NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Electrical and Electronic Engineering

UNIVERSAL MOTOR CONTROL

Graduation Project
EE 400

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I would like to express my deepest appreciation to my god who stood beside me all the time, who supported me in all my achievements and who has given me the power and patience to finish my college studies successfully.

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I would like to thank my parents and pay special regards for guiding me through my studies, which are enduring these all expenses and supporting me in all events. I am nothing without their prayers. They also encouraged me in crises. I shall never forget their sacrifices for my education so that I can enjoy my successful life as they are expecting. They may get peaceful life in heaven.

ABSRTACT

Electronic systems and controls have gained wide acceptance in power technology; consequently, it has become almost indispensable to know something about control power electronics in motor AC system.

We can explain in simple terms the behavior of a large number of electronic power circuit, including those most commonly used today.

As far as electronic devises are concerned, we will cover diodes and thyristors. They are found in all electronic systems involve the conversion of AC power to DC power and vice versa. We then go on to discuss the application of more recent devises such as silicon controlled rectifier thyristors (S.C.R), bipolar junction transistors (BJTs), metal oxide semiconductor field effect transistors (power MOSFETs), and insulated gate bipolar transistors (IGBTs). Their action on a circuit is basically no different from that of a thyristors and its associated switching circuitry. In power electronics all these devises act basically as high-speed switches; so much so, that much of power electronics can be explained by the opening and closing of circuit at precise instants of time. However, we should not conclude that circuits containing these components and devises that are simple, they are not, but their behavior can be understood without having an extensive background in semiconductor theory.

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INTRODUCTION

Power Electronics is presently playing an important role in modern technology and is used in a variety of high power products e.g. Motor controls, heat controls, light controls and power supplies.

Chapter one will present definition of power electronics, the power devices whose power handling capabilities and switching speeds have improved tremendously over the years such as; power diodes and thyristors and the power transistors bipolar junction transistors and power MOSFETs and IGBTs and also the capacitors and the resistors with its different types. And also will present the applications of motors and the types of motors, and especially the universal Motors.

Chapter two will present the practical project that will control the speed of universal motors(half-wave motor-speed controller, with transistor trigger, for use with motors with current ratings up to 3A).

CHAPTER ONE

1. POWER ELECTRONICS

1.1 Overview

Joining the history and definition of power electronics and become familiar with different types of power semiconductor devices, their characteristics and use, and identify the motor and learn the different types of motors.

1.2 Introduction of power electronics

Power electronics began with the introduction of the mercury arc rectifier in 1900. This was followed by the first electronic revolution which began in 1948 with the invention of the silicon transistor.

The second electronic revolution began in 1958 with the development of the thyristor. This caused the beginning of a new area for power electronics, since many power semiconductor devices and power conversion techniques were introduced using thyristors.

Next, was the microelectronics revolution which gave the ability to process a huge amount of data in a very short time. The power electronics revolution which merges power electronics and microelectronics provides the ability to control large amounts of power in a very efficient manner.

Power Electronics may be defined as the application of solid-state electronics for the control and conversion of electric power. Power Electronics is based on the switching of power semiconductor devices whose power handling capabilities and switching speeds have improved tremendously over the years.

Power Electronics is presently playing an important role in modern technology and is used in a variety of high power products e.g. Motor controls, heat controls, light controls and power supplies.

1.3 Power semiconductor devices

- Power semiconductor devices can be broken up into five different groups:

1. Power Diodes
2. Thyristors
3. Power Bipolar Junction Transistors (BJT)
4. Power MOSFETs
5. Insulated Gate Bipolar Transistors (IGBT)

1.3.1 Power Diodes

1.3.1.1 Diode Operation

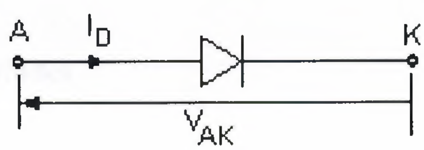


Fig 1.1 Diode Symbol

As shown in fig1.1, a diode is a two terminal device consisting of an anode and a cathode. The diode conducts when its anode voltage is more positive than that of the cathode. If the cathode voltage is more positive than its anode voltage, the diode is said to be in the blocking mode.

1.3.1.2 Forward Voltage Drop

Electricity uses up a little energy pushing its way through the diode, rather like a person pushing through a door with a spring. This means that there is a small voltage across a conducting diode, it is called the forward voltage drop and is about 0.7V for all normal diodes which are made from silicon. The forward voltage drop of a diode is almost constant whatever the current passing through the diode so they have a very steep characteristic (current-voltage graph).

1.3.1.3 Reverse Voltage

When a reverse voltage is applied a perfect diode does not conduct, but all real diodes leak a very tiny current of a few μA or less. This can be ignored in most circuits because it will be very much smaller than the current flowing in the forward direction. However, all diodes have a maximum reverse voltage (usually 50V or more) and if this is exceeded the diode will fail and pass a large current in the reverse direction, this is called breakdown.

1.3.1.4 Diode Types

- There are three types of power diodes:

1. Standard or general-purpose diodes.
2. High-Speed diodes(or fast recovery diodes).
3. Schottky diodes.

1.3.1.4.1 General Purpose Diodes

These diodes have a generally high reverse recovery time, typically around 25 μs. Used in low speed applications e.g. rectifiers and converters with frequencies up to 1 kHz, where the recovery time is not critical.

1.3.1.4.2 Fast-recovery Diodes

These diodes have a low recovery time, typically around 5 μs. They are used in applications where the recovery time is of critical importance such as dc-dc and dc-ac converters.

1.3.1.4.3 Schottky Diodes

It has a relatively low forward voltage drop and the leakage current is higher than that of a pn-junction diode. They are mainly used in high current low voltage power supplies.

1.3.1.5 P-N Junction

One of the crucial keys to solid state electronics is the natura of the P-N junction. When p-type and n-type materials are placed in contact with each other, the junction behaves very differently than either type of material alone. Specifically, current will flow readily in one direction (forward biased) but not in the other (reverse biased), creating the basic diode. This non-reversing behavior arises from the nature of the charge transport process in the two types of materials.

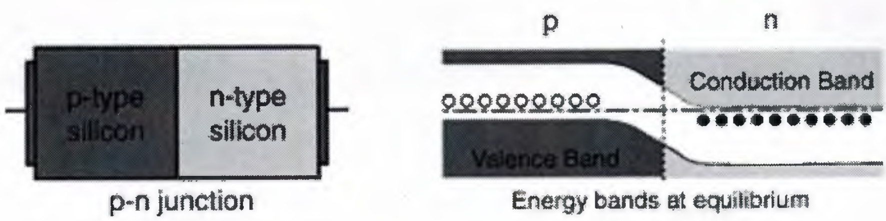


Fig 1.2 P-N junction and the energy bands at equilibrium

As shown in fig1.2,The open circles on the left side of the junction above represent "holes" or deficiencies of electrons in the lattice which can act like positive charge carriers. The solid circles on the right of the junction represent the available electrons from the n-type dopant. Near the junction, electrons diffuse across to combine with holes, creating a "depletion region". The energy level sketch above right is a way to visualize the equilibrium condition of the P-N junction. The upward direction in the diagram represents increasing electron energy.

1.3.1.5.1 Depletion Region

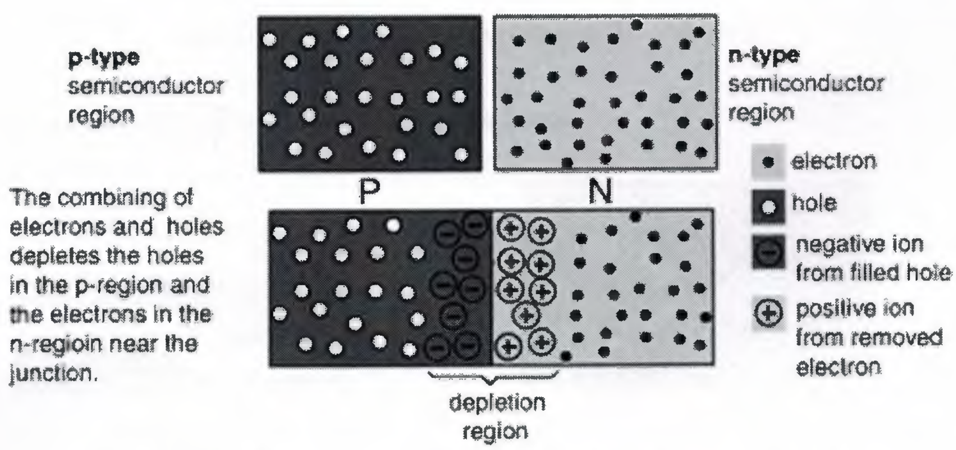


Fig 1.3 P-N junction while combining the electrons and holes

As shown in fig1.3, When a p-n junction is formed, some of the free electrons in the n-region diffuse across the junction and combine with holes to form negative ions. In so doing they leave behind positive ions at the donor impurity sites.

1.3.1.5.2 Depletion Region Details

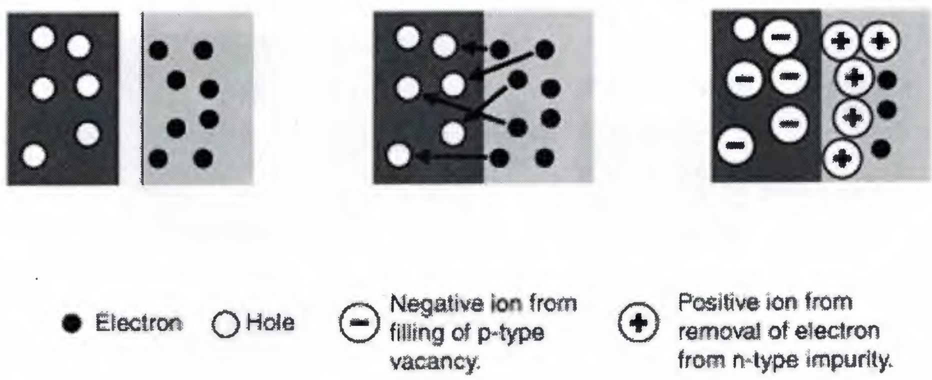


Fig 1.4 more details for the combination of P-N junction

As shown in fig1.4, In the p-type region there are holes from the acceptor impurities and in the n-type region there are extra electrons.

When a p-n junction is formed, some of the electrons from the n-region which have reached the conduction band are free to diffuse across the junction and combine with holes

Filling a hole makes a negative ion and leaves behind a positive ion on the n-side. A space charge builds up, creating a depletion region which inhibits any further electron transfer unless it is helped by putting a forward bias on the junction.

1.3.1.5.3 Bias effect on electrons in depletion zone

Fig 1.5 Bias electron in depletion zone

The electrons which had migrated across from the N to the P region in the forming of the depletion layer have now reached equilibrium. Other electrons from the N region cannot migrate because they are repelled by the negative ions in the P region and attracted by the positive ions in the N region as shown in fig1.5.

