the capacitor and resistor differs from the integrator. The capacitor is now the input element.

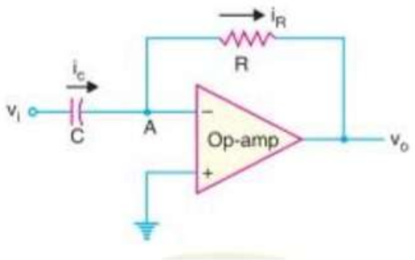



Fig 9.6

Differentiator will convert a triangular wave into square wave as shown in Fig 9.7

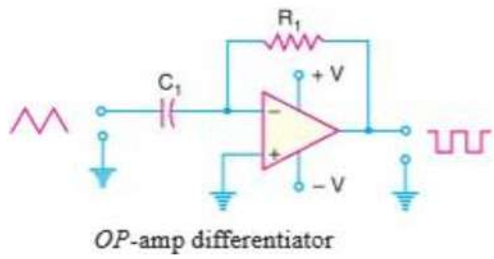



Fig 9.7

The output voltage of differentiator is given by

$$v_o = -RC\frac{dv_i}{dt}$$

## Voltage Follower

The voltage follower arrangement is a special case of noninverting amplifier where all of the output voltage is fed back to the inverting input as shown in Fig 9.8 Note that we remove Ri and Rf from the noninverting amplifier and short the output of the amplifier to the inverting input. The voltage gain for the voltage follower is calculated as under:

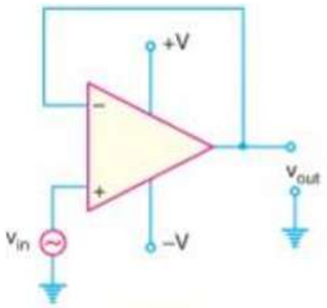



Fig 9.8

Thus the closed-loop voltage gain of the voltage follower is 1.The most important features of the voltage follower configuration are its very high input impedance and its very low output impedance. These features make it a nearly ideal buffer amplifier to be connected between high-impedance sources and low-impedance loads.

## Comparators

Often we want to compare one voltage to another to see which is larger. In this situation, a comparator may be used. A comparator is an OP-amp circuit without negative feedback and takes advantage of very high open-loop voltage gain of OP-amp. A comparator has two input voltages (noninverting and inverting) and one output voltage. Because of the high open-loop voltage gain of an OP-amp, a very small difference voltage between the two inputs drives the amplifier to saturation. For example, consider an OP-amp having AOL = 100,000. A voltage difference of only 0.25 mV between the inputs will produce an output voltage of (0.25 mV)(100,000) = 25V. However, most of OP-amps have output voltages of less than ± 15V because of their d.c. supply voltages. Therefore, a very small differential input voltage will drive the OP-amp to saturation. This is the key point in the working of comparator.

Fig 9.9 illustrates the action of a comparator. The input voltages are v1 (signal) and v2 (reference voltage).

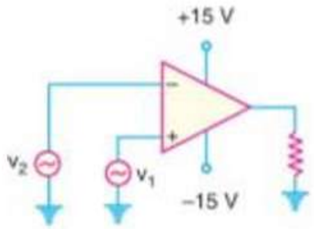



Fig 9.9

A comparator circuit has the following two characteristics:

(i) It uses no feedback so that the voltage gain is equal to the open-loop voltage gain (AOL) of OP-amp.

(ii) It is operated in a non-linear mode.

## Operation and amplifier stages connecting methods

Often, the voltage amplification or power gain or frequency response obtained with a single stage of amplification is insufficient to meet the requirements of either a composite electronic circuit or a load device. Hence, two or more single stages of amplification are frequently used to achieve greater voltage or current amplification or both. In such cases, the outputof one stage serves as input of the next stage as shown in Fig. 9.10 Such amplifiers may be divided into following two categories:

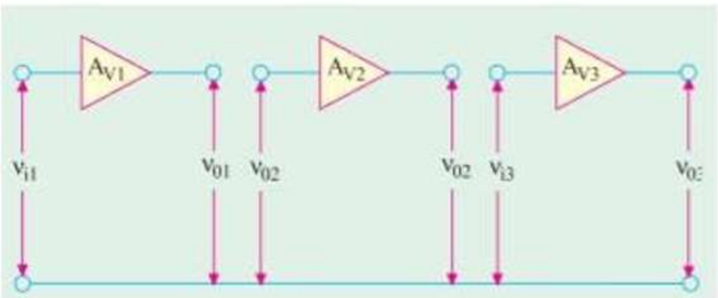



Fig. 9.10

(a) Cascaded Amplifiers In these amplifiers, each stage as well as the type of inter-stage coupling used are identical.

(b) Compound Amplifiers In these amplifiers, each stage may be different from the other (one may be CE and the other may be CC stage) and also different types of inter-stage couplings may be employed.

## Amplifier Coupling

All amplifiers need some coupling network. Even a single-stage amplifier has to be coupled to the input and output devices. In the case of multistage systems, there is inter-stage coupling. The type of coupling used determines the characteristics of the cascaded amplifier. In fact, amplifiers are classified according to the coupling network used.

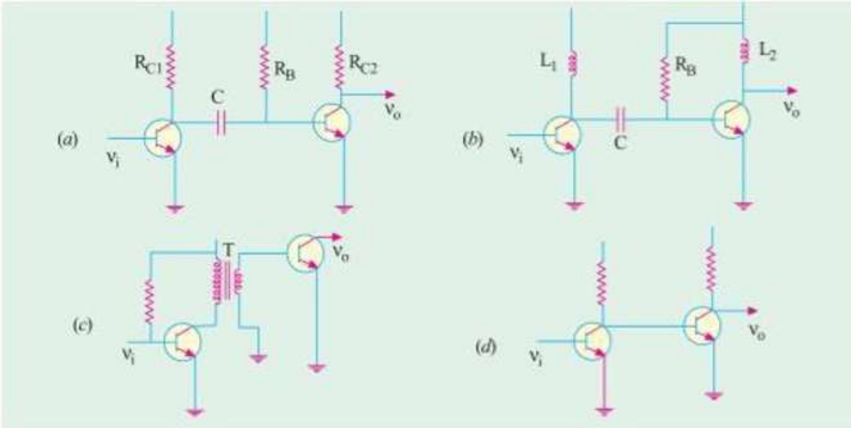



Fig9.11

## The Four Basic Methods Of Coupling Are:

1. Resistance-Capacitance (RC) Coupling

It is also known as capacitive coupling and is shown in Fig 9.11 (a). Amplifiers using this coupling are known as RC-coupled amplifiers. Here, RC coupling network consists of two resistors RC1 and RC2 and one capacitor C. The connecting link between the two stages is C. The function of the RC-coupling network is two-fold:

(a) To pass ac signal from one stage to the next

(b) To block the passage of dc voltages from one stage to the next.

2. Impedance Coupling or Inductive (IR) Coupling

It is also known as choke-capacitance coupling and is shown in Fig 9.11(b). Amplifiers using this coupling are known as impedance-coupled amplifiers. Here, the coupling network consists of L1, C and RB. The impedance of the coupling coil depends on

(i) its inductance and
(ii) Signal frequency.

3. Transformer Coupling

It is shown in Fig 9.11(c).Since secondary of the coupling transformer conveys the ac component of the signal directly to the base of the second stage, there is no need for a coupling capacitor. Moreover, the secondary winding also provides a base return path, hence there is no need for a base resistance. Amplifiers using this coupling are called transformer-coupled amplifiers.

4. Direct Coupling

It is shown in Fig 9.12 (d).This coupling is used where it is desirable to connect the load directly in series with the output terminal of the active circuit element. The examples of such loaddevices are (i) headphones (ii) loud-speakers (iii) dc meters (iv) relays and (v) input circuit of a transistor etc. Of course, direct coupling is permissible only when (i) dc component of the output does not disturb the normal operation of the load device, (ii) device resistance is so low that it does not appreciably reduce the voltage at the electrodes.

## Feedback Amplifiers

A feedback amplifier is one in which a fraction of the amplifier output is fed back to the input circuit. This partial dependence of amplifier output on its input helps to control the output. A feedback amplifier consists of two parts: an amplifier and a feedback circuit.

### (i) Positive feedback

If the feedback voltage (or current) is so applied as to increase the input voltage (i.e. it is in phase with it), then it is called positive feedback. Other names for it are: regenerative or direct feedback. Since positive feedback produces excessive distortion, it is seldom used in amplifiers. However, because it increases the power of the original signal, it is used in oscillator circuits.

### Advantages of Positive Feedback

Since positive feedback increases the amplifier gain. It is called regenerative feedback. If $\beta A = 1$, then mathematically, the gain becomes infinite which simply means that there is an output without any input! However, electrically speaking, this cannot happen. What actually happens is that the amplifier becomes an oscillator which supplies its own input.

In fact, two important and necessary conditions for circuit oscillation are 1. the feedback must be positive, 2. Feedback factor must be unity i.e. $\beta A = +1$.

### (ii) Negative feedback

If the feedback voltage (or current) is so applied as to reduce the amplifier input (i.e. it is 180° out of phase with it), then it is called negative feedback. Other names for it are : degenerative or inverse feedback. Negative feedback is frequently used in amplifier circuits

### Advantages of Negative Feedback

The numerous advantages of negative feedback outweigh its only disadvantage of reduced gain. Among the advantages are:

1. Higher fidelity i.e. more linear operation
2. highly stabilized gain
3. increased bandwidth i.e. improved frequency response
4. less amplitude distortion
5. less harmonic distortion
6. less frequency distortion
7. less phase distortion
8. reduced noise
9. input and output impedances can be modified as desired.

Disadvantage of Positive feedback:

Positive feedback produces excessive distortion

Disadvantage of Negative feedback:

Reduced Gain.

# UNIT 10 : PRINTED CIRCUIT BOARD

## 10.1. INTRODUCTION

Printed circuit board is the most common name but may also be called "printed wiring boards" or "printed wiring cards". Before the advent of the PCB circuits were constructed through a laborious process of point-to-point wiring. This led to frequent failures at wire junctions and short circuits when wire insulation began to age and crack.

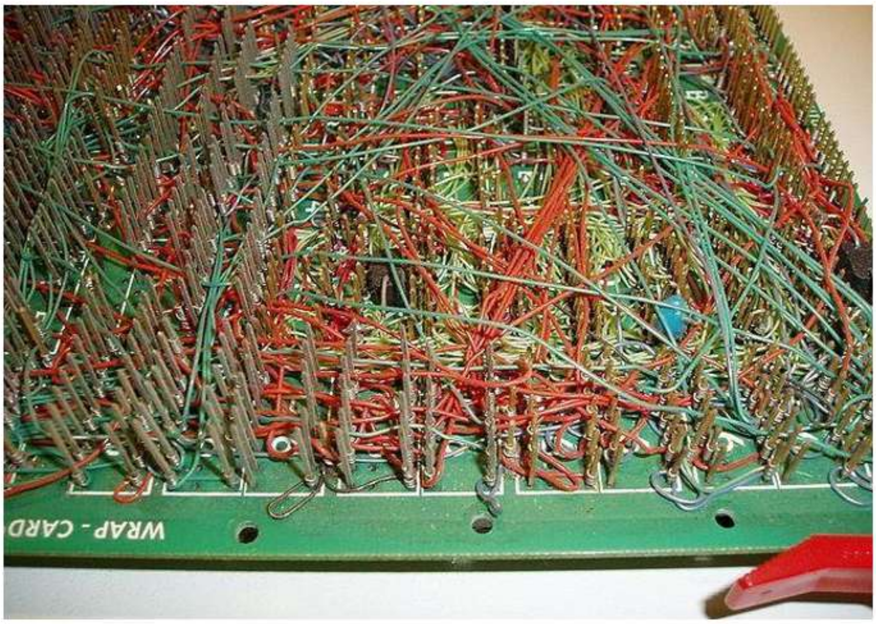



Fig 10.1

A significant advance was the development of wire wrapping, where a small gauge wire is literally wrapped around a post at each connection point, creating a gas-tight connection which is highly durable and easily changeable.

As electronics moved from vacuum tubes and relays to silicon and integrated circuits, the size and cost of electronic components began to decrease. Electronics became more prevalent in consumer goods and the pressure to reduce the size and manufacturing costs of electronic products drove manufacturers to look for better solutions. Thus was born the PCB.

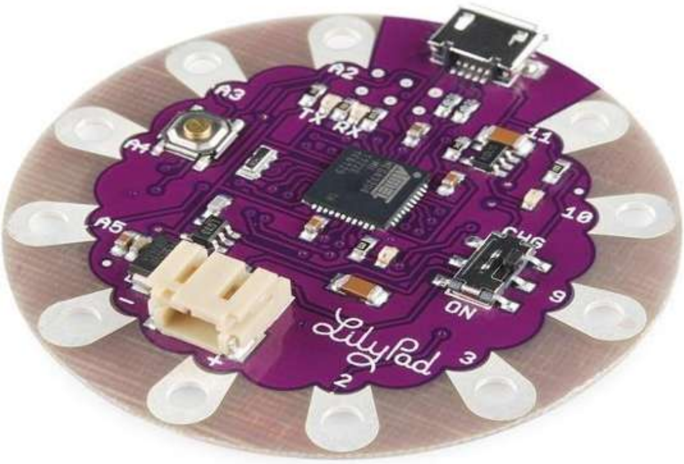



Fig 10.2

PCB is an acronym for printed circuit board. It is a board that has lines and pads that connect various points together. In the picture above, there are traces that electrically connect the various connectors and components to each other. A PCB allows signals and power to be routed between physical devices. Solder is the metal that makes the electrical connections between the surface of the PCB and the electronic components. Being metal, solder also serves as a strong mechanical adhesive.

## COMPOSITION

A PCB is sort of like a layer cake or lasagna- there are alternating layers of different materials which are laminated together with heat and adhesive such that the result is a single object.

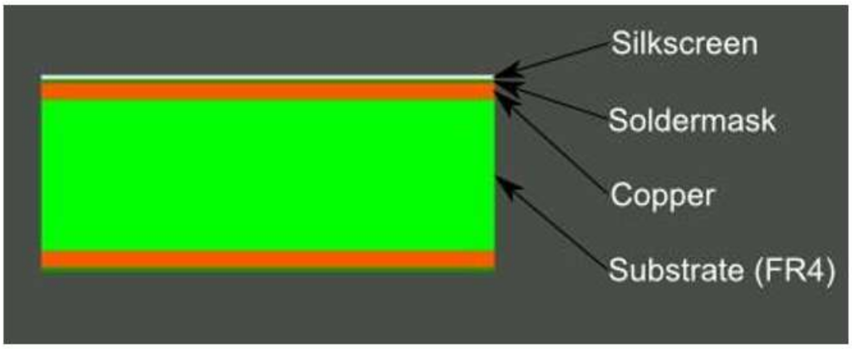



Fig 10.3

Let's start in the middle and work our way out.

## FR4

The base material, or substrate, is usually fibreglass. Historically, the most common designator for this fibreglass is "FR4". This solid core gives the PCB its rigidity and thickness. There are also flexible PCBs built on flexible high-temperature plastic (Kapton or the equivalent).

You will find many different thickness PCBs; the most common thickness for SparkFun products is 1.6mm (0.063"). Some of our products- LilyPad boards and Arduino Pro Micro boards- use a .8mm thick board.

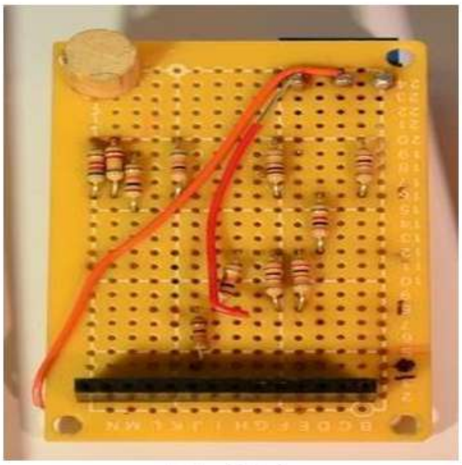


Fig 10.4

Cheaper PCBs and perf boards (shown above) will be made with other materials such as Epoxies or Phenolics which lack the durability of FR4 but are much less expensive. You will know you are working with this type of PCB when you solder to it - they have a very distinctive bad smell. These types of substrates are also typically found in low-end consumer electronics. Phenolics have a low thermal decomposition temperature which causes them to delaminate, smoke and char when the soldering iron is held too long on the board.

## COPPER

Fig 10.5

PCB with copper exposed, no solder mask or silkscreen.

The next layer is a thin copper foil, which is laminated to the board with heat and adhesive. On common, double sided PCBs, copper is applied to both sides of the substrate. In lower cost electronic gadgets the PCB may have copper on only one side. When we refer to a double sided or 2-layer board we are referring to the number of copper layers (2) in our lasagna. This can be as few as 1 layer or as many as 16 layers or more.

The copper thickness can vary and is specified by weight, in ounces per square foot. The vast majority of PCBs have 1 ounce of copper per square foot but some PCBs that handle very high power may use 2 or 3 ounce copper. Each ounce per square translates to about 35 micrometers or 1.4 thousandths of an inch of thickness of copper.

## SOLDERMASK

The layer on top of the copper foil is called the solder mask layer. This layer gives the PCB its green (or, at SparkFun, red) colour. It is overlaid onto the copper layer to insulate the copper traces from accidental contact with other metal, solder, or conductive bits. This layer helps the user to solder to the correct places and prevent solder jumpers.

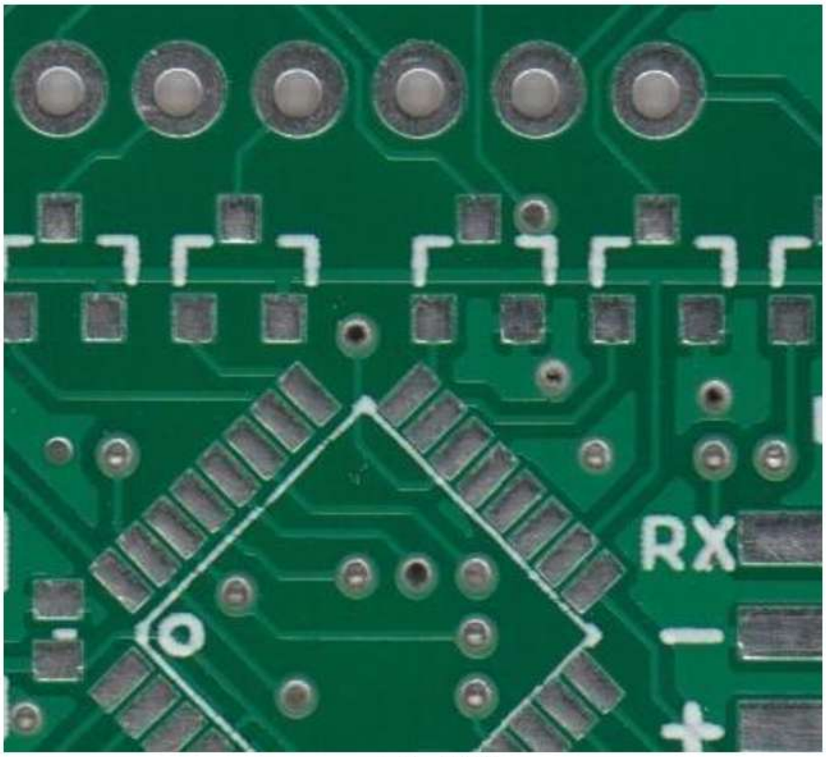



Fig 10.6

In the example above green solder mask is applied to the majority of the PCB, covering up the small traces but leaving the silver rings and SMD pads exposed so they can be soldered to.

Solder mask is most commonly green in colour but nearly any colour is possible. We use red for almost all the SparkFun boards, white for the IOIO board, and purple for the LilyPad boards.

## SILKSCREEN


Fig 10.7

The white silkscreen layer is applied on top of the solder mask layer. The silkscreen adds letters, numbers, and symbols to the PCB that allow for easier assembly and indicators for humans to better understand the board. We often use silkscreen labels to indicate what the function of each pin or LED.

Silkscreen is most commonly white but any ink colour can be used. Black, grey, red, and even yellow silkscreen colours are widely available; it is, however, uncommon to see more than one colour on a single board.

## 10.2. TERMINOLOGY AND COMPONENTS

Now that you've got an idea of what a PCB structure is, let's define some terms that you may hear when dealing with PCBs:

- ANNULAR RING: The ring of copper around a plated through hole in a PCB.

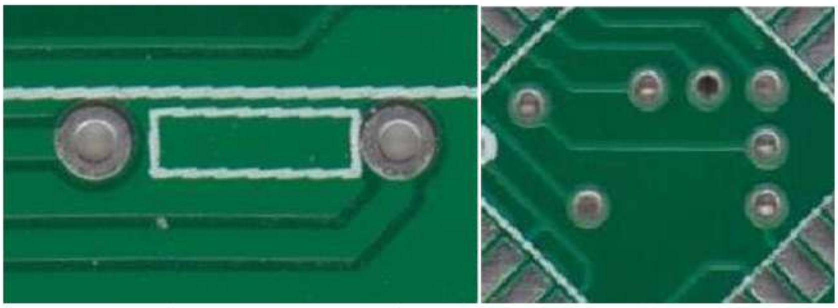


Fig 10.8: Examples of annular rings

- DRC: Design rule check. A software check of your design to make sure the design does not contain errors such as traces that incorrectly touch, traces too skinny, or drill holes that are too small.
- DRILL HIT: places on a design where a hole should be drilled, or where they actually were drilled on the board. Inaccurate drill hits caused by dull bits are a common manufacturing issue.

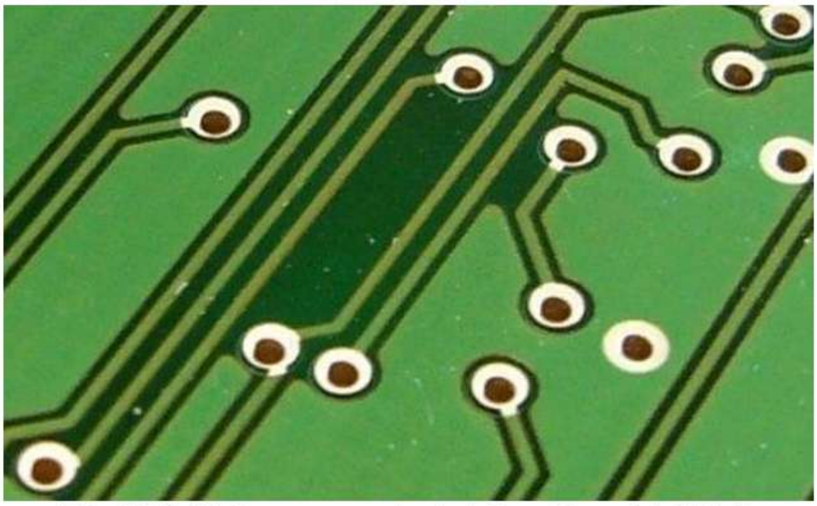


Fig 10.9:Not so accurate, but functional drill hits

- FINGER: Exposed metal pads along the edge of a board, used to create a connection between two circuit boards. Common examples are along the edges of computer expansion or memory boards and older cartridge-based video games.

- MOUSE BITES: An alternative to v-score for separating boards from panels. A number of drill hits are clustered close together, creating a weak spot where the board can be broken easily after the fact. See the SparkFun Protosnap boards for a good example.


Fig 10.10 : Mouse bites on the LilyPad ProtoSnap allow the PCB to be snapped apart easily

- PAD: A portion of exposed metal on the surface of a board to which a component is soldered.

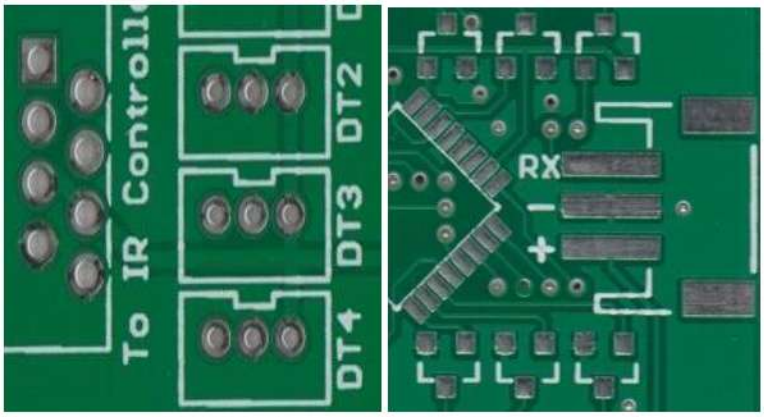



Fig 10.11 : PTH pads on the left, SMD pads on the right

- PANEL: A larger circuit board composed of many smaller boards which will be broken apart before use. Automated circuit board handling equipment frequently has trouble with smaller boards, and by aggregating several boards together at once, they process can be sped up significantly.

- PASTE STENCIL:A thin, metal (or sometimes plastic) stencil which lies over the board, allowing solder paste to be deposited in specific areas during assembly.

  Abe does a quick demonstration of how to line up a paste stencil and apply solder paste.

- PICK-AND-PLACE: The machine or process by which components are placed on a circuit board.
  Bob shows us the SparkFun MyData Pick and Place machine. It's pretty awesome.

- PLANE: A continuous block of copper on a circuit board, define by borders rather than by a path. Also commonly called a "pour".


Fig 10.12: Various portions of the PCB that have no traces but has a ground pour instead.

- PLATED THROUGH HOLE:A hole on a board which has an annular ring and which is plated all the way through the board. May be a connection point for a through hole component, a via to pass a signal through, or a mounting hole.

Fig 10.13: A PTH resistor inserted into the FabFM PCB, ready to be soldered. The legs of the resistor go through the holes. The plated holes can have traces connected to them on the front of the PCB and the rear of the PCB.

- POGO PIN:Spring-loaded contact used to make a temporary connection for test or programming purposes.


Fig 10.14: The popular pogo pin with pointed tip. We use tons of these on our test beds

- REFLOW:Melting the solder to create joints between pads and component leads.

- SILKSCREEN:The letters, number, symbols and imagery on a circuit board. Usually only one color is available, and resolution is usually fairly low.


Fig 10.15 : Silkscreen identifying this LED as the power LED

- SLOT: Any hole in a board which is not round. Slots may or may not be plated. Slots sometimes add to add cost to the board because they require extra cut-out time.

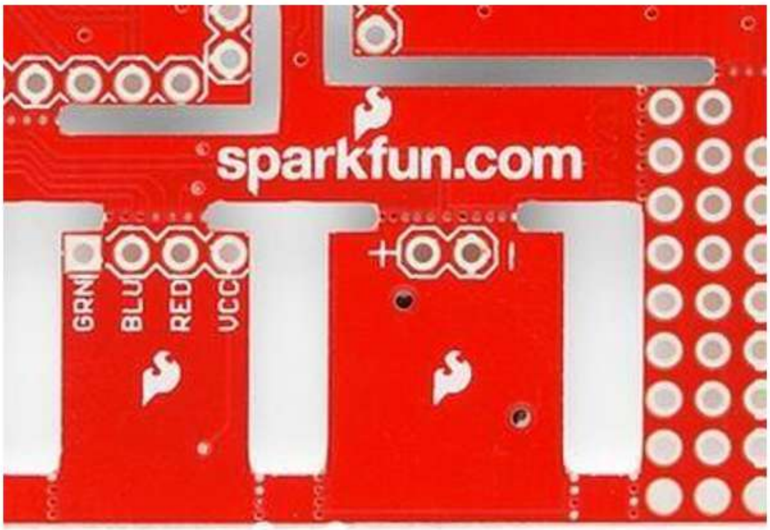



Fig 10.16 Complex slots cut into the ProtoSnap - Pro Mini. There are also many mouse bites shown. Note: the corners of the slots cannot be made completely square because they are cut with a circular routing bit.

- SOLDER PASTE: SMALL balls of solder suspended in a gel medium which, with the aid of a paste stencil, are applied to the surface mount pads on a PCB before the components are placed. During reflow, the solder in the paste melts, creating electrical and mechanical joints between the pads and the component.

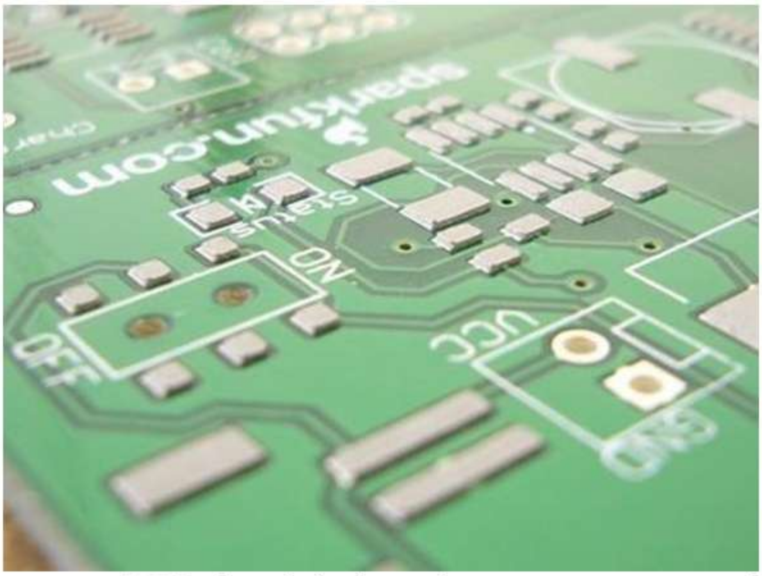



Fig 10.17: Solder paste on a PCB shortly before the components are placed. Be sure to read about paste stencil above as well.

- SOLDER POT: A pot used to quickly hand solder boards with through hole components. Usually contains a small amount of molten solder into which the board is quickly dipped, leaving solder joints on all exposed pads.

- SOLDERMASK: A layer of protective material laid over the metal to prevent short circuits, corrosion, and other problems. Frequently green, although other colors (SparkFun red, Arduino blue, or Apple black) are possible. Occasionally referred to as "resist".

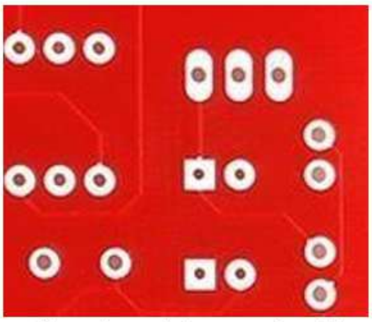


Fig 10.18: Solder mask covers up the signal traces but leaves the pads to solder to

- SOLDER JUMPER: A small, unwanted blob of solder connecting two adjacent pins on a component on a circuit board.

- SURFACE MOUNT: Construction method which allows components to be simply set on a board, not requiring that leads pass through holes in the board. This is the dominant method of assembly in use today, and allows boards to be populated quickly and easily.

- THERMAL: A small trace used to connect a pad to a plane. If a pad is not thermally relieved, it becomes difficult to get the pad to a high enough temperature to create a good solder joint. An improperly thermally relieved pad will feel “sticky” when you attempt to solder to it, and will take an abnormally long time to reflow.

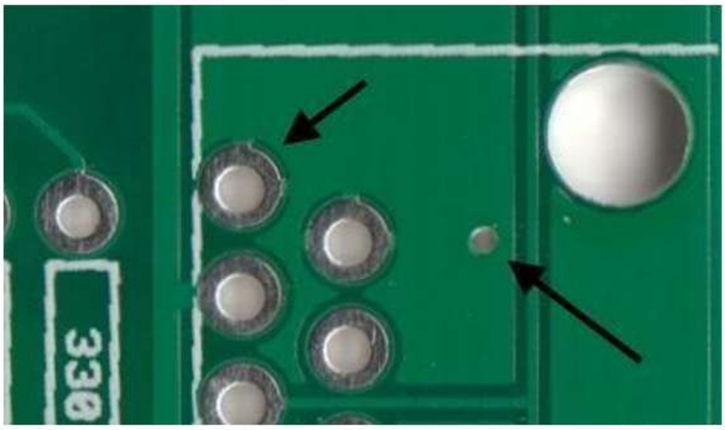



Fig 10.19: On the left, a solder pad with two small traces (thermals) connecting the pin to the ground plane. On the right, a via with no thermals connecting it completely to the ground plane.

- THIEVING: HATCHING, gridlines, or dots of copper left in areas of a board where no plane or traces exist. Reduces difficulty of etching because less time in the bath is required to remove unneeded copper.

- TRACE: A continuous path of copper on a circuit board.


Fig 10.20: A small trace connecting the Reset pad to elsewhere on the board. A larger, thicker trace connects to the 5V power pin.

- V-SCORE: A partial cut through a board, allowing the board to be easily snapped along a line.

