



NEAR EAST UNIVERSITY

Faculty of Engineering

**Department of Electrical and Electronic
Engineering**

POWER ELECTRONIC CONVERTERS

**Graduation Project
EE 400**

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Finally I'm wishing that I reached and get all your ambitions which you looking from me.

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ABSRTACT

Electronic systems and controls have gained wide acceptance in power technology; consequently, it has become almost indispensable to know something about applications of power electronics converters.

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 and resistors and capacitors. They are found in all electronic systems involve the conversion of AC power to DC power and vice versa. Then we explain circuits of rectifier (half –wave, full-wave bridge rectifier) with analysis output voltages with and with filter (dc capacitor) by using circuit maker.

Finally built my practical project (Three- phase bridge diode rectifier) and make experiment to see actual voltage outputs, and calculate rectification efficiency, and finally simulate output by using circuit maker.

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Chapter 1

Introduction to power electronics

1.1 interview

Power electronics has applications that span the whole field of electrical power systems, with the power range of these applications extending from a few VA/Watts to several MVA / MW.

The main task of power electronics is to control and convert electrical power from one form to another. The four main forms of conversion are:

- Rectification referring to conversion of ac voltage to dc voltage,
- DC-to-AC conversion,
- DC-to DC conversion and
- AC-to-AC conversion.

"Electronic power converter" is the term that is used to refer to a power electronic circuit that converts voltage and current from one form to another. These

converters can be classified as:

- Rectifier converting an ac voltage to a dc voltage,
- Inverter converting a dc voltage to an ac voltage,
- Chopper or a switch-mode power supply that converts a dc voltage to another dc voltage, and
- Cycloconverter and cycloinverter converting an ac voltage to another ac voltage.

In addition, SCRs and other power semiconductor devices are used as static switches.

1.2 Rectification

Rectifiers can be classified as uncontrolled and controlled rectifiers, and the controlled rectifiers can be further divided into semi-controlled and fully-controlled rectifiers. Uncontrolled rectifier circuits are built with diodes, and fully-controlled rectifier circuits are built with SCRs. Both diodes and SCRs are used in semi-controlled rectifier circuits.

There are several rectifier circuits rectifier configurations. The popular rectifier configurations are listed below.

- Single-phase semi-controlled bridge rectifier,
- Single-phase fully-controlled bridge rectifier,
- Three-phase three-pulse, star-connected rectifier,
- Double three-phase, three-pulse star-connected rectifiers with inter-phase transformer (IPT),
- Three-phase semi-controlled bridge rectifier,
- Three-phase fully-controlled bridge rectifier and
- Double three-phase fully-controlled bridge rectifiers with IPT.

Apart from the configurations listed above, there are series-connected and 12-pulse rectifiers for delivering high power output.

Power rating of a single-phase rectifier tends to be lower than 10 kW. Three-phase bridge rectifiers are used for delivering higher power output, up to 500 kW at 500 V dc or even more. For low voltage, high current applications, a pair of three-phase, three-pulse rectifiers interconnected by an inter-phase transformer(IPT) is used. For a high current output, rectifiers with IPT are preferred to connecting devices directly in parallel. There are many applications for rectifiers. Some of them are:

- Variable speed dc drives,
- Battery chargers,
- DC power supplies and Power supply for a specific application like electroplating

1.3 DC - To - AC Conversion

The converter that changes a dc voltage to an alternating voltage is called an inverter. Earlier inverters were built with SCRs. Since the circuitry required to turn the SCR off tends to be complex, other power semiconductor devices such as bipolar junction transistors, power MOSFETs, insulated gate bipolar transistors (IGBT) and MOS-controlled thyristors (MCTs) are used nowadays. Currently only the inverters with a high power rating, such as 500 kW or higher, are likely to be built with either SCRs or gate turn-off thyristors(GTOs). There are many inverter circuits and the techniques for controlling an inverter vary in complexity. Some of the applications of an inverter are listed below:

- Frequency Converter
- Emergency lighting systems,
- AC variable speed drives,
- Uninterrupted power supplies,

1.4 DC - To - DC Conversion

When the SCR came into use, a dc-to-dc converter circuit was called a chopper. Nowadays, an SCR is rarely used in a dc-to-dc converter. Either a power BJT or a power MOSFET is normally used in such a converter and this converter is called a switch-mode power supply. A switch-mode power supply can be of one of the types listed below:

- Step-down switch-mode power supply,
- Step-up chopper,
- Fly-back converter and
- Resonant converter.

The typical applications for a switch-mode power supply or a chopper are:

- DC drive
- Battery charger and
- DC power supply.

1.5 AC - To - AC Conversion

A cycloconverter or a cycloinverter converts an ac voltage, such as the mains supply, to another ac voltage. The amplitude and the frequency of input voltage to a cycloconverter tend to be fixed values, whereas both the amplitude and the frequency of output voltage of a cycloconverter tend to be variable. On the other hand, the circuit that converts an ac voltage to another ac voltage at the same frequency is known as an ac-chopper.