1.3.1.5.4 Reverse bias

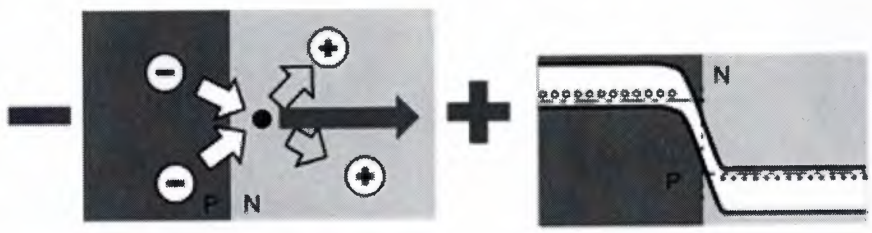


Fig 1.6 the reverse bias in P-N junction

An applied voltage with the indicated polarity further impedes the flow of electrons across the junction. For conduction in the device, as shown in fig1.6, electrons from the N region must move to the junction and combine with holes in the P region. A reverse voltage drives the electrons away from the junction, preventing conduction.

1.3.1.5.5 Forward bias

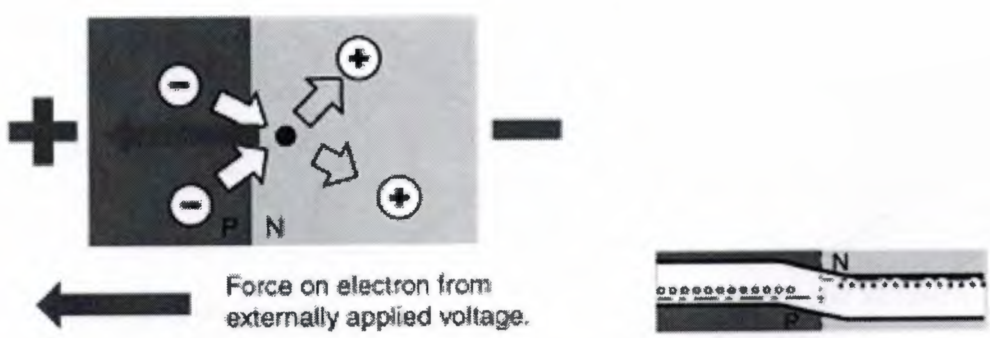


Fig 1.7 the forward bias in P-N junction

An applied voltage in the forward direction as indicated assists electrons in overcoming the coulomb barrier of the space charge in depletion region. Electrons will flow with very small resistance in the forward direction as shown in fig1.7.

1.3.1.6 Diac

Like all diodes, Shockley diodes are unidirectional devices; that is, they only conduct current in one direction. If bidirectional (AC) operation is desired, two Shockley diodes may be joined in parallel facing different directions to form a new kind of thyristor as shown in fig1.8.

Fig 1.8 DIAC equivalent Circuit and schematic symbol

A DIAC operated with a DC voltage across it behaves exactly the same as a Shockley diode. With AC, however, the behavior is different from what one might expect. Because alternating current repeatedly reverses direction, DIACs will not stay latched longer than one-half cycle. If a DIAC becomes latched, it will continue to conduct current only as long as there is voltage available to push enough current in that direction. When the AC polarity reverses, as it must twice per cycle, the DIAC will drop out due to insufficient current, necessitating another breakover before it conducts again. The result is a current waveform that looks like this that is shown in fig1.9.

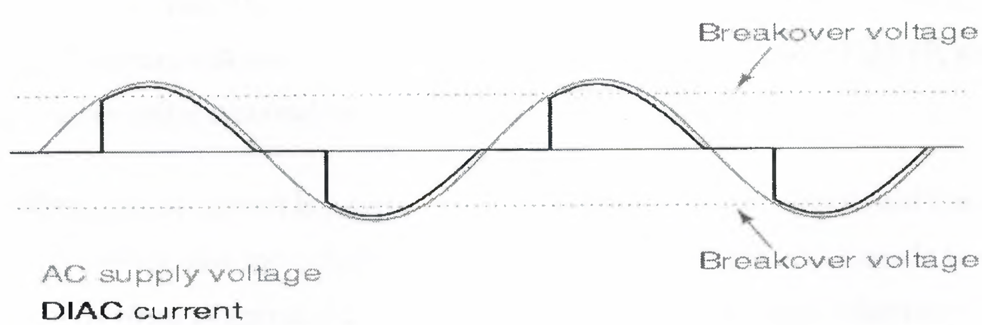


Fig 1.9 The diac current waveform by AC supply voltage

1.3.2 Thyristors

1.3.2.1 Thyristor Operation

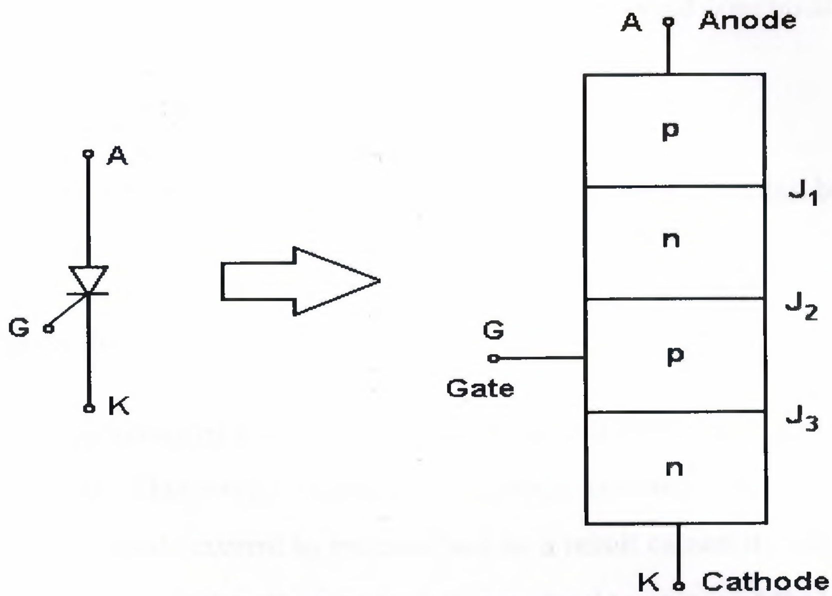


Figure 1.10 Thyristor Symbol & pn Junctions

A thyristor is a three terminal device consisting of an anode, a cathode and a gate. It is physically made up of four layers of alternate p-type and n-type silicon semiconductor. The terminals connected to the ending p-type and the n-type layers are the anode and cathode respictively. This configuration will give three p-n junctions. When the anode is held more positive than the cathode, two of the p-n junctions are foward biased, offering very little resistance, and one is reverse biased, offering high resistance.Fig1.10, shows the thyristor symbol and a sectional view of the three pn junctions.

When a small current is passed through the gate to cathode circuit, and the anode is at a higher potential than the cathode, the thyristor conducts current from anode to cathode. In other words when triggered the thyristor has aproximately the same characteristics as a single diode. Once the thyristor has been turned on, the gate circuit looses control of the thyristor and the forward voltage drop across the device is very small in the region of 0.5 to 2V.

Once on, the device losses control over the anode current, and the only way to turn it off is to reduce the anode current below some value referred to as the holding value. This can be acheived in one of two ways; by making the anode potential equal or less than the cathode potential, due to the sinusoidal nature of an ac voltage which is called line commutation or by the use of an auxilixry as in the case of forced-commutation.

1.3.2.2 Thyristor turn-on

A thyristor is turned on by increasing the anode current. This can be accomplished in the following ways:

1.3.2.2.1 Thermals

If the temperature of a thyristor is high, there will be an increase in the number of electron-hole pairs. This would increase the leakage current. This increase in leakage current causes the anode current to increase and as a result causes α_1 and α_2 to increase. Due to the regenerative action, the sum $\alpha_1 + \alpha_2$ may tend to unity and the thyristor may be turned on. This type of turn-on may cause thermal runaway and should be avoided.

1.3.2.2.2 Light

If light is allowed to strike the junction of a thyristor, the electron-hole pairs will increase and this may cause the thyristor to be turned on. This is the principle of operation of light activated thyristors.

1.3.2.2.3 High Voltage

If the forward anode to cathode voltage V_{AK} is increased beyond the forward breakdown voltage V_{BO} , high enough leakage currents will flow, causing regenerative turn-on. This type of turn-on is destructive and should be avoided.

1.3.2.2.4 dv/dt

if the rate or rise of the anode to cathode voltage is high, (for example, when there is a voltage spike), the charging current of the capacitive junctions may be high enough to turn on the thyristor. A high value of charging current may cause damage to the thyristor and must be avoided. Hence, thyristors must be protected against high dv/dt and must be operated within the manufacturer's dv/dt specifications.

1.3.2.2.5 Gate Current

The injection of gate current into a forward biased thyristor would turn-on the device. As the gate current is increased, the forward voltage required to turn-on the device decreases. This is shown in figure1.11.

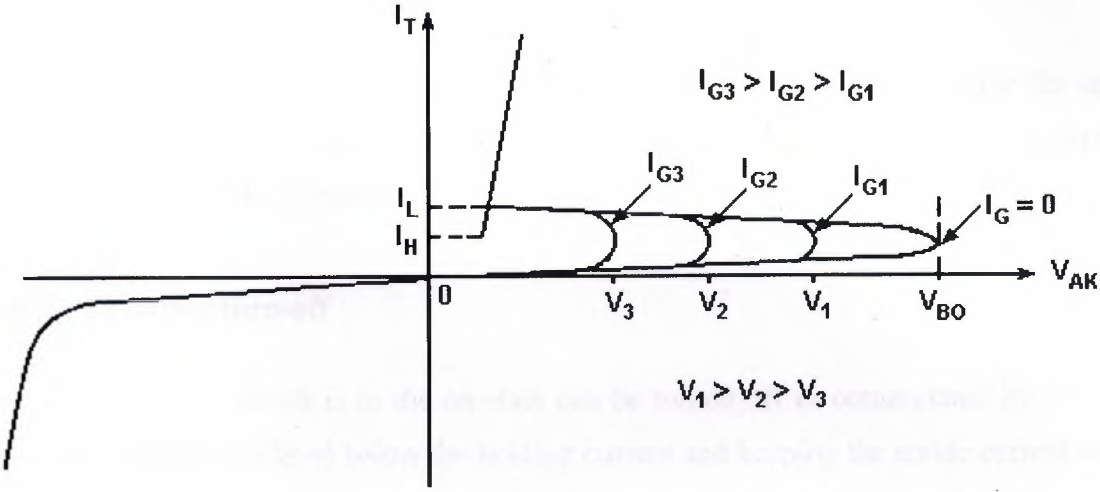


Figure 1.11 Effects of Gate Current on Forward Blocking Voltage

Because of the nature of the construction of a thyristor, there exists some capacitance between the anode and the gate. If a sharply rising voltage is applied to the thyristor, the associated inrush of charge can switch on the thyristor. These surges can be the result of switching in circuits, and can be accommodated for by providing RC circuits for diverting this surge.

All p-n junctions have a leakage current which increases with increasing temperature. If the temperature of operation of a thyristor were allowed to rise too much, the leakage current could rise enough to turn on the thyristor. A possible use of this feature is in the manufacture of a switching system, which needs to be turned on exceeding certain temperatures.