- VIA: A hole in a board used to pass a signal from one layer to another. Tented vias are covered by solder mask to protect them from being soldered to. Vias where connectors and components are to be attached are often untented (uncovered) so that they can be easily soldered.

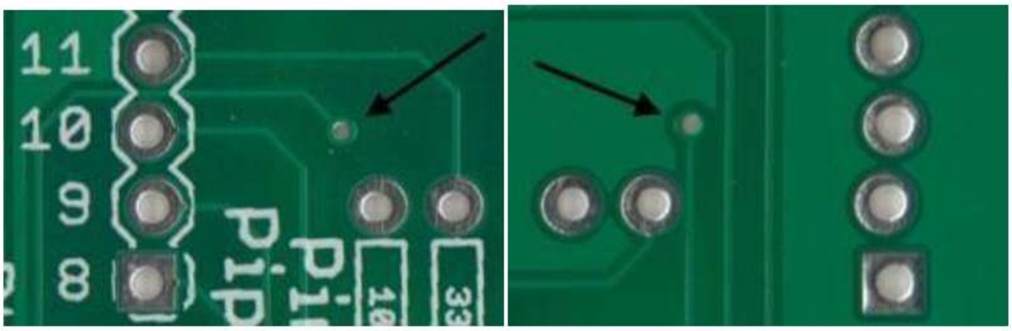



Fig 10.23 : Front and back of the same PCB showing a tented via. This via brings the signal from the front side of the PCB, through the middle of the board, to the back side.

- WAVE SOLDER: A method of soldering used on boards with through-hole components where the board is passed over a standing wave of molten solder, which adheres to exposed pads and component leads.

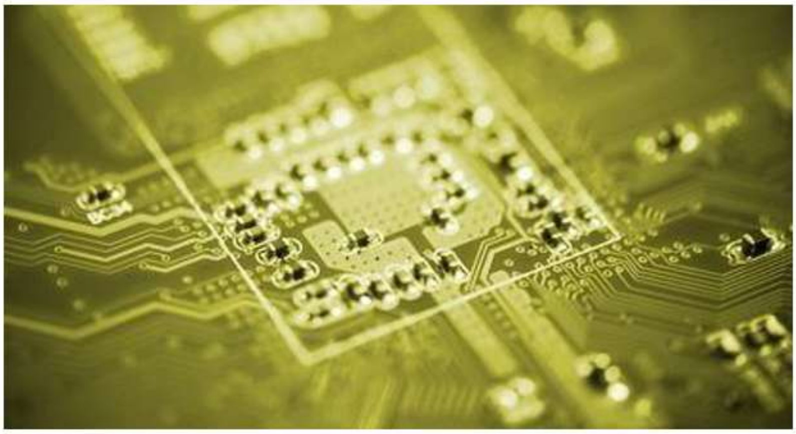


Fig 10.24

The surface of the PCB has several features. You will probably notice right away, when picking up any typical PCB, that the majority of the surface is covered with green stuff. This is called the solder mask, and it is a dielectric (insulator). It actually has several specific tasks. First, it is there to prevent corrosion, as the oxygen in our atmosphere is quite toxic to the copper on the top and bottom layers. Next, it has the job of preventing accidental shorts from occurring. The exposed copper is very vulnerable to paper clip drops and loose screws. Best to cover it up with green stuff that won't conduct.

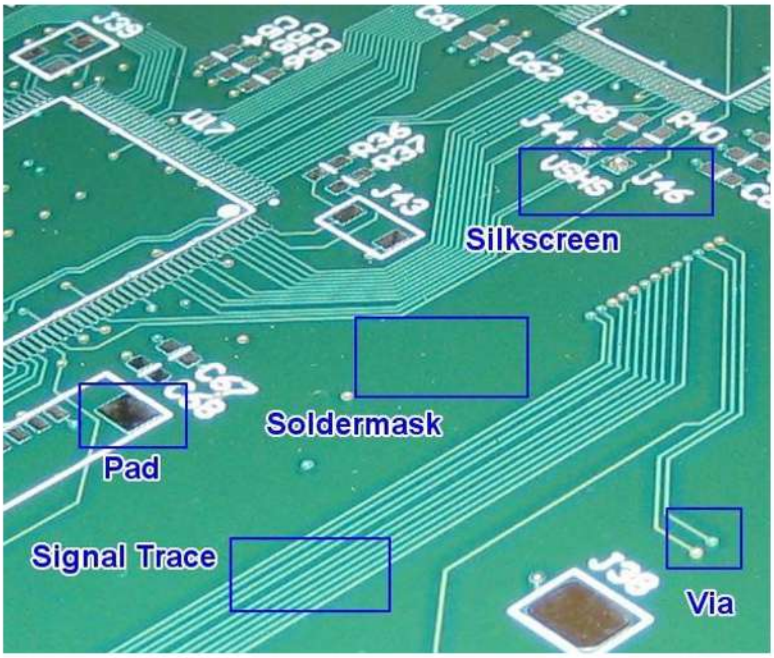



Fig 10.25

The next thing you will notice are the tiny lines that run across the surface of the board (albeit covered in green). They are the copper that reside on top of the PCB. This is how electrical connections are created from one electronic element to another. The term used to describe these lines is "signal trace" or just "trace"; they describe the trace that a copper takes from one point to another. Next, there are the pads. These are exposed bits of metal covered in tin (through electroplating). They are exposed so that the pins on your ICs and your resistors can be soldered onto the board. The tin does not oxidize, but is still conductive. This property protects the underlying copper, while still allowing an electrical connection to occur to the component being soldered. A plus side is that the metal tin is a major component in modern solder, such that the flow of the solder is facilitated by the tinned pads. Lastly, the colored letters and markings seen on top of the solder mask are called the silkscreens. They are aptly named since the markings are applied to the solder mask through a silkscreen process. It is essentially a stencil made with a thin membrane, onto which colored ink is applied. This layer allows the PCB designer to label the components, and indicate switches and functionality.

However, there are things underneath the surface that cannot be seen with the naked eye, but play a key role in the functionality of the board. Below is an example of a 4 layer PCB, typically very cheap to manufacture.

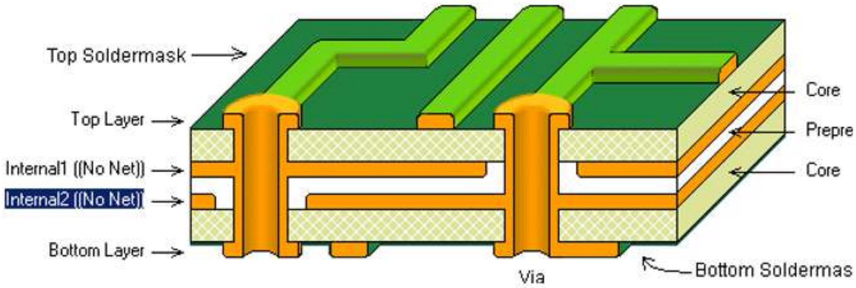



Fig 10.26

On any given PCB, you can only see the top and bottom copper traces. Underneath however, there may be many layers of copper creating connections between components. The cost of a PCB is generally dictated by the number of layer. These layers increase the number of possible connection options between components by allowing traces to intersect one another without shorting out. For very dense circuits such as mobile devices, more layers are need since the number of connection per area is high. On circuits with lower densities, a lower number of layers is preferred since it reduces manufacturing costs.
The round circle like things that can be seen on the surface of PCBs are called vias.

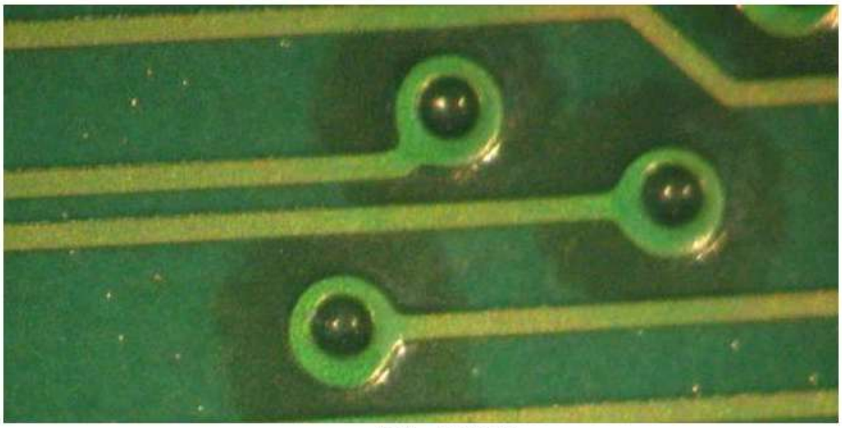


Fig 10.27

These are drilled holes that create the connections between the layers. The holes are actually drilled after the copper traces are created, and synthesized through copper electroplating. With a combination of traces and vias, the PCB designer is allowed to create circuits in three dimensions.

Finally, the layers between the copper (labelled “core” and “prepreg” in the above picture) are FR4 (most of the time). The abbreviation stands for Flame Retardant 4, created out of fibreglass and resin. These insulators create the structure of the board, and gives it rigidity. The copper on each of the conductive layers are grown onto the FR4, and then etched off in acid to create the traces. Each stack, consisting of one layer of copper and one layer of FR4, are then put together on a heated vacuum press, and allowed to meld together into a single board structure.

The goal of our manufacturing process is much less ambitious. We will be constructing a two layer board, with no solder mask, no pad tinning and no silkscreens. The process is usually called “barebone” since it only contains the bare essentials of a functioning PCB. As long as the signals pass through, it can be technically called a circuit board.

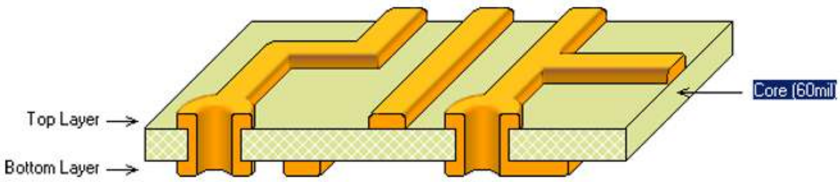



Fig 10.26

# MODULE 4.3: SERVOMECHANISM

## UNIT 11

### SERVO MOTOR THEORY

There are some special types of application of electrical motor where rotation of the motor is required for just a certain angle not continuously for long period of time. For these applications some special types of motor are required with some special arrangement which makes the motor to rotate a certain angle for a given electrical input (signal). For this purpose servo motor comes into picture. This is normally a simple DC motor which is controlled for specific angular rotation with help of additional servomechanism (a typical closed loop feedback control system). Now day's servo system has huge industrial applications. Servo motor applications are also commonly seen in remote controlled toy cars for controlling direction of motion and it is also very commonly used as the motor which moves the tray of a CD or DVD player. Beside these there are other hundreds of servo motor applications we see in our daily life. The main reason behind using a servo is that it provides angular precision, i.e. it will only rotate as much we want and then stop and wait for next signal to take further action. This is unlike a normal electrical which starts rotating as and when power is applied to it and the rotation continues until we switch off the power. We cannot control the rotational progress of electrical motor; but we can only control the speed of rotation and can turn it ON and OFF.

### SERVOMECHANISM

A servo system mainly consists of three basic components - a controlled device, an output sensor, a feedback system.

This is an automatic closed loop control system. Here instead of controlling a device by applying variable input signal, the device is controlled by a feedback signal generated by comparing output signal and reference input signal.

When reference input signal or command signal is applied to the system, it is compared with output reference signal of the system produced by output sensor, and a third signal produced by feedback system. This third signal acts as input signal of controlled device. This input signal to the device presents as long as there is a logical difference between reference input signal and output signal of the system. After the device achieves its desired output, there will be no longer logical difference between reference input signal and reference output signal of the system. Then, third signal produced by comparing theses above said signals will not remain enough to operate the device further and to produce further output of the system until the next reference input signal or command signal is applied to the system. Hence the primary task of a servomechanism is to maintain the output of a system at the desired value in the presence of disturbances.

### WORKING PRINCIPLE OF SERVO MOTOR

A servo motor is basically a DC motor (in some special cases it is AC motor) along with some other special purpose components that make a DC motor a servo. In a servo unit, you will find a small DC motor, a potentiometer, gear arrangement and an intelligent circuitry. The intelligent circuitry along with the potentiometer makes the servo to rotate according to our wishes.

As we know, a small DC motor will rotate with high speed but the torque generated by its rotation will not be enough to move even a light load. This is where the gear system inside a servomechanism comes into picture. The gear mechanism will take high input speed of the motor (fast) and at the output; we will get an output speed which is slower than original input speed but more practical and widely applicable.

Say at initial position of servo motor shaft, the position of the potentiometer knob is such that there is no electrical signal generated at the output port of the potentiometer. This output port of the potentiometer is connected with one of the input terminals of the error detector amplifier. Now an electrical signal is given to another input terminal of the error detector amplifier. Now difference between these two signals, one comes from potentiometer and another comes from external source, will be amplified in the error detector amplifier and feeds the DC motor. This amplified error signal acts as the input power of the dc motor and the motor starts rotating in desired direction. As the motor shaft progresses the potentiometer knob also rotates as it is coupled with motor shaft with help of gear arrangement. As the position of the potentiometer knob changes there will be an electrical signal produced at the potentiometer port. As the angular position of the potentiometer knob progresses the output or feedback signal increases. After desired angular position of motor shaft

the potentiometer knob is reaches at such position the electrical signal generated in the potentiometer becomes same as of external electrical signal given to amplifier. At this condition, there will be no output signal from the amplifier to the motor input as there is no difference between external applied signal and the signal generated at potentiometer. As the input signal to the motor is nil at that position, the motor stops rotating. This is how a simple conceptual servo motor works.

## SERVO MOTOR CONTROL

For understanding servo motor control let us consider an example of servomotor that we have given a signal to rotate by an angle of 45° and then stop and wait for further instruction.

The shaft of the DC motor is coupled with another shaft called output shaft, with help of gear assembly. This gear assembly is used to step down the high rpm of the motor's shaft to low rpm at output shaft of the servo system.

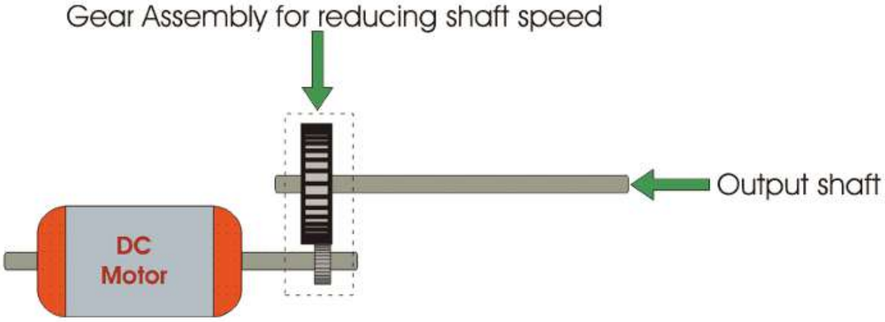



Fig 11.1

The voltage adjusting knob of a potentiometer is so arranged with the output shaft by means of another gear assembly, that during rotation of the shaft, the knob also rotates and creates a varying electrical potential according to the principleof potentiometer. This signal i.e. electrical potential is increased with angular movement of potentiometer knob along with the system shaft from 0° to 45°. This electrical potential or voltage is taken to the error detector feedback amplifier along with the input reference commends i.e. input signal voltage.

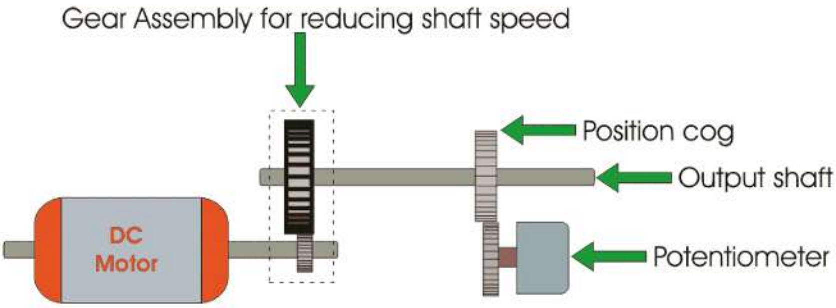



Fig 11.2

As the angle of rotation of the shaft increases from 0° to 45° the voltage from potentiometer increases. At 45° this voltage reaches to a value which is equal to the given input command voltage to the system. As at this position of the shaft, there is no difference between the signal voltage coming from the potentiometer and reference input voltage (command signal) to the system, the output voltage of the amplifier becomes zero.

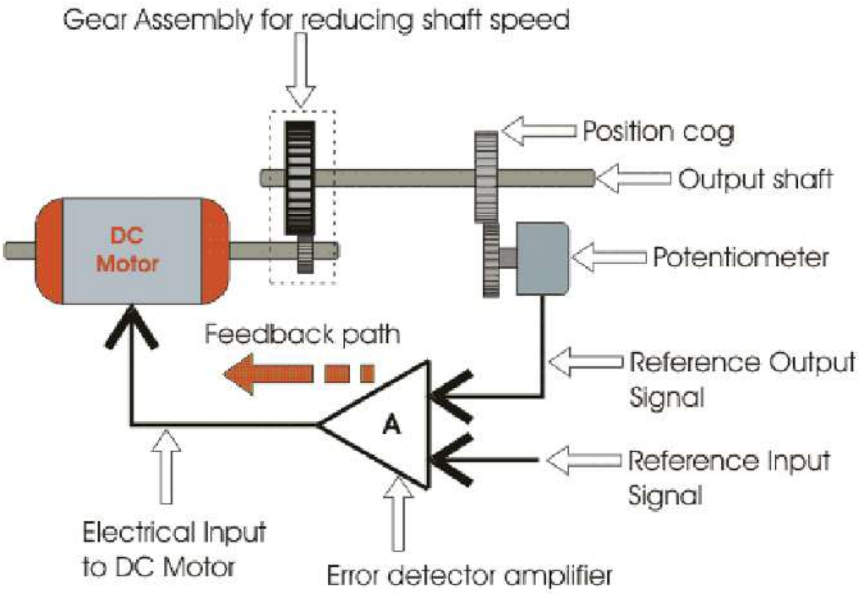



Fig 11.3

Servomechanisms are involved with the electrical remote controlofsystems/sub systems. In general the controlcircuitry can beeither Open Loop or Closed Loop control. With an open loopsystem a control signal is sent to operate a component and nofeed-back signal is returned to indicate the configuration of thecomponent. In a closed loop system a feed-back signal is returnedto the origin to indicate some parameter of the component- speed,position etc.In general feed-back can bepositive feed-back or negative feed-back. With positive feed-back the returning signalincreases the original signal (rare), and negative feed-backreducesor negates the original control signal.

## OPEN LOOP CONTROL SYSTEM

Suppose that we wish to control the position of a radar scanner.Supposealso that we have a motor capable of driving the scannerand some means of controlling the motor. Such an arrangement isillustrated in figure

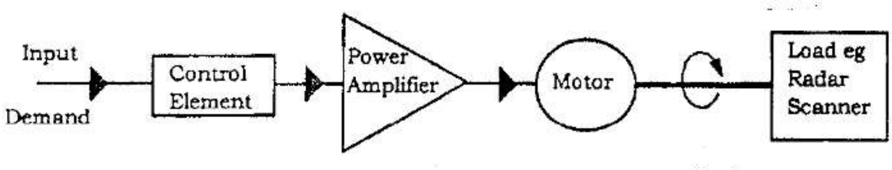


Fig 11.4 : Open Loop Control System

The control element controls the magnitude and direction of theinput to a power amplifier, whose output drives the motor at the desired speed in the required direction. The motor, in turn,moves the load in accordance with the input demand.

The control element could be calibrated with ascale indicatingthe required position of the load. Then when the control dial is set forthe required position, we hope that the load (possibly unseen) isdoing what has been selected.

In practice, however, the accuracy of control is limited because of several factors, other than the input, that affect the output (e.g.variations in theoutput load, in the amplifier characteristics or inthe motor circuit). There areno means of controlling thesevariations in the open loop system and, because of the resultinginaccuracy; open loop systems are hardly ever used.

## CLOSED LOOP CONTROL SYSTEM

If an observer checks on whatthe load is doing and makesappropriate corrections at the input, the system is no longer openloop and is, in effect, a closed loop system with the humanoperator completing the feed-back loop between output and input.

He / she compare the desired effect with the actual effect andadjust the system so as to reduce the error between them.He/she is, in effect, an 'error detector', and the amount of error whichis observed determines how he/she adjusts the input to producethe desired results.

A more effective and efficient control can be obtained byreplacing the human operator with an automatic control system.The response of the automatic system is generally quicker andmore accurate than that of a human operator, and the automaticarrangement is not subject to fatigue. In addition, of course, theautomatic system gives a saving in manpower. The essentialfeatures of the closed loop system are:

1. The feed-back of information concerning the behavior of the load.
2. The comparison of this information with the behavior demanded by the input.
3. The production of an error signal proportional to the difference between the desired behavior and the actual behavior.
4. The amplification of the error signal to control the power into a servomotor.
5. The movement of the load by the servomotor in such a direction as to reduce the error signal to zero, at which point the output is the same as that demanded by the input.

A schematic diagram of a basic closed loop control system is illustrated below.

In this arrangement:

a. Øi is the input demand, which in this case is in the form of a shaft angle.
b. Øo is the output shaft angle of the load.
c. The control element converts the demand ej into some form suitable for operation of the error detector, eg produces a voltage proportional to Øi.
d. The feed-back element does the same for the output angle 80, eg produces a voltage proportional to Øi.
e. The error detector has two inputs applied to it, one due to 8j and the other due to 80; it produces an error signal e proportional to the difference between the two inputs, (Øi-Øo).

f. The error signal operates the amplifier which, in turn, causes the motor to rotate until Øo equals Øi (output equals demand); at this point the error signal is zero and the drive from the motor ceases, the output load having taken up the position demanded by the input.

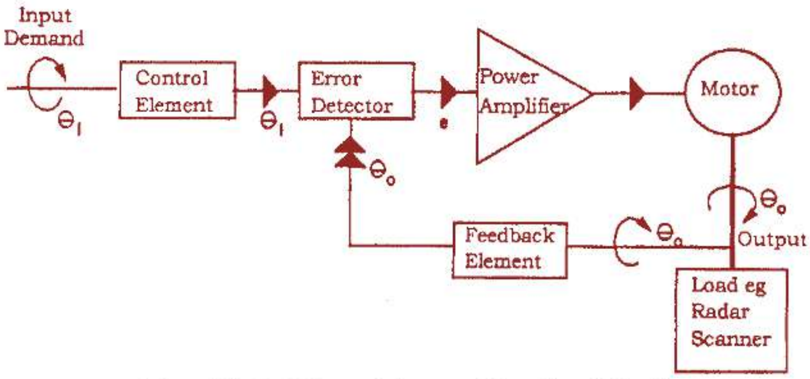



Fig. 11.5: Closed Loop Control System

## PRACTICAL CLOSED LOOP CONTROL SYSTEM

The input demand 8j sets the angle of the transmitter (CX) rotor. The resulting alternating field in the control transformer stator induces a voltage in the transformer rotor and this voltage is fed as an error or misalignment signal to the amplifier. The amplifier output is used to drive an ac servomotor which turns the output shaft and also the rotor of the control transformer through output angle Theta.

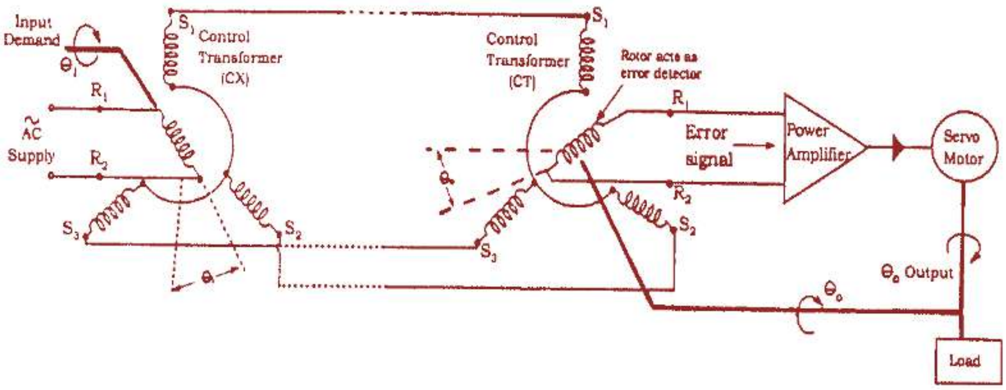



Fig 11.7

When the output shaft is turned into alignment with the setting of the input shaft (80 = 8j) the transformer rotor is at right angles to the transmitter rotor and its own stator field. In this position there is no error signal induced in the transformer rotor, there is no input to the amplifier or servomotor, and the motor stops. The output has now taken up the position demanded by the input.

## 11.1. SERVOMECHANISM AND ITS TYPE

To be classed as a servomechanism, an automatic control system must have:

a. Error actuation.

b. Power amplification.
c. Closed loop control.
d. Continuous operation, or 'follow-up' properties, i.e. if the load is disturbed from the demanded position, it always tends to return to it.

The system is said to be error actuated because it is the error between the output demanded by the input and the actual output which starts the action. The final net input to the amplifier is the error signal and not the input demand.

Torque amplification is required to be able to drive heavy loads. The servo therefore contains an amplifier which supplies the necessary driving power to the servomotor; the motor provides the required torque.

The servo also has a closed loop system:

Error detector - amplifier - motor and load - error detector

## FOLLOW UP PROPERTIES

Finally continuous operation is assured in a servomechanism because any variation in the output from that demanded by the input automatically produces a difference between output and input, and hence an error signal. The error signal again starts the correcting action.

A servomechanism has many applications, covering a wide range of power requirements.

## TYPES OF SERVO

There are two main classes of servomechanism - Remote Position Control (RPC) servos and speed control servos.

### a. RPC SERVOS

These are used to control the angular or linear position of a load.

### b. SPEED CONTROL SERVOS

These are used to control the speed of a load. In this case, the speed of the driving motor is made proportional to the input demand (usually a voltage).

## 11.4. SERVOMECHANISM COMPONENTS

Servomechanisms may be AC or DC operated.

## DC SERVO COMPONENTS

The positional feedback signal would be from a potentiometer in most cases. The error detector would be potentiometer circuits or electronic circuits producing an error signal proportional to the difference between input and output shaft rotations.

The servo amplifiers must produce sufficient power to drive the servomotor, this power requirement will depend on the system. The power amplifiers used in conjunction with voltage amplifiers (to provide gain) will thus vary in power output.

dc servomotors must be capable of being reversed and the torque developed must be proportional to the error signal input. As torque is proportional to the product of the armature current and the field current, the armature current is kept constant, and the torque can be controlled by varying the field current (error signal). So separate supplies are used, the armature current being fed from a constant current source and the field being fed from theservo amplifier. Figure shows a dc operated servomotor. Attached to the motor is a servo amplifier, feedback is provided by a potentiometer, the wiper of which is driven by the motor.

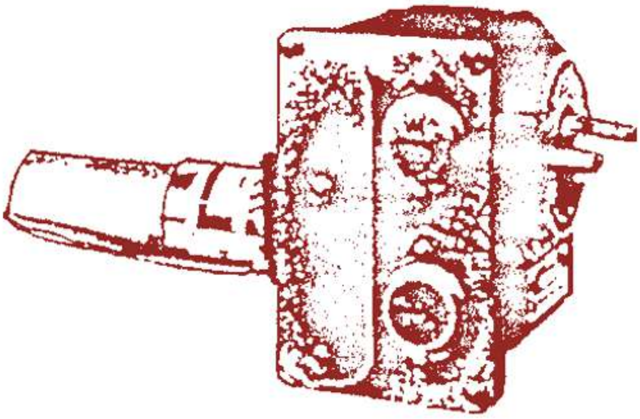


Fig. 11.22 : DC Operated Servomotor

The de tacho-generator mounted on the output shaft of the servomechanism is a small, separately excited dc generator. It will therefore produce a de voltage which is directly proportional to the speed at which it is driven and whose polarity depends on the direction of rotation.

## AC SERVO COMPONENTS

The positional feedback signal may be from potentiometers, Synchro, LVDT's (Linear Variable Differential Transducers), RVDT's (Rotary Variable Differential Transducers). The servo amplifier is a conventional transistorized amplifier with voltage and power amplifiers.

Note. Some text books use the word Transformer in place of Transducer. ac servomotors capable of producing moderately high torque are usually induction motors. Induction motors run at a constant speed (related to the frequency of the ac supply), but their torque and their direction of rotation can be controlled fairly easily by the amplified error signal, without the use of complex circuitry.

Two-phase and three-phase induction motors are in common use in ac servo systems; the two-phase type is more usual.

The two-phase induction motor requires two ac supply voltages900 out of phase with each other. One phase is fed to the control system and then through the servo amplifier to one stator winding of the motor; this supply is controlled by the error signal. The other phase, known as the 'reference phase', is fed directly to the other phase winding of the motor.

When the reference phase to one stator winding and the error-controlled phase to the other winding are both present, a rotating magnetic field is produced; the squirrel-cage rotor follows this field and so rotates.

The direction of rotation depends upon the sense of the error signal, ie on the direction of misalignment between input and output shafts of the servo.

As the misalignment signal passes through the zero error signal position, the phase of the error-controlled voltage reverses and this reverses the direction of rotation of the motor. When the error is zero, the error-controlled phase voltage is zero also and no rotating magnetic field is produced; the motor thus stops. The torque developed by the motor depends upon the magnitude of the error signal; the greater the error, the larger is the torque.

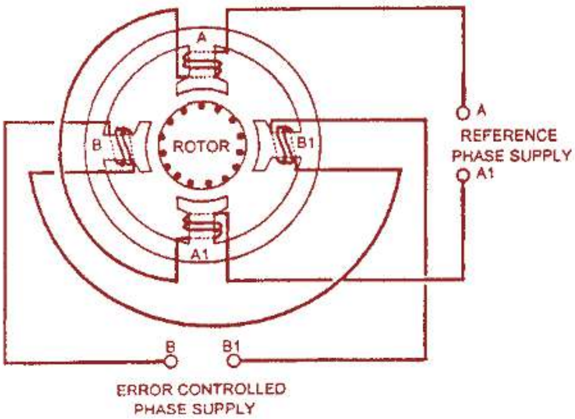



Fig. 11.23 : Two – Phase Induction Motor

Hysteresis motors may also be used as ac servomotors. A typical arrangement is shown in figure. A two-phase supply is required, the reference phase voltage being applied to phase windings AA], and the error-controlled voltage to BBI' At one instant, A will act as a N-pole and At as as-pole; Band B1 will be neutral.

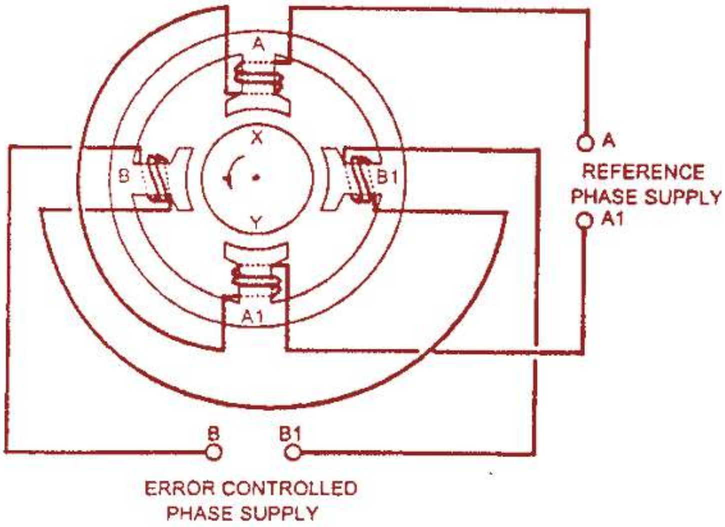



Fig. 11.24: Hysteresis Servomotor

The rotor - a cobalt steel ring - will therefore have a S-pole induced at X and a N-pole at Y. A quarter of a cycle later, B will act as a N-pole and B. as a S- pole; A and A] will be neutral. However, the rotor, which is made of a large hysteresis loop material, will have retained its S-pole at X and its N-pole at Y.

So point X on the rotor is attracted to the B stator winding and Y is attracted to B1.

Since a torque is being exerted on the rotor it will turn to follow the rotating magnetic field and will continue to do so until the error signal falls to zero. The direction of rotation depends upon the phase of the error-controlled voltage relative to the reference voltage and this, in turn, depends upon the sense of the error. The torque developed depends upon the magnitude of the error.

## SERVOMOTOR CONSTRUCTION

Figure shows a two-phase induction motor, the two phase winding accommodated in slots in the stator. The rotor is of the squirrel cage construction generally with aluminum conductors.

The stator and rotor slots are skewed, this prevents the reluctance of the rotor to move away from one of a number of positions where the slots in the rotor and stator are aligned and so ensures smooth torque output. .