A typical application of a cycloconverter is to use it for controlling the speed of an ac traction motor and most of these cycloconverters have a high power output, of the order a few megawatts and SCRs are used in these circuits. In contrast, low cost, low power cycloconverters for low power ac motors are also in use and many of these circuit tend to use triacs in place of SCRs. Unlike an SCR which conducts in only one direction, a triac is capable of conducting in either direction and like an SCR, it is also a three terminal device. It may be noted that the use of a cycloconverter is not as common as that of an inverter and a cycloinverter is rarely used.

1.6 Additional Insights into Power Electronics

There are several striking features of power electronics, the foremost among them being the extensive use of inductors and capacitors. In many applications of power electronics, an inductor may carry a high current at a high frequency. The implications of operating an inductor in this manner are quite a few, such as necessitating the use of litz wire in place of single-stranded or multi-stranded copper wire at frequencies above 50 kHz, using a proper core to limit the losses in the core, and shielding the inductor properly so that the fringing that occurs at the air-gaps in the magnetic path does not lead to electromagnetic interference. Usually the capacitors used in a power electronic

application are also stressed. It is typical for a capacitor to be operated at a high frequency with current surges passing through it periodically. This means that the current rating of the capacitor at the operating frequency should be checked before its use. In addition, it may be preferable if the capacitor has self-healing property. Hence an inductor or a capacitor has to be selected or designed with care, taking into account the operating conditions, before its use in a power electronic circuit.

In many power electronic circuits, diodes play a crucial role. A normal power diode is usually designed to be operated at 400 Hz or less. Many of the inverter and switch-mode power supply circuits operate at a much higher frequency and these circuits need diodes that turn ON and OFF fast. In addition, it is also desired

that the turning-off process of a diode should not create undesirable electrical transients in the circuit. Since there are several types of diodes available, selection of a proper diode is very important for reliable operation of a circuit.

Analysis of power electronic circuits tends to be quite complicated, because these circuits rarely operate in steady-state. Traditionally steady-state response refers to the state of a circuit characterized by either a dc response or a sinusoidal response. Most of the power electronic circuits have a periodic response, but this response is not usually sinusoidal. Typically, the repetitive or the periodic response contains both a steady-state part due to the forcing function and a transient part due to the poles of the network. Since the responses are nonsinusoidal, harmonic analysis is often necessary. In order to obtain the time response, it may be necessary to resort to the use of a computer program.

Power electronics is a subject of interdisciplinary nature. To design and build control circuitry of a power electronic application, one needs knowledge of several areas, which are listed below.

- Design of analogue and digital electronic circuits, to build the control circuitry.
- Microcontrollers and digital signal processors for use in sophisticated applications.

- Many power electronic circuits have an electrical machine as their load. In ac variable speed drive, it may be a reluctance motor, an induction motor or a synchronous motor. In a dc variable speed drive, it is usually a dc shunt motor.
- In a circuit such as an inverter, a transformer may be connected at its output and the transformer may have to operate with a nonsinusoidal waveform at its input.
- A pulse transformer with a ferrite core is used commonly to transfer the gate signal to the power semiconductor device. A ferrite-cored transformer with a relatively higher power output is also used in an application such as a high frequency inverter.
- Many power electronic systems are operated with negative feedback. A linear controller such as a PI controller is used in relatively simple applications, whereas a controller based on digital or state-variable feedback techniques is used in more sophisticated applications.
- Computer simulation is often necessary to optimize the design of a power electronic system. In order to simulate, knowledge of software package such as MATLAB and Circuit Maker and the know-how to model nonlinear systems may be necessary.

The study of power electronics is an exciting and a challenging experience. The scope for applying power electronics is growing at a fast pace. New devices keep coming into the market, sustaining development work in power electronics.

CHAPTER 2

ELCTRONIC COMPONENTS

2.1 Overview

This section describes a single diode-thyristor circuit and loads (capacitors, resistors) . Most of the power electronic component operate at a relative high voltage and in such cases, the voltage drop across the power diode tends to be small. It is quite often justifiable to use the ideal diode model. An ideal diode has zero conduction drop when it is forward-biased and has zero current when it is reverse-biased. The explanation and the analysis presented below is based on the ideal diode model.

This chapter gives an introduction to electronic components which used to implement intercom system and Safety guidelines while making the project.

2.2 Diodes

2.2.1 Construction

Diodes are non-linear circuit elements. It is made of two different types of semiconductors exactly next to each other. We can just think of an ideal diode has two regions, a conduction region of zero resistance and an infinite resistance non-conduction region. For many circuit applications, the behavior of a (junction) diode depends on its polarity in the circuit. If the diode is reverse biased (positive potential on N-type material) the current through the diode is very small. The following figure is shown the characteristic of diode.