1.3.2.3 Gate Control Circuit Design

Consideration must be given to the following points when designing gate control circuits:

- The gate signal should be removed after the thyristor has been turned on. A continuous gate signal will increase the power loss in the gate junction.

- No gate signal should be applied when the thyristor is reversed biased. If a gate signal is applied under these conditions, the thyristor may fail due to an increased leakage current.

The width of the gate pulse must be greater than the time required for the anode current to rise to the holding current. In practice, the gate pulse width is made wider than the turn-on time of the thyristor.

1.3.2.4 Thyristor turn-off

A thyristor which is in the on-state can be turned off or commutated by reducing the anode current to a level below the holding current and keeping the anode current below this level for a sufficiently long time so that the excess carriers in the four layers are swept out or recombined.

Thyristors can either be line commutated or forced commutated. Figure1.12 displays the turn-off characteristics of a line commutated thyristor.

For this line commutated thyristor, a reverse voltage appears across the thyristor immediately after the forward current goes through the zero value. This reverse voltage will accelerate the turn-off process by sweeping out excess carriers in junctions $\mathbf{J_1}$ and $\mathbf{J_3}$.

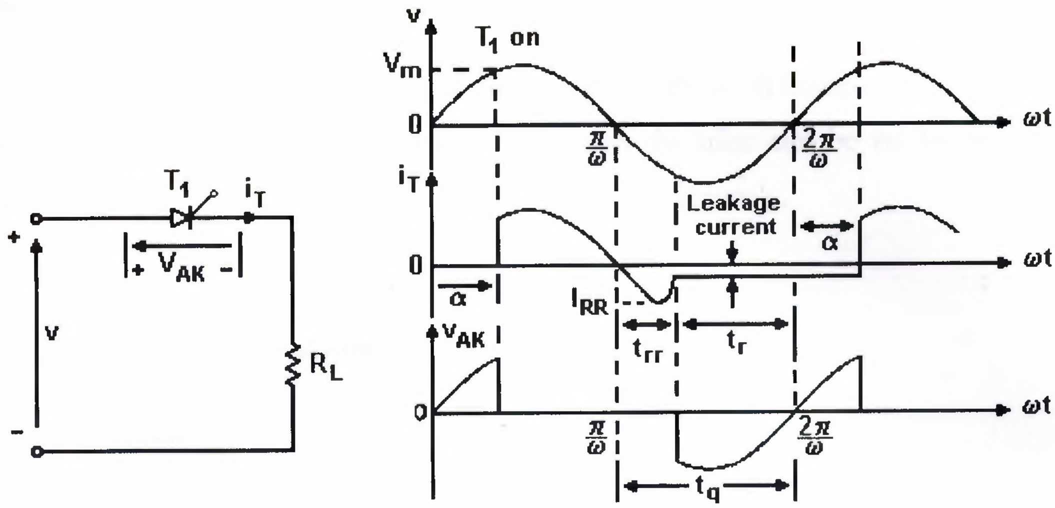


Figure 1.12 Turn-Off Characteristics of Line Commutated Thyristor

The inner junction J_2 will require a time known as the recombination time t_{rc} to recombine the excess carriers and the negative reverse voltage reduces this recombination time.

- Turn-off Time t_q

This is the sum of the reverse recovery time t_{rr} and the recombination time t_{rc}. It is defined as the time interval between the instant when the on-state current has decreased to zero and the instant when the thyristor is capable of withstanding forward voltage without turning on. It depends on the peak value of on-state current and the instantaneous on-state voltage.

- Reverse Recovery Charge Q_{RR}

This is defined as the amount of charge which has to be recovered during the turn-off process. Its magnitude is determined by the area enclosed by the path of the reverse recovery current and depends on:

1. The rate of fall of on-state current and
2. The peak value of on-state current before turn-off

1.3.2.5 Triac

Triacs can be considered as two thyristors connected in inverse parallel and having only one gate terminal. The current flow through the triac can be controlled in either direction. They are used in simple heat, light and motor controls.

1.3.3 Bipolar Power Transistors

1.3.3.1 Definition

These are three terminal devices consisting of emitter, base and collector which is operated as a switch in the common emitter configuration. These devices are turned-on when the base-emitter junction is forward biased with the base current sufficiently large to drive the device into saturation. Under these conditions, the collector-emitter voltage drops in a range of 0.5 to 1.5V. If the base-emitter junction is reversed biased the device switches to the off or non-conducting state.

Transistors amplify current, for example they can be used to amplify the small output current from a logic chip so that it can operate a lamp, relay or other high current device. In many circuits a resistor is used to convert the changing current to a changing voltage, so the transistor is being used to amplify voltage.

A transistor may be used as a switch (either fully on with maximum current, or fully off with no current) and as an amplifier (always partly on).

1.3.3.2 Types of transistor

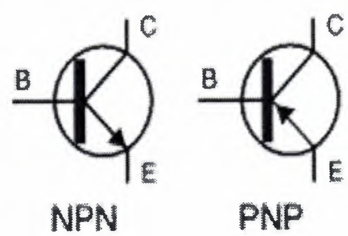


Fig 1.13 Transistor circuit symbols

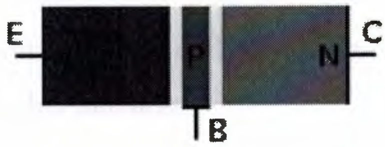


Fig1.14 NPN transistor operation

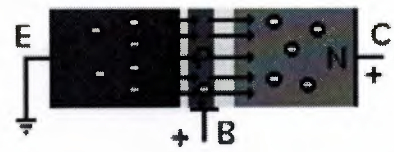


Fig1.15 NPN with voltage source

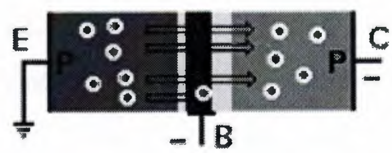


Fig 1.16 PNP with voltage source

A basic two-junction semiconductor must necessarily have one type of region sandwiched between two of the other type. Which is shown in Figure1.14 is an example of a semiconductor device consisting of a narrow P-type region between two N-type regions. For reasons we will see shortly, the three regions are designated the emitter (E), base (B), and collector (C), respectively. In modern versions of this device, the emitter region is heavily doped with the appropriate impurity, while the base region is very lightly doped. The collector region has a moderate doping level so it will have a low internal resistance.

We have shown a device consisting of N, P, and N regions in order, but there is no reason not to build equivalent devices in P, N, and P order instead. In fact, it is often very useful to have both types of devices available.

With no electrical voltages applied, of course, this semiconductor will of course just sit there and do nothing. So let's move forward and see what happens when we apply bias voltages to the device.

In fig1.15 we see the same semiconductor device as above, with a small forward bias applied to the emitter-base junction, and a larger reverse bias applied to the collector-base junction. As we will see, these are the normal operating conditions of this device.

Since we already know how a single-junction device, the diode, behaves, we would normally expect the base voltage to be about 0.65 to 0.7 volt positive with respect to the emitter, and to have electrons move from emitter to base, and leave the device at that point. With the collector junction reverse biased, we would expect no current to flow through that junction.

But a funny thing happens inside the base region. The forward bias on this junction does indeed attract electrons from the emitter into the base, but there the forward momentum of the electrons carries them across most of the base region and into the depletion region around the collector junction. From there, the higher positive collector voltage attracts these electrons across the collector junction and into the collector region. (Remember that the electrons are minority current carriers within the P-type pase region, and can therefore cross the reverse-biased junction as a leakage current.)

A small amount of current does still leave the device through the base contact, but most of the current is diverted through the collector instead. In this way, the small base bias current controls the much larger collector current. If a small varying current is applied to the base along with the bias, the collector current will vary to a much greater degree. Thus, this device can not only be used to control a varying signal; it can amplify that signal as well.

Because of the way this device operates to transfer current (and its internal resistances) from the original conduction path to another, it's name is a combination of the words "transfer" and "resistor:" transistor.

It's also quite possible to build a transistor with the region types reversed,as shown in fig1.16. In this case, holes will be drawn from the emitter into the base region by the forward bias, and will then be pulled into the collector region by the higher negative bias. Otherwise, this device works the same way and has the same general properties as the one described above.

1.3.4 Power MOSFETs

These are three terminal devices consisting of gate, source and drain. It is a fast switching device with a high input impedance and has applications in high switching frequency circuits. MOSFETs are available in both N-channel and P-channel types. To turn-on an N-channel device, the drain is made positive with respect to the source and a small positive voltage is applied to the gate with respect to the source. The device is turned-off when the gate voltage is removed.

1.3.5 IGBTs

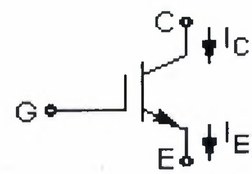


Fig 1.17 IGBTs circuit symbol

The insulated gate bipolar transistor (IGBT) is a three terminal device consisting of gate, emitter and collector(see fig1.17).It combines the low on-state voltage drop characteristics of the BJT with the excellent switching characteristics and high input impedance of the MOSFET. They are available in current and voltage ratings much higher than those found in MOSFETs.

To turn-on the N-channel IGBT the collector must be at a positive potential with respect to the emitter and a positive gate potential will turn-on the device. The removal of this positive gate voltage would turn-off the device

1.4 Control characteristics of power devices

Power semiconductor devices can be operated as switches by applying control signals to the gate of thyristors, to the base of power transistors, to the gate of power MOSFETs and to the gate of IGBTs. The required output voltage is obtained by varying the conduction time of these devices.

1.5 classification of power semiconductor switching devices

Power semiconductor devices can be classified as follows:

1. Uncontrolled turn on and off (Diode)
2. Controlled turn on and uncontrolled turn off (SCR)
3. Controlled turn on and off characteristics (BJT, MOSFET, GTO, SITH, IGBT, SIT MCT)
4. Continuous gate signal requirement (BJT, MOSFET, IGBT, SIT)
5. Pulse gate requirements (SCR, GTO, MCT)
6. Bipolar voltage-withstanding capability (SCR, GTO)
7. Unipolar voltage-withstanding capability (BJT, MOSFET, GTO, IGBT, MCT)
8. Bidirectional current capability (TRIAC, RCT)

1.6 Capacitors

A capacitor is a device that stores an electrical charge when a potential difference (voltage) exists between two conductors which are usually two plates separated by a dielectric material (an insulating material like air, paper, or special chemicals). Capacitors block DC voltages and pass AC voltages. They are used as filters, AC coupling capacitors and as by-pass capacitors. They are also used in conjunction with resistors and inductors to form tuned circuits and timing circuits. A capacitors value C (in Farads) is dependent upon the ratio of the charge Q (in Coulombs) divided by the V (in volts). Common capacitors come in values of microfarads or Pico farads. Often you will have to convert between Pico farads and micro farads. A chart is provided below to assist in the conversion.

1.6.1 Capacitor Value Conversions

Some capacitors may be marked in micro farads and others of the same capacitance value marked in Pico farads. One Pico farad equals one micro-micro farad. You may need to make conversions between the two equivalents.