The ac tacho-generator is used to provide velocity feedback damping in ac servo systems, is mounted on the output shaft so that it rotates at the same speed as the load.

The ac tacho-generator is usually a drag-cup generator which produces an alternating voltage of the same frequency as the ac supply. However, the amplitude of the voltage depends upon the speed of rotation; and the phase of the voltage leads or lags the ac supply depending upon the direction of rotation.

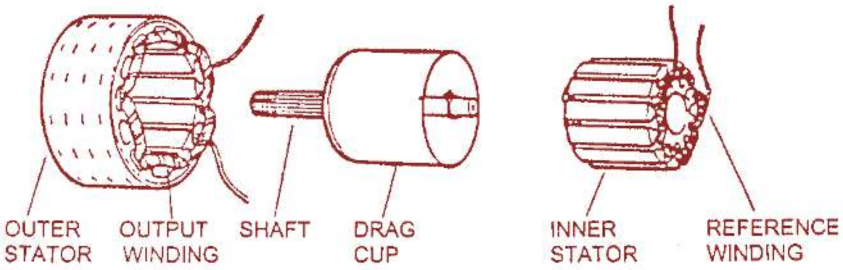



Fig 11.26

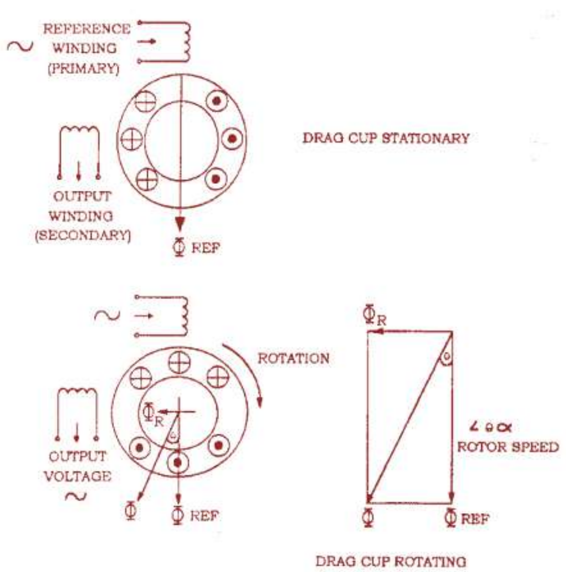



Fig 11.27 : AC Tacho-Generator Phase Details

The drag-cup generator has a two-coil stator whose axes are at right angles, as in a two-phase induction motor. The rotor, however, is a copper or brass cup with a stationary iron cylinder fitted inside it to complete the magnetic path for the stator.

AC is applied to only one stator coil - the primary coil. As the rotor is driven by the output shaft, voltages are induced in it by interaction with the field produced by the current in the primary stator. At any instant, maximum voltage is induced in that part of the cup passing through the primary axis.

Maximum circulating (eddy) currents are therefore in this axis, and these currents produce a secondary magnetic field which is at right angles to the axis of the primary field.

This secondary field alternates at the frequency of the supply current but its magnitude depends upon the amplitude of the circulating eddy currents induced in the rotor by the primary field; this, in turn, depends upon the speed or rotation. The secondary stator winding of the tache-generator is at right angles to the primary axis and so has a voltage induced in it by the secondary field only.

This is the output voltage whose amplitude is proportional to the speed of rotation and whose phase relative to the reference ac supply depends upon the direction of rotation. A typical ac tache-generator provides a velocity feedback voltage of O.SV per 1,000 rpm of the rotor.

We shall now look at servos used in automatic flight control systems. An overview only is given here as each area will be covered in greater depth in the following autopilot books in this series.

The basic requirements of an automatic flight control system are:

a. Sensing of attitude change of the aircraft.
b. Producing an error signal from this change.
c. Converting the error signal into a signal suitable to drive a servomotor.
d. Servomotor drive to control surface or selection of hydraulic PFCU.

Sensing of altitude change can be achieved by gyroscopes or accelerometers. Figure shows a roll control channel (the aircraft may also have pitch and yaw control channels). There is no need to commit it to memory but you should have a general understand of how it works.

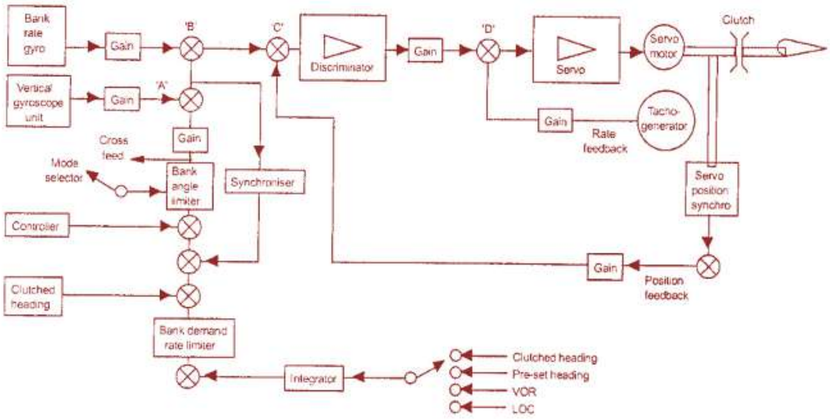



Fig 11.28

## 11.5. SERVO FEEDBACK SYSTEMS

An important interconnection of systems which is used extensively in control systems, is the "feedback configuration". In feedback systems, a fraction of the output signal is "fed back" and either added to or subtracted from the original input signal. The result is that the output of the system is continually altering or updating its input with the purpose of modifying the response of a system to improve stability. A feedback system is also commonly referred to as a "Closed-loop System" as shown.

## CLOSED-LOOP FEEDBACK SYSTEM

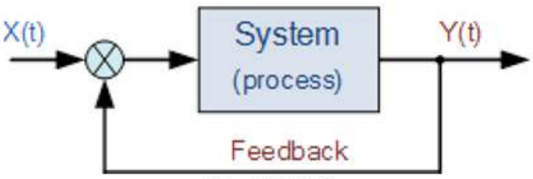



Fig 11.29

Feedback systems are used a lot in most practical electronic system designs to help stabilise the system and to increase its control. If the feedback loop reduces the value of the original signal, the feedback loop is known as "negative feedback". If the feedback loop adds to the value of the original signal, the feedback loop is known as "positive feedback".

An example of a simple feedback system could be a thermostatically controlled heating system in the home. If the home is too hot, the feedback loop will switch "OFF" the heating system to make it cooler. If the home is too cold, the feedback loop will switch "ON" the heating system to make it warmer. In this instance, the system comprises of the heating system, the air temperature and the thermostatically controlled feedback loop.

## TRANSFER FUNCTION OF SYSTEMS


Fig 11.30

Any subsystem can be represented as a simple block with an input and output as shown. Generally, the input is designated as: θi and the output as: θo. The ratio of output over input represents the gain, ( G ) of the subsystem and is therefore defined as: G = θo/θi

In this case, G represents the Transfer Function of the system or subsystem. When discussing electronic systems in terms of their transfer function, the complex operator, s is used, then the equation for the gain is rewritten as: G(s) = θo(s)/θi(s)

## SUMMARY

We have seen that a simple Electronic System consists of an input, a process, an output and possibly feedback. Electronic systems can be represented using interconnected block diagrams where the lines between each block or subsystem represents both the flow and direction of a signal through the system.

Block diagrams need not represent a simple single system but can represent very complex systems made from many interconnected subsystems. These subsystems can be connected together in series, parallel or combinations of both depending upon the flow of the signals.

We have also seen that electronic signals and systems can be of continuous-time or discrete-time in nature and may be analogue, digital or both. Feedback loops can be used be used to increase or reduce the performance of a particular system by providing better stability and control. Control is the process of making a system variable adhere to a particular value, called the reference value.

In the next tutorial about Electronic Systems, we will look at a types of electronic control system called an Open-loop System which generates an output signal, y(t) based on its present input values and as such does not monitor its output or make adjustments based on the condition of its output.

## 11.6. THE OPEN-LOOP SYSTEM

In the last tutorial about Electronic Systems, we saw that a system can be a collection of subsystems which direct or control an input signal. The function of any electronic system is to automatically regulate the output and keep it within the systems desired input value or "set point". If the systems input changes for whatever reason, the output of the system must respond accordingly and change itself to reflect the new input value.

Likewise, if something happens to disturb the systems output without any change to the input value, the output must respond by returning back to its previous set value. In the past, electrical control systems were basically manual or what is called an Open-loop System with very few automatic control or feedback features built in to regulate the process variable so as to maintain the desired output level or value.

For example, an electric clothes dryer. Depending upon the amount of clothes or how wet they are, a user or operator would set a timer (controller) to say 30 minutes and at the end of the 30 minutes the drier will automatically stop and turn-off even if the clothes are still wet or damp.

In this case, the control action is the manual operator assessing the wetness of the clothes and setting the process (the drier) accordingly.

So in this example, the clothes dryer would be an open-loop system as it does not monitor or measure the condition of the output signal, which is the dryness of the clothes. Then the accuracy of the drying process, or success of drying the clothes will depend on the experience of the user (operator).

However, the user may adjust or fine tune the drying process of the system at any time by increasing or decreasing the timing controllers drying time, if they think that the original drying process will not be met. For example, increasing the timing controller to 40 minutes to extend the drying process. Consider the following open-loop block diagram.

## OPEN-LOOP DRYING SYSTEM

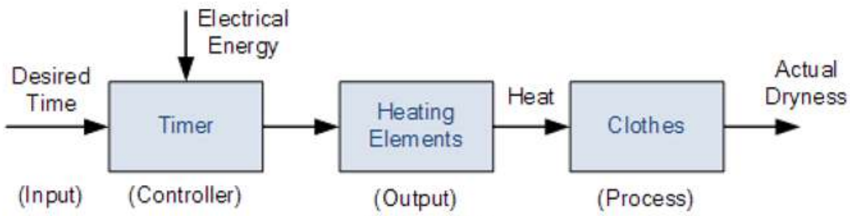



Fig 11.31

Then an Open-loop system, also referred to as non-feedback system, is a type of continuous control system in which the output has no influence or effect on the control action of the input signal. In other words, in an open-loop control system the output is neither measured nor "fed back" for comparison with the input. Therefore, an open-loop system is expected to faithfully follow its input command or set point regardless of the final result.

Also, an open-loop system has no knowledge of the output condition so cannot self-correct any errors it could make when the preset value drifts, even if this results in large deviations from the preset value.

Another disadvantage of open-loop systems is that they are poorly equipped to handle disturbances or changes in the conditions which may reduce its ability to complete the desired task. For example, the dryer door opens and heat is lost. The timing controller continues regardless for the full 30 minutes but the clothes are not heated or dried at the end of the drying process. This is because there is no information fed back to maintain a constant temperature.

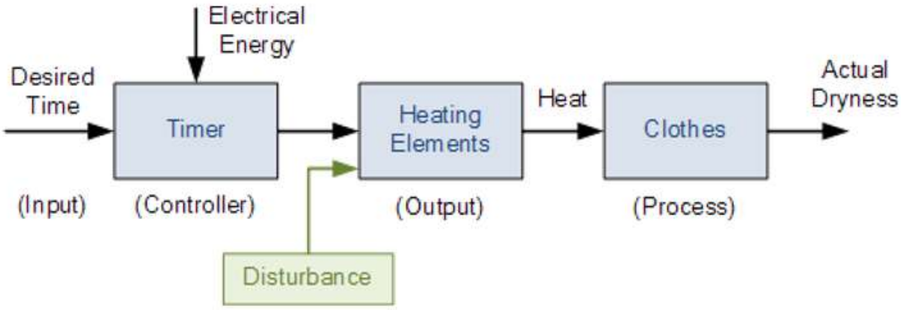



Fig 11.32

Then we can see that open-loop system errors can disturb the drying process and therefore requires extra supervisory attention of a user (operator). The problem with this anticipatory control approach is that the user would need to look at the process temperature frequently and take any corrective control action whenever the drying process deviated from its desired value of drying the clothes. This type of manual open-loop control which reacts before an error actually occurs is calledFeed forward Control.

The objective of feed forward control, also known as predictive control, is to measure or predict any potential open-loop disturbances and compensate for them manually before the controlled variable deviates too far from the original set point. So for our simple example above, if the dryers door was open it would be detected and closed allowing the drying process to continue.

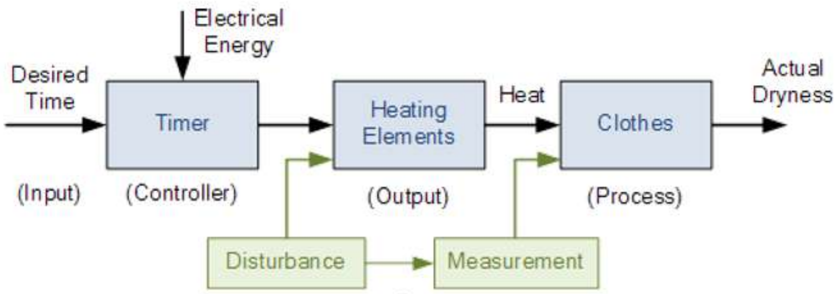



Fig 11.33

If applied correctly, the deviation from wet clothes to dry clothes at the end of the 30 minutes would be minimal if the user responded to the error situation (door open) very quickly. However, this feed forward approach may not be completely accurate if the system changes, for example the drop in drying temperature was not noticed during the 30 minute process.

Then we can define the main characteristics of an "Open-loop system" as being:

- There is no comparison between actual and desired values.
- An open-loop system has no self-regulation or control action over the output value.
- Each input setting determines a fixed operating position for the controller.
- Changes or disturbances in external conditions does not result in a direct output change. (unless the controller setting is altered manually)

Any open-loop system can be represented as multiple cascaded blocks in series or a single block diagram with an input and output. The block diagram of an open-loop system shows that the signal path from input to output represents a linear path with no feedback loop and for any type of control system the input is given the designation θi and the output θo.

Generally, we do not have to manipulate the open-loop block diagram to calculate its actual transfer function. We can just write down the proper relationships or equations from each block diagram, and then calculate the final transfer function from these equations as shown.

## OPEN-LOOP CONTROL SYSTEMS SUMMARY

We have seen that a controller can manipulate its inputs to obtain the desired effect on the output of a system. One type of control system in which the output has no influence or effect on the control action of the input signal is called an Open-loop system.
An "open-loop system" is defined by the fact that the output signal or condition is neither measured nor "fed back" for comparison with the input signal or system set point. Therefore open-loop systems are commonly referred to as "Non-feedback systems".

Also, as an open-loop system does not use feedback to determine if its required output was achieved, it "assumes" that the desired goal of the input was successful because it cannot correct any errors it could make, and so cannot compensate for any external disturbances to the system.

## OPEN-LOOP MOTOR CONTROL

So for example, assume the DC motor controller as shown. The speed of rotation of the motor will depend upon the voltage supplied to the amplifier (the controller) by the potentiometer. The value of the input voltage could be proportional to the position of the potentiometer.

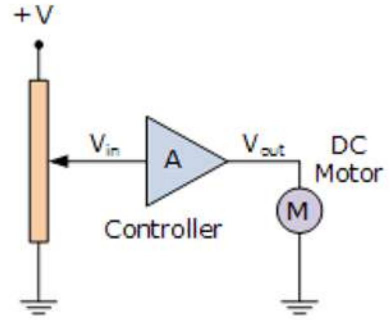



Fig 11.34

If the potentiometer is moved to the top of the resistance the maximum positive voltage will be supplied to the amplifier representing full speed. Likewise, if the potentiometer wiper is moved to the bottom of the resistance, zero voltage will be supplied representing a very slow speed or stop.

Then the position of the potentiometers slider represents the input, θi which is amplified by the amplifier (controller) to drive the DC motor (process) at a set speed N representing the output, θo of the system. The motor will continue to rotate at a fixed speed determined by the position of the potentiometer.

As the signal path from the input to the output is a direct path not forming part of any loop, the overall gain of the system will the cascaded values of the individual gains from the potentiometer, amplifier, motor and load. It is clearly desirable that the output speed of the motor should be identical to the position of the potentiometer, giving the overall gain of the system as unity.

However, the individual gains of the potentiometer, amplifier and motor may vary over time with changes in supply voltage or temperature, or the motors load may increase representing external disturbances to the open-loop motor control system.

But the user will eventually become aware of the change in the systems performance (change in motor speed) and may correct it by increasing or decreasing the potentiometers input signal accordingly to maintain the original or desired speed.

The advantages of this type of "open-loop motor control" is that it is potentially cheap and simple to implement making it ideal for use in well-defined systems were the relationship between input and output is direct and not influenced by any outside disturbances. Unfortunately this type of open-loop system is inadequate as variations or disturbances in the system affect the speed of the motor. Then another form of control is required.

In the next tutorial about Electronics Systems, we will look at the effect of feeding back some of the output signal to the input so that the systems control is based on the difference between actual and desired values. This type of electronics control system is called Closed-loop Control.

## 11.7. CLOSED-LOOP SYSTEMS

In the previous tutorial we saw that systems in which the output quantity has no effect upon the input to the control process are called open-loop control systems, and that open-loop systems are just that, open ended non-feedback systems. But the goal of any electrical or electronic control system is to measure, monitor, and control a process.

One way in which we can accurately Control the Process is by monitoring its output and "feeding" some of it back to compare the actual output with the desired output so as to reduce the error and if disturbed, bring the output of the system back to the original or desired response. The measure of the output is called the "feedback signal" and the type of control system which uses feedback signals to control itself is called a Close-loop System.

A Closed-loop Control System, also known as a feedback control system is a control system which uses the concept of an open loop system as its forward path but has one or more feedback loops (hence its name) or paths between its output and its input. The reference to "feedback", simply means that some portion of the output is returned "back" to the input to form part of the systems excitation.

Closed-loop systems are designed to automatically achieve and maintain the desired output condition by comparing it with the actual condition. It does this by generating an error signal which is the difference between the output and the reference input. In other words, a "closed-loop system" is a fully automatic control system in which its control action being dependent on the output in some way.

So for example, consider our electric clothes dryer from the previous open-loop tutorial. Suppose we used a sensor or transducer (input device) to monitor the temperature or dryness of the clothes and fed the signal back to the controller as shown below.

## CLOSED-LOOP CONTROL

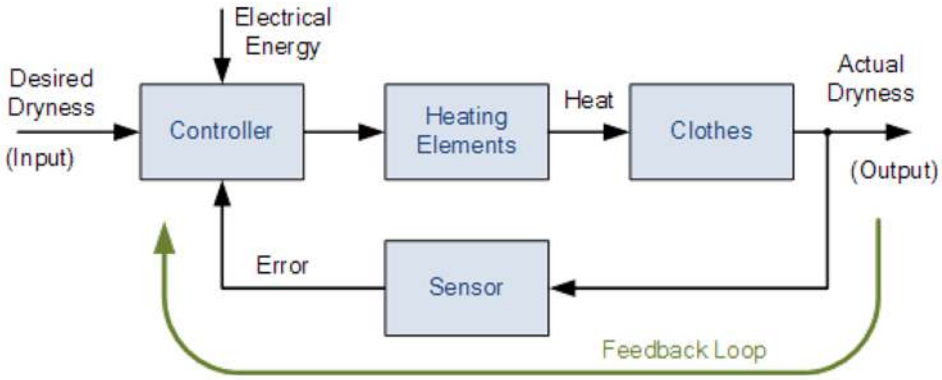



Fig 11.35

This sensor would monitor the actual dryness of the clothes and compare it with (or subtract it from) the input reference. The error signal (error = required dryness – actual dryness) is amplified by the controller, and the controller output makes the necessary correction to the heating system to reduce any error. For example if the clothes are too wet the controller may increase the temperature, if the clothes are nearly dry it may reduce the temperature so as not to overheat or burn the clothes, etc.

Then the closed-loop configuration is characterised by the feedback signal, derived from the sensor in our clothes drying system. The magnitude and polarity of the resulting error signal, would be directly related to the difference between the required dryness and actual dryness of the clothes.

Also, because a closed-loop system has some knowledge of the output condition, it is better equipped to handle any system disturbances or changes in the conditions which may reduce its ability to complete the desired task.

For example, as before, the dryer door opens and heat is lost. This time the deviation in temperature is detected by the feedback sensor and the controller self-corrects the error to maintain a constant temperature within the limits of the preset value. Or possibly stops the process and activates an alarm.

As we can see, in a closed-loop control system the error signal, which is the difference between the input signal and the feedback signal (which may be the output signal itself or a function of the output signal), is fed to the controller so as to reduce the systems error and bring the output of the system back to a desired value. In our case the dryness of the clothes. Clearly, when the error is zero the clothes are dry.

The term Closed-loop control always implies the use of a feedback control action in order to reduce any errors within the system, and its "feedback" which distinguishes the main differences between an open-loop and a closed-loop system.

The accuracy of the output thus depends on the feedback path, which in general can be made very accurate and within electronic control systems and circuits, feedback control is more commonly used than open-loop or feed forward control.

Closed-loop systems have many advantages over open-loop systems. The primary advantage of a closed-loop feedback control system is its ability to reduce a system's sensitivity to external disturbances, for example opening of the dryer door, giving the system a more robust control as any changes in the feedback signal will result in compensation by the controller.

Then we can define the main characteristics of Closed-loop Control as being:

- To reduce errors by automatically adjusting the systems input.
- To improve stability of an unstable system.
- To increase or reduce the systems sensitivity.
- To enhance robustness against external disturbances to the process.
- To produce a reliable, repeatable performance.

Whilst a good closed-loop system can have many advantages over an open-loop control system, its main disadvantage is that in order to provide the required amount of control, a closed-loop system must be more complex by having one or more feedback paths. Also, if the gain of the controller is too sensitive to changes in its input commands or signals it can become unstable and start to oscillate as the controller tries to over-correct itself, and eventually something would break. So we need to "tell" the system how we want it to behave.

## CLOSED-LOOP SUMMING POINTS

For a closed-loop feedback system to regulate any control signal, it must first determine the error between the actual output and the desired output. This is achieved using a summing point, also referred to as a comparison element, between the feedback loop and the systems input. These summing points compare a systems set point to the actual value and produce a positive or negative error signal which the controller responds too.

Where: Error = Set Point – Actual

Fig 11.36

The symbol used to represent a summing point in closed-loop systems block-diagram is that of a circle with two crossed lines as shown. The summing point can either add signals together in which a Plus ( + ) symbol is used showing the device to be a "summer" (used for positive feedback), or it can subtract signals from each other in which case a Minus ( − ) symbol is used showing that the device is a "comparator" (used for negative feedback) as shown.

SUMMING POINT TYPES


Fig 11.37

Note that summing points can have more than one signal as inputs either adding or subtracting but only one output which is the algebraic sum of the inputs. Also the arrows indicate the direction of the signals. Summing points can be cascaded together to allow for more input variables to be summed at a given point.

## CLOSED-LOOP SYSTEM TRANSFER FUNCTION

The Transfer Function of any electrical or electronic control system is the mathematical relationship between the systems input and its output, and hence describes the behaviour of the system. Note also that the ratio of the output of a particular device to its input represents its gain. Then we can correctly say that the output is always the transfer function of the system times the input. Consider the closed-loop system below.

## CLOSED-LOOP MOTOR CONTROL

So how can we use Closed-loop Systems in Electronics? Well consider our DC motor controller from the previous open-loop tutorial. If we connected a speed measuring transducer, such as a tachometer to the shaft of the DC motor, we could detect its speed and send a signal proportional to the motor speed back to the amplifier. A tachometer, also known as a tacho-generator is simply a permanent-magnet DC generator which gives a DC output voltage proportional to the speed of the motor.

Then the position of the potentiometers slider represents the input, θi which is amplified by the amplifier (controller) to drive the DC motor at a set speed N representing the output, θo of the system, and the tachometer T would be the closed-loop back to the controller. The difference between the input voltage setting and the feedback voltage level gives the error signal as shown.

CLOSED-LOOP MOTOR CONTROL

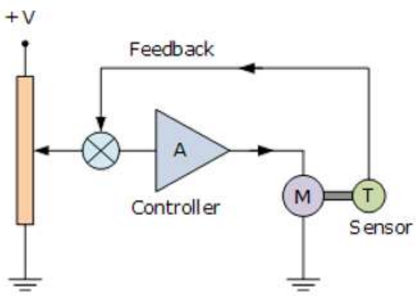


Fig 11.38

Any external disturbances to the closed-loop motor control system such as the motors load increasing would create a difference in the actual motor speed and the potentiometer input set point.

This difference would produce an error signal which the controller would automatically respond too adjusting the motors speed. Then the controller works to minimize the error signal, with zero error indicating actual speed which equals set point.

Electronically, we could implement such a simple closed-loop tachometer-feedback motor control circuit using an operational amplifier (op-amp) for the controller as shown.

## CLOSED-LOOP MOTOR CONTROLLER CIRCUIT

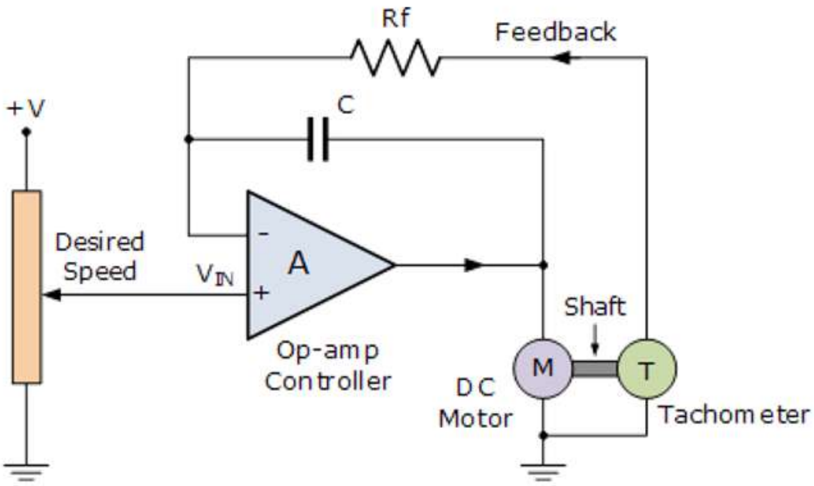


Fig 11.39

This simple closed-loop motor controller can be represented as a block diagram as shown.

## BLOCK DIAGRAM FOR THE FEEDBACK CONTROLLER

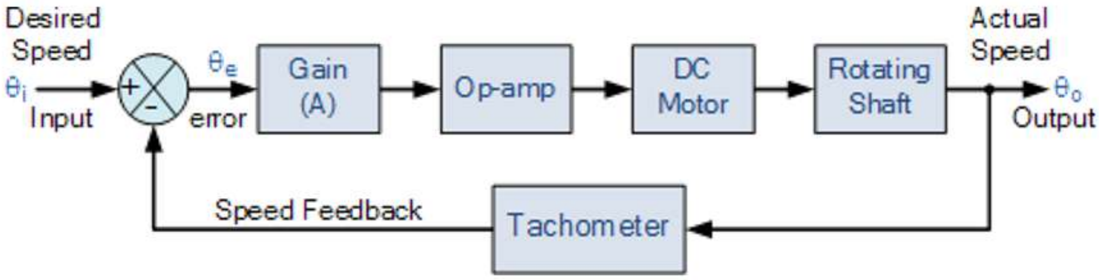


Fig 11.40

A closed-loop motor controller is a common means of maintaining a desired motor speed under varying load conditions by changing the average voltage applied to the input from the controller. The tachometer could be replaced by an optical encoder or Hall-effect type positional or rotary sensor.

## CLOSED-LOOP SYSTEMS SUMMARY

We have seen that an electronic control system with one or more feedback paths is called a Closed-loop System. Closed-loop control systems are also called "feedback control systems" are very common in process control and electronic control systems. Feedback systems have part of their output signal "fed back" to the input for comparison with the desired set point condition. The type of feedback signal can result either in positive feedback or negative feedback.

In a closed-loop system, a controller is used to compare the output of a system with the required condition and convert the error into a control action designed to reduce the error and bring the output of the system back to the desired response. Then closed-loop control systems use feedback to determine the actual input to the system and can have more than one feedback loop.

Closed-loop control systems have many advantages over open-loop systems. One advantage is the fact that the use of feedback makes the system response relatively insensitive to external disturbances and internal variations in system parameters such as temperature. It is thus possible to use relatively inaccurate and inexpensive components to obtain the accurate control of a given process or plant.

However, system stability can be a major problem especially in badly designed closed-loop systems as they may try to over-correct any errors which could cause the system to loss control and oscillate.

In the next tutorial about Electronics Systems, we will look at the different ways in which we can incorporate a summing point into the input of a system and the different ways in which we can feed signals back to it.

## FEEDBACK SYSTEMS

Feedback Systems process signals and as such are signal processors. The processing part of a feedback system may be electrical or electronic, ranging from a very simple to highly complex circuits. Simple analogue feedback control circuits can be constructed using individual or discrete components, such as transistors, resistors and capacitors, etc, or by using microprocessor-based and integrated circuits (IC's) to form more complex digital feedback systems.

As we have seen, open-loop systems are just that, open ended, and no attempt is made to compensate for changes in circuit conditions or changes in load conditions due to variations in circuit parameters, such as gain and stability, temperature, supply voltage variations and/or external disturbances. But the effects of these "open-loop" variations can be eliminated or at least considerably reduced by the introduction of Feedback.

A feedback system is one in which the output signal is sampled and then fed back to the input to form an error signal that drives the system. In the previous tutorial about Closed-loop Systems, we saw that in general, Feedback is comprised of a sub circuit that allows a fraction of the output signal from a system to modify the effective input signal in such a way as to produce a response that can differ substantially from the response produced in the absence of such feedback.

Feedback Systems are very useful and widely used in amplifier circuits, oscillators, process control systems as well as other types of electronic systems. But for feedback to be an effective tool it must be controlled as an uncontrolled system will either oscillate or fail to function. The basic model of a feedback system is given as:

FEEDBACK SYSTEM BLOCK DIAGRAM MODEL

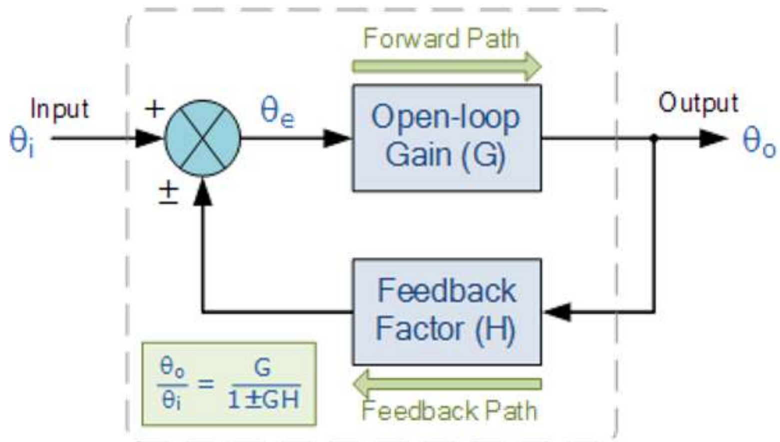



Fig 11.41

This basic feedback loop of sensing, controlling and actuation is the main concept behind a feedback control system and there are several good reasons why feedback is applied and used in electronic circuits:

- Circuit characteristics such as the systems gain and response can be precisely controlled.
- Circuit characteristics can be made independent of operating conditions such as supply voltages or temperature variations.
- Signal distortion due to the nonlinear nature of the components used can be greatly reduced.

- The Frequency Response, Gain and Bandwidth of a circuit or system can be easily controlled to within tight limits.

Whilst there are many different types of control systems, there are just two main types of feedback control namely: Negative Feedback and Positive Feedback.

## POSITIVE FEEDBACK SYSTEMS

In a "positive feedback control system", the set point and output values are added together by the controller as the feedback is "in-phase" with the input. The effect of positive (or regenerative) feedback is to "increase" the systems gain, i.e., the overall gain with positive feedback applied will be greater than the gain without feedback. For example, if someone praises you or gives you positive feedback about something, you feel happy about yourself and are full of energy, you feel more positive.

However, in electronic and control systems to much praise and positive feedback can increase the systems gain far too much which would give rise to oscillatory circuit responses as it increases the magnitude of the effective input signal.

An example of positive feedback systems could be an electronic amplifier based on an operational amplifier, or op-amp as shown.