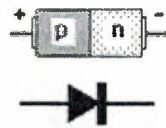


Figure 2.1 Diode

A typical diode characteristic is more like the following

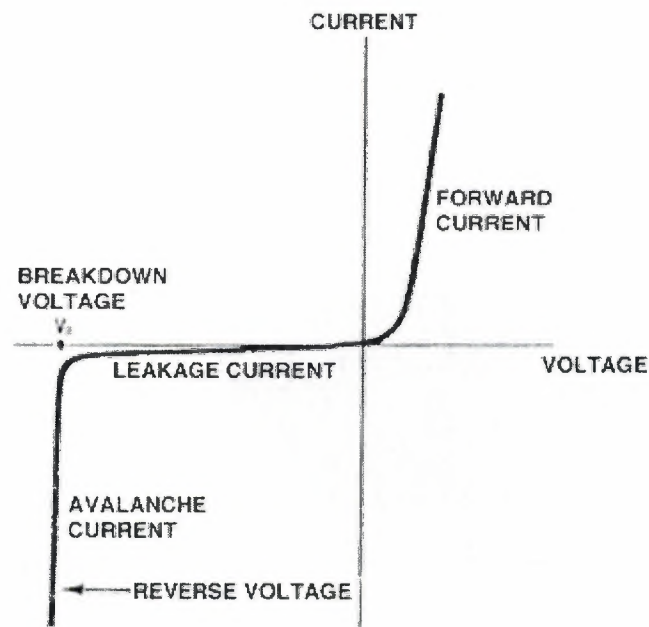


Figure 2.2 diode characteristic

Forward Biased P-N Junction: forward biasing the p-n junction drives holes to the junction from the p-type material and electrons to the junction from the n-type material. At the junction the electrons and holes combine so that a continuous current can be maintained.

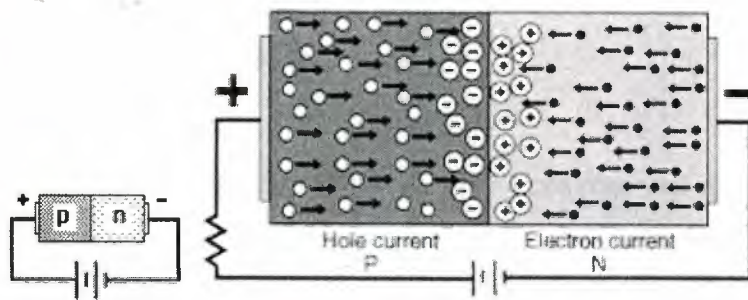


Figure 2.3 Forward Biased P-N Junction

Reverse Biased P-N Junction: the application of a reverse voltage to the p-n junction will cause a transient current to flow as both electrons and holes are pulled away from the junction. When the potential formed by the widened depletion layer equals the applied voltage, the current will cease except for the small thermal current.

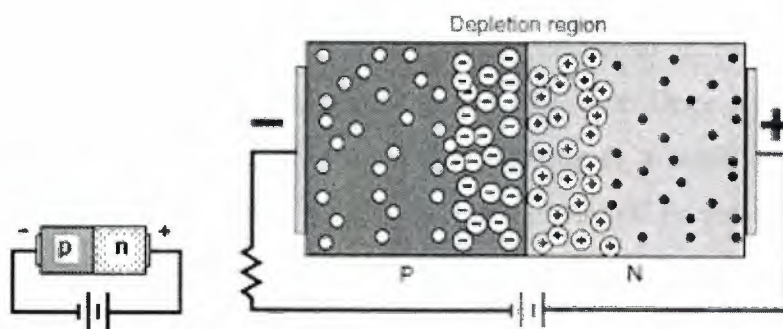


Figure 2.4 Reverse Biased P-N Junction

2.3 Silicon Control Rectifier (SCR)

The Silicon Controlled Rectifier (SCR) is simply a conventional rectifier controlled by a gate signal. The main circuit is a rectifier; however the application of a forward voltage is not enough for conduction. A gate signal controls the rectifier conduction. *The schematic representation is:*

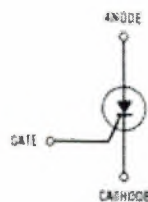


Figure 2.5 SCR

The rectifier circuit (anode-cathode) has a low forward resistance and a high reverse resistance. It is controlled from an off state (high resistance) to the on state (low resistance) by a signal applied to the third terminal, the gate. Once it is turned on it remains on even after removal of the gate signal, as long as a minimum current, the holding current, I_H , is maintained in the main or rectifier circuit. To turn off an SCR the anode-cathode current must be reduced to less than the holding current, I_H . *The characteristic curve is as shown below.*

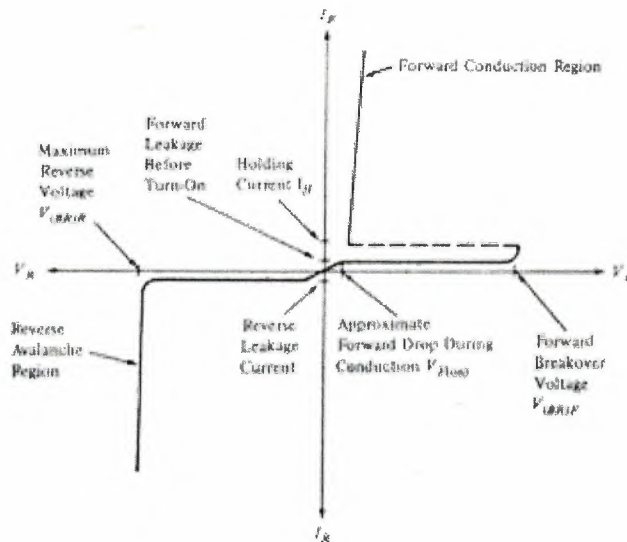


Figure 2.6 SCR characteristics

Notice the reverse characteristics are the same as discussed previously for the rectifier or diode, having a breakover voltage with its attending avalanche current; and a leakage current for voltages less than the breakover voltage. However, in the forward direction with open gate, the SCR remains essentially in an off condition (notice though that there is a small forward leakage) up until the forward breakover voltage is reached. At that point the curve snaps back to a typical forward rectifier characteristic. The application of a small forward gate voltage switches the SCR onto its standard diode forward characteristic for voltages less than the forward breakover voltage.