Prefix	Power of 10	Example
Mili	10^{-3}	.001
Micro	10^{-6}	.000001
Nano	10^{-9}	.000000001
Pico	10^{-12}	.000000000001

Table 1.1 units and thier conversions value

In micro farad	In pico farad
0.001uf	0.000000001pf
0.005uf	0.000000005pf
0.009uf	0.000000009pf
0.0001uf	0.0000000001pf
0.0005uf	0.0000000005pf
0.0009uf	0.0000000009pf

Table 1.2 comparison between pico and micro farad units

1.6.2 AC capacitor circuits

Capacitors do not behave the same as resistors. Where as resistors allow a flow of electrons through them directly proportional to the voltage drop, capacitors oppose *changes* in voltage by drawing or supplying current as they charge or discharge to the new voltage level. The flow of electrons "through" a capacitor is directly proportional to the *rate of change* of voltage across the capacitor. This opposition to voltage change is another form of *reactance*, but one that is precisely opposite to the kind exhibited by inductors.

Expressed mathematically, the relationship between the current "through" the capacitor and rate of voltage change across the capacitor is as such:

$$I = C\frac{de}{dt} \quad \text{...........(1.1)}$$

The expression **de/dt** is one from calculus, meaning the rate of change of instantaneous voltage (e) over time, in volts per second. The capacitance (C) is in Farads, and the instantaneous current (i), of course, is in amps. Sometimes you will find the rate of instantaneous voltage change over time expressed as dv/dt instead of de/dt: using the lower-case letter "v" instead or "e" to represent voltage, but it means the exact same thing. To show what happens with alternating current, let's analyze a simple capacitor Circuit as shown in fig1.18.

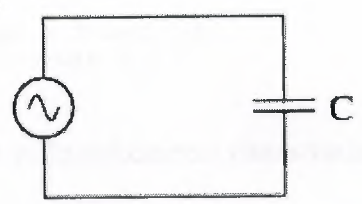


Fig 1.18 Simple circuit contains of AC source and 1 capacitor

If we were to plot the current and voltage for this very simple circuit, it would look something like this as shown in fig1.19.

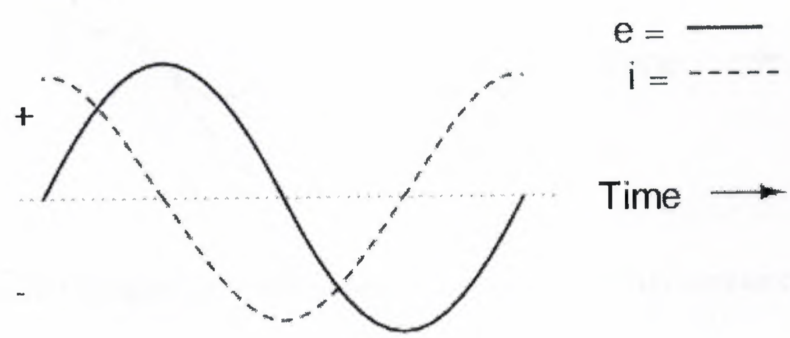


Fig 1.19 Voltage&current characteristics for the simple circuit

Remember, the current through a capacitor is a reaction against the *change* in voltage across it. Therefore, the instantaneous current is zero whenever the instantaneous voltage is at a peak (zero change, or level slope, on the voltage sine wave), and the instantaneous current is at a peak wherever the instantaneous voltage is at maximum change (the points of steepest slope on the voltage wave, where it crosses the zero line). This results in a voltage wave that is -90° out of phase with the current wave. Looking at the graph shown in fig1.20, the current wave seems to have a "head start" on the voltage wave; the current "leads" the voltage, and the voltage "lags" behind the current.

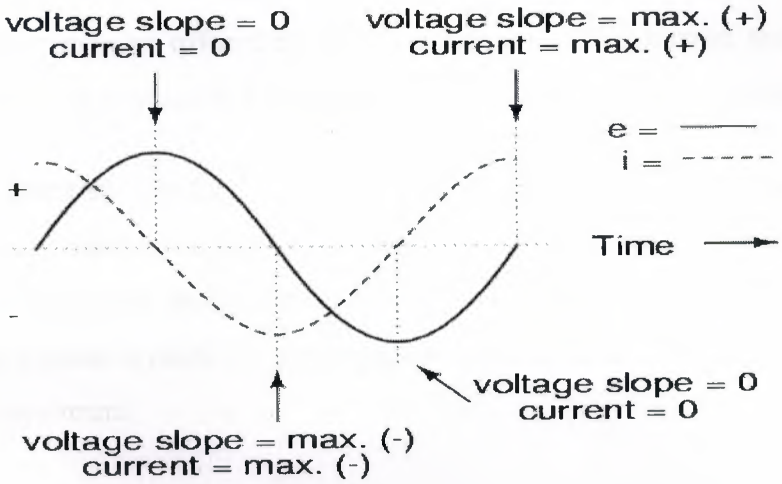


Fig 1.20 More details for voltage&current characteristics for the simple circuit

As you might have guessed, the same unusual power wave that we saw with the simple inductor circuit is present in the simple capacitor circuit as shown in fig1.21.

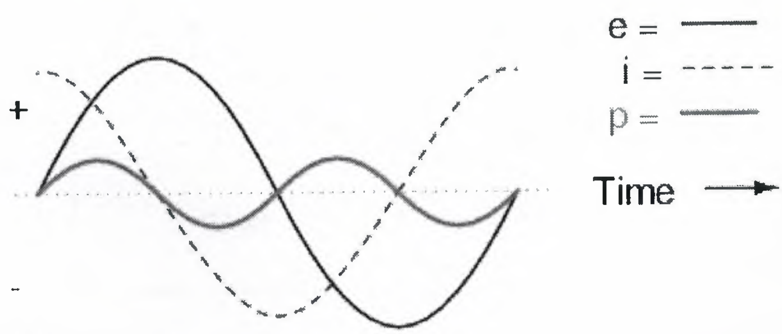


Fig 1.21 Voltage& current& power characteristics for the simple circuit

As with the simple inductor circuit, the 90 degree phase shift between voltage and current results in a power wave that alternates equally between positive and negative. This means that a capacitor does not dissipate power as it reacts against changes in voltage; it merely absorbs and releases power, alternately.

A capacitor's opposition to change in voltage translates to an opposition to alternating voltage in general, which is by definition always changing in instantaneous magnitude and direction. For any given magnitude of AC voltage at a given frequency, a capacitor of given size will "conduct" a certain magnitude of AC current. Just as the current through a resistor is a function of the voltage across the resistor and the resistance offered by the resistor, the AC current through a capacitor is a function of the AC voltage across it, and the reactance offered by the capacitor. As with inductors, the reactance of a capacitor is expressed in ohms and symbolized by the letter X (or X_C to be more specific).

Since capacitors "conduct" current in proportion to the rate of voltage change, they will pass more current for faster-changing voltages (as they charge and discharge to the same voltage peaks in less time), and less current for slower-changing voltages. What this means is that reactance in ohms for any capacitor is inversely proportional to the frequency of the alternating current:

$$X_C = \frac{1}{2\Pi f C} \text{..........(1.2)}$$

For a 100 uF capacitor:

Frequency (Hertz)	Reactance (Ohms)
60	26.5258
120	13.2629
2500	0.6366

Table 1.3 The relationship between capacitive reactance and frequency

Please note that the relationship of capacitive reactance to frequency is exactly opposite from that of inductive reactance. Capacitive reactance (in ohms) decreases with increasing AC frequency. Conversely, inductive reactance (in ohms) increases with increasing AC frequency. Inductors oppose faster changing currents by producing greater voltage drops; capacitors oppose faster changing voltage drops by allowing greater currents.

As with inductors, the reactance equation's 2πf term may be replaced by the lower-case Greek letter Omega (ω), which is referred to as the *angular velocity* of the AC circuit. Thus, the equation $X_C = 1/(2\pi fC)$ could also be written as $X_C = 1/(\omega C)$, with ω cast in units of *radians per second.*

Alternating current in a simple capacitive circuit is equal to the voltage (in volts) divided by the capacitive reactance (in ohms), just as either alternating or direct current in a simple resistive circuit is equal to the voltage (in volts) divided by the resistance (in ohms). The following circuit illustrates this mathematical relationship by example:

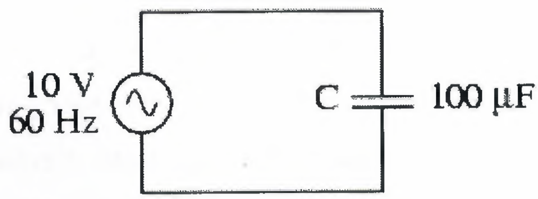


Fig 1.22 Simple capacitive circuit

$$X_C = 26.5258\Omega$$

$$I = \frac{E}{X} \text{.......}\mathbf{(1.3)}$$

$$I = \frac{10v}{26.5258\Omega}$$

$$I = 0.3770\text{A}$$

However, we need to keep in mind that voltage and current are not in phase here. As was shown earlier, the current has a phase shift of $+90^{\circ}$ with respect to the voltage. If we represent these phase angles of voltage and current mathematically, we can calculate the phase angle of the inductor's reactive opposition to current.

$$Opposition = \frac{Voltage}{Current} \text{........}\mathbf{(1.4)}$$

$$Opposition = \frac{10v\angle 0^{\circ}}{0.3770\text{A}\angle 90^{\circ}} \qquad Opposition = 26.5258\Omega\angle -90^{\circ}$$

For a capacitor:

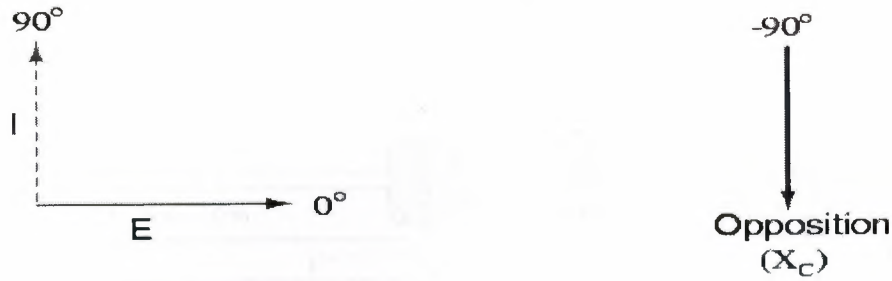


Fig 1.23 hase angles for the curent and voltage and reactive of a capacitor's opposition

Mathematically, we say that the phase angle of a capacitor's opposition to current is -90°,as shown in fig 1.23, meaning that a capacitor's opposition to current is a negative imaginary quantity. This phase angle of reactive opposition to current becomes critically important in circuit analysis, especially for complex AC circuits where reactance and resistance interact. It will prove beneficial to represent any component's opposition to current in terms of complex numbers, and not just scalar quantities of rsistance and reactance.