POSITIVE FEEDBACK SYSTEM

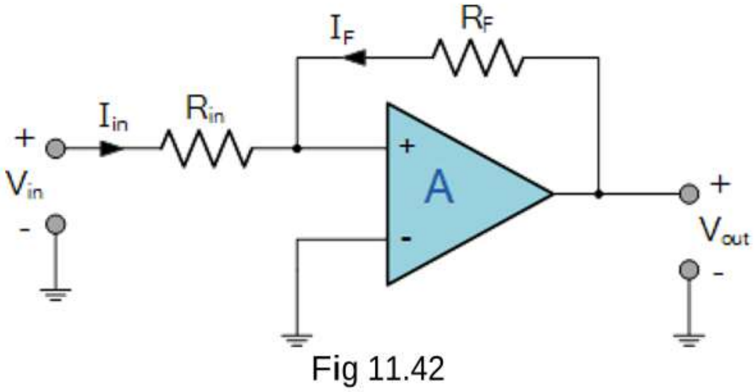



Fig 11.42

Positive feedback control of the op-amp is achieved by applying a small part of the output voltage signal at Vout back to the non-inverting ( + ) input terminal via the feedback resistor, $R_F$.

If the input voltage Vin is positive, the op-amp amplifies this positive signal and the output becomes more positive. Some of this output voltage is returned back to the input by the feedback network.

Thus the input voltage becomes more positive, causing an even larger output voltage and so on. Eventually the output becomes saturated at its positive supply rail.

Likewise, if the input voltage Vin is negative, the reverse happens and the op-amp saturates at its negative supply rail. Then we can see that positive feedback does not allow the circuit to function as an amplifier as the output voltage quickly saturates to one supply rail or the other, because with positive feedback loops "more leads to more" and "less leads to less".

Then if the loop gain is positive for any system the transfer function will be: Av = G / (1 – GH). Note that if GH = 1 the system gain Av = infinity and the circuit will start to self-oscillate, after which no input signal is needed to maintain oscillations, which is useful if you want to make an oscillator.

Although often considered undesirable, this behaviour is used in electronics to obtain a very fast switching response to a condition or signal. One example of the use of positive feedback is hysteresis in which a logic device or system maintains a given state until some input crosses a preset threshold. This type of behaviour is called "bi-stability" and is often associated with logic gates and digital switching devices such as multi vibrators.

We have seen that positive or regenerative feedback increases the gain and the possibility of instability in a system which may lead to self-oscillation and as such, positive feedback is widely used in oscillatory circuits such as Oscillators and Timing circuits.

## NEGATIVE FEEDBACK SYSTEMS

In a "negative feedback control system", the set point and output values are subtracted from each other as the feedback is "out-of-phase" with the original input. The effect of negative (or degenerative) feedback is to "reduce" the gain. For example, if someone criticises you or gives you negative feedback about something, you feel unhappy about yourself and therefore lack energy, you feel less positive.

Because negative feedback produces stable circuit responses, improves stability and increases the operating bandwidth of a given system, the majority of all control and feedback systems is degenerative reducing the effects of the gain.

An example of a negative feedback system is an electronic amplifier based on an operational amplifier as shown.

NEGATIVE FEEDBACK SYSTEM

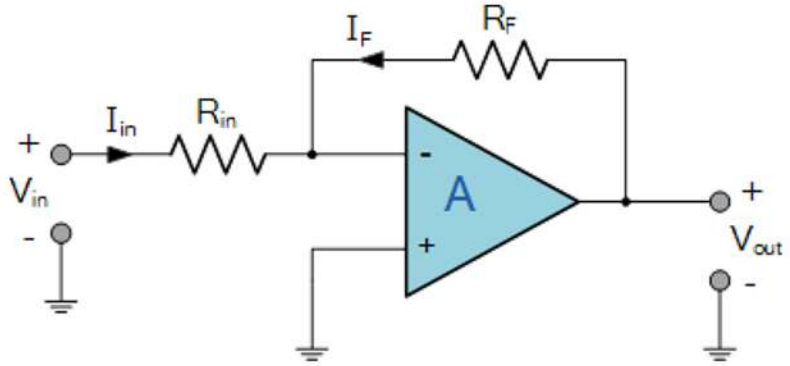



Fig 11.43

Negative feedback control of the amplifier is achieved by applying a small part of the output voltage signal at $V_{out}$ back to the inverting (-) input terminal via the feedback resistor, Rf.

If the input voltage $V_{in}$ is positive, the op-amp amplifies this positive signal, but because its connected to the inverting input of the amplifier, and the output becomes more negative. Some of this output voltage is returned back to the input by the feedback network of Rf.

Thus the input voltage is reduced by the negative feedback signal, causing an even smaller output voltage and so on. Eventually the output will settle down and become stabilised at a value determined by the gain ratio of $R_f \div R_{in}$.

Likewise, if the input voltage $V_{in}$ is negative, the reverse happens and the op-amps output becomes positive (inverted) which adds to the negative input signal. Then we can see that negative feedback allows the circuit to function as an amplifier, so long as the output is within the saturation limits.

So we can see that the output voltage is stabilised and controlled by the feedback, because with negative feedback loops "more leads to less" and "less leads to more".

Then if the loop gain is positive for any system the transfer function will be: $Av = G / (1 + GH)$.

The use of negative feedback in amplifier and process control systems is widespread because as a rule negative feedback systems are more stable than positive feedback systems, and a negative feedback system is said to be stable if it does not oscillate by itself at any frequency except for a given circuit condition.

Another advantage is that negative feedback also makes control systems more immune to random variations in component values and inputs. Of course nothing is for free, so it must be used with caution as negative feedback significantly modifies the operating characteristics of a given system.

## 11.09. SENSORS AND TRANSDUCERS

Simple stand alone electronic circuits can be made to repeatedly flash a light or play a musical note, but in order for an electronic circuit or system to perform any useful task or function it needs to be able to communicate with the "real world" whether this is by reading an input signal from an "ON/OFF" switch or by activating some form of output device to illuminate a single light.

In other words, an Electronic System or circuit must be able to "do" something and Sensors and Transducers are the perfect components for doing this.

The word "Transducer" is the collective term used for both Sensors which can be used to sense a wide range of different energy forms such as movement, electrical signals, radiant energy, thermal or magnetic energy etc, and Actuators which can be used to switch voltages or currents.

There are many different types of Sensors and Transducers, both analogue and digital and input and output available to choose from. The type of input or output transducer being used, really depends upon the type of signal or process being "Sensed" or "Controlled" but we can define a sensor and transducers as devices that converts one physical quantity into another.

Devices which perform an "Input" function are commonly called Sensors because they "sense" a physical change in some characteristic that changes in response to some excitation, for example heat or force and covert that into an electrical signal. Devices which perform an "Output" function are generally called Actuators and are used to control some external device, for example movement or sound.

Transducers

Electrical Transducers are used to convert energy of one kind into energy of another kind, so for example, a microphone (input device) converts sound waves into electrical signals for the amplifier to amplify (a process), and a loudspeaker (output device) converts these electrical signals back into sound waves and an example of this type of simple Input/Output (I/O) system is given below.

SIMPLE INPUT/OUTPUT SYSTEM USING SOUND TRANSDUCERS

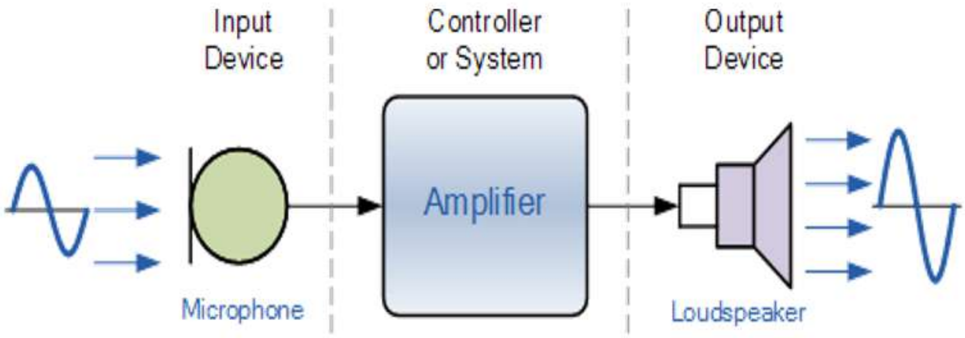



Fig 11.50

There are many different types of sensors and transducers available in the marketplace, and the choice of which one to use really depends upon the quantity being measured or controlled, with the more common types given in the table below.

COMMON SENSORS AND TRANSDUCERS

| Quantity being Measured | Input Device (Sensor) | Output Device (Actuator) |
|---|---|---|
| Light Level | Light Dependant Resistor (LDR) | |
| | Photodiode | Lights & Lamps |
| | Photo-transistor | LED's & Displays |
| | Solar Cell | Fiber Optics |
| Temperature | Thermocouple | |
| | Thermistor | Heater |
| | Thermostat | Fan |
| | Resistive Temperature Detectors | |

| | | |
|---|---|---|
| Force/Pressure | Strain Gauge | Lifts & Jacks |
| | Pressure Switch | Electromagnet |
| | Load Cells | Vibration |
| Position | Potentiometer | |
| | Encoders | Motor |
| | Reflective/Slotted Opto-switch | Solenoid |
| | LVDT | Panel Meters |
| Speed | Tacho-generator | AC and DC Motors |
| | Reflective/Slotted Opto-coupler | Stepper Motor |
| | Doppler Effect Sensors | Brake |
| Sound | Carbon | Bell |
| | Microphone | Buzzer |
| | Piezo-electric Crystal | Loudspeaker |

Input type transducers or sensors, produce a voltage or signal output response which is proportional to the change in the quantity that they are measuring (the stimulus). The type or amount of the output signal depends upon the type of sensor being used. But generally, all types of sensors can be classed as two kinds, either Passive Sensors or Active Sensors.

Generally, active sensors require an external power supply to operate, called an excitation signal which is used by the sensor to produce the output signal. Active sensors are self-generating devices because their own properties change in response to an external effect producing for example, an output voltage of 1 to 10v DC or an output current such as 4 to 20mA DC.

A good example of an active sensor is a strain gauge which is basically a pressure-sensitive resistive bridge network. It does not generate an electrical signal itself, but by passing a current through it (excitation signal), its electrical resistance can be measured by detecting variations in the current and/or voltage across it relating these changes to the amount of strain or force being applied.

Unlike an active sensor, a passive sensor does not need any additional energy source and directly generates an electric signal in response to an external stimulus. For example, a thermocouple or photo-diode. Passive sensors are direct sensors which change their physical properties, such as resistance, capacitance or inductance etc. As well as analogue sensors, Digital Sensors produce a discrete output representing a binary number or digit such as a logic level “0” or a logic level “1”.

# UNIT: 12 SYNCHRO SYSTEM

## 12.1. SYNCHRO FUNDAMENTALS

Synchro plays a very important role in the operation of Navy equipment. Synchro is found in just about every weapon system, communication system, underwater detection system, and navigation system used in the Navy. The importance of Synchro is sometimes taken lightly because of their low failure rate. However, the technician who understands the theory of operation and the alignment procedures for Synchro is well ahead of the problem when a malfunction does occur. The term "Synchro" is an abbreviation of the word "synchronous." It is the name given to a variety of rotary, electromechanical, position-sensing devices. Figure shows a phantom view of typical Synchro. A Synchro resembles a small electrical motor in size and appearance and operates like a variable transformer. The Synchro, like the transformer, uses the principle of electromagnetic induction.

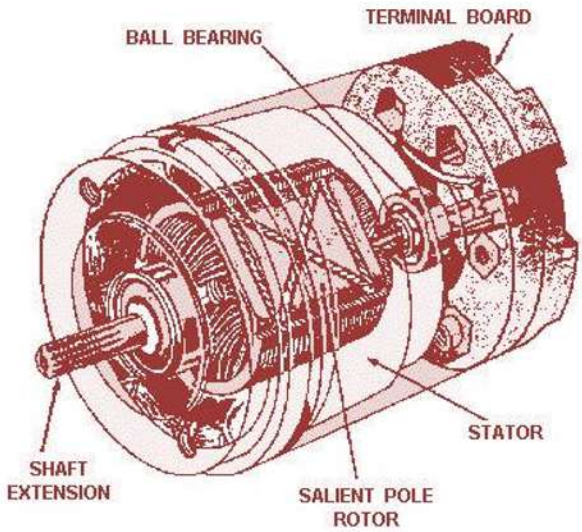



Figure 12.1: Phantom view of a Synchro

Synchro is used primarily for the rapid and accurate transmission of information between equipment and stations. Examples of such information are changes in course, speed, and range of targets or missiles; angular displacement (position) of the ship's rudder; and changes in the speed and depth of torpedoes. This information must be transmitted quickly and accurately. Synchro can provide this speed and accuracy. They are reliable, adaptable, and compact. Figure shows a simple Synchro system that can be used to transmit different as of data or information in this system, a single Synchro transmitter furnishes information to two Synchro receivers located in distant spaces. Operators put information into the system by turning the hand wheel. As the hand wheel turns, its attached gear rotates the transmitter shaft (which has a dial attached to indicate the value of the transmitted information). As the Synchro transmitter shaft turns, it converts the mechanical input into an electrical signal, which is sent through interconnecting wiring to the two Synchro receivers. The receiver shafts rotate in response to the electrical signal from the transmitter. When these shafts turn, the dials attached to the shafts indicate the transmitted information.

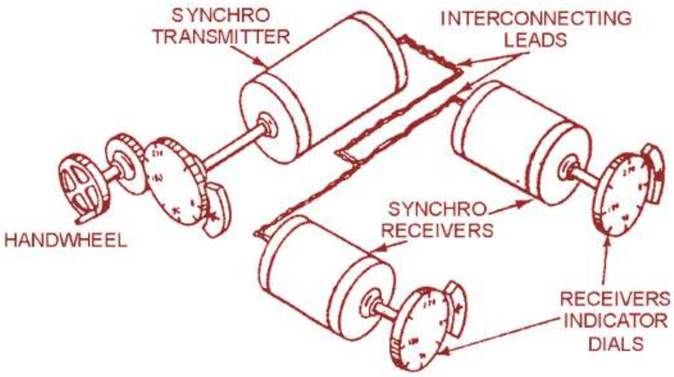



Fig12.2: Data transfer with Synchro

By studying the simple Synchro system, you can see that information can be transmitted over long distances, from space to space, and from equipment to equipment.

In addition to supplying data by positioning dials and pointers, Synchro is also used as control devices in servo systems. When the Synchro and the servo are combined, they work as a team to move and position heavy loads. The methods used to accomplish this are covered in detail in the next chapter.

## SYNCHRO CLASSIFICATION

Synchro work in teams. Two or more Synchro interconnected electrically forms a Synchro system. There are two general classifications of Synchro systems—TORQUE SYSTEMS AND CONTROL SYSTEMS. Torque-Synchro systems use torque Synchro and control-Synchro systems use control Synchro. The load dictates the type of Synchro system, and thus the type of Synchro.

Torque-Synchro systems are classified "torque" because they are mainly concerned with the torque or turning force required to move light loads such as dials, pointers, or similar indicators. The

positioning of these devices requires a relatively low amount of torque. Control Synchro are used in systems that are designed to move heavy loads such as gun directors, radar antennas, and missile launchers.

In addition to the two general classifications, Synchro are grouped into seven basic functional classes as shown in table 1-1. Four of these are the torque type and three are the control type. Each Synchro is described in the table by name, abbreviation, input, output, and the other Synchro units that may be connected to it. Generally, torque and control Synchro may not be interchanged. The functional operation of each of these seven Synchro is covered later in this text.

Table 1.1: Synchro Information

| Functional Classification | Abbreviation | Input | Output |
|---|---|---|---|
| Torque transmitter | TX | Mechanical input to rotor (rotor energized from AC source) | Electrical output from stator representing angular position of rotor to TDX, TDR, or TR. |

| | | | |
|---|---|---|---|
| Control transmitter | CX | Same as TX | Same as TX except it is supplied to CDX or CT |
| Torque differential transmitter | TDX | Mechanical input to rotor, electrical input to stator from TX or another TDX. | Electric output from rotor representing algebraic sum or difference between rotor angle and angle represented by electrical input to TR, TDR, or another TDX. |
| Control differential transmitter | CDX | Same as TDX except electrical input is from CX or another CDX. | Same as TDX except output to CT or another CDX. |
| Torque receiver | TR | Electrical input to stator from TX or TDX. (Rotor energized from AC source) | Mechanical output from rotor. Note: Rotor has mechanical inertia damper. |
| Torque differential receiver | TDR | Electrical input to stator from TX or TDX, another electrical input to rotor from TX or TDX. | Mechanical output from rotor representing algebraic sum or difference between angles represented by electrical inputs. Has inertia damper. |

| Functional Classification | Abbreviation | Input | Output |
|---|---|---|---|
| Control transformer | CT | Electric input to stator from CX or CDX, mechanical input to rotor. | Electrical output from rotor proportional to the sine of the angle between rotor position and angle represented by electrical input to stator. Called error signal. |
| Torque receiver | TRX | Depending on application, same as TX. | Depending on application, same as TX or TR. |

Synchro are also classified according to their operating frequency. This classification was brought about by the development of the 400-Hz Synchro. Prior to this time, the 60-Hz Synchro was the only one in use. Synchro operating frequencies are covered in detail in the section on Synchro characteristics.

## STANDARD MARKINGS AND SYMBOLS

Synchro used in the Navy can be grouped into two broad categories: MILITARY STANDARD SYNCHROS and PRESTANDARD NAVY SYNCHROS. Military standard Synchro conform to specifications that are uniform throughout the armed services. New varieties of equipment use Synchro of this type. Pre standard Synchro was designed to meet Navy, rather than service wide, specifications. Each category has its own designation code for identification.

## MILITARY STANDARD SYNCHRO CODE

The military standard designation code identifies standard Synchro by their physical size, functional purpose, and supply voltage characteristics. The code is alphanumerical and is broken down in the following manner. The first two digits indicate the diameter of the Synchro in tenths of an inch, to the next higher tenth. For example, a Synchro with a diameter of 1.75 inches has the numeral 18 as its first two digits. The first letter indicates the general function of the Synchro and of the Synchro system-C for control or T for torque. The next letter indicates the specific function of the Synchro, as follows:

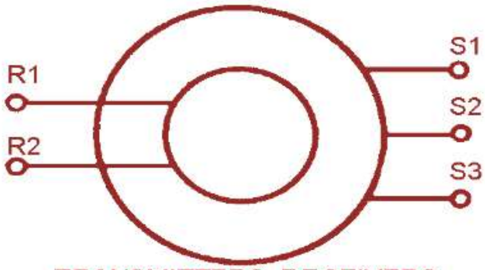
| LETTER | DEFINITION |
|---|---|
| D | Differential |
| R | Receiver |
| T | Transformer |
| X | Transmitter |

If the letter B follows the specific function designation, the Synchro has a rotatable stator. The last number in the designation indicates the operating frequency-6 for 60 Hz and 4 for 400 Hz. The upper-case letter following the frequency indicator is the modification designation. The letter "A" indicates that the Synchro design is original. The first modification is indicated by the letter "B." Succeeding modifications are indicated by the letters "C," "D," and so on, except for the unused letters "I," "L," "O," and "Q."

## SCHEMATIC SYMBOLS

Schematic symbols for Synchro are drawn by various manufacturers in many different ways. Only five symbols (as shown in figure), however, meet the standard military specifications for schematic diagrams of Synchro and Synchro connections. When a symbol is used on a schematic, it will be accompanied by the military abbreviation of one of the eight Synchro functional classifications (TR, TX, TDX, etc.).

The symbols shown in views A and B of figure are used when it is necessary to show only the external connections to a Synchro, while those shown in views C, D, and E are used when it is important to see the positional relationship between the rotor and stator. The letters R and S, in conjunction with an Arabic number, are used to identify the rotor and stator connections; for example, R1, R2, S1, S2, and S3. The small arrow on the rotor symbol indicates the angular displacement of the rotor; in figure the displacement is zero degrees.




TRANSMITTERS, RECEIVERS
CONTROLS TRANSFORMERS
A

Fig12.3: Schematic symbols for Synchro

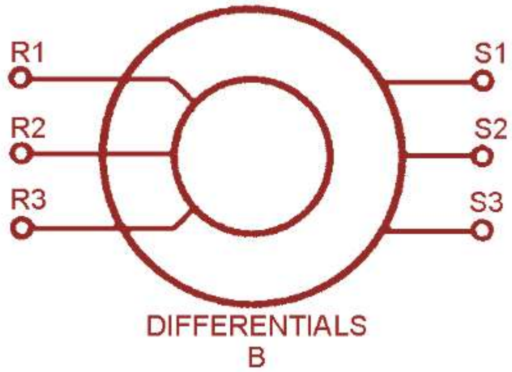



Fig12.4: Schematic symbols for Synchro

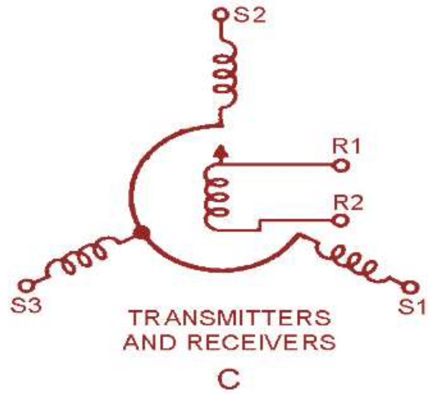



Fig12.5: Schematic symbols for Synchro

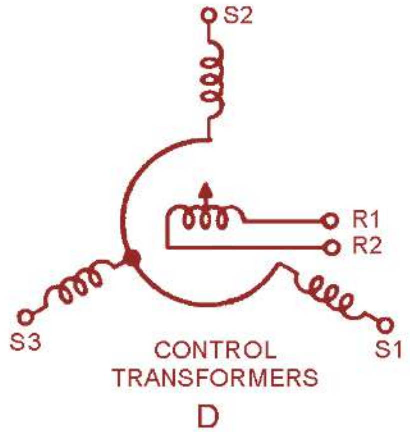



Fig12.6: Schematic symbols for Synchro

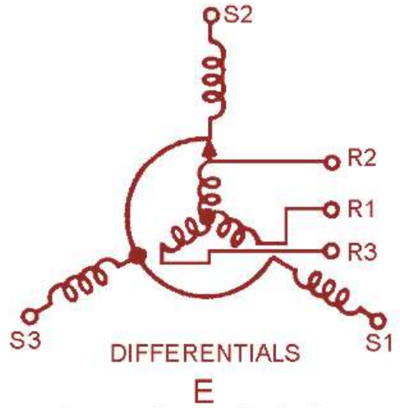



Fig12.7: Schematic symbols for Synchro

## 12.2. SYNCHRO CONSTRUCTION

Figure shows a cutaway view of a typical Synchro. Having the knowledge of how a Synchro is constructed should enable you to better understand how Synchro operates.

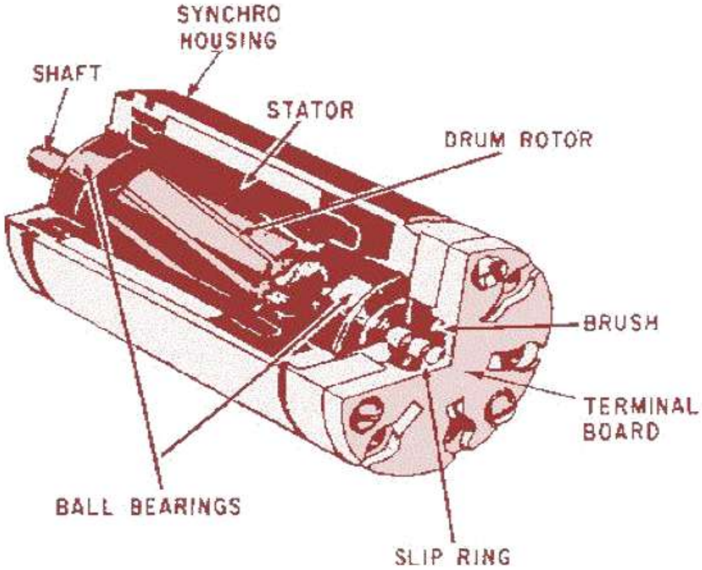



Fig12.8: Typical Synchro assembly

In this section we will discuss how rotors and stators are constructed and how the Synchro is assembled. Each Synchro contains a rotor, similar in appearance to the armature in a motor, and a stator, which corresponds to the field in a motor. The Synchro stator is composed of three Y-connected windings (S1, S2, and S3). The rotor is composed of one single winding (R1 and R2). As you can see in the figure, the rotor winding is free to turn inside the stator. The rotor is usually the primary winding and receives its voltage (excitation) from an external voltage source. The stator receives its voltage from the rotor by magnetic coupling.

## ROTOR CONSTRUCTION

There are two common types of Synchro rotors in use-the SALIENT-POLE ROTOR and the DRUM or WOUND ROTOR. The salient-pole rotor shown in figure has a single coil wound on a laminated core. The core is shaped like a "dumb-bell" or the letter "H."

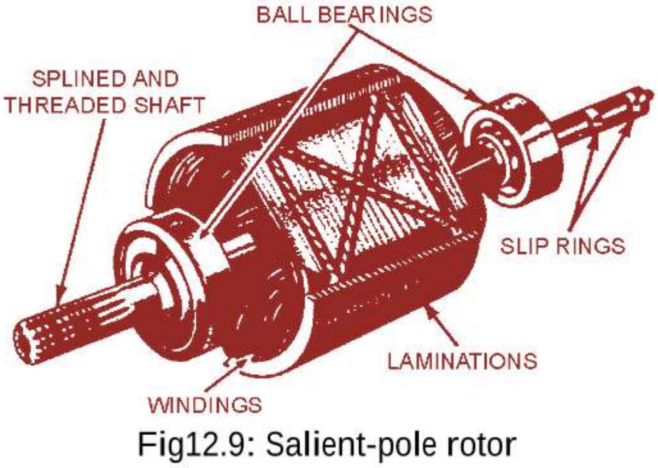



Fig12.9: Salient-pole rotor

This type of winding is frequently used in both transmitters and receivers.

The drum or wound rotor has coils wound in slots in a laminated core as shown in figure. This type of rotor is used in most Synchro control transformers and differential units, and occasionally in torque transmitters. It may be wound continuously with a single length of wire or may have a group of coils connected in series. The single continuous winding provides a distributed winding effect for use in transmitters. When the rotor is wound with a group of coils connected in series, a concentrated winding effect is provided for use in control transformers. When used in differential units, the rotor is wound with three coils so their magnetic axes are 120º apart.


Fig12.10: Drum or wound rotor

Both types of Synchro rotors have their coils wound on laminated cores that are rigidly mounted on a shaft. To enable the excitation voltage to be applied to the rotor winding, two slip rings are mounted on one end of the shaft and insulated from the shaft to prevent shorting. An insulated terminal board, mounted on the end of the cylindrical frame, houses the brushes, which ride on the slip rings. These brushes provide continuous electrical contact to the rotor during its rotation. Also mounted on the rotor shaft are low-friction ball bearings, which permit the rotor to turn easily.

## STATOR CONSTRUCTION

The stator of a Synchro is a cylindrical structure of slotted laminations on which three Y-connected coils are wound with their axes 120º apart. In figure , view A shows a typical stator assembly consisting of the laminated stator, stator windings, and cylindrical frame; view B shows the stator lamination and the slots in which the windings are placed. Some Synchro are constructed so both the stator and the rotor may be turned. Electrical connections to this type of stator are made through slip rings and brushes.

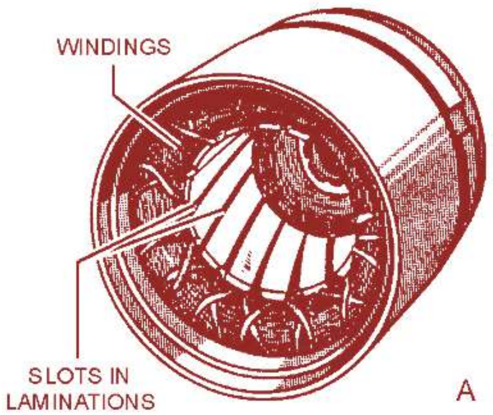



Fig12.11: Typical stator

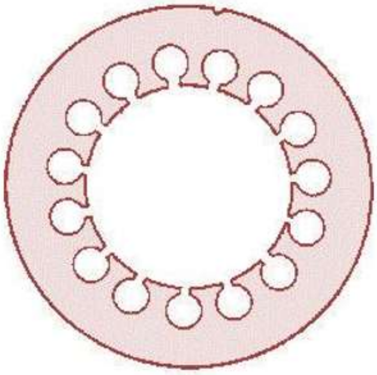


Fig12.22: Stator lamination

Now, refer to figure for a view of a completed Synchro assembly. The rotor has been placed in the stator assembly, and a terminal board has been added to provide a point at which internal and external connections can be made.

## SYNCHRO CHARACTERISTICS

Synchro characteristics play a very important part in Synchro troubleshooting and maintenance. By closely observing these characteristics, you can generally tell if a Synchro or Synchro system is working properly. Low torque, overheating, and improper operating voltages are just a few of the abnormal

Characteristics found in Synchro systems. In general, the load capacity of a Synchro system is limited by the number and types of receiver units loading the transmitter, the loads on these receiver units, and the operating temperature.

### TORQUE

Torque is simply a measure of how much load a machine can turn. In torque Synchro, only small loads are turned; therefore, only a small amount of torque is required. The measure of torque is the product of the applied force and the distance between the point of application and the center of rotation. For instance, if a 3 ounce weight is suspended from a Synchro pulley having a radius of 2 inches, the torque required to move the weight is 6 ounce-inches. In heavy machinery, torque may be expressed in pound-feet, but torque Synchro measurements are in ounce-inches.

NOTE: The unit of torque is the pound-foot or ounce-inch. Do not confuse this with foot-pounds, which is the measurement of work. Many times in referring to torque, tools are marked in foot-pounds. While this use of foot-pounds is technically incorrect, common usage has made it acceptable.

The torque developed in a Synchro receiver results from the tendency of two electromagnets to align themselves. Since the rotor can be turned and the stator usually cannot, the stator must exert a force (torque) tending to pull the rotor into a position where the primary and secondary magnetic fields are in line. The strength of the magnetic field produced by the stator determines the torque. The field strength depends on the current through the stator coils. As the current through the stator is increased, the field strength increases and more torque is developed.

## OPERATING VOLTAGES AND FREQUENCIES

Military standard and Navy pre standard Synchro are designed to operate on either 115 volts or 26 volts. Synchro used in shipboard equipment are designed predominately for 115 volts, while most aircraft Synchro operate on 26 volts.

Synchro are also designed to operate on a 60- or 400-Hz frequency. But like transformers, they are more efficient at the higher frequency. Operating a Synchro at a higher frequency also permits it to be made physically smaller. This is because the lines of flux produced by the 400-Hz excitation voltage are much more concentrated than those produced by the 60-Hz excitation voltage. Hence, the core of the 400-Hz Synchro can be made smaller than the core of the 60-Hz Synchro. However, some 400-Hz Synchro units are identical in size to their 60-Hz counterparts. This is done so that 60- and 400-Hz units can be physically interchanged without special mounting provisions. The operating voltage and frequency of each Synchro is marked on its nameplate.

The use of the smaller size Synchro permits the construction of smaller and more compact equipment. The most widely used frequency for airborne equipment is 400 Hz. It is being used increasingly in shipboard equipment as well. The newer gun and missile fire-control systems use 400-Hz Synchro almost exclusively.

A Synchro designed for 60-Hz operation may occasionally be used with a 400-Hz supply. There may be considerable loss of accuracy, but the Synchro will not be damaged. This should be done only in the case of an emergency when the specified replacement is not available, and system accuracy is not critical.

## 12.3. THEORY OF OPERATION

Synchro, as stated earlier, are simply variable transformers. They differ from conventional transformers by having one primary winding (the rotor), which may be rotated through 360º and three stationary secondary windings (the stator) spaced 120º apart. It follows that the magnetic field within the Synchro may also be rotated through 360º. If an iron bar or an electromagnet were placed in this field and allowed to turn freely, it would always tend to line up in the direction of the magnetic field. This is the basic principle underlying all Synchro operations.

We will begin the discussion of Synchro operation with a few basic points on electromagnets. Look at figure. In this figure, a simple electromagnet is shown with a bar magnet pivoted in the electromagnet's field. In view A, the bar is forced to assume the position shown, since the basic law of magnetism states that like poles of magnets repel and unlike poles attract. Also notice that when the bar is aligned with the field, the magnetic lines of force are shortest. If the bar magnet is turned from this position and held as shown in view B, the flux is distorted and the magnetic lines of force are lengthened. In this condition, a force (torque) is exerted on the bar magnet. When the bar magnet is released, it snaps back to its original position. When the polarity of the electromagnet is reversed, as shown in view C, the field reverses and the bar magnet is rotated 180º from its original position.