Obviously, the SCR can also be switched by exceeding the forward breakover voltage, however this is usually considered a design limitation and switching is normally controlled with a gate voltage. One serious limitation of the SCR is the rate of rise of voltage with respect to time, dV/dt . A large rate of rise of circuit voltage can trigger an SCR into conduction. This is a circuit design concern. Most SCR applications are in power switching, phase control, chopper, and inverter circuits.

2.4 Resistors

Electrons move easily through some materials more than others when a voltage is applied. In metals the electrons are held so loosely that they move almost without any difficulty. We call the opposition of current flow in any material Resistivity.

Resistors are electronic components like capacitors and inductors which are commonly used on the circuit boards of electronic equipment such as intercom systems. they are made of different kinds of materials and used for different purposes Carbon film resistor, Composite resistor, Metal film resistor, Metal oxide resistor, Thick film resistor, thin film resistor and Wire wound resistor

Resistors are color coded with stripes to reveal their resistance value (in ohms) as well as their manufacturing tolerance.

The main function of resistors in a circuit is to control the flow of current to other components. The higher the value of resistance the lower the current will be. When a current flows through a resistor energy is wasted and the resistor heats up.

2.4.1 Types of resistor

Mainly there are two types of resistors which are used in circuits:

1-Fixed value resistors

2-Variable resistors

2.4.2 Fixed value resistors

It is resistor which comes from the manufacturing companies with a fixed value such as $10k = 10\,000$ ohms it is difficult to make a resistor with an exact value. Resistances are given with a certain accuracy or tolerance. This is expressed as a percentage plus or minus. For example a 10% resistor with a value of 100 ohms could have a resistance between 90 ohms and 110 ohms.

2.4.3 Resistor Color Code

The resistor color code is a way of showing the value of a resistor. Instead of writing the value of the resistance on its body, which would often be too small to read, color code uses ten different colors for representing the numbers from 0 to 9. The first two colored bands on the body are the first two digits of the resistance, and the third band is the multiplier which means the number of zeroes to add after the first two digits. for example a resistor with red, red, red bands has a resistance of 2 followed by 2 followed by 2 zeroes, which is the representation of 2 200 ohms.

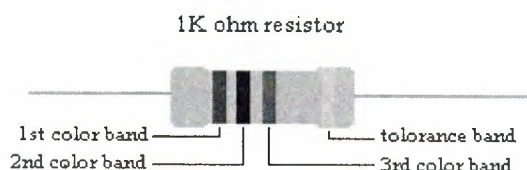


Figure2.7 Resistor

Color	1stBand	2nd Band	3rd Band	Multiplier x	Tolerances \pm %
Black	0	0	0	1	
Brown	1	1	1	10	\pm 1%
Red	2	2	2	100	\pm 2 %
Orange	3	3	3	1000	
Yellow	4	4	4	10,000	
Green	5	5	5	100,000	\pm 0.5 %
Blue	6	6	6	1,000,000	\pm 0.25 %
Violet	7	7	7	10,000,000	\pm 0.10 %
Grey	8	8	8	100,000,000	\pm 0.05 %

White	9	9	9	1,000,000,000	
Gold				0.1	$\pm 5 \%$
Silver				0.01	$\pm 10 \%$
None					$\pm 20 \%$

Table 2.1 Resistor color code

2.4.4 Resistors in series and parallel

In a series circuit, the current flowing is the same at all points. The circuit diagram shows two resistors connected in series with a voltage source V

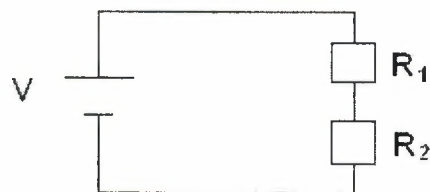


Figure 2.8 Resistors in series.

It does not matter where in the circuit the current is measured the result will be the same.

The total resistance is given by:

$$R_{\text{Total}} = R_1 + R_2$$

The next circuit shows two resistors connected in parallel to a voltage source

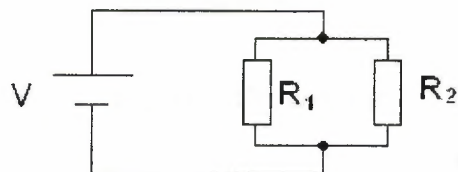


Figure 2.9 Resistors in parallel.

Parallel circuits always provide alternative pathways for current flow.