1.7 RESISTOR

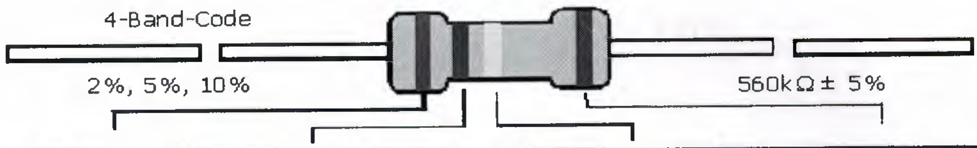
Resistors are electronic components which resist(reduce) the flow of electronic current.

The higher the value of resistance (measured in ohms) the lower the current will be. This was discovered by Mr Ohm.

The simplest resistors are made from carbon rod with end caps and wire leads, Other types are carbon film which is a thin layer of carbon on a ceramic rod, and metal oxide and metal glaze on glass rods.

1.7.1 RESISTOR COLOR CODES

Resistors use color coded stripes to indicate their value in ohms.



COLOR	1st BAND	2nd BAND	3rd BAND	MULTIPLIER	TOLERANCE
Black	0	0	0	1Ω	
Brown	1	1	1	10Ω	± 1% (F)
Red	2	2	2	100Ω	± 2% (G)
Orange	3	3	3	1KΩ	
Yellow	4	4	4	10KΩ	
Green	5	5	5	100KΩ	±0.5% (D)
Blue	6	6	6	1MΩ	±0.25% (C)
Violet	7	7	7	10MΩ	±0.10% (B)
Grey	8	8	8		±0.05%
White	9	9	9		
Gold				0.1	± 5% (J)
Silver				0.01	± 10% (K)

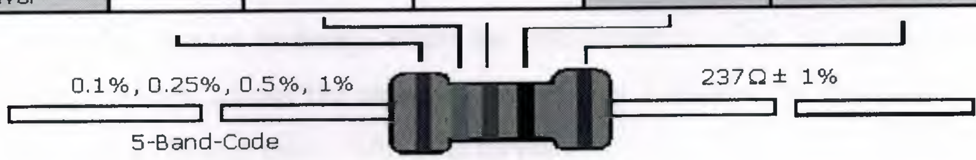


Fig 1.24 Resistor color codes

1.7.2 AC resistor circuits

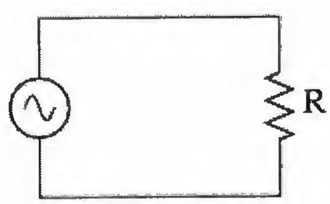


Fig 1.24 Simple AC circuit consisting of a source and resistor

If we were to plot the current and voltage for a very simple AC circuit consisting of a source and a resistor, it would look something as shown in fig1.25.

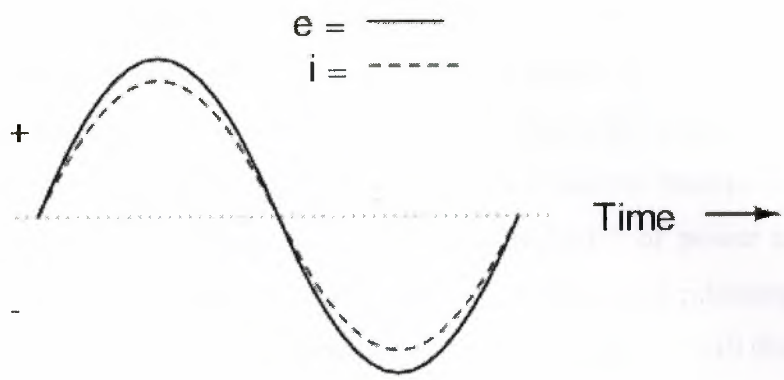


Fig 1.25 Voltage and current characteristics in simple AC circuit consisting of a source and resistor

Because the resistor simply and directly resists the flow of electrons at all periods of time, the waveform for the voltage drop across the resistor is exactly in phase with the waveform for the current through it. We can look at any point in time along the horizontal axis of the plot and compare those values of current and voltage with each other (any "snapshot" look at the values of a wave are referred to as *instantaneous values*, meaning the values at that *instant* in time). When the instantaneous value for current is zero, the instantaneous voltage across the resistor is also zero. Likewise, at the moment in time where the current through the resistor is at its positive peak, the voltage across the resistor is also at its positive peak, and so on. At any given point in time along the waves, Ohm's Law holds true for the instantaneous values of voltage and current.

We can also calculate the power dissipated by this resistor, and plot those values on the same graph:

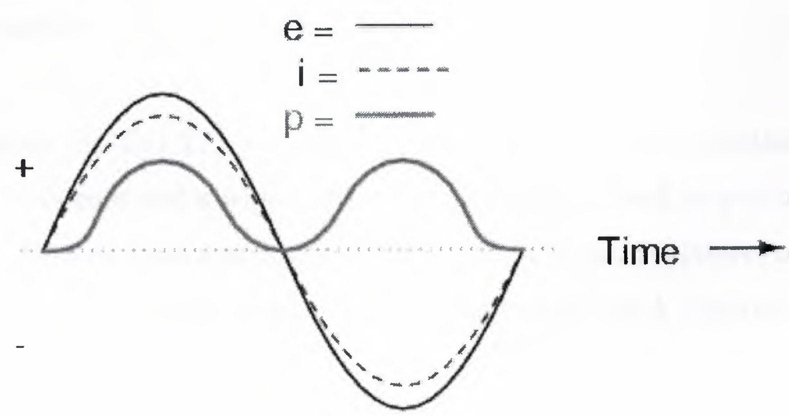


Fig 1.26 Voltage and current and power characteristics

Note that the power is never a negative value. When the current is positive (above the line), the voltage is also positive, resulting in a power (p=ie) of a positive value. Conversely, when the current is negative (below the line), the voltage is also negative, which results in a positive value for power (a negative number multiplied by a negative number equals a positive number). This consistent "polarity" of power tells us that the resistor is always dissipating power, taking it from the source and releasing it in the form of heat energy. Whether the current is positive or negative, a resistor still dissipates energy.

1.7.3 Variable resistor

1.7.3.1 Definition

A variable resistor is a potentiometer with only two connecting wires instead of three. However, although the actual component is the same, it does a very different job. The pot allows us to control the potential passed through a circuit. The variable resistance lets us adjust the resistance between two points in a circuit.

A variable resistance is useful when we don't know in advance what resistor value will be required in a circuit. By using *pots* as an adjustable resistor we can set the right value once the circuit is working. Controls like this are often called 'presets' because they are set by the manufacturer before the circuit is sent to the customer. They're usually hidden away inside the case of the equipment, away from the fingers of the users.

1.7.3.2 Construction

As shown in fig1.27, variable resistors consist of a resistance track with connections at both ends and a wiper which moves along the track as you turn the spindle. The track may be made from carbon, cermet (ceramic and metal mixture) or a coil of wire (for low resistances). The track is usually rotary but straight track versions, usually called sliders, are also available.

Variable resistors may be used as a rheostat with two connections (the wiper and just one end of the track) or as a potentiometer with all three connections in use. Miniature versions called presets are made for setting up circuits which will not require further adjustment.

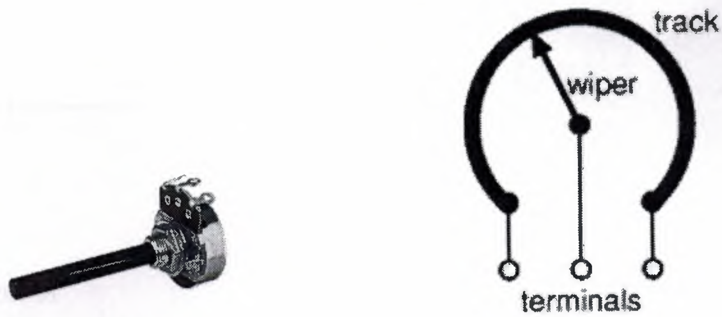


Fig 1.27 Standard Variable Resistor

1.7.4 Presets

1.7.4.1 Definition

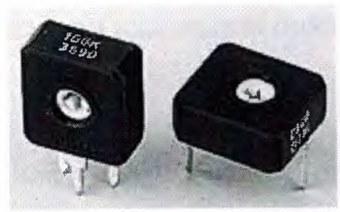
These are miniature versions of the standard variable resistor. They are designed to be mounted directly onto the circuit board and adjusted only when the circuit is built. For example to set the frequency of an alarm tone or the sensitivity of a light-sensitive circuit. A small screwdriver or similar tool is required to adjust presets.

Presets are much cheaper than standard variable resistors so they are sometimes used in projects where a standard variable resistor would normally be used.

1.7.4.2 Multiturn presets

are used where very precise adjustments must be made. The screw must be turned many times (10+) to move the slider from one end of the track to the other, Giving very fine control.

PresetSymbol



Presets
(closed style)

Fig 1.28 Preset symbol and closed style

1.8 Rocker switches

A rocker switch is an on/off switch that "rocks" when pressed, which means one side of the switch is raised while the other side is depressed much like a rocking horse rocks back and forth. A rocker switch may have a circle (for "on") on one end and a horizontal dash or line (for "off") on the other to let the user known if the device is on or off. Rocker switches are used in surge protectors, display monitors, computer power supplies, and many other devices and applications, see fig 1.29.

Fig 1.29 Rocker switches

1.9 Motors

1.9.1 Definition

Electric motors are used to efficiently convert electrical energy into mechanical energy. Magnetism is the basis of their principles of operation. They use permanent magnets, electromagnets, and exploit the magnetic properties of materials in order to create these amazing machines.

There are two main classes of motors: AC and DC. AC motors require an alternating current or voltage source (like the power coming out of the wall outlets in your house) to make them work. DC motors require a direct current or voltage source (like the voltage coming out of batteries) to make them work. Universal motors can work on either type of power. Not only is the construction of the motors different, but the means used to control the speed and torque created by each of these motors also varies, although the principles of power conversion are common to both.

1.9.2 Motors are used just about everywhere

In your house, there is a motor in your furnace for the blower, for the intake air, in the sump well, dehumidifier, in the kitchen in the exhaust hood above the stove, microwave fan, refrigerator compressor and cooling fan, can opener, garbage disposer, dish washer pump, clocks, computer fans, ceiling fans, and many more items.

In industry, motors are used to move, lift, rotate, accelerate, brake, lower and spin material in order to coat, paint, punch, plate, make or form steel, film, paper, tissue, aluminum, plastic and other raw materials.

They range in power ratings from less than 1/100 hp to over 100,000 hp. The rotate as slowly as 0.001 rpm to over 100,000 rpm. They range in physical size from as small as the head of a pin to the size of a locomotive engine.

1.9.3 AC motors

AC motors operate from alternating current (AC) power sources. The magnetic fields typically are generated using coils on the rotor and stator, and the field movement occurs naturally in the stator due to the alternating nature of the input power. These motors are inexpensive to build and operate, reliable, and usually run from standard line power. The power supply frequency determines the speed of an AC motor, so if operated from line power, the speed of rotation is always the same. Variable frequency power drives control the speed of AC motors, but such drives are expensive. Different industries use lots of electrical motors in their applications. Electric motor drive systems are estimated to consume over half of all electricity in the United States and over 70% of all electricity in industrial applications.