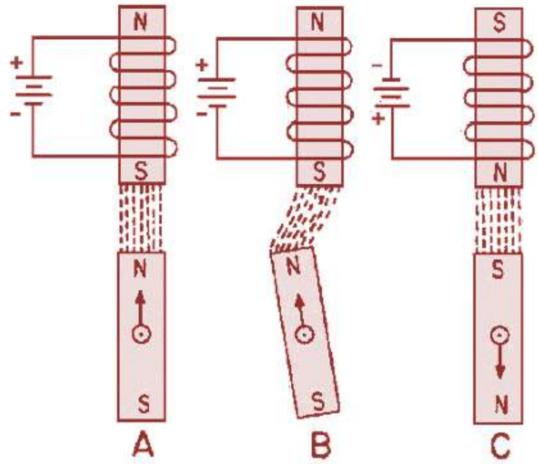


Fig12.33: Operation of an electromagnet with a bar-magnet rotor

Keeping in mind these basic points, consider how the bar magnet reacts to three electromagnets spaced 120º apart as illustrated in figure. In this figure, stator coils S1 and S3, connected in parallel, together have the same field strength as stator coil S2. The magnetic field is determined by current flow through the coils. The strongest magnetic field is set up by stator coil S2, since it has twice the current and field strength as either S1 or S3 alone. A resultant magnetic field is developed by the combined effects of the three stator fields. Coil S2 has the strongest field, and thus, the greatest effect on the resultant field, causing the field to align in the direction shown by the vector in view B of the figure. The iron-bar rotor aligns itself within the resultant field at the point of greatest flux density. By convention, this position is known as the zero-degree position. The rotor can be turned from this position to any number of positions by applying the proper combination of voltages to the three coils, as illustrated in figure , view (A), view (B), view (C), view (D), view (E), view (F).

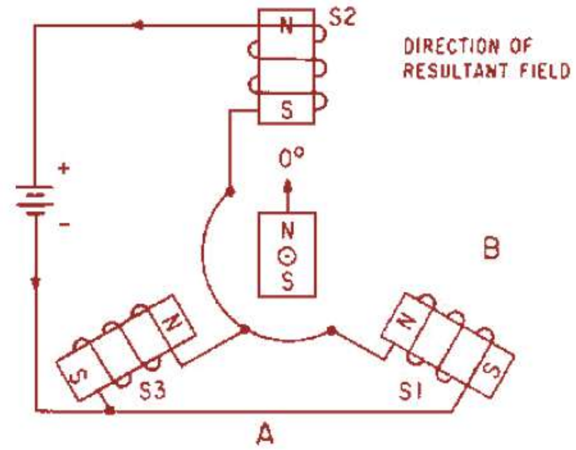


Fig12.34: Operation of three electromagnets spaced 120º apart

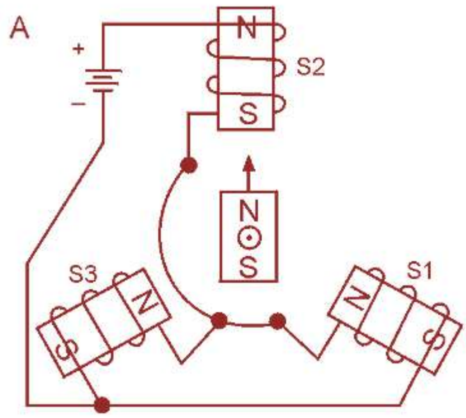



Fig12.35: Positioning of a bar magnet with three electromagnets

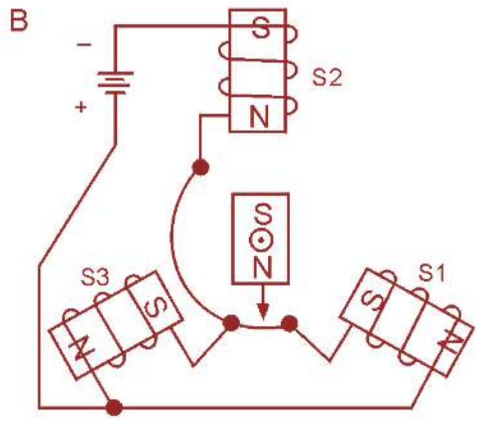



Fig12.36: Positioning of a bar magnet with three electromagnets

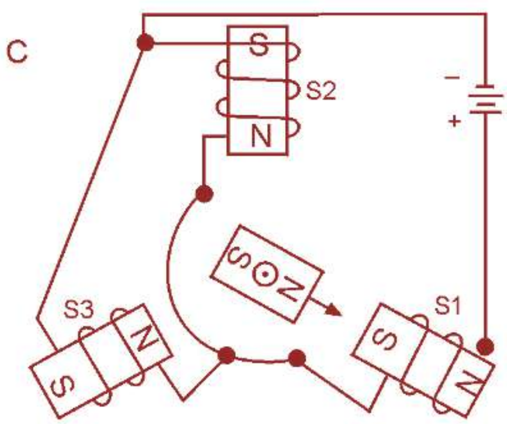



Fig12.37: Positioning of a bar magnet with three electromagnets

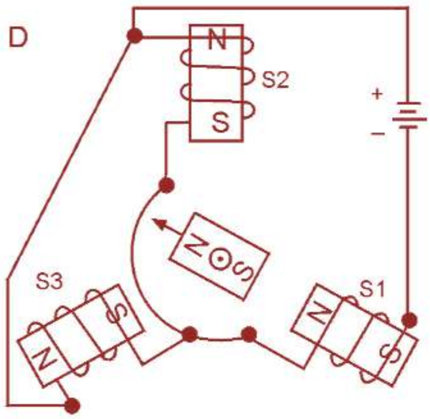



Fig12.38: Positioning of a bar magnet with three electromagnets

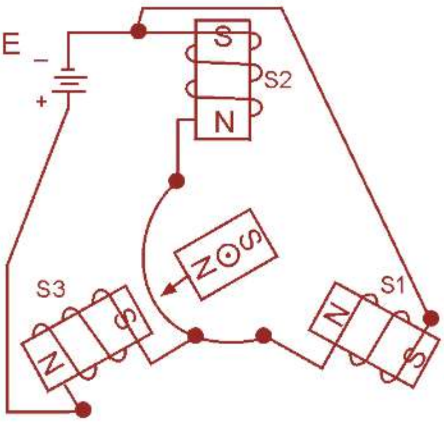



Fig12.39: Positioning of a bar magnet with three electromagnets

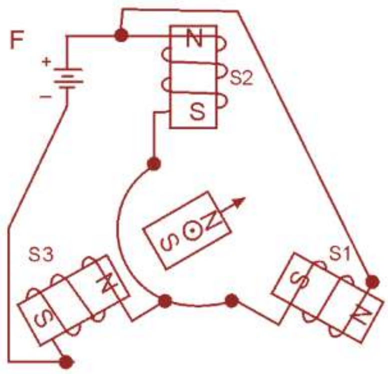



Fig12.40: Positioning of a bar magnet with three electromagnets

Notice in figure, in views A C, and E, that the rotor positions are achieved by shifting the total current through different stator windings (S1, S2, and S3). This causes the rotor to move toward the coil with the strongest magnetic field. To obtain the rotor positions in views B, D, and F, it was necessary only to reverse the battery connections. This causes the direction of current flow to reverse and in turn reverses the direction of the magnetic field. Since the rotor follows the magnetic field the rotor also changes direction. By looking closely at these last three rotor positions, you will notice that they are exactly opposite the first three positions we discussed. This is caused by the change in the direction of current flow. You can now see that by varying the voltages to the three stator coils, we can change the current in these coils and cause the rotor to assume any position we desire.

In the previous examples, dc voltages were applied to the coils. Since Synchro operate on ac rather than dc, consider what happens when ac is applied to the electromagnet in figure. During one complete cycle of the alternating current, the polarity reverses twice.

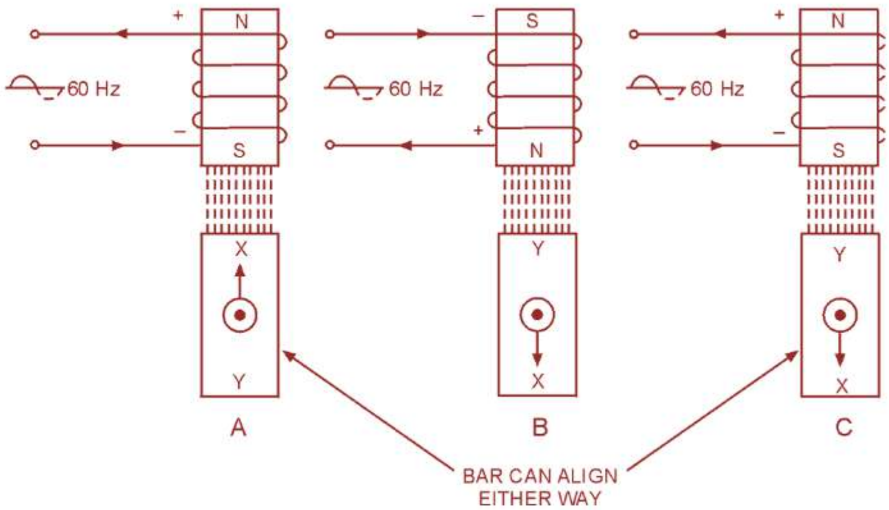



Fig12.41: Operation of an electromagnet with ac voltage

Therefore, the number of times the polarity reverses each second is twice the excitation frequency, or 120 times a second when a 60-Hz frequency is applied. Since the magnetic field of the electromagnet follows this alternating current, the bar magnet is attracted in one direction during one-half cycle (view A) and in the other direction during the next half cycle (view B). Because of its inertia, the bar magnet cannot turn rapidly enough to follow the changing magnetic field and may line up with either end toward the coil (view C). This condition also causes weak rotor torque. For these reasons, the iron-bar rotor is not practical for ac applications. Therefore, it must be replaced by an electromagnetic rotor as illustrated in figure.

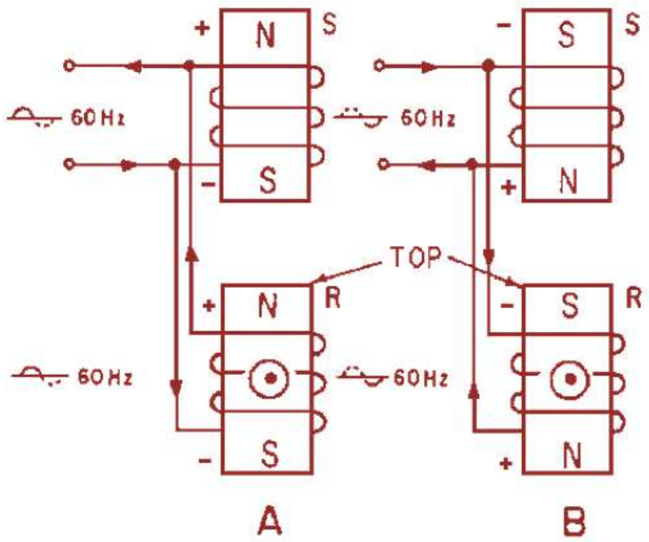


Fig12.42: Operation of fixed and moveable electromagnets with ac voltage

In this figure, both stationary and rotating coils are connected to the same 60-Hz source. During the positive alternation (view A), the polarities are as shown and the top of the rotor is attracted to the bottom of the stationary coil. During the negative alternation (view B), the polarities of both coils reverse, thus keeping the rotor aligned in the same position. In summary, since both magnetic fields change direction at the same time when following the 60-Hz ac supply voltage, the electromagnetic rotor does not change position because it is always aligned with the stationary magnetic field.

## 12.4. Torque Synchro System

### SYNCHRO TORQUE TRANSMITTER

The Synchro transmitter converts the angular position of its rotor (mechanical input) into an electrical output signal.

When a 115-volt ac excitation voltage is applied to the rotor of a Synchro transmitter, such as the one shown in figure, the resultant current produces an ac magnetic field around the rotor winding. The lines of force cut through the turns of the three stator windings and, by transformer action, induce voltage into the stator coils. The effective voltage induced in any stator coil depends upon the angular position of that coil's axis with respect to the rotor axis. When the maximum effective coil voltage is known, the effective voltage induced into a stator coil at any angular displacement can be determined.

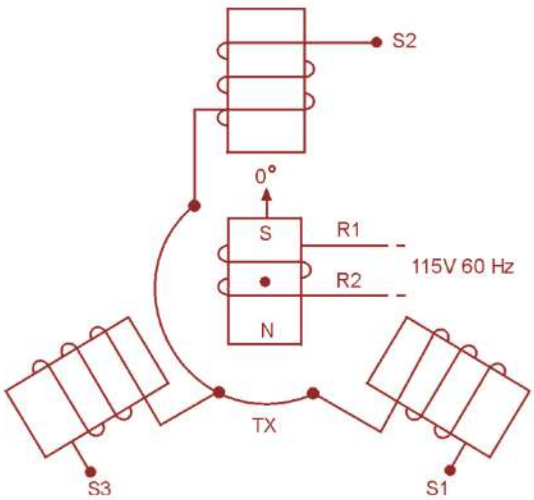



Fig12.43: Synchro transmitter

Figure illustrates a cross section of a Synchro transmitter and shows the effective voltage induced in one stator coil as the rotor is turned to different positions. The turn's ratios in Synchro may vary widely, depending upon design and application, but there is commonly a 2.2:1 step-down between the rotor and a single coil. Thus, when 115 volts is applied to the rotor, the highest value of effective voltage induced in any one stator coil is 52 volts. The maximum induced voltage occurs each time there is maximum magnetic coupling between the rotor and the stator coil (views A, C, and E). The effective voltage induced in the secondary winding is approximately equal to the product of the effective voltage on the primary; the secondary-to-primary turns ratio, and the magnetic coupling between primary and secondary. Therefore, because the primary voltage and the turn's ratio are constant, it is commonly said that the secondary voltage varies with the angle between the rotor and the stator.

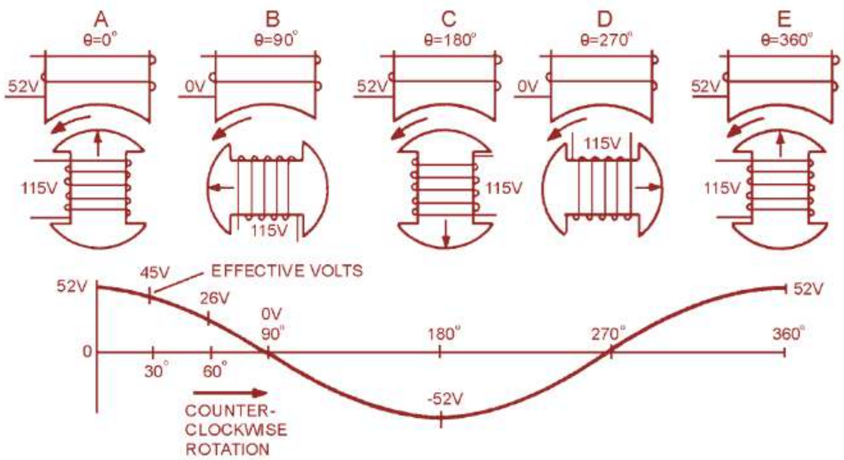



Fig12.44: Stator voltage vs rotor position

When stator voltages are measured, reference is always made to terminal-to-terminal voltages (voltage induced between two stator terminals) instead of to a single coil's voltage. This is because the

Voltage induced in one stator winding cannot be measured because the common connection between the stator coils is not physically accessible.

In summary, the Synchro transmitter converts the angular position of its rotor into electrical stator signals, which are sent through interconnecting wires to other Synchro devices.

## SYNCHRO TORQUE RECEIVER

Synchro torque receivers, commonly called Synchro receivers, are electrically identical to torque transmitters of the same size except for the addition of some form of damping. In some sizes of 400-Hz Synchro, units are designated as torque receivers but may be used as either transmitters or receivers.

Unlike the transmitter, the receiver has an electrical input to its stator and a mechanical output from its rotor. The Synchro receiver's function is to convert the electrical data supplied to its stator from the transmitter, back to a mechanical angular position through the movement of its rotor. This function is accomplished when the rotor is connected to the same ac source as the transmitter and assumes a position determined by the interaction of its magnetic field with the magnetic field of the stator. If you recall, this is the same concept discussed earlier under the operation of electromagnets.

Normally, the receiver rotor is unrestrained in movement except for brush and bearing friction. When power is first applied to a system, the transmitter position changes quickly; or if the receiver is switched into the system, the receiver rotor turns to correspond to the position of the transmitter rotor. This sudden motion can cause the rotor to oscillate (swing back and forth) around the synchronous position If the movement of the rotor is great enough, it may even spin. Some method of preventing oscillations or spinning must be used. Any method that accomplishes this task is termed DAMPING.

There are two types of damping methods ELECTRICAL and MECHANICAL. In small Synchro the electrical method is used more frequently than the mechanical method. This method uses an additional winding placed in the Synchro to retard oscillations. In larger units, a mechanical device, known as an inertia damper, is more effective. Several variations of the inertia damper are in use. One of the more common types consists of a heavy brass flywheel (inertia damper), which is free to rotate around a bushing that is attached to the rotor shaft . A tension spring on the bushing rubs against the flywheel so that the bushing and flywheel turn together during normal operation. If the rotor shaft turns or tends to change its speed or direction of rotation suddenly, the inertia of the damper opposes the changing condition.

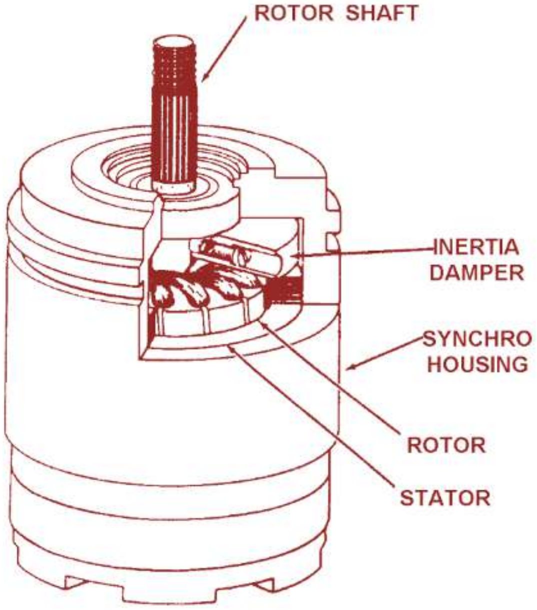



Fig12.45: Cutaway view of torque receiver with inertia damper

## TORQUE SYNCHRO SYSTEM

A torque transmitter (TX) and a torque receiver (TR) make up a simple torque-Synchro system. Basically, the electrical construction of Synchro transmitters and receivers is similar, but their intended functions are different. The rotor of a Synchro transmitter is usually geared to a manual or mechanical input. This gearing may drive a visual indicator showing the value or quantity being transmitted. The rotor of the receiver synchronizes itself electrically with the position of the rotor of the transmitter and thus responds to the quantity being transmitted.

## BASIC SYNCHRO SYSTEM OPERATION

A simple Synchro transmission system consisting of a torque transmitter connected to a torque receiver (TX-TR) is illustrated in figure. As you can see, in this system the rotors are connected in parallel across the ac line. The stators of both Synchro have their leads connected S1 to S1, S2 to S2, and S3 to S3, so the voltage in each of the transmitter stator coils opposes the voltage in the corresponding coils of the receiver. The voltage directions are indicated by arrows for the instant of time shown by the dot on the ac line voltage.

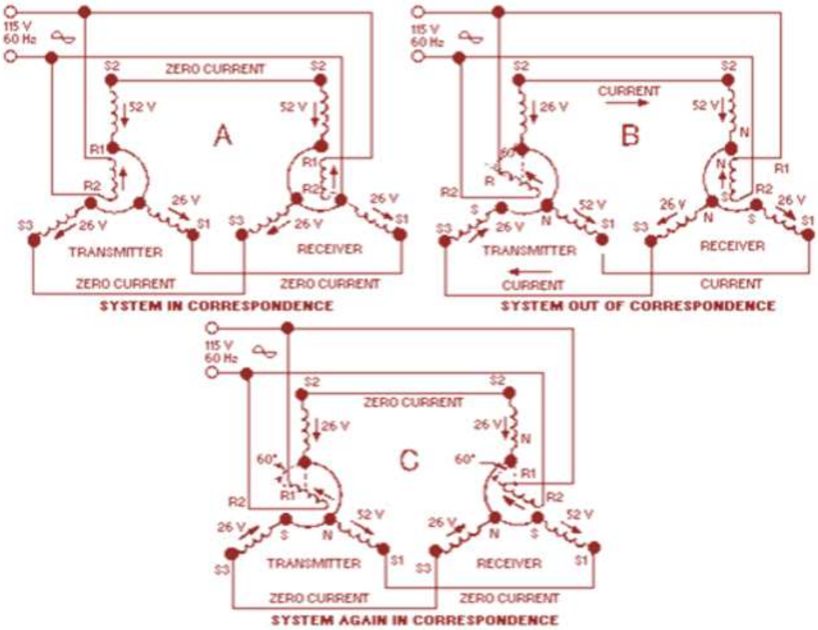



Fig12.46: A simple Synchro transmission system

When both transmitter and receiver rotors in a Synchro system are on zero or displaced from zero by the same angle, a condition known as CORRESPONDENCE exists. In view A of figure , the transmitter and receiver are shown in correspondence. In this condition, the rotor of the TR induces voltages in its stator coils (S2 = 52V; S1 and S3 = 26V) that are equal to and opposite the voltages induced into the TX stator coils (S2 = 52V; S1 and S3 = 26V). This causes the voltages to cancel and reduces the stator currents to zero. With zero current through the coils, the receiver torque is zero and the system remains in correspondence.

The angle through which a transmitter rotor is mechanically rotated is called a SIGNAL. In view B of figure , the signal is 60º. Now, consider what happens to the two Synchro in correspondence when this signal is generated

When the transmitter rotor is turned, the rotor field follows and the magnetic coupling between the

rotor and stator windings changes. This results in the transmitter S2 coil voltage decreasing to 26 volts, the S3 coil voltage reversing direction, and the S1 coil voltage increasing to 52 volts. This imbalance in voltages, between the transmitter and receiver, causes current to flow in the stator coils in the direction of the stronger voltages. The current flow in the receiver produces a resultant magnetic field in the receiver stator in the same direction as the rotor field in the transmitter. A force (torque) is now exerted on the receiver rotor by the interaction between its resultant stator field and the magnetic field around its rotor. This force causes the rotor to turn through the same angle as the rotor of the transmitter. As the receiver
approaches correspondence, the stator voltages of the transmitter and receiver approach equality. This action decreases the stator currents and produces a decreasing torque on the receiver. When the receiver and the transmitter are again in correspondence, as shown in view C, the stator voltages between the two Synchro are equal and opposite (S1 = 52V; S2 and S3 = 26V), the rotor torque is zero, and the rotors are displaced from zero by the same angle (60º). This sequence of events causes the transmitter and receiver to stay in correspondence.

In the system we just explained, the receiver reproduced the signal from the transmitter. As you can see, a Synchro system such as this could provide a continuous, accurate, visual reproduction of important information to remote locations.

## RECEIVER ROTATION

When the teeth of two mechanical gears are meshed and a turning force is applied, the gears turn in opposite directions. If a third gear is added, the original second gear turns in the same direction as the first. This is an important concept, because the output of a Synchro receiver is often connected to the device it operates through a train of mechanical gears. Whether or not the direction of the force applied to the device and the direction in which the receiver rotor turns are the same depends on whether the number of gears in the train is odd or even. The important thing, of course, is to move the dial or other device in the proper direction. Even when there are no gears involved, the receiver rotor may turn in the direction opposite to the direction you desire. To correct this problem, some method must be used to reverse the receiver's direction of rotation. In the transmitter-receiver system, this is done by reversing the S1 and S3 connections so that SI of the transmitter is connected to S3 of the receiver and vice versa , view (A) and view (B).

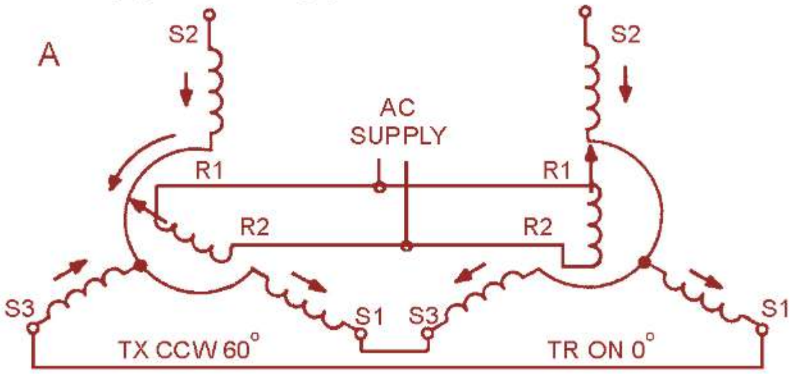



Fig 12.47: Effect of reversing the S1 and S3 connections between the transmitter and the receiver

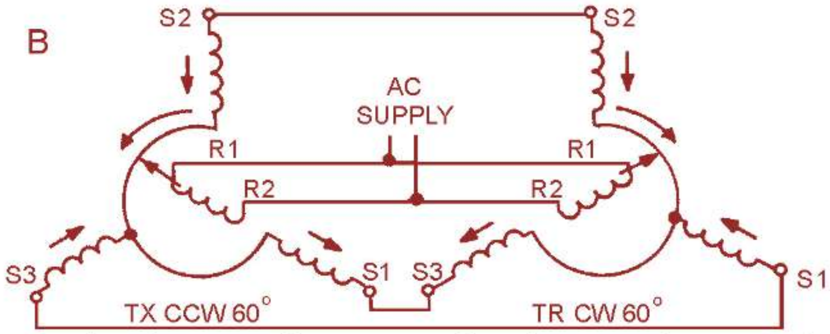


Fig 12.48: Effect of reversing the S1 and S3 connections between the transmitter and the receiver

Even when the S1 and S3 connections are reversed, the system at 0º acts the same as the basic Synchro system we previously described at 0º. This is because the voltages induced in the S1 and S3 stator windings are still equal and oppose each other. This causes a canceling effect, which results in zero stator current and no torque. Without the torque required to move the receiver rotor, the system remains in correspondence and the reversing of the stator connections has no noticeable effect on the system at 0º.

Suppose the transmitter rotor is turned counterclockwise 60º, as shown in view A of figure. The TX rotor is now aligned with S1. This results in maximum magnetic coupling between the TX rotor and the S1 winding. This maximum coupling induces maximum voltage in S1. Because S1 is connected to S3 of the TR, a voltage imbalance occurs between them. As a result of this voltage imbalance, maximum current flows through the S3 winding of the TR causing it to have the strongest magnetic field. Because the other two fields around S2 and S1 decrease proportionately, the S3 field has the greatest effect on the resultant TR stator field. The strong S3 stator field forces the rotor to turn 60º clockwise into alignment with itself, as shown in view B. At this point, the rotor of the TR induces canceling voltages in its own stator coils and causes the rotor to stop. The system is now in correspondence. Notice that by reversing S1 and S3, both Synchro rotors turn the same amount, but in OPPOSITE DIRECTIONS.

We must emphasize that the only stator leads ever interchanged, for the purpose of reversing receiver rotation, are S1 and S3. S2 cannot be reversed with any other lead since it represents the electrical zero position of the Synchro. As you know, the stator leads in a Synchro are 120º apart. Therefore, any change in the S2 lead causes a 120º error in the Synchro system and also reverses the direction of rotation

.

## REVERSAL OF SYNCHRO LEADS

In new or modified Synchro systems, a common problem is the accidental reversal of the R1 and R2 leads on either the transmitter or receiver. This causes a 180º error between the two Synchro, but the direction of rotation remains the same.

## REVERSED ROTOR CONNECTIONS

are common problems in new or modified Synchro systems and should not be confused with the deliberate reversal of the stator connections. The reversal of the R1 and R2 connections on a Synchro rotor causes a 180º error between the Synchro transmitter and the Synchro receiver, but the direction of rotor rotation still remains the same.

SYNCHRO ERRORS

This system has the advantage of very little power consumption when at rest as it only draws power when the TX and TR are displaced (not in correspondence).
This system has some problems:

HUNTING

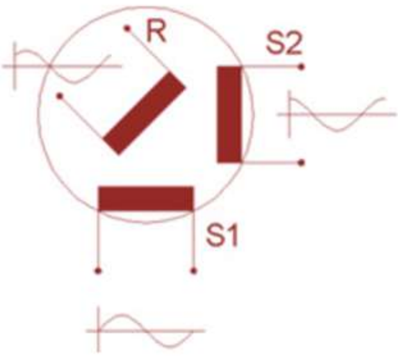
This error is most pronounced when there is a large angular input to the rotor of the TX over a short period of time. This causes the rotor of the TR to FOLLOW UP quickly to correspondence.
The momentum generated causes the TR rotor to overshoot the required position. The feedback is now producing an error in the other direction which causes the TR rotor to take up the required position.
To reduce hunting, the TR in most torque systems is fitted with an eddy current damping disc. It is not necessary to fit it to the TX, however, the synchros are manufactured so that the TX and TR are interchangeable.

DEADBAND

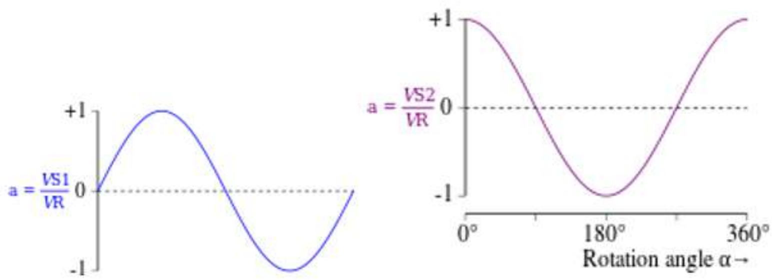
This error occurs because of imperfections and friction in the system.
As the TR rotor is reaching its position of correspondence, the torque on the rotor is reducing. It eventually becomes so small that it cannot overcome the imperfections and friction, leaving the TR rotor out of correspondence with the TX.
The angular difference between the Tx and TR is known as the DEADBAND.

## 12.8. Resolver Synchro

**DESCRIPTION**




CONCEPT OF ROTOR EXCITED RESOLVER



## ROTOR EXCITATION AND RESPONSE

The most common type of resolver is the brushless transmitter resolver (other types are described at the end). On the outside, this type of resolver may look like a small electrical motor having a stator and rotor. On the inside, the configuration of the wire windings makes it different. The stator portion of the resolver houses three windings: an exciter winding and two two-phase windings (usually labelled "x" and "y") (case of a brushless resolver). The exciter winding is located on the top; it is in fact a coil of a turning (rotary) transformer. This transformer induces current in the rotor without a direct electrical connection, thus there are no wires to the rotor limiting its rotation and no need for brushes. The two other windings are on the bottom, wound on a lamination. They are configured at

90 degrees from each other. The rotor houses a coil, which is the secondary winding of the turning transformer, and a separate primary winding in a lamination, exciting the two two-phase windings on the stator.

The primary winding of the transformer, fixed to the stator, is excited by a sinusoidal electric current, which by electromagnetic induction induces current in the rotor. As these windings are arranged on the axis of the resolver, the same current is induced no matter what its position. This current then flows through the other winding on the rotor, in turn inducing current in its secondary windings, the two-phase windings back on the stator. The two two-phase windings, fixed at right (90°) angles to each other on the stator, produce a sine and cosine feedback current. The relative magnitudes of the two-phase voltages are measured and used to determine the angle of the rotor relative to the stator. Upon one full revolution, the feedback signals repeat their waveforms. This device may also appear in non-brushless type, i.e., only consisting in two lamination stacks, rotor and stator.

Resolvers can perform very accurate analogue conversion from polar to rectangular coordinates. Shaft angle is the polar angle, and excitation voltage is the magnitude. The outputs are the [x] and [y] components. Resolvers with four-lead rotors can rotate [x] and [y] coordinates, with the shaft position giving the desired rotation angle.

Resolvers with four output leads are general sine/cosine computational devices. When used with electronic driver amplifiers and feedback windings tightly coupled to the input windings, their accuracy is enhanced, and they can be cascaded ("resolver chains") to compute functions with several terms, perhaps of several angles, such as gun (position) orders corrected for ship's roll and pitch.

For the position evaluation, Resolver-to-Digital Converters are commonly used. They convert sine and cosine signal to binary signal (10 to 16 bit wide) that can more easily be used by the controller.

## TYPES

Basic resolvers are two-pole resolvers, meaning that the angular information is the mechanical angle of the stator. These devices can deliver the absolute angle position. Other types of resolver are multi pole resolvers. They have 2*p poles, and thus can deliver p cycles in one rotation of the rotor: electrical angle = mechanical angle * p. where p is the no. of pole pairs. Some types of resolvers include both types, with the 2-pole windings used for absolute position and the multi pole windings for accurate position. Two-pole resolvers can usually reach angular accuracy up to about +/-5′, whereas multi pole resolver can provide better accuracy, up to 10″ for 16-pole resolvers, to even 1″, for instance for 128-pole resolvers.