The total resistance is calculated as:

$$\frac{1}{R_{\text{Total}}} = \frac{1}{R_1} + \frac{1}{R_2}$$

2.4.5 Variable Resistors

Variable resistors are resistors whose resistance can be varied or adjusted by the user. The variable resistors have a metal wiper resting on a circular track of carbon. The wiper moves along the track as the preset is turned. The current flows through the wiper and then through part of the carbon track. The more of the track it has to go through the greater the resistance.

Variable resistors are used in circuits to vary things that need changing, like volume etc.

2.5 Capacitors

A capacitor is an electronic storage device which stores electricity. Capacitor can be charged up with energy from a source, then return that energy back later. The capacitance of a capacitor is a measure of how much energy or charge it can hold.

In its simplest form a capacitor consists of two metal plates separated by a small gap. Air or another non-conductor fills the gap. The bigger the plates the bigger the capacitance.

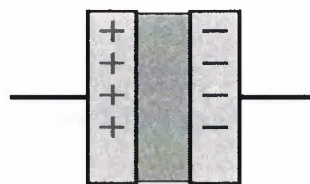


Figure 2.10 capacitor

2.5.1 Capacitor and DC voltage

When a DC voltage source is applied to a capacitor there is an initial flow of current, when the voltage across the terminals of the capacitor is equal to the applied voltage, the current flow stops.

2.5.2 Capacitors and AC voltage

Generally, if an AC voltage source is connected to a capacitor, the current will flow through the capacitor until the source is removed. There are exceptions to this situation and the A.C. current flow through any capacitor is dependent on the frequency of the applied A.C. signal and the value of the capacitor.

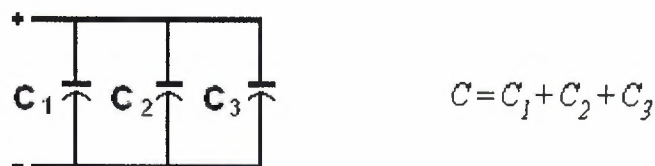


Figure 2.11 Capacitors in parallel

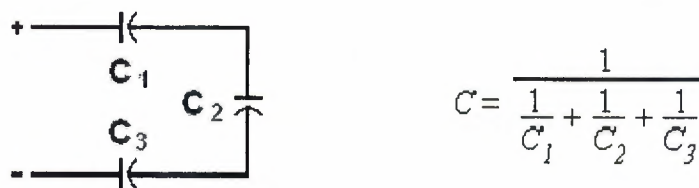


Figure 2.12 Capacitors in series

Chapter 3

Converters applications

3.1 Overview

After introducing the electrical components in the previous chapter and knowing their characteristics, this chapter will deal with the supply circuit, Half wave Bridge (diode-thyristor) Rectifier, Fully Controlled 3 - PH Bridge SCR Rectifier, Uncontrolled 3 - PH Bridge Diode Rectifier, the simulation program which is used to draw the circuits and simulate the output.

3.2 AC and DC

An alternating current (AC) is an electrical current where the magnitude and direction of the current varies cyclically, as opposed to direct current, where the direction of the current stays constant. The usual waveform of an AC power circuit is a sine wave, as this results in the most efficient transmission of energy. However in certain applications different waveforms are used, such as triangular or square waves.

AC refers to the form in which electricity is delivered to businesses and residences. However, audio and radio signals carried on electrical wire are also examples of alternating current. In these applications, an important goal is often the recovery of information encoded (or modulated) onto the AC signal.

Alternating currents are usually associated with alternating voltages. An AC voltage v can be described mathematically as a function of time by the following equation

$$v(t) = A * \sin(\omega t) \quad (1)$$

where

A is the amplitude in volts (also called the peak voltage),

ω is the angular frequency in radians per second, and

t is the time in seconds.

f is the frequency in hertz.

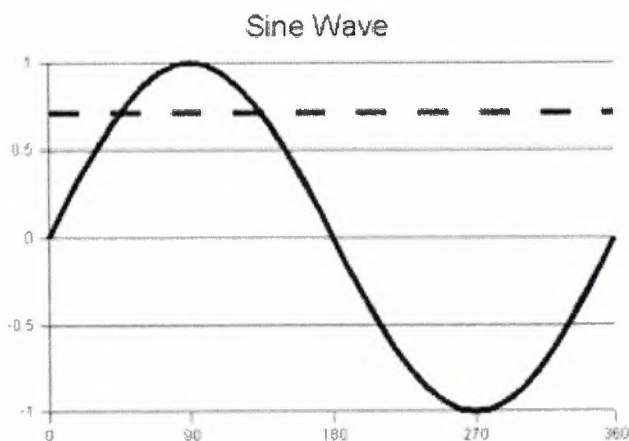


Figure 3.1 sine wave

The peak-to-peak value of an AC voltage is defined as the difference between its positive peak and its negative peak. Since the maximum value of $\sin(x)$ is +1 and the minimum value is -1, an AC voltage swings between +A and -A. The peak-to-peak voltage, written as V_{p-p} , is therefore $(+A) - (-A) = 2 \times A$.