It is necessary to design the right motor to the right application. You need a motor that can handle the work you need (gives the speed and power you need), can be powered from the power source you want it to be powered with, can work in the conditions you have and is not too expensive for the application (to buy and maintain). Typically you will need to know the operating power (voltage, freqency, single or three phase), needed motor type and needed power.

A Torque and synchronous motors are the two main categories of ac motors. The induction motor is a common form of asynchronous motor and is basically an ac transformer with a rotating secondary. The primary winding (stator) is connected to the power source and the shorted secondary (rotor) carries the induced secondary current. Torque is produced by the action of the rotor (secondary) currents on the air-gap flux. The synchronous motor differs greatly in design and operational characteristics, and is considered a separate class of motor.

In some AC motor applications devices called motor starters are needed.AC motor starters are intended to start and accelerate motors to normal speed, to ensure continuous operation of motors, and to provideo protection against overloads (switch power of if overload occurs). There are many different type of starters. They all provide protection against overloads (quite often use thermal electrical relays for motor protection,sometimes more advanced electronic circuit). Here is an overvied of most common starter types:

1) Direct-on-line (full-on) AC starters start and accelerare motor to fullspeed by connecting full line voltage immediatly to motor.

2) Reduced voltage AC starters start and accelerate motor to normal speed by connecting the line voltage to motor in increasing steps.

3) Delta-star starters start three-phase motor in star-connection (reduced start current) and then operate motor at delta wiring (full power).

4) Two-step auto-transformer starters start and accelerate the AC induction motor with rediced torque to normal speed.

Generally electrical motors draw a large current when they started (typically 5-8 times more for starting time, even more for few mains cycles). How large this current is, and how quickly it diminishes depends on the motor type, how its controlled, and what its mechnical load is. A 5HP 240v 3ph motor have a full load rating of about 15 amps but on initial start it may draw 90 amps or more for the brief period of starting time. The mains connector blades have to be able to handle this brief current surge without arcing. To get this working installers sometimes need to goto larger rated plugs which have better contact mating characteristics - hence the HP rating in some mains plugs. Mains plug ratings are really based on current handling capability, and the horsepower rating is derived from that, based on the current required by a given size motor to start.

In some applications where large current and mechanical shock cause by the motor starting is not allowed, soft starters are used to start the motor softly (more expensive alternative to soft starting is using frequncy converter to speed up and control the motor). In soft starter motor terminal voltage is reduced. This will reduce the starting torque, taken current and mechanical shock. Electronics soft starters is are generally implemented so that thyristors reduce the motor terminal voltage in the device by usingphase control principles. This this can achieved by using a pair of thyristors per motor phase. Alternatively for 3 phase motors in some cases spft starting can be made to work with controlling only two of the phases. Siemens claims in their web pages that from a technical point of view, 2 and 3-phase control is almost identical. Soft-starts prevent unnecessary high starting current by reducing the peak current by as much as 50%. A Controlled soft-start limits the inrush of current, prevents unnecessary excess torque and reduces line disturbances on the power distribution system. Soft-starting AC induction motors on power distribution systems with low voltage, or weak capacity, will substantially reduce nuisance trips of circuit breakers and contactors. Across-the-line industrial motor starters are made in sizes up to those capable of carrying 600 amperes. Contacts of power relays used for motor control must be capable of opening at six to eight times the rated steady current in case a motor should stall. The running of the motor can be controlled with a contactor or an electrical circuit.

As far as standards are concerned, contactors and soft starters are equivalent. Both are switching devices that enable functional switching.

Furthermore, a switching device is required that implements a break function. This is usually a circuit-breaker. A motor draws well above run current during start-up, and this needs to be taken into acount when desiging over current protection for the motor. A fuse or breaker will tolerate overcurrent of a limited amount and duration only before it trips. Again, what exactly it tolerates depends on the characteristics of the breaker/fuse. So whether your motor/breaker combination will run or not depends on a lot more than just the ratio of motor run power to breaker capacity. Note also that breaker characteristics vary a lot between eg US and European countries. European domestic breakers are normally type B, whereas US breakers are closer to our type D, which are a lot more tolerant of overload than type B. The typical US breaker tolerates quite a bit of short-term overload, but for long-term, the overload limit is a lot closer.

1.9.4 DC motors

The direct current (DC) motor is one of the first machines devised to convert electrical power into mechanical power. Permanent magnet (PM) direct current convert electrical energy into mechanical energy through the interaction of two magnetic fields. One field is produced by a permanent magnet assembly, the other field is produced by an electrical current flowing in the motor windings. These two fields result in a torque which tends to rotate the rotor. As the rotor turns, the current in the windings is commutated to produce a continuous torque output. The stationary electromagnetic field of the motor can also be wire-wound like the armature (called a wound-field motor) or can be made up of permanent magnets (called a permanent magnet motor).

In either style (wound-field or permanent magnet) the commutator. acts as half of a mechanical switch and rotates with the armature as it turns. The commutator is composed of conductive segments (called bars), usually made of copper, which represent the termination of individual coils of wire distributed around the armature. The second half of the mechanical switch is completed by the brushes. These brushes typically remain stationary with the motor's housing but ride (or brush) on the rotating commutator. As electrical energy is passed through the brushes and consequently through the armature a torsional force is generated as a reaction between the motor's field and the armature causing the motor's armature to turn. As the armature turns, the brushes switch to adjacent bars on the commutator. This switching action transfers the electrical energy to an adjacent winding on the armature which in turn perpetuates the torsional motion of the armature.

High-volume everyday items, such as hand drills and kitchen appliances, use a dc servomotor known as a universal motor. Those unisversal motors are series-wound DC motors, where the stationary and rotating coils are wires in series. Those motors can work well on both AC and DC power. One of the drawbacks/precautions about series-wound DC motors is that if they are unloaded, the only thing limiting their speed is the windage and friction losses. Some can literally tear themselves apart if run unloaded.

1.9.5 Types of Motors

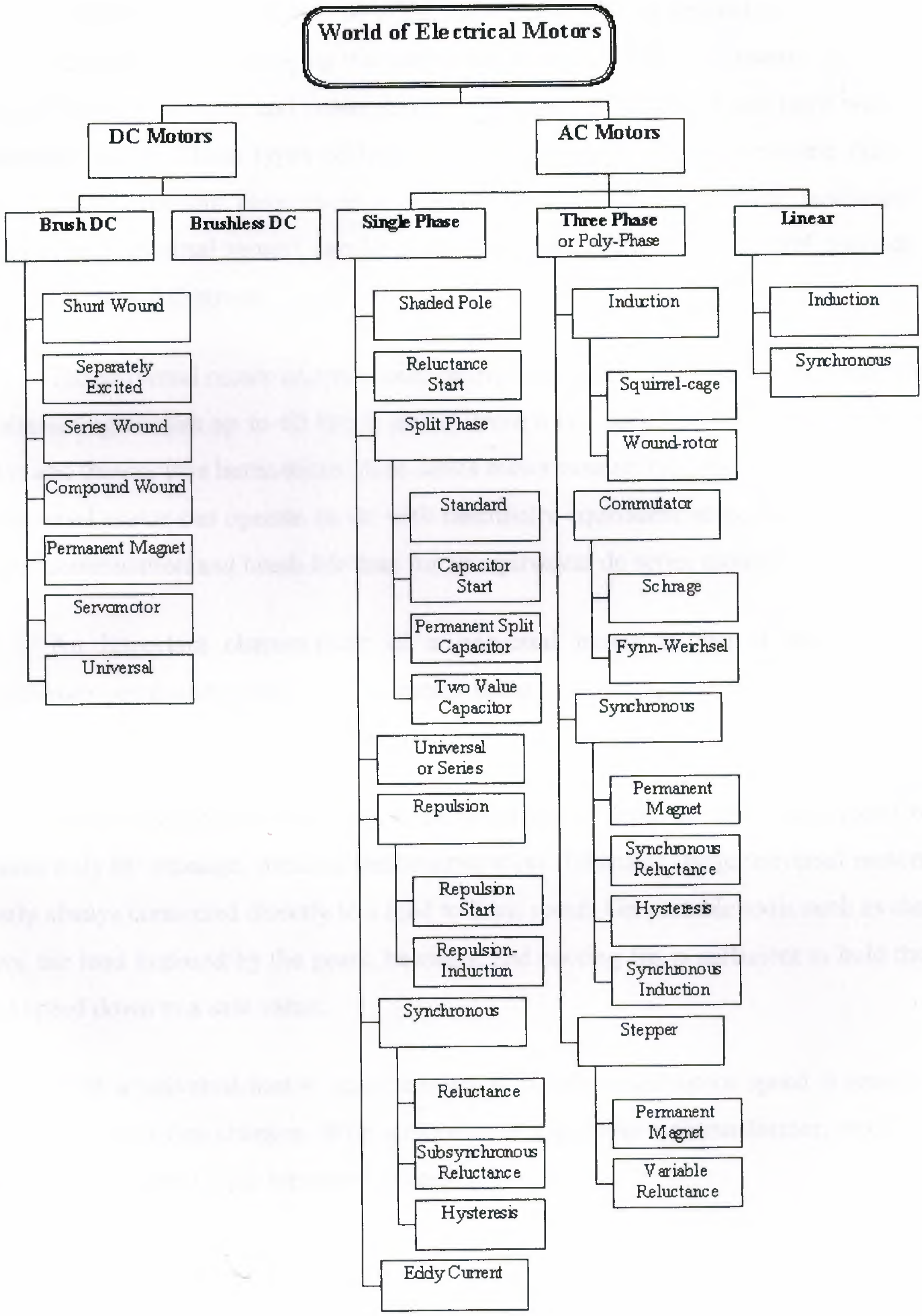


Fig 1.30 Types of motors

1.9.6 Universal motor

It is basically constructed like brush-type DC motor which has both rotor and stator coils. This motor is constructed so that when coils are wired in one way, it rotates to the same direction, no matter if AC or a DC in any direction is applied to it (changing of rotation direction needs changing the connection of coils). Universal motors are generally used on home appliances and power tools which run on AC power and have wide speed adjustment range. These types of home appliances are for example electric drills with speed control, vacuum cleaners with power control and some washing machines. The speed of an "universal motor" can be easily controlled using PWM control methods like phase control of AC power.

The universal motor operates with nearly equivalent performance on direct current or alternating current up to 60 Hz. It differs from a DC series motor because of winding ratios and thinner iron laminations. A dc series motor runs on AC, but with poor efficiency. A universal motor can operate on dc with essentially equivalent ac performance, but with poorer commutation and brush life than for an equivalent dc series motor.

An important characteristic of a universal motor is that it has the highest horsepower-per-pound ratio of any ac motor because it can operate at speeds many times higher than that of any other 60-Hz motor.

When operated without load, a universal motor tends to run away, speed being limited only by windage, friction, and commutation. Therefore, large universal motors are nearly always connected directly to a load to limit speed. On portable tools such as electric saws, the load imposed by the gears, bearings, and cooling fan is sufficient to hold the no-load speed down to a safe value.