Multi pole resolvers may also be used for monitoring multi pole electrical motors. This device can be used in any application in which the exact rotation of an object relative to another object is needed, such as in a rotary antenna platform or a robot. In practice, the resolver is usually directly mounted to an electric motor. The resolver feedback signals are usually monitored for multiple revolutions by another device. This allows for geared reduction of assemblies being rotated and improved accuracy from the resolver system.

Because the power supplied to the resolvers produces no actual work, the voltages used are usually low (<24 VAC) for all resolvers. Resolvers designed for terrestrial use tend to be driven at 50–60 Hz (mains power frequency), while those for marine or aviation use tend to operate at 400 Hz (the frequency of the on-board generator driven by the engines). Aerospace applications utilize 2930 Hz to 10kHz at voltages ranging from 4vrms to 10vrms. Many of the aerospace applications are used to determine the position of an actuator or torque motor position. Control systems tend to use higher frequencies (5 kHz).

### OTHER TYPES OF RESOLVER INCLUDE:

### RECEIVER RESOLVERS

These resolvers are used in the opposite way to transmitter resolvers (the type described above). The two diphase windings are energized, the ratio between the sine and the cosine representing the electrical angle. The system turns the rotor to obtain a zero voltage in the rotor winding. At this position, the mechanical angle of the rotor equals the electrical angle applied to the stator.

### DIFFERENTIAL RESOLVERS

These types combine two diphase primary windings in one of the stacks of sheets, as with the receiver, and two diphase secondary windings in the other. The relation of the electrical angle delivered by the two secondary windings and the other angles is secondary electrical angle, mechanical angle, and primary electrical angle. These types were used, for instance, as analog trigonometric-function calculators.

A related type is also the transolver, combining a two-phase winding like the resolver and a triphased winding like the synchro.

## 12.7. Differential Synchro

### TORQUE DIFFERENTIAL SYNCHRO SYSTEMS

The demands on a Synchro system are not always as simple as positioning an indicating device in response to information received from a single source (transmitter). For example, an error detector used in checking weapons equipment uses a Synchro system to determine the error in a gun's position with respect to the positioning order. To do this, the Synchro system must accept two signals, one containing the positioning order and the other corresponding to the actual position of the gun. The system must then compare the two signals and position an indicating dial to show the difference between them, which is the error.

Obviously, the simple Synchro transmitter-receiver system discussed so far could not handle a job of this sort. A different type of Synchro is needed, one which can accept two signals simultaneously, add or subtract the signals, and furnish an output proportional to their sum or difference. This is where the SYNCHRO DIFFERENTIAL enters the picture. A differential can perform all of these functions.

There are two types of differential units - differential transmitters and differential receivers. The differential transmitter (TDX) accepts one electrical input and one mechanical input and produces one electrical output. The differential receiver (TDR) accepts two electrical inputs and produces one mechanical output. A comparison of the TDX and TDR is shown in figure. The torque differential transmitter and the torque differential receiver can be used to form a DIFFERENTIAL SYNCHRO SYSTEM. The system can consist either of a torque transmitter (TX), a torque differential transmitter (TDX), and a torque receiver (TR), (TX-TDX-TR); or two torque transmitters (TXs) and one torque differential receiver (TDR), (TX-TDR-TX). Before beginning a discussion of the systems using differentials, we need to provide a brief explanation on the newly introduced Synchro, the TDX and the TDR.

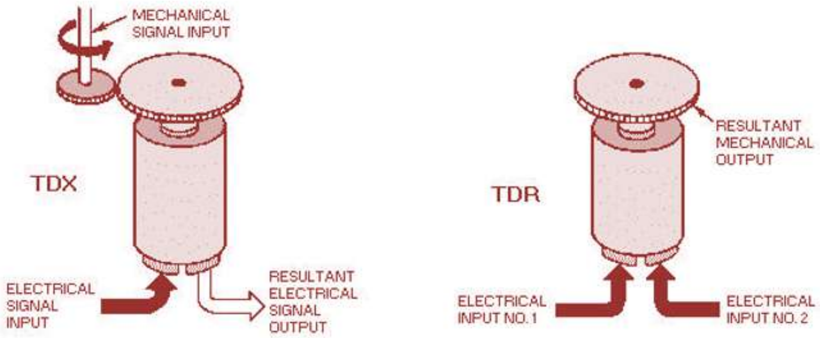



Fig12.49: Torque differentials

## TORQUE DIFFERENTIAL TRANSMITTER

In the torque differential transmitter, BOTH the rotor and stator windings consist of three Y-connected coils, as illustrated in view A of figure. The stator is normally the primary, and receives its input signal from a Synchro transmitter. The voltages appearing across the differential's rotor terminals (R1, R2, and R3) are determined by the magnetic field produced by the stator currents, the physical positioning of the rotor, and the step-up turns ratio between the stator and the rotor. The magnetic field, created by the stator currents, assumes an angle corresponding to that of the magnetic field in the transmitter supplying the signal. The position of the rotor controls the amount of magnetic coupling that takes place between the stator magnetic field and the rotor, and therefore, the amount of voltage induced into the rotor windings. If the rotor position changes in response to a mechanical input, then the voltages induced into its windings also change. Therefore, the output voltage of the TDX varies as a result of either a change in the input stator voltage or a change in the mechanical input to the rotor. This electrical output of the TDX may be either the SUM or the DIFFERENCE of the two inputs depending upon how the three units (the TX, the TDX, and the TR) are connected.

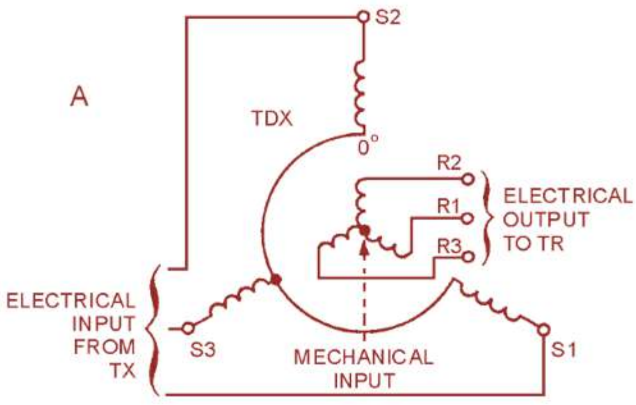



Fig12.50: Torque differential transmitter

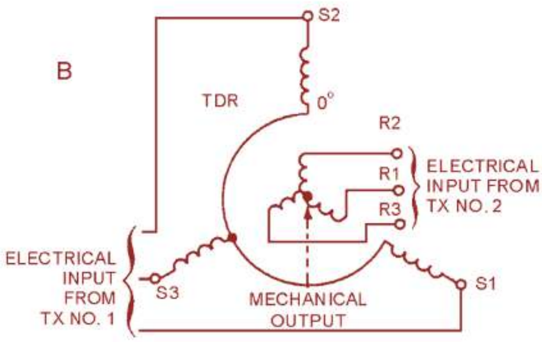



Fig12.51: Torque differential receiver

## TORQUE DIFFERENTIAL RECEIVER

The torque differential transmitter (TDX) and the torque differential receiver (TDR) are ELECTRICALLY IDENTICAL. The only difference in their construction is that the receiver (TDR) has a damper, which serves the same purposes as the damper in the TR — it prevents the rotor from oscillating. The real difference in the receiver lies in its application. It provides the mechanical output for a differential Synchro system usually as the sum or difference of two electrical inputs from Synchro transmitters. As in the case with the TDX, the TDR addition or subtraction function depends upon how the units in the system are connected.

Basically, the torque differential receiver operates like the electromagnets we discussed earlier in this chapter. In view B, the rotor and stator of the torque differential receiver receive energizing currents from two torque transmitters. These currents produce two resultant magnetic fields, one in the rotor and the other in the stator. Each magnetic field assumes an angle corresponding to that of the magnetic field in the transmitter supplying the signal. It is the interaction of these two resultant magnetic fields that causes the rotor in the TDR to turn.

## TX-TDX-TR SYSTEM OPERATION (SUBTRACTION)

Now that you know how the individual units work, we can continue our discussion with their application in different systems. The following sections explain how the TDX and TDR are used with other Synchro to add and subtract.

To understand how a TDX subtracts one input from another, first consider the conditions in a TX-TDX-TR system when all the rotors are on 0º, as in view A of figure. In this case, the TDX is on electrical zero and merely passes along the voltages applied to its windings without any change. Therefore, the TX stator voltages are felt at the TDX rotor. With the system in perfect balance, the TDX rotor voltages equal and oppose the TR stator voltages so that no current flows in the circuit. Since there is no current to produce the torque required to move the TR rotor, the system will remain in this condition, thus solving the equation $0^o - 0^o = 0^o$.

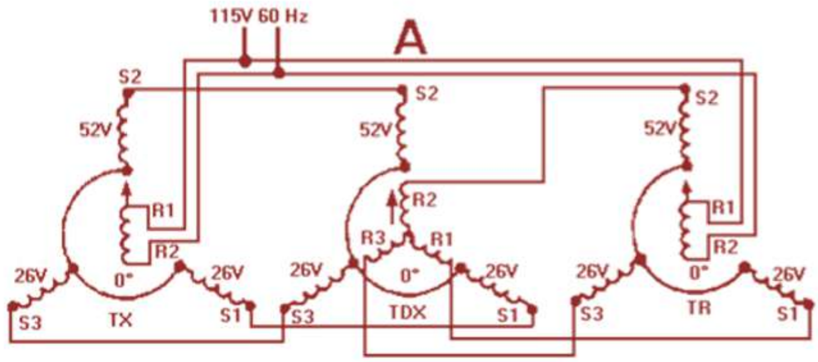



Fig12.52: TX-TDX-TR system operation (subtraction)

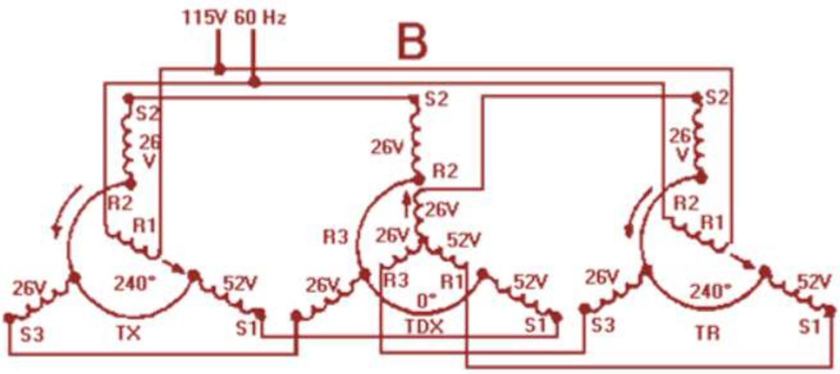



Fig12.53: TX-TDX-TR system operation (subtraction)

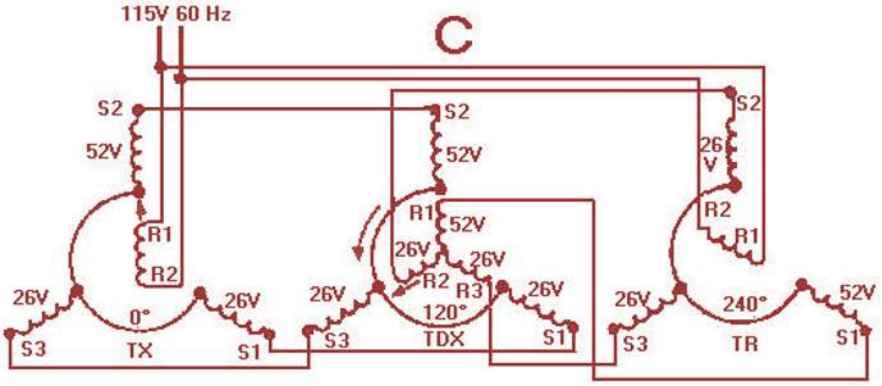



Fig12.54: TX-TDX-TR system operation (subtraction)

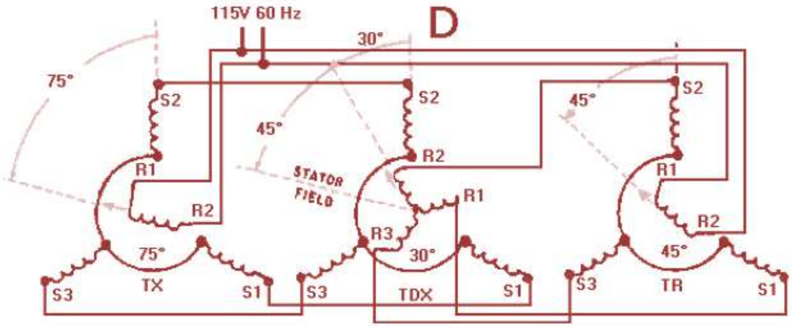



Fig12.55: TX-TDX-TR system operation (subtraction)

Up to this point, we have discussed the number of degrees a rotor is turned. Now, it is important to point out the labeling of Synchro positions. Labeling is necessary to determine the actual position of the Synchro rotor. Notice that Synchro rotor positions are labeled from 0º, increasing in a counterclockwise direction. It is common practice to refer to a Synchro transmitter as being on 120º when its rotor is pointing toward the S3 winding. Do not confuse these positions with the number of degrees a rotor is turned.

Assume that a 240º input is applied to the system, as indicated in view B, by turning the TX rotor to its 240º position. At this position maximum voltage is induced into the S1 winding of the TX and coupled to S1 of the TDX. Since the TDX rotor is on 0º, it passes this maximum voltage (via R1) along to the S1 winding of the TR. The stator magnetic field in the receiver now lines up in the direction of the S1 winding and causes the rotor to turn counterclockwise to the 240º position. This illustrates an important point:

Whenever the TDX rotor is at 0º, the TR rotor follows the TX rotor exactly. In the present case, the system has just solved the equation $240^\circ - 0^\circ = 240^\circ$.

Before we go to another example, you need to understand that when you subtract a higher value of degrees from a lower value of degrees, you add 360º to the lower value and subtract directly.

For example: 10º - 260º

Add 360º to lower value: 10º + 360º = 370º

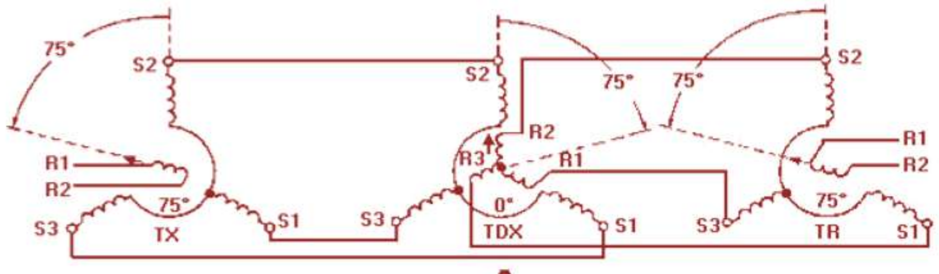
Subtract: 370º − 260º = 110º

In the next example, hold the TX rotor on 0º and turn the TDX rotor to 120º, as illustrated in view C of figure. In this situation, R1 of the TDX has maximum voltage induced in its winding since it is in line with S2. With R1 of the TDX connected to S1 of the TR, the TR stator magnetic field lines up in the direction of S1 and causes the TR rotor to turn clockwise to the 240º position. Given, then, that the TX is on 360º (or the 0º position), and subtracting the 120º displacement of the TDX rotor, the difference is 240º. This is the position at which the TR rotor comes to rest. Therefore, the system has solved the equation 360º − 120º = 240º. The actual subtraction operation of the TDX is a little more apparent in the next example.

Now, consider what happens in view D when the TX rotor is turned manually to 75º and the TDX rotor is set manually on 30º. When the TX rotor is turned to 75º, magnetic coupling increases between the rotor and S1. This, in turn, increases the voltage in S1 and, therefore, the magnetic field surrounding it. At the same time, the field in S2 and S3 decreases proportionately. This causes the resultant TX stator field to line up in the direction of its rotor. The increased voltage in S1 of the TX also causes an increase in current flow through S1 in the TDX, while decreased currents flow through S2 and S3. Therefore, a strong magnetic field is established around the S1 winding in the TDX. This field has the greatest effect on the resultant TDX stator field and causes it to line up in the same relative direction as the TX stator field (75º). The TDX stator field does not move from this 75º position because it is controlled by the position of the TX rotor. However, its angular position with respect to the R2 winding decreases by 30 when the TDX rotor is turned. Therefore, the signal induced into the TDX rotor and transmitted to the TR is 45º. The TR rotor responds to the transmitted signal and turns counterclockwise to 45º. This system has just solved the equation 75º − 30º = 45º.

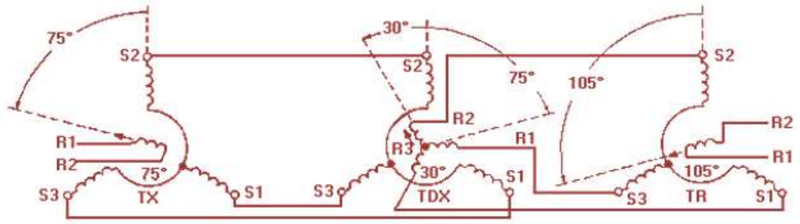
## TX-TDX-TR SYSTEM OPERATION (ADDITION)

Frequently it is necessary to set up a TX-TDX-TR system for addition. This is done by reversing the S1 and S3 leads between the TX and the TDX, and the R1 and R3 leads between the TDX and the TR. With these connections, the system behaves as illustrated in figure. Consider what happens when the TX rotor is turned to 75º, while the TDX is set at 0º view A. In the TX, with the rotor at 75º, increased coupling between the rotor and S1 increases the current in, and consequently the magnetic field around, that coil. At the same time, the field strengths of S2 and S3 decrease proportionately. This causes the resultant field of the TX stator to rotate counterclockwise and align itself with its rotor field. The system is now connected so the increased current in S1 of the TX flows through S3 of the TDX, while decreased currents flow through S1 and S2. Therefore, in the TDX, the resultant stator field is shifted 75º clockwise because of the stronger field around S3. Since the rotor of the TDX is on 0º, the voltage in the rotor is not changed but simply passed on to the TR. Remember, the R1 and R3 leads between the TDX and the TR have also been reversed. Just as in the simple TX-TR system with S1 and S3 leads interchanged, torque is developed in the TR, which turns the rotor in a direction opposite to the rotation of the TDX stator field. Therefore, the TR rotor rotates 75º counterclockwise and aligns itself with the TX rotor. Thus, the TX-TDX-TR system connected for addition behaves in the same way as the system connected for subtraction as long as the TDX rotor remains on 0º. When this condition exists, the TR rotor follows the TX rotor exactly. As you can see the system in view. A just solved the equation 75º + 0º = 75º.




A

Fig 12.56: TX-TR system operation (addition)




B

Fig 12.57 : TX-TR system operation (addition)

Now, with the TX in the same position (75º), the TDX rotor is turned to 30º (view B). The angle between the TDX stator field and R2 is then increased by 30º. This appears to the TR as an additional rotation of the TDX stator field. In transmitting the TX signal to the TR, the TDX adds the amount its own rotor has turned. The TR rotor now turns to 105º. Thus, the equation 75º + 30º = 105º is solved.

## TX-TDR-TX SYSTEM OPERATION (SUBTRACTION)

As we previously explained, the differential receiver differs chiefly from the differential transmitter in its application. The TDX in each of the previous examples combined its own input with the signal from a Synchro transmitter (TX) and transmitted the sum or difference to a Synchro receiver (TR). The Synchro receiver then provided the system's mechanical output. When the differential receiver (TDR) is used, the TDR itself provides the system's mechanical output. This output is usually the sum or difference of the electrical signals received from two Synchro transmitters. Figure shows a system consisting of two TXs (No. 1 and No. 2) and a TDR connected for subtraction.

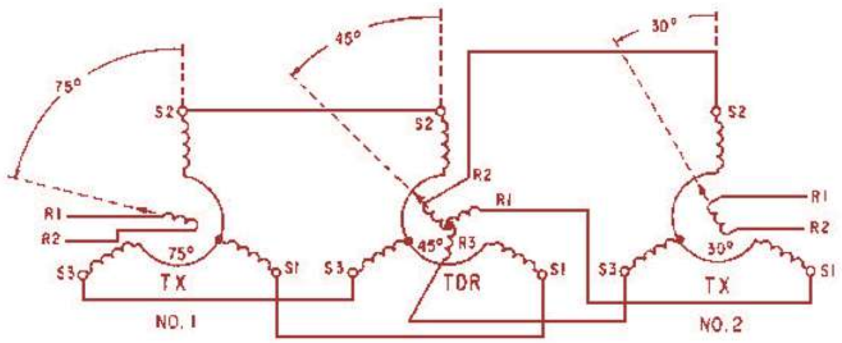



Fig 12.58 : TX-TDR-TX system operation (subtraction)

In this figure the signal from TX No. 1 rotates the resultant TDR stator field 75º counterclockwise. In a similar manner, the signal from TX No. 2 rotates the resultant TDR rotor field counterclockwise

30°. Since the two resultant fields are not rotated by equal amounts, a torque is exerted on the rotor to bring the two fields into alignment. This torque causes the rotor to turn to 45°, the point at which the two fields are aligned. To bring the two fields into alignment, the TDR rotor need turn only through an angle equal to the difference between the signals supplied by the two TXs.

## TX-TDR-TX SYSTEM OPERATION (ADDITION)

To set up the previous system for addition, it is necessary to reverse only the R1 and R3 leads between the TDR rotor and TX No. 2. With these connections reversed, the system operates as shown in Figure.

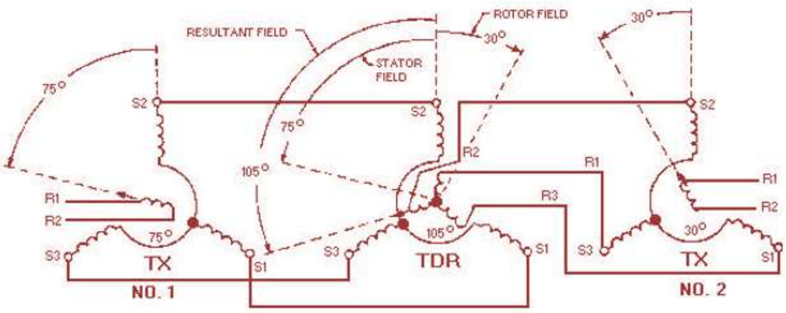



Fig 12.59: TX-TDR-TX system operation (addition)

Assume the TDR rotor is initially at 0°. TX No. 1 is turned to 75°, and TX rotor No. 2 is turned to 30°. The TDR stator field still rotates counterclockwise 75°, but because R1 and R3 on the TDR rotor are reversed, its rotor field rotates 30° clockwise. The angular displacement of the two fields then, with respect to each other, is the sum of the signals transmitted by the two TXs. The magnetic force pulling the TDR rotor field into alignment with that of the stator turns the TDR rotor to 105°. Therefore, the system solves the equation 75° + 30° = 105°.

## 12.6. CONTROL SYNCHRO SYSTEMS

It should be clear to you from our discussion of torque Synchro systems that, since they produce a relatively small mechanical output, they are suitable only for very light loads. Even when the torque system is moderately loaded, it is never entirely accurate because the receiver rotor requires a slight amount of torque to overcome its static friction.

When large amounts of power and a higher degree of accuracy are required, as in the movement of heavy radar antennas and gun turrets, torque Synchro systems give way to the use of CONTROL

SYNCHROS. Control Synchro by themselves cannot move heavy loads. However, they are used to "control" servo systems, which in turn do the actual movement. Servo systems are covered in depth in the next chapter in this module.

There are three types of control Synchro: the CONTROL TRANSMITTER (CX), the CONTROL TRANSFORMER (CT), and the CONTROL DIFFERENTIAL TRANSMITTER (CDX). The control transmitter (CX) and the control differential transmitter (CDX) are identical to the TX and the TDX we discussed previously except for higher impedance windings in the CX and CDX. The higher impedance windings are necessary because control systems are based on having an internal voltage provide an output voltage to drive a large load. Torque systems, on the other hand, are based on having an internal current provide the driving torque needed to position an indicator. Since we discussed the theory and operation of the TX and the TDX earlier, we will not discuss their counterparts, the CX and CDX. However, we will cover the third control Synchro, the CT, in depth during this discussion.

## CONTROL TRANSFORMERS

A control transformer is just what its name implies-a control Synchro device accurately governing some type of power amplifying device used for moving heavy equipment. Figure shows a phantom view of a typical CT and its schematic symbols.

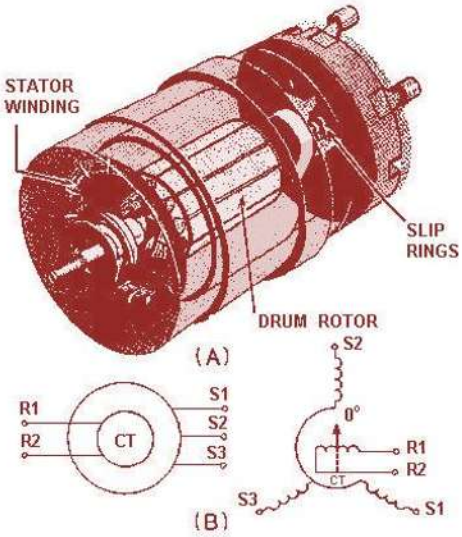



Fig12.60: Phantom view of a typical CT; (B) CT schematic symbols

The CT compares two signals, the electrical signal applied to its stator and the mechanical signal applied to its rotor. Its output is a difference signal that controls a power amplifying device and thus the movement of heavy equipment.

The unit construction and physical characteristics of a control transformer are similar to those of a control transmitter or torque receiver, except that there is no damper and the rotor is a drum or wound rotor rather than a salient-pole rotor.

An interesting point about the rotor is that it is never connected to an ac supply and, therefore, induces no voltages in the stator coils. As a result, the CT stator currents are determined solely by the voltages applied to the high-impedance stator windings. The rotor itself is wound so that its position has very little effect on the stator currents. Also, there is never any appreciable current flowing in the rotor because its output voltage is always applied to a high-impedance load. As a result, the CT rotor does not try to follow the magnetic field of its stator and must be turned by some external force.

The stator windings of the CT are considered to be the primary windings, and the rotor windings the secondary windings. The output, which is taken off the R1 and R2 rotor leads, is the voltage induced in the rotor windings. The phase and amplitude of the output voltage depend on the angular position of the rotor with respect to the magnetic field of the stator.

## CONTROL SYNCHRO SYSTEM OPERATION

A control Synchro system consisting of a control transmitter and a control transformer is illustrated in figure. The stator windings of the CX are connected to the stator windings of the CT and both Synchro are shown on 0º. Notice, that at 0º, the CT rotor is perpendicular to its S2 winding. This is contrary to what we have learned so far about Synchro, but it is just another peculiarity of the CT. When the rotor of the CX is on 0º, the rotor's magnetic field points straight up as shown (the black arrow). The voltages induced in the CX stator windings, as a result of this field, are impressed on the CT stator windings through the three leads connecting the S1, S2, and S3 terminals. Exciting currents proportional to these voltages flow in the CT stator windings and establish a magnetic field in the CT in the same direction (white arrow) as the magnetic field (black arrow) in the CX. Observe that the rotor of the CT is perpendicular to the stator magnetic field and, therefore, the induced voltage in the rotor is zero, as indicated by the straight line on the oscilloscope presentation.

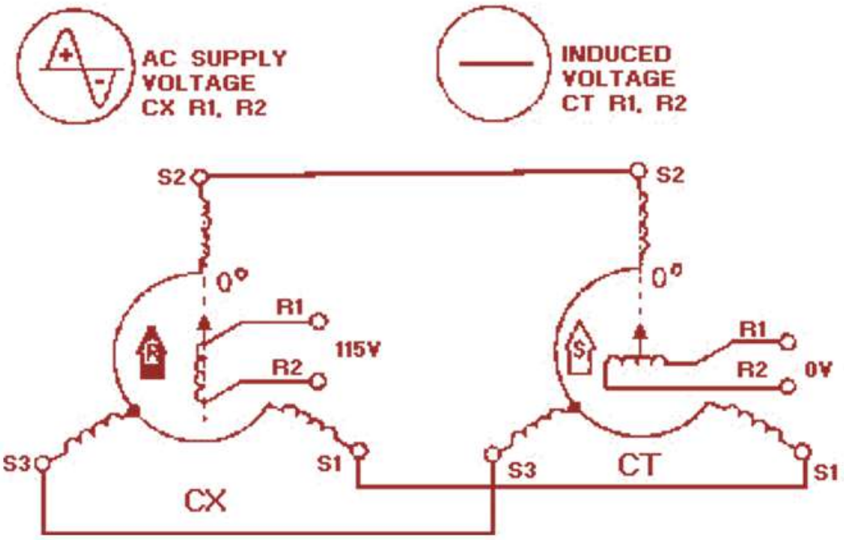



Fig 12.61 : CX-CT system operation with rotor in correspondence

When the CT rotor is rotated 90º, as shown in figure, the rotor is parallel to the resultant stator field Maximum magnetic coupling occurs between the rotor and stator fields at this point. As a result of this coupling, the stator windings induce a maximum of 55 volts into the rotor winding. The phase of this voltage depends upon the direction in which the CT rotor is turned. The rotor of the CT is wound so that clockwise rotation of the stator magnetic field induces a voltage across the rotor which is proportional to the amount of rotation and in phase with the ac supply voltage. Counterclockwise rotation of the stator magnetic field produces a voltage that is still proportional to the amount of rotation, but 180º out of phase with the supply voltage. Keep in mind that the clockwise rotation of the CT stator magnetic field is the same as the counterclockwise rotation of the CT rotor. This phase relationship between the ac supply voltage and the CT output voltage becomes more apparent in Figure 12.62

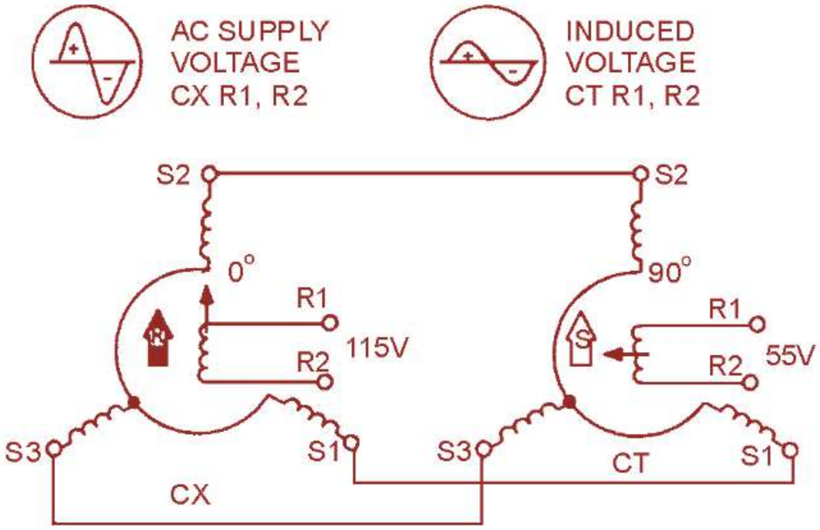



Fig 12.62: CX-CT system operation with the CX rotor at 0º and the CT rotor at 90º

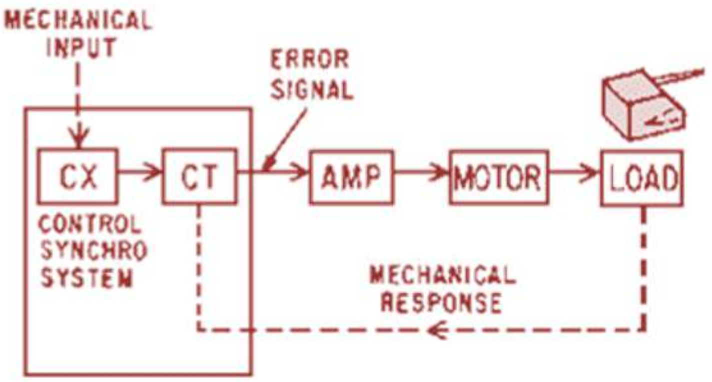



Figure 12.63 : Control Synchro system operation

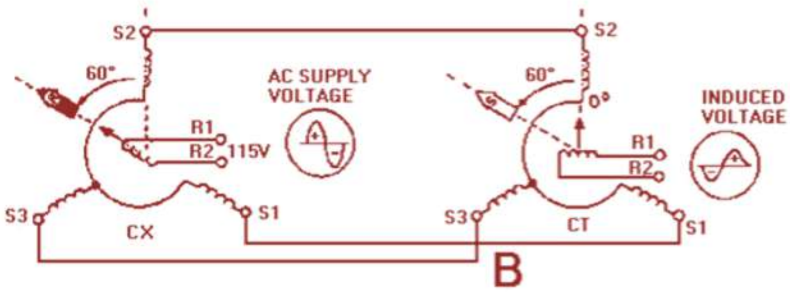
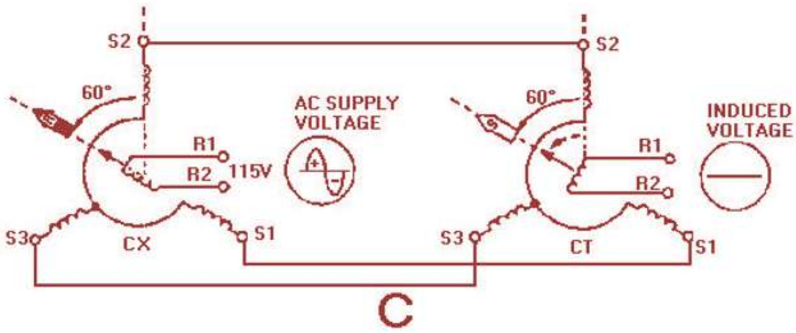



Figure 12.64 : Control Synchro system operation

Figure 12.65 : Control Synchro system operation



When the rotor of the CX in view A of figure12.63 is turned 60º clockwise, the magnetic field in the CX (black arrow) and the magnetic field in the CT (white arrow) also rotate 60º clockwise. This action induces a voltage in the CT rotor that is in phase with the ac supply, as indicated by the oscilloscope presentation. If the rotor of the CX in view B is turned 60º in a counterclockwise direction from its 0º position, the magnetic field (white arrow) in the CT also rotates counterclockwise through the same number of degrees as the CX. Since the magnetic field in the stator of the CT cuts through the rotor in the opposite direction, the induced voltage in the rotor is now out of phase with the ac supply to the CX, as shown in the oscilloscope presentation.