In power distribution, the AC voltage is nearly always given as a root mean square (rms) value, written V_{rms} . For a sinusoidal voltage:

$$V_{rms} = \frac{A}{\sqrt{2}}$$

V_{rms} is useful in calculating the power consumed by a load. If a DC voltage of V_{DC} delivers a certain power P into a given load, then an AC voltage of V_{rms} will deliver the same average power P into the same load if $V_{rms} = V_{DC}$. Because of this fact rms is the normal means of measuring voltage in mains (power) systems

Direct current (DC or "continuous current") is the constant flow of electric charge from high to low potential. This is typically in a conductor such as a wire, but can also be through semiconductors, insulators, or even through a vacuum as in electron or ion beams. In direct current, the electric charges flow always in the same direction, which distinguishes it from alternating current (AC).



Figure 3.2 DC

AC is used for current transmission because it can easily be stepped up or down in voltage by a simple transformer. High voltage power lines transmit the same power at lower current (which causes lower heat) and it is then stepped down by substation transformers to the more manageable voltages. Converting the voltage level of DC is much more complicated. One method is actually to convert to AC (using a device called an inverter), use a transformer to change the voltage, and then rectify it back to DC. DC is a requirement of the internal circuits of many everyday electrical and electronic items. Computers, telephones, television sets, clocks, solid state lighting, etc., are all designed to run on DC.

3.3 Introduction to circuit maker

To simulate any circuit we can use simulation program such as pspice or circuit maker, I prefer to use circuit maker.

First of all we have to open the start menu all programs circuit maker student circuit maker as shown in the figure below

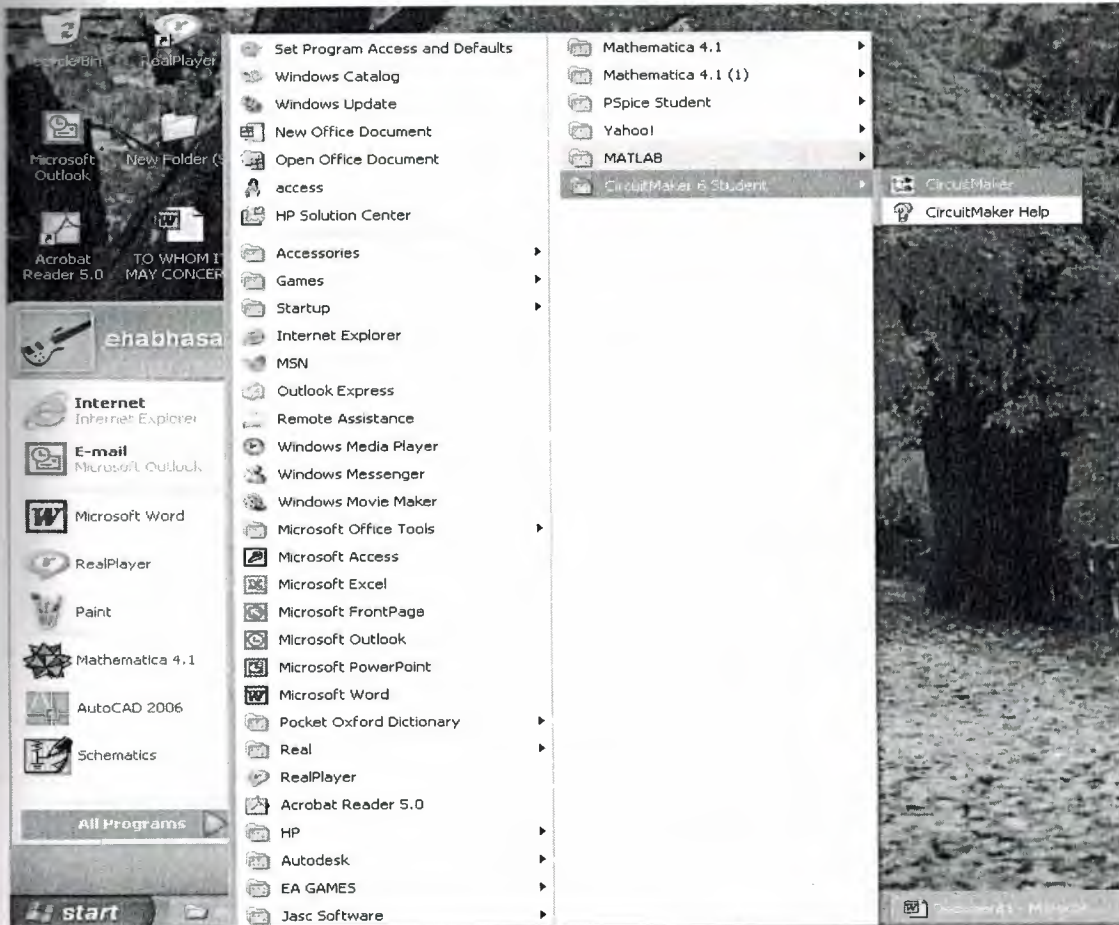


Figure 3.3 opining circuit maker

Once it opens we can see an empty page which we will start drawing the circuit on it.

To get the parts we can directly use the hot keys or from the menu as shown in the figure below.