With a universal motor, speed control is simple, since motor speed is sensitive to both voltage and flux changes. With a rheostat or adjustable autotransformer, motor speed can be readily varied from top speed to zero.

CHAPTER TWO

PRACTICAL PROJECT

2. UNIVERSAL MOTOR CONTROL

2.1 Overview

My project is explaining the operation of controlling the universal motors which Work on both AC or DC sources in other words the operation of half-wave motor-speed controller, with transistor trigger, for use with motors with current ratings up to 3A.

2.2 Circuit diagram

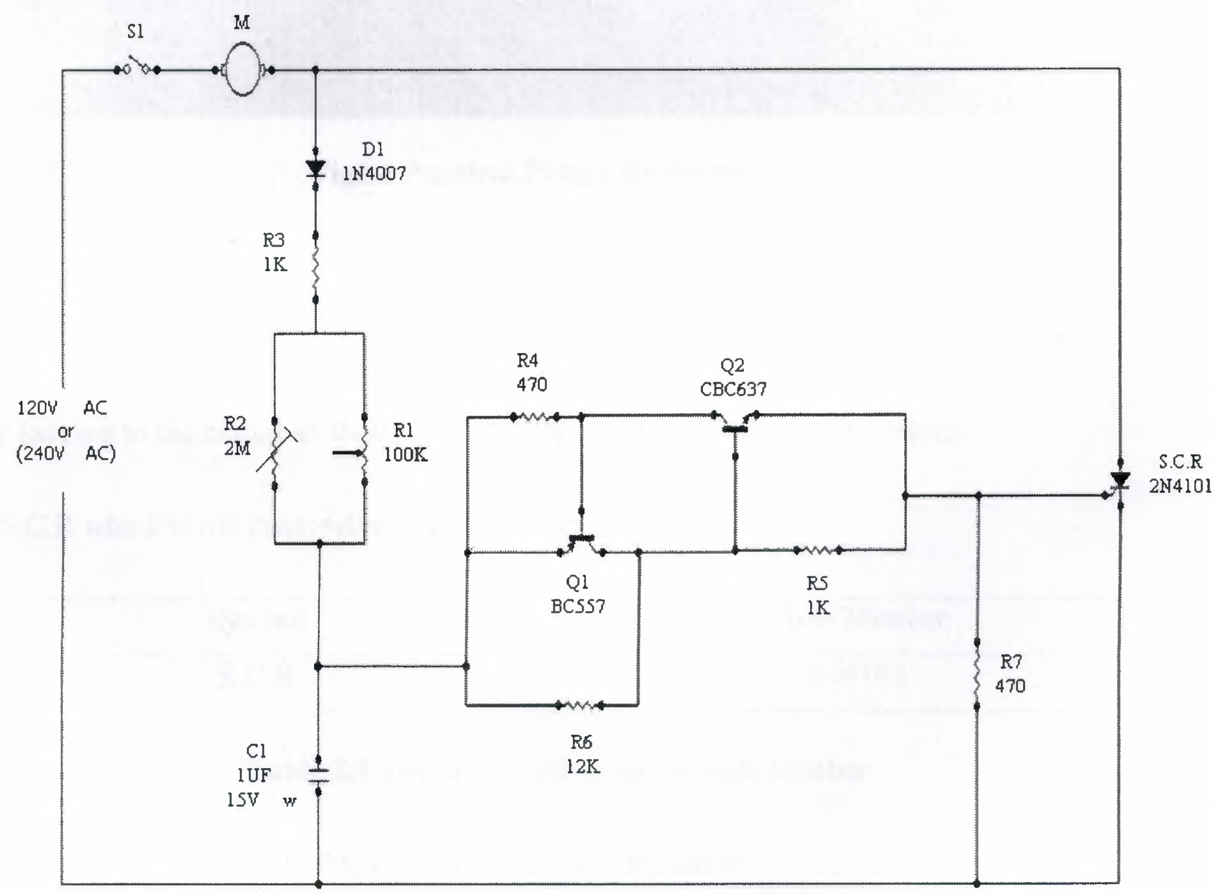


Fig 2.1 Half-wave motor-speed controller, with transistor trigger, for use with Motors with current ratings up to 3A

Fig 2.1 shows the Circuit that is going to control the universal motors with current ratings up to 3A, and with applying a voltage up to 240VAC.

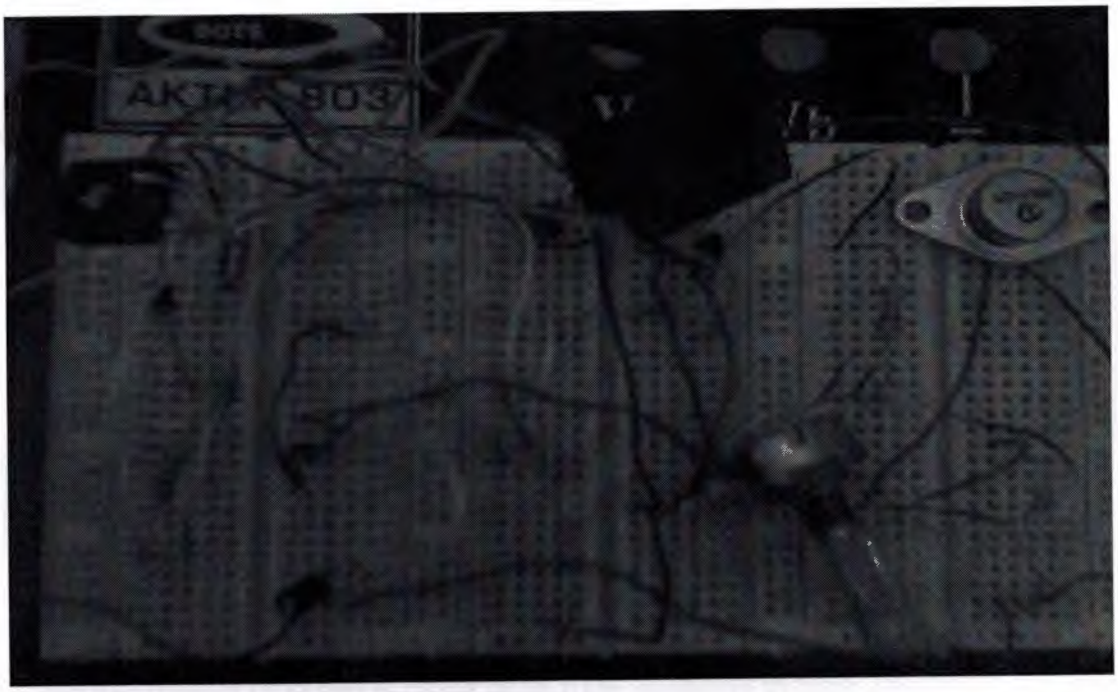


Fig2.2 Practical Picture for the project

Fig2.2, Shows the practical circuit diagram for controlling the speed of universal Motors.

By looking to the circuit as shown in fig2.1, we see that consists of 9 devices:

1)S.C.R which is a thyristor device as shown in table1.1.

Symbol	Code Number
S.C.R	2N4101

Table 2.1 Thyristor symbol and its code number

2)A switch on or off (S1) which is a type of rocker switches

3)A diode (D1) which is a standard diode as shown in table2.2.

Symbol	Code Number
D1	1N4007

Table 2.2 Diode symbol and its code number

4)5 fixed resistors which have a values as shown in table2.3.

Resistor number	Resistance value
R3	1k
R4	470
R5	1k
R6	12k
R7	470

Table 2.3 Resistors values

5)A variable resistor (R1) that is rating up to 100K as shown in table 2.4

Resistor number	Resistance value
R1	100K

Table 2.4 Resistor symbol and its resistance value

6)A multiturn preset (R2) that is rating up to 2M as shown in table2.5.

Resistor number	Resistance value
R2	2M

Table 2.5 Resistor symbol and its resistance value

7)A capacitor (C1) which has a value of 1uF, 50V as shown in table2.6.

Symbol	Resistance value
C1	1uF, 50v

Table 2.6 Capacitor symbol and its resistance value

8)PNP transistor (Q1) as shown in table2.7.

Symbol	Code Number
Q1	BC557

Table 2.7 Transistor symbol and its code number

9)NPN transistor (Q2) as shown in table2.8.

Symbol	Code Number
Q2	CBC637

Table 2.8 Transistor symbol and its code number

2.3 Circuit Operation

Explaining the circuit that is shown in fig2.1, the circuit will be divided in two parts:

1)Power parts which is the surface part of the circuit including the diode device that is shown in the circuit.

2)Trigger devices control part which is on the depth of the circuit starting with R3.

2.3.1 Power parts

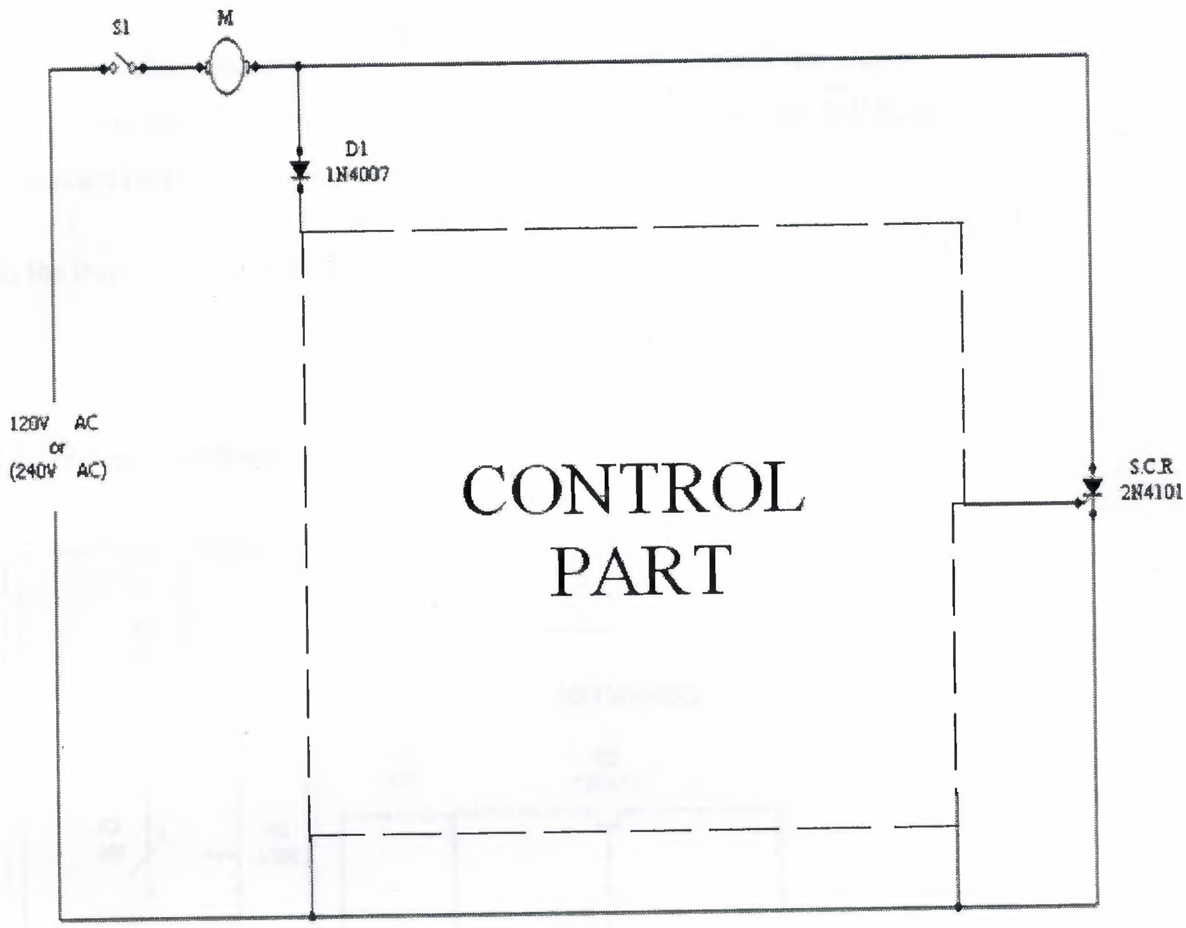


Fig 2.3 Power part of the circuit

By switching on the power supply which is connected to the part of circuit and by switching on the rocker switch (S1) that we have it in the circuit, the current will start to move in the circuit as shown in fig2.2, the current will try to pass through the diode and through the S.C.R.