At times it is necessary, because the CT is used to control servo systems, to have the CT output reduced to zero volts to prevent any further movement of a load. To accomplish this, it is necessary to turn the rotor of the CT through the same number of degrees and in the same direction as the rotor of the CX. This places the CT rotor perpendicular to its own stator field and reduces its output to zero volts as illustrated in view C.

The CT output voltage discussed throughout this section is commonly referred to as an ERROR SIGNAL. This is because the voltage represents the amount and direction that the CX and CT rotors are out of correspondence. It is this error signal that eventually is used in moving the load in a typical servo system.

Now that we have covered the basic operation of the control Synchro system, let us see how this system works with a servo system to move heavy equipment. Figure 12.65 shows a block diagram of a typical servo system that uses a control Synchro system. Assume the shaft of the CX in this system is turned by some mechanical input. This causes an error signal to be generated by the CT because the CX and the CT rotors are now out of correspondence. The error signal is amplified by the servo amplifier and applied to the servomotor. The servomotor turns the load, and through a mechanical linkage called RESPONSE, also turns the rotor of the CT. The servomotor turns the rotor of the CT so that it is once again in correspondence with the rotor of the CX, the error signal drops to zero volts, and the system comes to a stop.

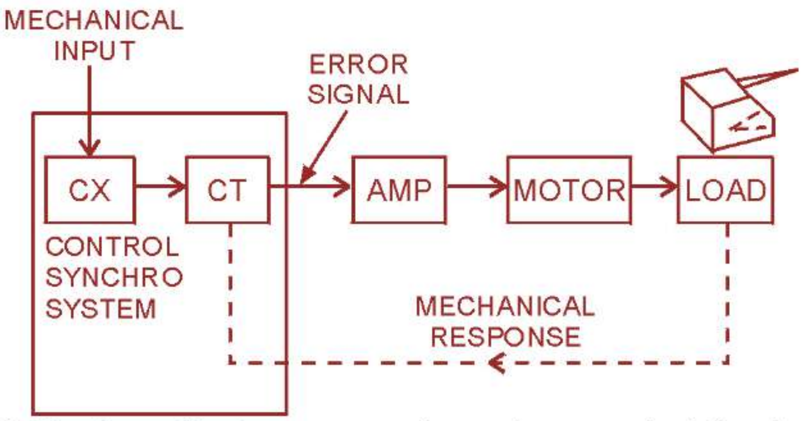



Figure 12.66 : A positioning servo system using a control Synchro system

## 12.10. SYNCHRO CAPACITORS TRANSMITTER

As we stated earlier, the speed and accuracy of data transmission are most important. With the use of more complex Synchro, like the differential and the control transformer, the accuracy of the Synchro systems may be affected. The following discussion will deal with how complex Synchro affect the accuracy of Synchro systems and what can be done to keep this accuracy as high as possible. Synchro capacitors play a major role in maintaining a high degree of accuracy in Synchro systems.

When a torque transmitter is connected to a torque receiver (TX-TR), very little, if any, current flows in the stators when the rotors are in correspondence. This is because the voltages induced in the TR windings almost exactly balance out the voltages induced in the TX windings. As a result, the TR is very sensitive to small changes in the position of the TX rotor, causing the TR to follow the TX with a high degree of accuracy.

When a Synchro system contains differential Synchro (TDX or CDX), the stator currents at correspondence are greater than they are in a single TX-TR system. The reason is the step-up turns ratio between the stator and rotor in the differential Synchro.

In a Synchro system that uses a CT, stator current at correspondence is also greater than in a TX-TR system. In this case, however, this reason is that the CT rotor is not energized and as a result no voltage is induced in the stator to oppose the voltage in the transmitter stator. The overall effect of this increase in stator current is to reduce the accuracy of the system. To maintain high accuracy in a Synchro system containing either differential units or CTs, the stator currents must be kept to a minimum. This is done by connecting Synchro capacitors in the circuit.

To understand the operation of a Synchro capacitor and how it reduces current drain on the transmitter requires a recollection of the voltage and current relationships in inductive and capacitive circuits. As you learned in module 2 of this series, current lags voltage by 90º in a purely inductive circuit. You also know that an ideal inductor is impossible to make because there is always resistance present. Therefore, an inductor has a combination of inductive reactance and resistance. Since current and voltage are always in phase in a resistive circuit and 90º out of phase in an inductive circuit, we can say that there are two currents in an inductor-the loss current, which is the resistive (in-phase) current, and the magnetizing current, which is the inductive (out-of-phase) current. It is this magnetizing current that we would like to eliminate in the stator coils of the TDX, CDX, and CT because it makes up most of the line current.

Keeping in mind that current leads voltage by 90º in a capacitive circuit, let's see what happens to magnetizing current when a capacitor is added to the circuit.

Suppose a capacitor is hooked up across one of the stator coils of a TDX and its capacitance is adjusted so that its reactance equals the reactance of the coil. Since the two reactances are equal, the current they draw from the line must also be equal. However, these currents are going to be 180º out of phase, because the current in the coil lags the line voltage, while the capacitor's current leads it. Since the two currents are equal in magnitude but opposite in phase, they cancel. The total line current is reduced by this effect and, if a capacitor is placed across each coil in the TDX, the line current decreases even further. This, in effect, increases torque in Synchro systems near the point of correspondence and, therefore, increases overall system accuracy.

Connecting capacitors across individual stator windings is impractical because it requires that the stator winding's common connection be outside the Synchro. Since this is not done with Synchro, another method has been devised to connect up the capacitors which work just as well.

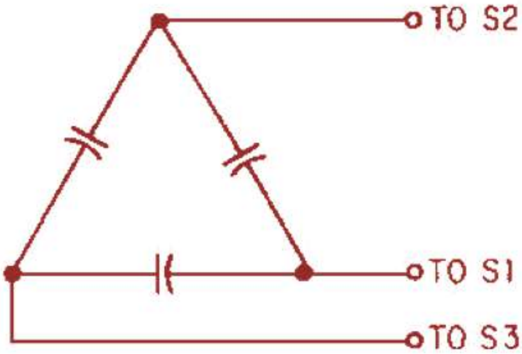



Fig 12.67: The Synchro capacitor

The three delta-connected capacitors, shown in figure, usually come as a unit mounted in a case with three external connections. The entire unit is called a SYNCHRO CAPACITOR. The Synchro capacitor is made in many sizes to meet the requirements of all sizes of standard differentials and control transformers. The Synchro capacitor is rated by its total capacity, which is the sum of the individual capacities in the unit.

Figure shows how a Synchro capacitor affects the operation of a control Synchro system. In this figure, the capacitor is placed between the CX and the CT. Two current meters are also placed in the circuit to show the effect the capacitor has on stator current. The meter connected between the capacitor and the CT reads normal stator current, 32 mill amperes (mA). This current would normally flow in the stator of the CX if the Synchro capacitor were not connected. The other meter reads 10 mA, which is what is left of the original stator current after the magnetizing current has been canceled by the Synchro capacitor. By reducing the current drain on the transmitter, the sensitivity and accuracy of the system increase.

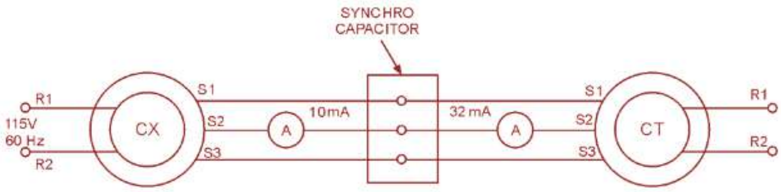



Fig 12.68 : the use of a Synchro capacitor with a CT

Figure 12.68 shows another application of a Synchro capacitor; this time in a differential system in this circuit the capacitor is placed between a TX and a TDX. The meter readings show the same comparison between currents as in the previous paragraph. The only significant difference between this circuit and the one in figure 12.70 is that the differential draws more stator current than the CT.

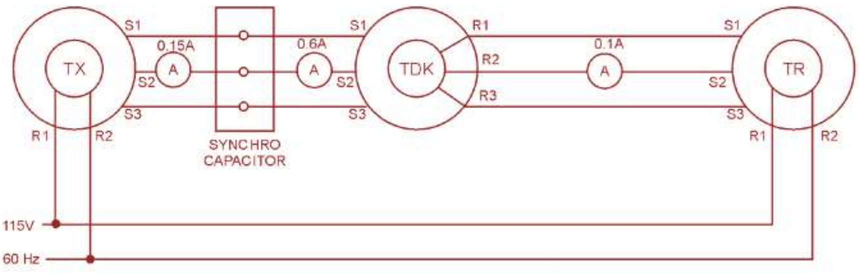



Fig 12.69 : the use of a Synchro capacitor with a TDX

Some Synchro systems contain a differential and a control transformer, as illustrated in 12.71 In this figure, there are large stator currents flowing in the CX, since it supplies all the losses as well as the magnetizing current for both Synchro. Two meters are placed in the circuit to show the value of stator current for the CDX and CT. Another meter is placed in series with the ac excitation voltage to show the amount of current being drawn from the ac line is 0.9 ampere.

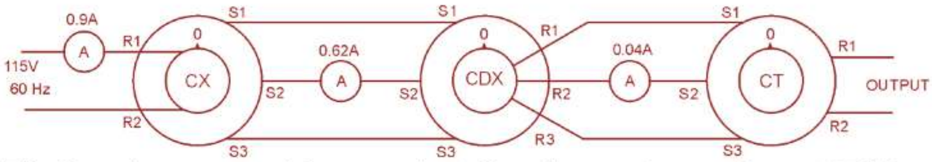


Fig 12.70: Synchro current in a control Synchro system using a CDX and a CT

Adding Synchro capacitors to this system, as shown in Figure 12. 70, greatly reduces the stator currents and improves the efficiency of the system. Also, notice that the line current is reduced from 0.9 ampere to 0.65 ampere in figure

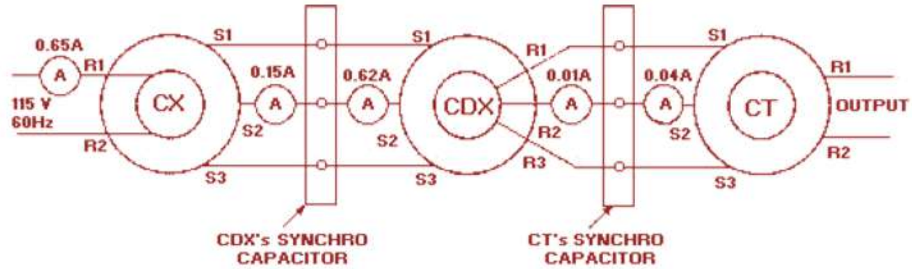


Fig 12.71: The effects of Synchro capacitors in a control Synchro system using a CDX and a CT

When a Synchro capacitor is used, it is always placed physically close to the differential or control transformer whose current it corrects. This is done to keep the connections as short as possible, because high currents in long leads increase the transmitter load and reduce the accuracy of the system.

We must stress that the Synchro capacitor should never be used in a simple transmitter-receiver system. This is because stator currents in this system are zero at correspondence and the addition of a Synchro capacitor would only increase the stator current and throw the system out of balance.

## 12.11. SERVOMECHANISM DEFECTS

First, let's consider some of the more common problem areas you should avoid when working with Synchro. As with any piece of electrical or electronic equipment, if it works—leave it alone. Do not attempt to zero a Synchro system that is already zeroed just because you want to practice. More often than not, the system will end up more out of alignment than it was before you attempted to rezero it. Do not attempt to take a Synchro apart, even if it is defective. A Synchro is a piece of precision equipment that requires special equipment and techniques for disassembly. Disassembly should be done only by qualified technicians in authorized repair shops. A Synchro, unlike an electric motor, does not require periodic lubrication. Therefore, never attempt to lubricate a Synchro. Synchro also require careful handling. Never force a Synchro into place, never use pliers on the threaded shaft, and never force a gear or dial onto the shaft. Finally, never connect equipment that is not related to the Synchro system to the primary excitation bus. This will cause the system to show all the symptoms of a shorted rotor when the equipment is turned on; but, the system will check out good when the equipment is off.

Trouble in a Synchro system that has been in operation for some time is usually one of two types. First, the interconnecting Synchro wiring often passes through a number of switches; at these points opens, shorts, or grounds may occur. You will be expected to trace down these troubles with an ohmmeter. You can find an open easily by checking for continuity between two points. Similarly, you can find a ground by checking the resistance between the suspected point and ground. A reading of zero ohms means that the point in question is grounded. Secondly, the Synchro itself may become defective, due to opens and shorts in the windings, bad bearings, worn slip rings, or dirty brushes. You can do nothing about these defects except replace the Synchro.

Troubles in new and modified Synchro systems are most often because of
(1) improper wiring
(2) misalignment caused by Synchro not being zeroed. You are responsible for finding and correcting these troubles. You can check for improper wiring with an ohmmeter by making a point-to-point continuity and resistance check. You can correct misalignment of a Synchro system by rezeroing the entire system.

## TROUBLE INDICATORS

When trouble occurs in an electronic installation that contains a large number of Synchro systems, it may be very difficult to isolate the trouble to one particular system. Since it is vital that maintenance personnel locate the point of trouble and fix it in as short a time as possible, indicators, which aid in locating the trouble quickly, are included in the equipment. These indicators are usually signal lights, mounted on a central control board and connected to the different Synchro systems. When trouble occurs in a Synchro system, the signal light connected to it may either light or flash. Maintenance personnel identify the defective system by reading the name or number adjacent to the light.

Signal lights indicate either overload conditions or blown fuses. Overload indicators are usually placed in the stator circuit of a torque Synchro system because the stator circuit gives a better indication of mechanical loading than does the current in the rotor circuit. One version of this type of indicator, as shown in figure, consists of a neon lamp connected across the stator leads of a Synchro system by two transformers. The primaries, consisting of a few turns of heavy wire, are in series with two of the stator leads; the secondaries, consisting of many turns of fine wire, are in series with the lamp. The turns ratios are designed so that when excess current flows through the stator windings, the neon lamp lights. For example, when the difference in rotor positions exceeds about 18°, the lamp lights, indicating that the load on the motor shaft is excessive.

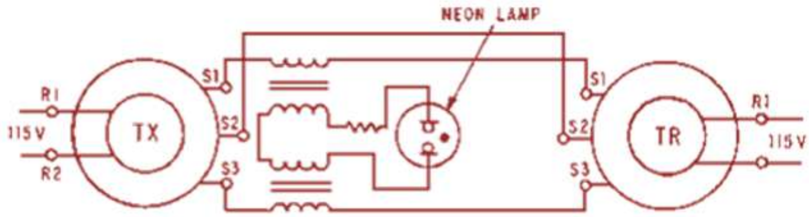



Fig 12.72 : Overload stator current indicator

Blown fuse indicators are front panel lights which light when a protective fuse in series with the rotor blows. Figure shows a typical blown fuse indicator. If excessive current flows in the rotor windings of this circuit because of a short or severe mechanical overload, one of the fuses will blow and the neon lamp across the fuse will light.

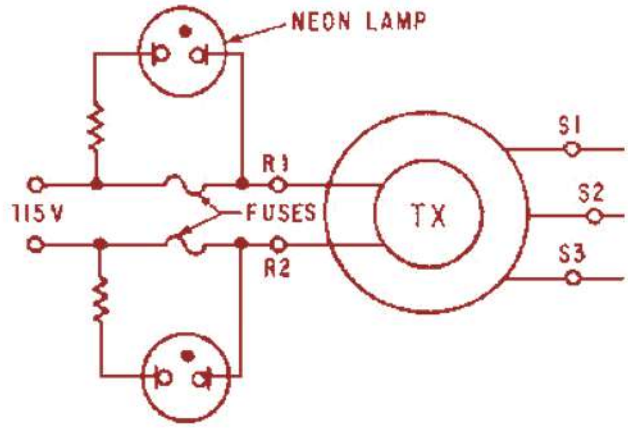



Figure 12.73 : Simple blown fuse indicator

Another type of blown fuse indicator uses a small transformer having two identical primaries and a secondary connected, as shown in figure. With both fuses closed, equal currents flow through the primaries. This induces mutually canceling voltages in the secondary. If a fuse blows, the induced voltage from just one primary is present in the secondary, and the lamp lights.

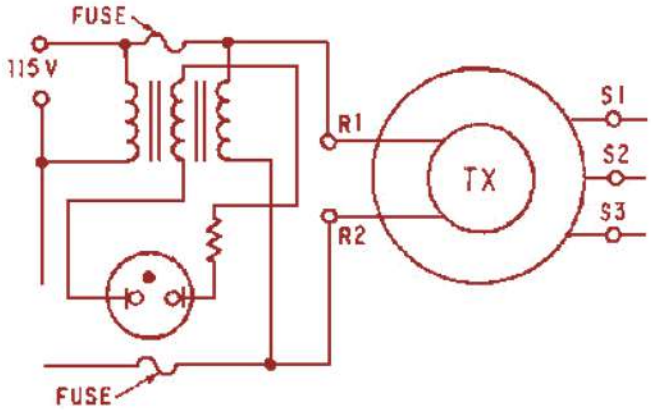



Fig 12.74 : Blown fuse indicator requiring only one lamp

## SYMPTOMS AND CAUSES

To help the technician further isolate Synchro problems, many manufacturers furnish tables of trouble symptoms and probable causes with their equipment. These tables are a valuable aid in isolating trouble areas quickly. Tables 1-2 through 1-7 summarize, for a simple TX-TR system, some typical trouble symptoms and their probable causes. Keep in mind, if two or more receivers are connected to one transmitter, similar symptoms occur. However, if all the receivers act up, the trouble is usually in the transmitter or main bus. If the trouble appears in one receiver only, check the unit and its connections.

The angles shown in these tables do not apply to systems using differentials, or to systems whose units are incorrectly zeroed.

Table 1.2 : General Symptoms

| Preliminary Actions: Be sure TR is not jammed physically. Turn TX slowly in one direction and observe TR. | |
|---|---|
| SYMPTOMS | TROUBLE |
| Overload Indicator lights Units hum at all TX settings One unit overheats TR follows smoothly but reads wrong | Rotor circuit open or shorted. See table 1-3. |
| Overload Indicator lights Units hum at all except two opposite TX settings Both units overheat TR stays on one reading half the time, then swings abruptly to the opposite one. TR may oscillate or spin. | Stator circuit shorted. See table 1-4. |
| Overload Indicator lights Units hum on two opposite TX settings Both units get warm TR turns smoothly on one direction, then reverses | Stator circuit open. See table 1-5. |
| TR reads wrong or turns backward, follows TX smoothly | Unit interconnections wrong. Unit not zeroed. See tables 1-6 and 1-7. |

Table 1.3 : Open or Shorted Rotor

| Preliminary Action: Set TX to 0˚ and turn rotor smoothly counterclockwise. | |
|---|---|
| SYMPTOMS | TROUBLE |
| TR turns counterclockwise from 0º in a jerky or | TX rotor open |

| | |
|---|---|
| erratic manner, and gets hot. | |
| TR turns counterclockwise from 0º or 180º in a jerky or erratic manner. TX gets hot. | TR rotor open |
| TR turns counterclockwise from 90º or 270º, torque is about normal, motor gets hot, and TX fuses blow. | TX rotor shorted |
| TR turns counterclockwise from 90˚ or 270˚, torque is about normal, TX gets hot, and TR fuses blow. | TR rotor shorted |

Table 1.4 : Shorted Stator

| Symptoms | | Trouble |
|---|---|---|
| Setting OR Conditions | Indication | |
| When TX is on 120º or 300º but when TX is between 340º and 80º, or between 160º and 260º | Overload Indicator goes out and TR reads correctly overload Indicator lights, units get hot and hum, and TR stays on 120º or 300º, or may swing suddenly from one point to the other. | Stator circuit shorted from S1 to S2 |
| When TX is on 60 º or 240º but when TX is between 280º and 20º, or between 100º and 200º | Overload Indicator goes out and TR reads correctly overload Indicator lights, units get hot and hum, and TR stays on 60º or 240ºor may swing suddenly from one point to the other | Stator circuit shorted from S2 to S3Stator circuit shorted from S2to S3 |
| When TX is on 0º or 180º but when TX is between 40º and 140º, or between 220º and 320º | Overload Indicator goes out and TR reads correctly overload Indicator lights, units get hot and hum, and TR stays on 0º or 180º,or may swing suddenly from one point to the other | Stator circuit shorted from S1 to S3 Stator circuit shorted from S1 to S3 |

Table 1.5 : Open Stator

| Setting OR Conditions | Indication | Trouble |
|---|---|---|
| When TX is on 150º or 330º and | TR reverses or stalls and Overload indicator lights TR | S1 stator circuit open |

| | | |
|---|---|---|
| when TX is held on $0^o$ | moves between $300^o$ and $0^o$ in a jerky or erratic manner | |
| When TX is on $90^o$ or $270^o$ and when TX is held on $0^o$ | TR reverses or stalls and Overload Indicator lights TR moves to $0^o$ or $180^o$, with fairly normal torque | S2 Stator circuit open |
| When TX is on $30^o$ or $210^o$ and when TX is held on $0^o$ | TR reverses or stalls and Overload Indicator lights TR moves between $0^o$ and $60^o$ in a jerky or erratic manner | S3 stator circuit open |
| When TX is set at 0˚, and then moved smoothly counter clockwise | | |

Table 1.6 : Wrong Stator Connections, Rotor Wiring Correct

| Setting OR Conditions | Indication | Trouble |
|---|---|---|
| TX set to $0^o$ and rotor turned smoothly counterclockwise | TR indication is wrong, turns clockwise from $240^o$ | S1 and S2 stator connections are reversed |
| | TR indication is wrong, turns clockwise from $120^o$ | S2 and S3 stator connections are reversed |
| | TR indication is wrong, turns clockwise from $0^o$ | S1 and S3 stator connections are reversed |
| | TR indication is wrong, turns counter clockwise from $120^o$ | S1 is connected to S2, S2 is connected to S3, and S3 is connected to S1 |
| | TR indication is wrong ,turns counterclockwise from $240^o$ | S1 is connected to S3, S2 is connected to S1, and S3 is connected to S2 |

Table 1.7: Wrong Stator and/or Reversed Rotor Connections

| Setting OR Conditions | Indication | Trouble |
|---|---|---|

| | | |
|---|---|---|
| TX set to 0º and rotor turned smoothly counterclockwise | TR indication is wrong, turns counterclockwise from 180º | Stator connects are correct, but rotor connections are reversed |
| | TR indication is wrong, turns clockwise from 60º | Stator connections S1 and S2 are reversed, and rotor connections are reversed |
| | TR indication is wrong, turns clockwise from 300º | Stator connections S2 and S3 are reversed, and rotor connections are reversed |
| | TR indication is wrong, turns clockwise from 180º | Stator connections S1 and S3 are reversed, and rotor connections are reversed |
| | TR indication is wrong, turns counterclockwise from 300º | S1 is connected to S2, S2 is connected to S3, S3 is connected to S1, and rotor connections are reversed |
| | TR indication is wrong, turns counterclockwise from 60º | S1 is connected to S3, S2 is connected to S1, S3 is connected to S2, and rotor connections are reversed |

In a control system, the trouble may be slightly more difficult to isolate. However, the existence of trouble is readily indicated when the system does not properly respond to an input order. For control systems, it is easier to locate the trouble by using a Synchro tester or by checking the operating voltages.

## SUMMARY

Now that you have completed this chapter, a short review is in order. The following review will refresh your memory of Synchro, their principles of operation, and how they are tied together to form Synchro systems.

A SYNCHRO resembles a small electric motor in size and appearance and operates like a variable transformer.

Synchro are used primarily for the rapid and accurate transmission of data. They are also used as control devices in servo systems.

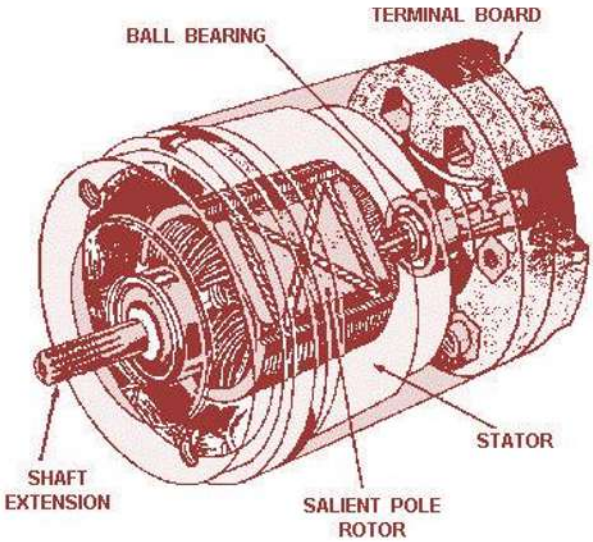


Fig 12.75

A SYNCHRO SYSTEM consists of two or more Synchro interconnected electrically.

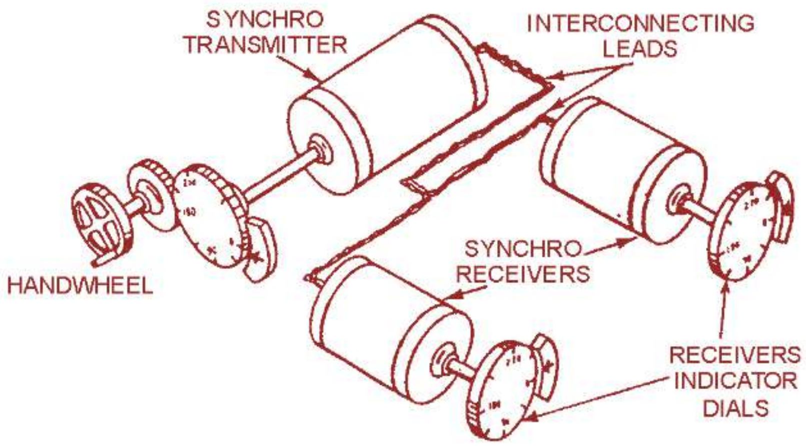


Fig 12.76

TORQUE SYNCHRO SYSTEMS are systems that use torque Synchro to move light loads, suchas dials and pointers.

CONTROL SYNCHRO SYSTEMS are systems that use control Synchro to control servo systems.The servo system, in conjunction with the control Synchro system, is used to move heavy loads such as gun directors, radar antennas, and missile launchers.

MILITARY STANDARD SYNCHROS are Synchro that conform to specifications that are uniform throughout the Armed Services. They replace the pre standard Navy Synchro. A typical example of a military standard Synchro designation code is 18TR6A. This code has the following interpretation:

18—Synchro diameter of 1.71 to 1.80 inches

T—Torque

R—Receiver

6—60-Hz frequency

A—Original design

PRESTANDARD NAVY SYNCHROS are Synchro designed to meet Navy, rather than service-wide, specifications. A typical example of a pre standard Navy Synchro designation code is 5DG. This code has the following interpretation:

5—Synchro diameter of 3 3/8 to 3 5/8 inches, length

1/2 inches, weight 5 lbs.

DG—Differential transmitter

SCHEMATIC SYMBOLS for Synchro are drawn in two different forms. Two of the five standard military symbols are drawn to show only the external connections to the Synchro. The other three symbols are drawn to show both the external connections and the internal relationship between the rotor and the stator.

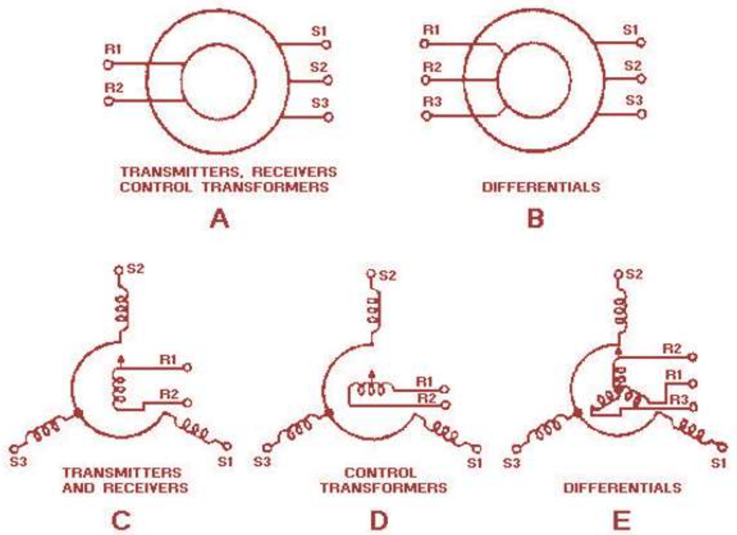



Fig 12.77

SYNCHROS ARE CONSTRUCTED like motors. Each contains a rotor, similar in appearance to the armature in a motor, and a stator which corresponds to the field in a motor.

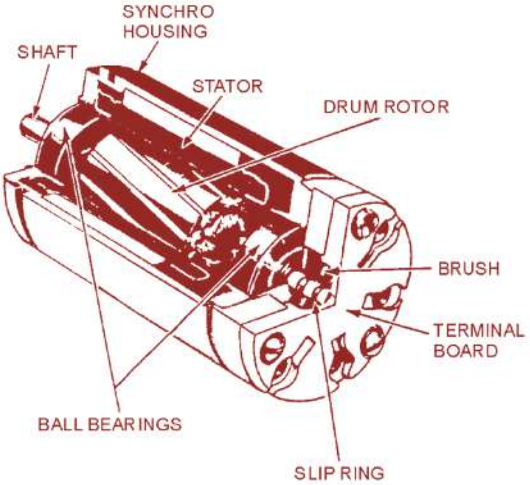


Fig 12.78

A SYNCHRO ROTOR is composed of either a single coil of wire wound on a laminated core or a group of coils wound in slots in a laminated core. The laminated core is rigidly mounted on a shaft that is free to turn inside the stator. Two slip rings are mounted on one end of the shaft to supply excitation voltage to the rotor. There are two common types of Synchro rotors - the salient-pole rotor and the drum or wound rotor.

The SALIENT-POLE ROTOR has a single coil of wire wound on a laminated core, shaped like a dumbbell or the letter "H." This type of rotor is frequently used in transmitters and receivers.