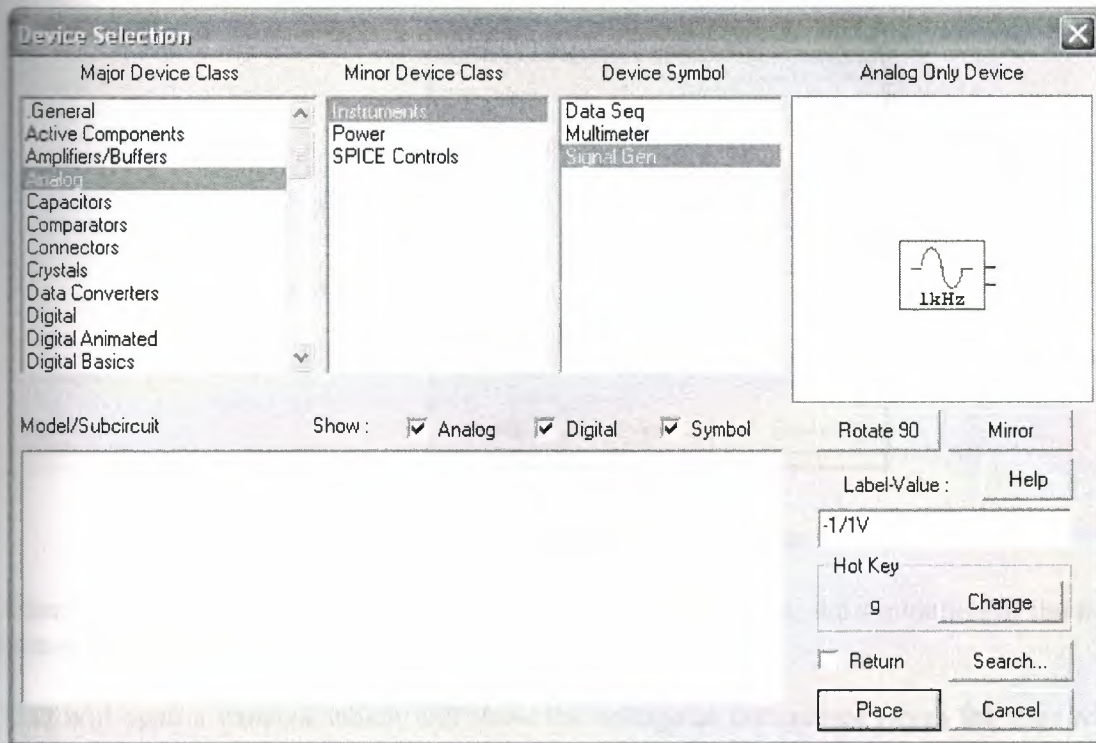


Figure 3.4 device selecting menu

After getting all the parts which we need to implement our circuit we start connecting them by using the wire tool.

We can change the value of the components by double clicking on the component, a small window will open it will show the values which we can change

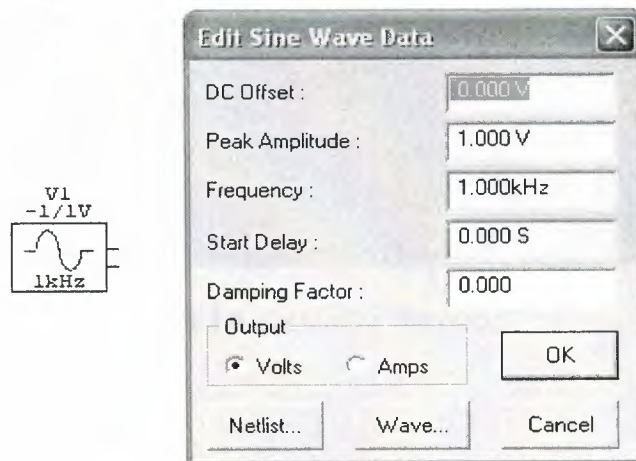
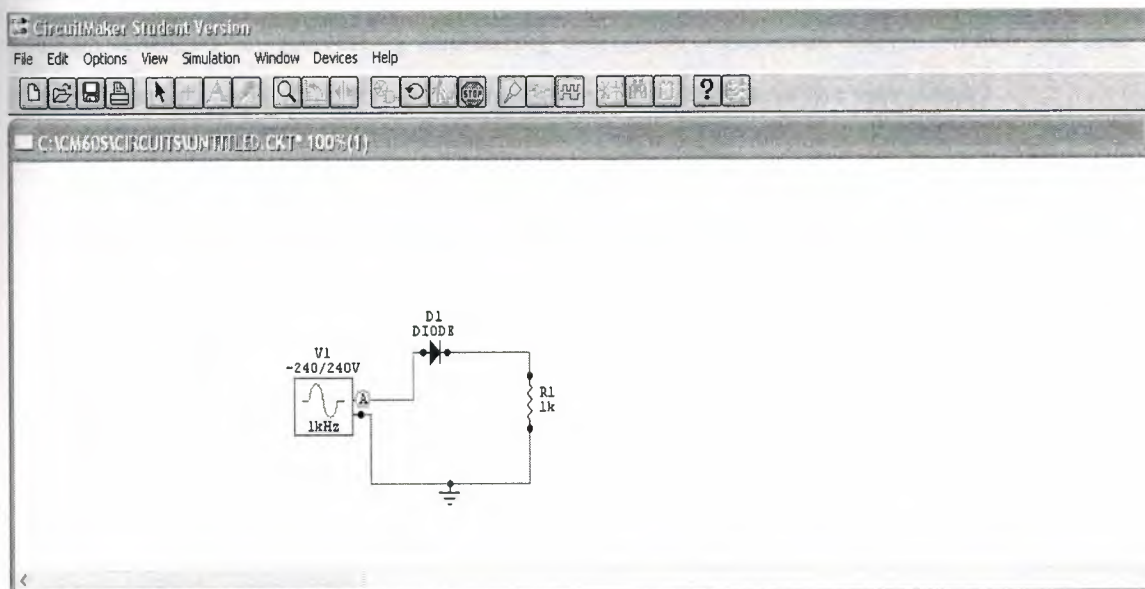