The diode is connected in the forward bias with our direction of current as shown in fig2.2, so while the anode have a value of current more positive than the value of the current at the cathode, the diode will conduct, in other words the diode is going to be as short circuit on the positive half-cycle and is going to be as open circuit in the negative half-cycle.

The silicon controlled rectifier is connected also in the forward bias with our direction of current, so while the anode have a value of current more positive than the value of the current at the cathode, the S.C.R. is going to be conducted until gate current of the S.C.R.(trigger gate) has done.

In other words the S.C.R. is going to be fired until the current pass through its current gate but if no current pass through its current gate, the S.C.R. is not going to be conducted (will not never turn on).

So the important job now will be on the second part of the circuit.

2.3.2 Trigger devices control part

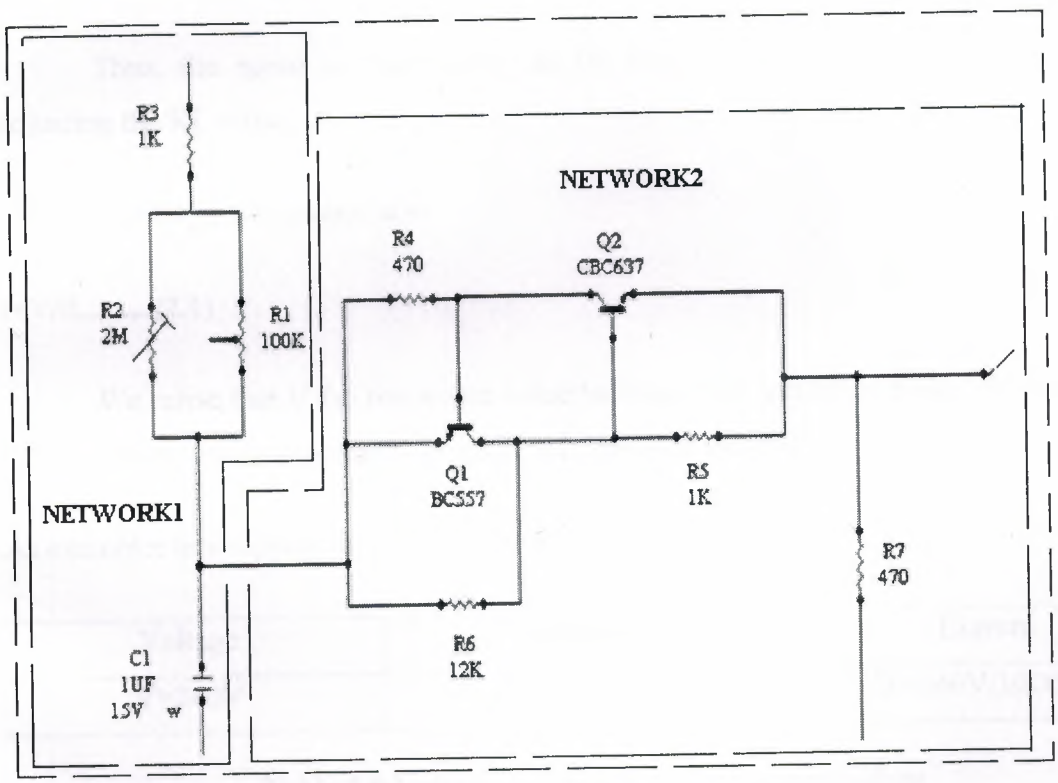


Fig 2.4 Trigger devices control part

2.3.2.1 Network'1'

As shown in fig2.3, starting with R3 the current is going to pass through the part, R3 is used to limit the peak charging current of C1 to a safe value when R1 is set close to zero resistance.

R1 is wired in parallel with R2, enables the circuit to be set so that the motor speed just falls to near-zero at the maximum resistance setting of R1, thus giving a maximum R1 control range.

When R1 is set to its minumum value, the R1-C1 network provides negligible phase shift or low attenuation, so the S.C.R. fires shortly after the start of each positive half-cycle, and high power is applied to the motor, which operates at high speed.

When R1 is set to its maximum value, the R1-C1 network provides a large phase shift and high attenuation, so the S.C.R. triggers on a few degrees before the end of each positive half-cycle and very little power is applied to the motor, which operates at low speed.

Thus, the speed of the motor can be fully varied from maximum to zero by adjusting the R1 value.

In other words by using ohm law:

I=V/R.........**(2.1)**

We relise that if the resistance value increase, the current is going to decrease, but if the resistance value decrease, the current is going to increase.

As example: lets suppose as shown in table2.9.

Voltage	Resistance	Current
V=240V	R=1K	I=V/R=240V/1000=0.24A

Table 2.9 Voltage and resistance and current values

By increasing the resistance value as shown in table2.10.

Voltage	Resistance	Current
V=240V	R=5K	I=V/R=240V/5000=0.048A

Table 2.10 Voltage and current values with the increasing of the resistance value

By decreasing the resistance value as shown in Table 2.11.

Voltage	Resistance	Current
V=240V	R=240	I=V/R=240V/240=1A

Table 2.11 Voltage and current values with the decreasing of the resistance value

So if we increase the resistance value R1, the current which is passing to the rest of the circuit is going to be decreased and the charging and discharging operations of the capacitor will be more slowly and the current will be sent more slowly to the trigger gate and then a very little power is applied to the motor, but if we decrease the resistance value R1, the current which is passing to the rest of the circuit is going to be increased and the charging and discharging operations of the capacitor will be more quickly and the current will be sent more quickly to the trigger gate and then a high power is applied to the motor.

2.3.2.2 Network'2'

R4, R7 provide discharge path for C1 on negative half-cycles, and ensures that the circuit operates with negligible blacklesh.

Q1 and Q2 act as a high impedance until the voltage across them rises to roughly 7.5V, at which point the two transistors regenerate and go into a low impedance state, thus discharging C1 into the S.C.R. gate, the trigger voltage is determined by the R5-R6 ratio.

CONCLUSION

1. **Electronic systems and controls have gained wide acceptance in power technology consequently, it has become almost indispensable to know something about control power electronics in motor AC system.**

2. **The devices which is responsible to control the speed of motor in my project are**

- **Variable resistor**
- **Ac capacitor**
- **Thyristor**

3. **The universal motor is a rotating electric machine similar to a DC motor but designed to operate either from direct current or single-phase alternating current. The stator and rotor windings of the motor are connected in series through the rotor commutator. Therefore the universal motor is also known as an AC series motor or an AC commutator motor. The universal motor can be controlled either as a phase-angle drive.**
4. **In the phase-angle application, the phase-angle control technique is used to adjust the voltage applied to the motor. A phase shift of the gate's pulses allows the effective voltage, seen by the motor, to be varied. The phase-angle drive requires just a triac.**

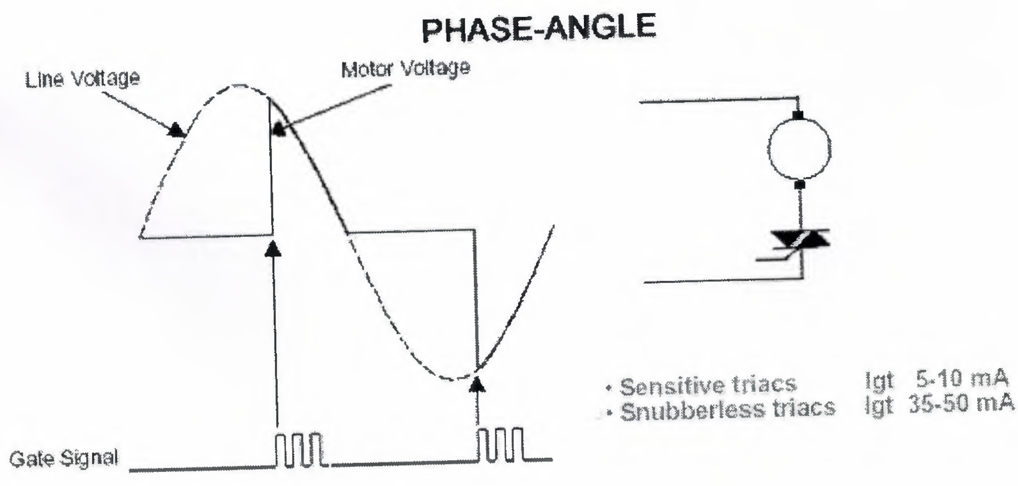


Fig 2.5 Phase angle technique using just a triac

5. **We can build simillar circuit to the one that i have been done in this project to control the motor by using s.u.s. as the trigger device to make same operation.**
6. **There are many applications to power electronic in the modern industrial life such as**

- **Emergency lights**
- **Frequencey converter**

REFERENCES

[1] http://www.semiconductors.philips.com/acrobat_download/datasheets

[2] http://octopus.freeyellow.com/octopus.html

[3] http://www.howstuffworks.com/motor.htm

[4] http://www.members.home.net/rdoctors/

[5] http://fly.hiwaay.net/~palmer/motor.html

[6] http://www.exploratorium.edu/snacks/stripped_down_motor.html

[7] http://www.hb.quik.com/~norm/motor/

[8] http://members.tripod.com/simplemotor/

[9] http://store.jalts.com/elmogekit.html

[10] http://www.qkits.com/serv/qkits/diy/pages/QK77.asp

[11] http://www.ebm.com/

[12] J. Baliga and D. Y. Chen (Eds.), Power Transistors: Device Design and Applications

[13] Blicher, Thyristor Physics, Springer-Verlag New York Inc.,1976.

[14] G. Hoft, Semiconductor Power Electronics, Van Nostrand Reinhold Company Inc.

[15] B. K. Bose, Power Electronics and AC Drives, Prentice Hall, Englewood Cliffs, 1986.

[16] B. Dewan and A. Straughen, Power Semiconductor Circuits, John Wiley & Sons, Inc.