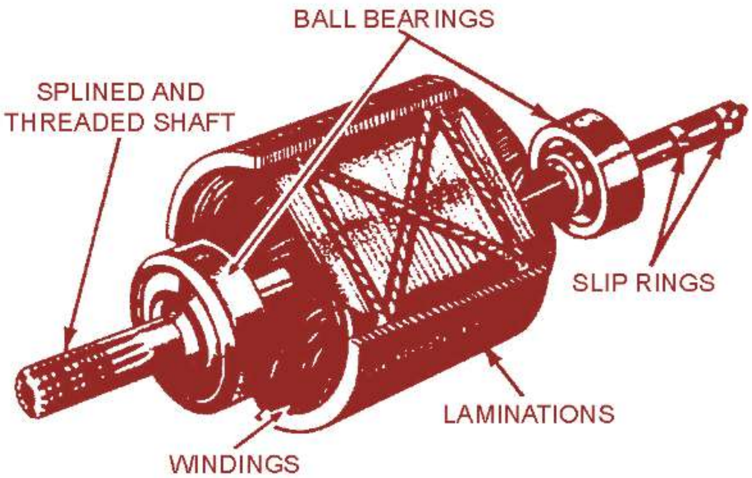


Fig 12.79

The DRUM OR WOUND ROTOR may be wound continuously with a single length of wire or may have a group of coils connected in series. This type of rotor is used in most Synchro control transformers and differential units, and occasionally in torque transmitters. When used in differential units, the rotor is wound with three coils so their magnetic axes are 120 degrees apart.

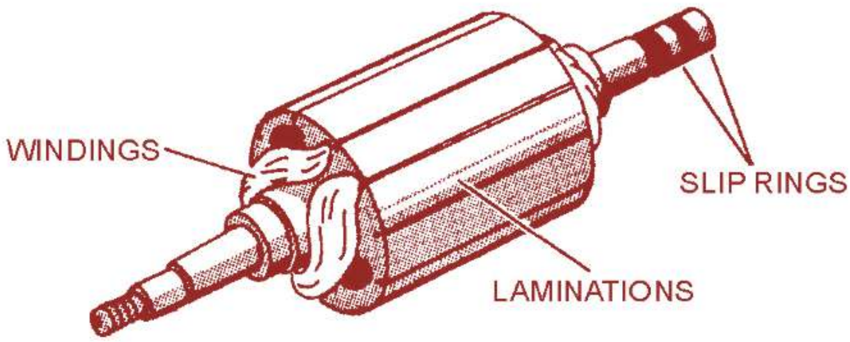



Fig 12.80

A SYNCHRO STATOR is a cylindrical structure of slotted lamination on which three Y-connected coils are wound with their axes 120º apart.

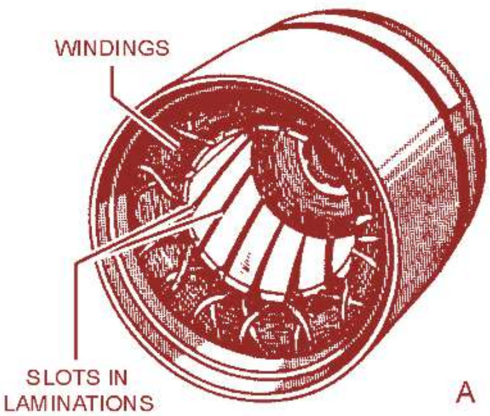



Fig 12.81

TORQUE is simply a measure of how much load a machine can turn. In heavy machinery, it is expressed in pound-feet and in torque Synchro systems, it is expressed in ounce-inches.

SYNCHRO OPERATING VOLTAGES AND FREQUENCIES vary with different equipment. Synchro are designed for use on either a 115-volt or a 26-volt power source. They also operate on either a 60- or 400-Hz frequency.

ELECTROMAGNETIC THEORY forms the basis for understanding all Synchro operations.

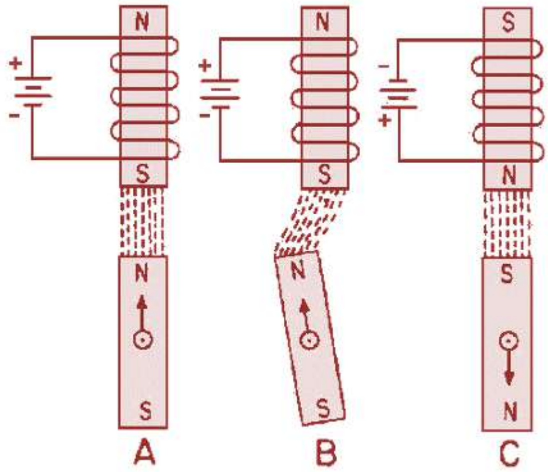



Fig 12.82

The RESULTANT MAGNETIC FIELD in a Synchro is the result of the combined effects of three stator fields spaced 120º apart. The stator coil with the strongest field has the greatest effect on the position of the resultant field.

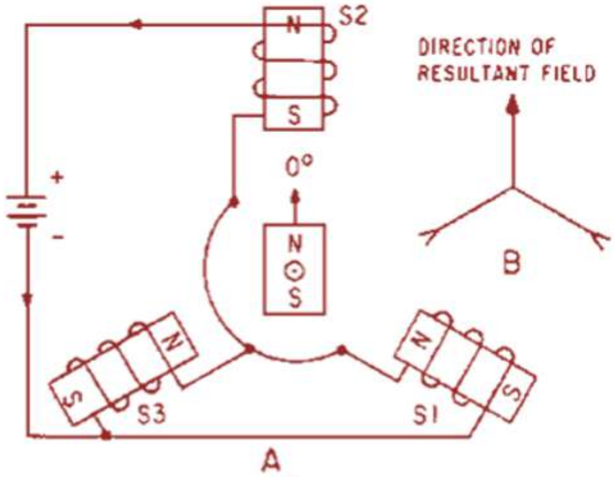



Fig 12.83

The ZERO-DEGREE POSITION of a Synchro, transmitter is the position where the rotor and the S2 stator winding are parallel.

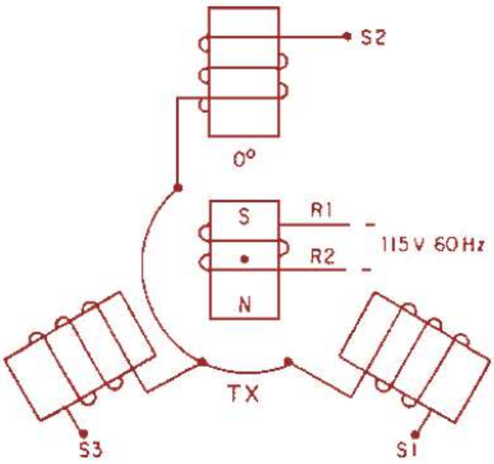



Fig 12.84

The SYNCHRO TRANSMITTER (TX) converts a mechanical input, which is the angular position of the rotor, into an electrical output signal. The output is taken from the stator windings and is used by a TDX, a TDR, or a TR to move light loads, such as dials and pointers.

MAXIMUM INDUCED STATOR VOLTAGE occurs in a single Synchro stator coil each timethere is maximum magnetic coupling between the rotor and the stator coil. This voltage is approximately equal to the product of the effective voltage on the primary; the secondary-to-primary turns ratio, and the magnetic coupling between the rotor and the stator coil.

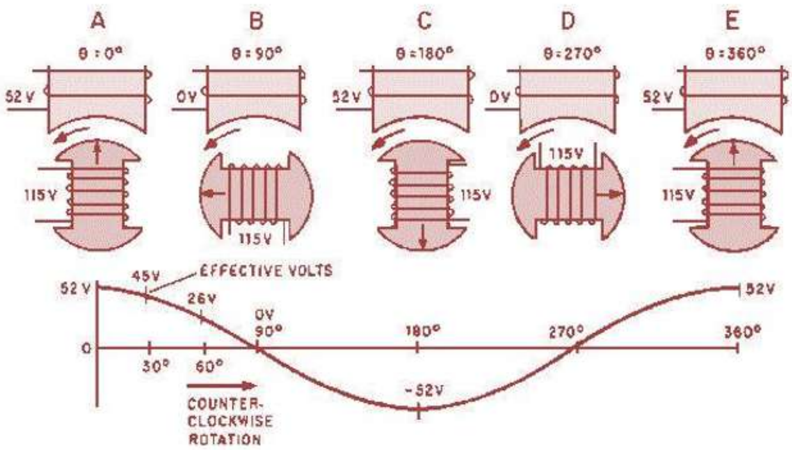



Fig 12.85

The SYNCHRO RECEIVER (TR) is electrically identical to the Synchro transmitter. The receiver, however, uses some form of rotor damping that is not present in the transmitter. This real difference between a Synchro transmitter and a Synchro receiver lies in their applications. The receiver converts the electrical data, supplied to its stator from the transmitter, back to a mechanical angular output through the movement of its rotor.
‘

## DAMPING

Itis a method used in Synchro receivers to prevent the rotor from oscillating or spinning.There are two types of damping methods - ELECTRICAL and MECHANICAL. The electrical method is commonly used in small Synchro, while the mechanical method is more effective in larger Synchro.

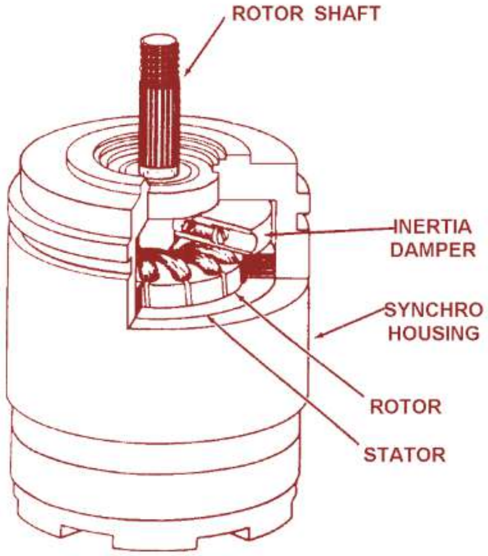


Fig 12.86

A TORQUE SYNCHRO SYSTEM consists of a torque transmitter (TX) electrically connected to a torque receiver (TR). In this system, the mechanical input to the TX is transmitted electrically to the TR. The TR reproduces the signal from the TX and positions either a dial or a pointer to indicate the transmitted information.

CORRESPONDENCE is the term given to the positions of the rotors of a Synchro transmitter and a Synchro receiver when both rotors are on 0º or displaced from 0º by the same angle.

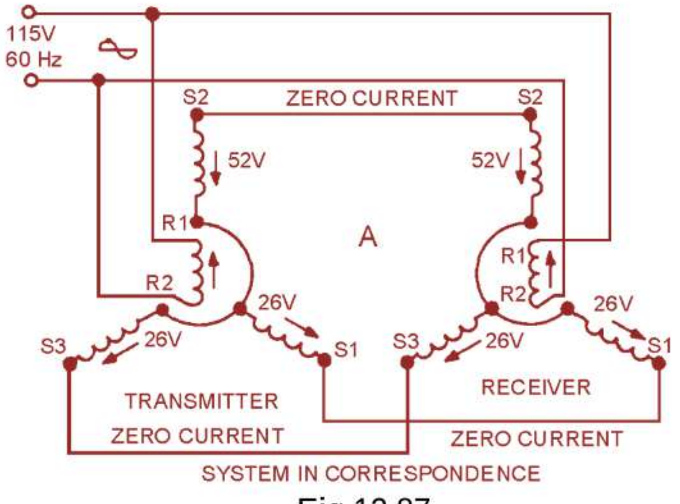


Fig 12.87

SIGNAL is defined as the angle through which a transmitter rotor is mechanically turned. This term has the same meaning as "transmitter's mechanical input."

RECEIVER ROTATION may be in a direction opposite to that desired. When it is necessary to reverse receiver rotation, reverse the S1 and S3 connections on either the Synchro transmitter or the Synchro receiver. The causes both Synchro rotors to turn through the same angle but in opposite directions.

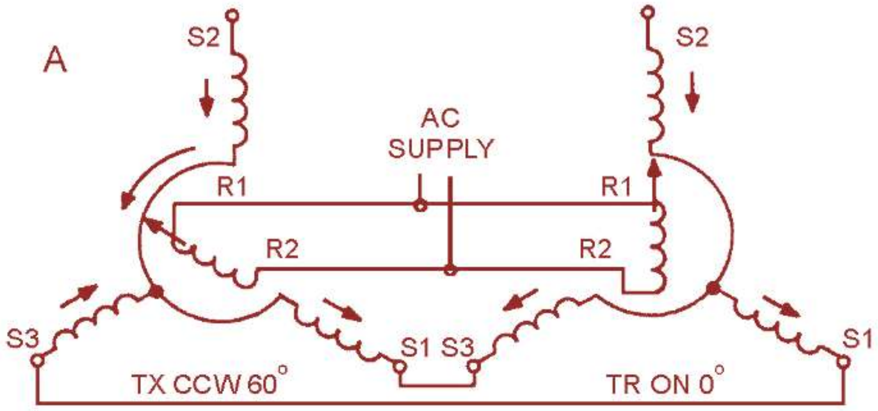


Fig 12.88

A TORQUE DIFFERENTIAL SYNCHRO SYSTEM consists either of a TX, a TDX, (torque differential transmitter), and a TR; or two TXs and one TDR (torque differential receiver). The system is used in applications where it is necessary to compare two signals, add or subtract the signals, and finish an output proportional to the sum of or difference between the two signals.

The TORQUE DIFFERENTIAL TRANSMITTER (TDX) has one electrical input to the stator and one mechanical input to the rotor. The TDX either adds or subtracts these inputs, depending upon how it is connected in the system, and provides an electrical output from its rotor proportional to the sum of or difference between the two signals.

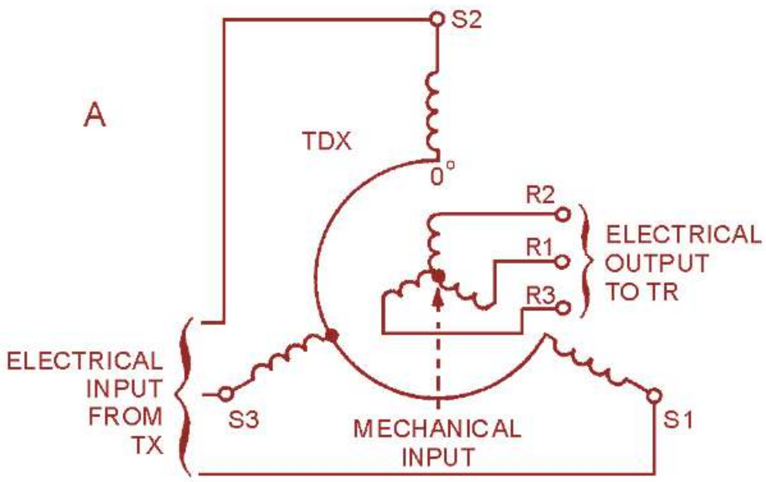


Fig 12.89

The TORQUE DIFFERENTIAL RECEIVER (TDR) is electrically identical to the TDX. The only difference in their construction is that the TDR has some form of damping. The real difference between the two differentials lies in their applications. The TDR has two electrical inputs, one to the rotor and the other to the stator. The output is the mechanical position of the rotor. As is the case with the TDX, the addition or subtraction function of the TDR depends upon how it is connected in the system.

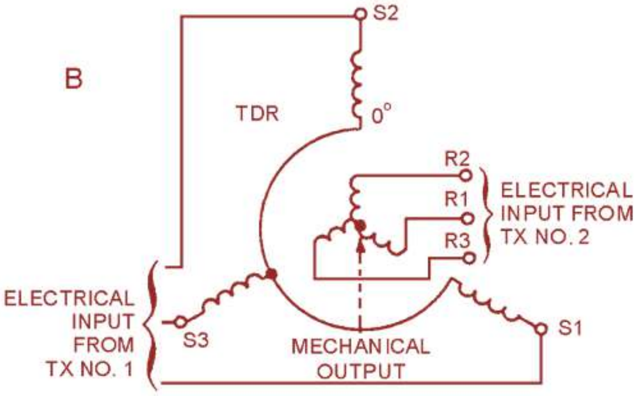


Fig 12.90

The TX-TDX-TR SYSTEM performs subtraction when the system contains standard Synchro connections. Addition can also be performed with this system by reversing the S1 and S3 leads between the TX and the TDX, and the R1 and R3 leads between the TDX and the TR. Remember, this system works like a basic Synchro system when the rotor of the TDX is on 0º; in this condition the TR rotor follows the TX rotor exactly.

The TX-TDR-TX SYSTEM performs subtraction when the system contains standard Synchro connections. Addition can also be performed with this system when the R1 and R3 leads between the TDR rotor and TX No. 2 are reversed.

CONTROL SYNCHRO SYSTEMS contain control Synchro and are used to control large amounts of power with a high degree of accuracy. These Synchro systems control servos that generate the required power to move heavy loads.

CONTROL SYNCHROS are of three different types: the control transmitter (CX), the control transformer (CT), and the control differential transmitter (CDX). The CX and the CDX are identical to the TX and the TDX except for higher impedance windings. In theory, the CX and CDX are the same as the TX and TDX, respectively.

The CONTROL TRANSFORMER (CT) is a Synchro device that compares two signals, the electrical signal applied to its stator, and the mechanical signal applied to its rotor. The output is an electrical voltage, which is taken from the rotor winding and used to control some form of power amplifying device. The phase and amplitude of the output voltage depend on the angular position of the rotor with respect to the magnetic field of the stator.

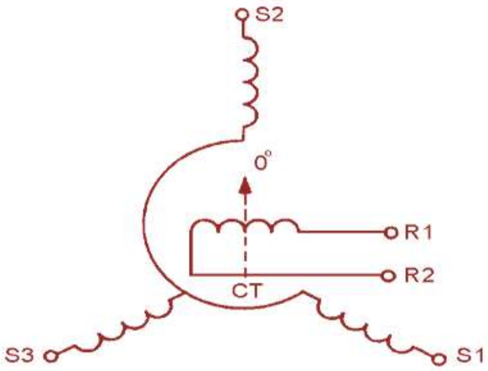



Fig 12.91

ERROR SIGNAL is the name given to the electrical output of a CT. The reason is that the electricaloutput voltage represents the amount and direction that the CX and CT rotors are out of correspondence. It is this error signal that eventually is used in moving the load in a typical servo system.

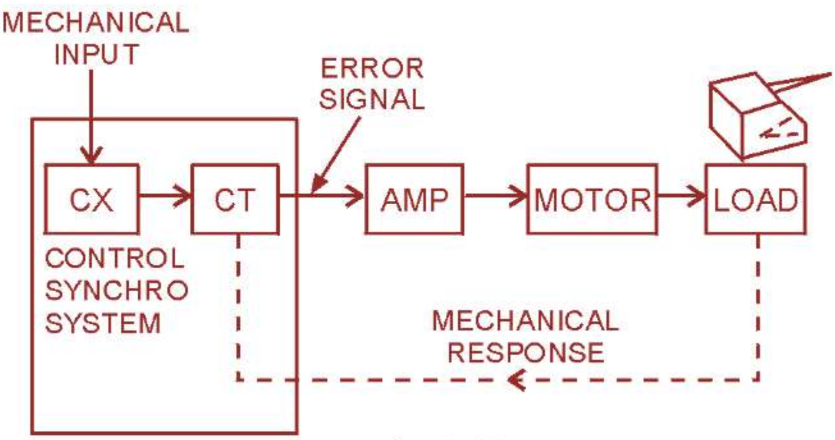



Fig 12.92

The SYNCHRO CAPACITOR is a unit containing three delta-connected capacitors. It is used in Synchro systems containing either differential transmitters or CTs. The addition of the Synchro capacitor to these systems greatly reduces the stator current and therefore increases the accuracy of the systems.

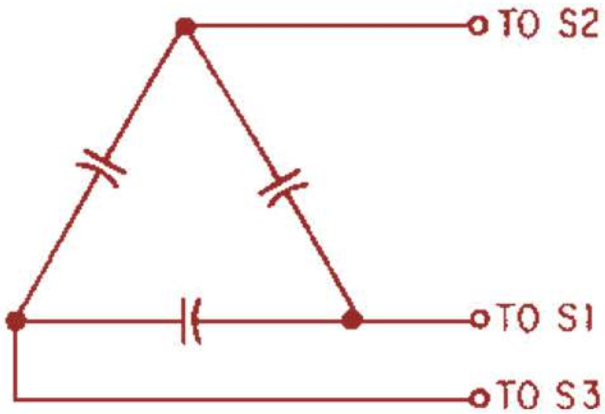



Fig 12.93

The SPEED OF DATA TRANSMISSION is simply the number of times a Synchro transmitter rotor must turn to transmit a full range of values. You refer to the speed of data transmission as being 1-speed, 2-speed, 36-speed, or some other definite numerical ratio.

MULTISPEED SYNCHRO SYSTEMS transmit a wide range of data at different speeds and still maintain a high degree of accuracy. To indicate the number of different speeds at which data is transmitted, refer to the system as being a single-speed, dual-speed, or tri-speed Synchro system.

A DOUBLE RECEIVER consists of a fine and a coarse receiver enclosed in a common housing. It has a two-shaft output (one inside the other), and its operation may be likened to the hour and minute hands of a clock.

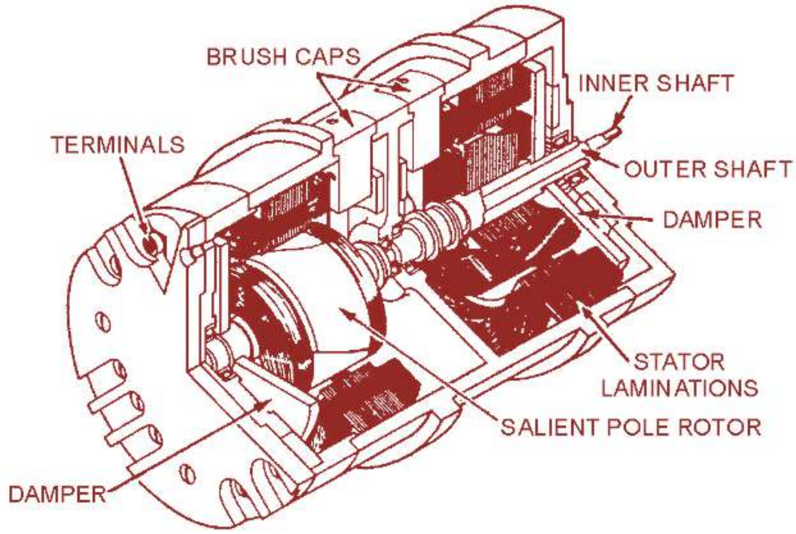



Fig 12.94

STICKOFF VOLTAGE is a low voltage used in multispeed Synchro systems that contain CTs to prevent false synchronizations. The voltage is usually obtained from a small transformer and applied across the rotor terminals of the coarse CT.

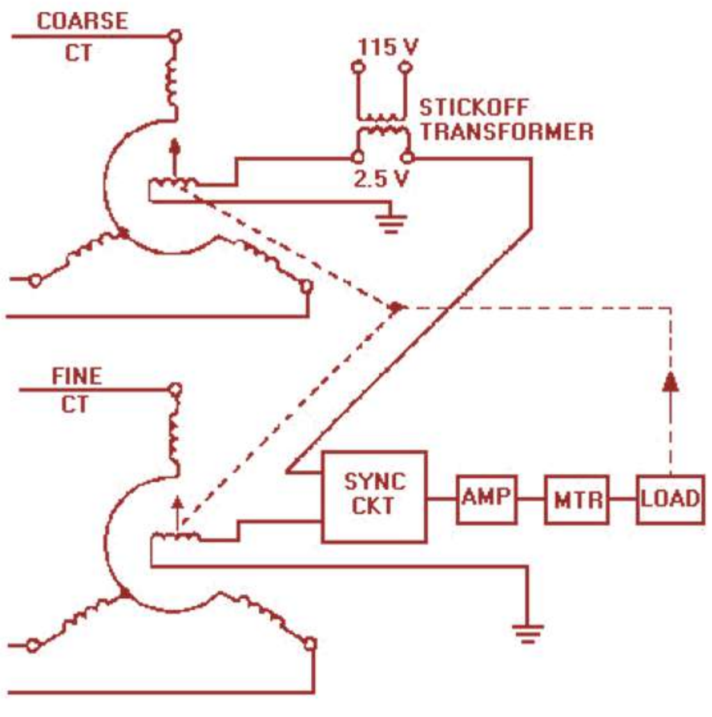



Fig 12.95

ELECTRICAL ZERO is the reference point for alignment of all Synchro units.

SYNCHRO ZEROING METHODS are various and depend upon the facilities and tools available ,and how the Synchro are connected in the system. Some of the more common zeroing methods are the voltmeter, the electric-lock, and the Synchro-tester methods.

The VOLTMETER ZEROING METHOD is the most accurate and requires a precision voltmeter. This method has two major steps-the coarse or approximate setting and the fine setting. The coarse setting ensures the Synchro is not zeroed 180º away from its reference. This setting may be approximated physically by aligning two marks on the Synchro. The fine setting is where the Synchro is precisely set on 0º.

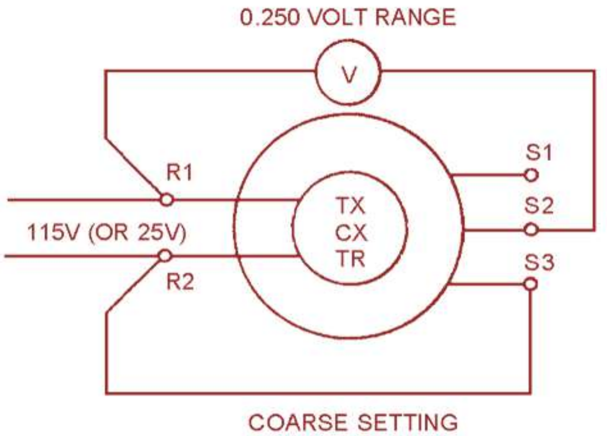


Fig 12.96

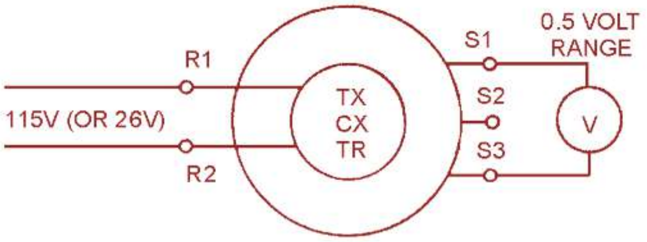


Fig 12.97

ELECTRICAL-LOCK ZEROING METHOD is perhaps the fastest. However, this method can be used only if the rotors of the Synchro are free to turn and the leads are accessible. For this reason, this method is usually used on TRs.

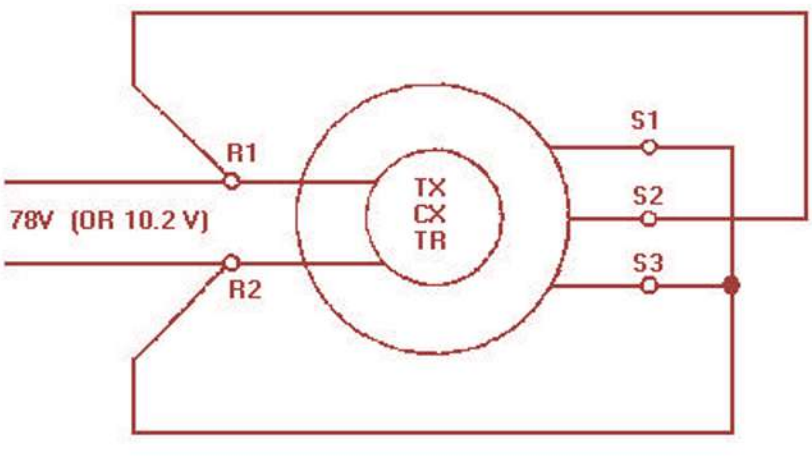


Fig 12.98

## 12.9. E AND I TRANSFORMERS

The E and I-transformer is a type of magnetic unit that is used as an error detector in systems in which the load is not required to move through large angles.

In the basic E and I-transformer shown in figure , an AC voltage is applied to the primary coil (2) located on the centre leg of the laminated, E - shaped core. Two secondary coils (1 and 3) are wound series-opposing on the outer poles of the core. The magnetic coupling between the primary (coil 2) and the two secondaries varies with the position of the armature. The armature can be physically moved left or right (or rotated clockwise or counter-clockwise) in the magnetic circuit by mechanical linkage to the load. This changes the reluctance between either pole and the armature.

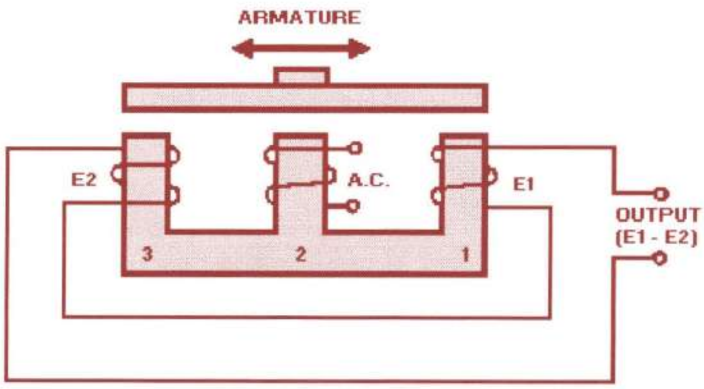



Figure 12.99 a : Basic - E and I transformer

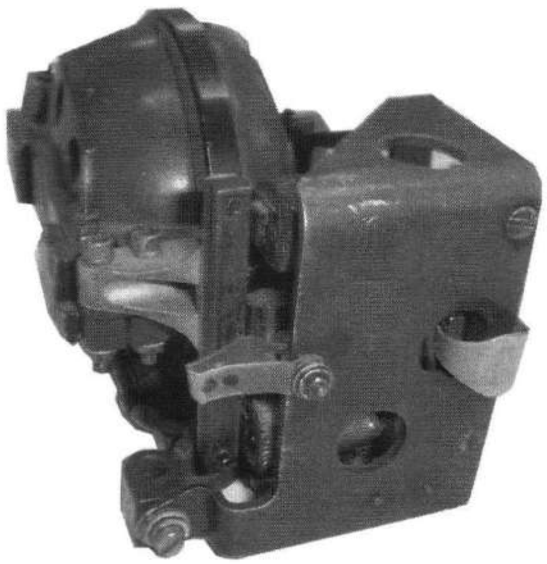


Fig 12.99 b : Photograph of an E and I transformer, operated by a position gyro

When the armature is located in the centre of the E - shaped core, as shown in the fig, equal and opposite voltages are induced in the secondary coils. The difference between them is zero. Thus, the voltage at the output terminals is also zero.

But, if the armature is moved, say to the tight, the voltage induced in coil 1 increases, while the voltage induced in coil 3 decreases. The two voltages are then unequal, so that the difference is no longer zero. A net voltage results at the output terminals. The amplitude of this voltage is directly proportional to the distance the armature has been moved from its centre position. The phase of this output voltage, relative to the AC on the primary, controls the direction the load moves in correcting the error.

The basic E and I -transformer will detect movement of the armature in one axis only (either the horizontal or vertical depending upon the way the unit is mounted). To detect movement in both the horizontal and vertical axes, a crossed E and I transformer is used.

If you place two E-transformers at right angles to each other and replace the bar armature with a dome-shaped one, you have the basic configuration of what is known as the crossed-E transformer, or

pickoff. In most applications the dome-shaped armature is attached to a gyro, and the core assembly is fixed to a gimbal, which is the servo load.

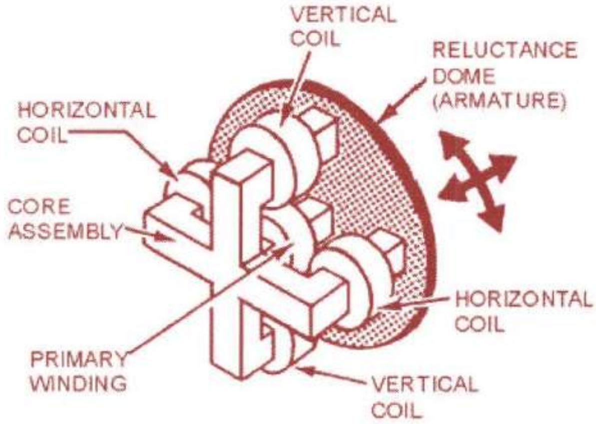



Fig 12.100: Crossed - E transformer

The crossed - E and I transformer assembly consists of five legs (poles). Each leg is encased by a coil. The coil around the centre leg is the primary, which is excited by an alternating voltage. The remaining four coils are the secondaries. From this view, you can see how it gets the name, crossed - E and I.

When the reluctance dome (armature) is moved to the left of center, more flux links the left leg with the primary coil, and the voltage induced in the left secondary increases. The right leg has fewer flux linkages with the center coil; therefore, the voltage induced in the right coil will be less than that in the left coil. Thus there will now be a net voltage out of the pickoff. The phase of the output will be that of the larger voltage. If the dome were moved to the right, the opposite condition would exist. From this brief description, you can see that the crossed-E transformer works on the same fundamental principle as the basic type described earlier. The major difference between the two is in shape and the number of secondaries, and in the fact that the armature has universal movement.