Figure 3.5 editing data

After butting all the values we can simulate or run the circuit by the simulation or the run button which is placed on the toolbar

That will open a window which will show the voltage or the current which the user will choose



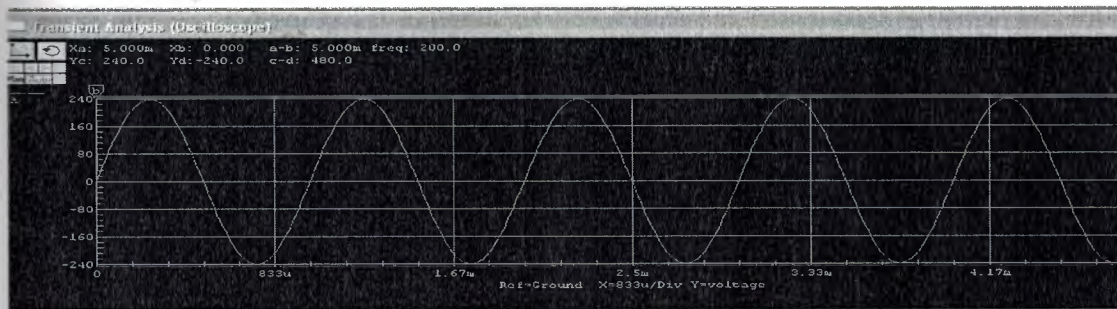


Figure 3.6 simulating the circuit

3.4 Rectifier

Rectification is a process where alternating current (AC) is converted into direct current. (DC) Almost all rectifiers contains a number of diodes in a specific arrangement for more efficiently convert AC to DC than is possible with just a single diode. Rectification is commonly performed by semiconductor diodes.

rectifier is an electrical device, comprising one or more semiconductive devices (such as diodes) arranged for converting alternating current to continuous current. When just one diode is used to rectify AC (by blocking the negative portion of the waveform) .

3.4.1 Half-wave bridge diode rectifier.

3.4.1.1 Circuit operation

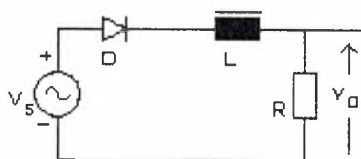


Figure 3.7 single diode and an RL load.

A circuit with a single diode and an RL load is shown above. The source v_s is an alternating sinusoidal source. If $v_s = E \sin(\omega t)$, v_s is positive when $0 < \omega t < \pi$, and v_s is negative when $\pi < \omega t < 2\pi$. When v_s starts becoming positive, the diode starts conducting and the positive source keeps the diode in conduction till ωt reaches π radians. At that instant defined by $\omega t = \pi$ radians, the current through the circuit is not zero and there is some energy stored in the inductor. The voltage across an inductor is positive when the current through it is increasing and it becomes negative when the current through it tends to fall. When the voltage across the inductor is negative, it is in such a direction as to forward-bias the diode. The polarity of voltage across the inductor is as shown in the sketches shown below.

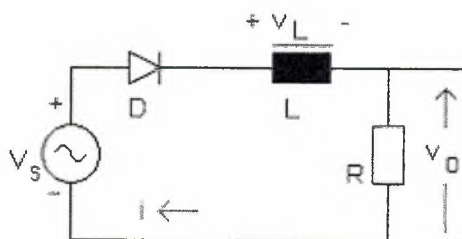


Figure3.8 current i increasing

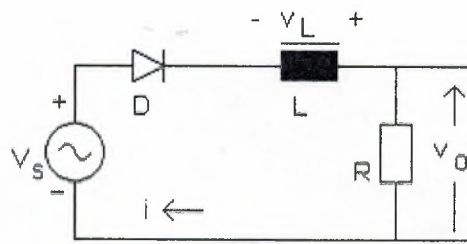


Figure 3.9 current i decreasing

When V_s changes from a positive to a negative value, there is current through the load at the instant $\omega t = \pi$ radians and the diode continues to conduct till the Energy stored in the inductor becomes zero. After that the current tends to flow in the reverse direction and the diode blocks conduction. The entire applied voltage now appears across the diode

3.4.1.2 Simulate output Using circuit maker

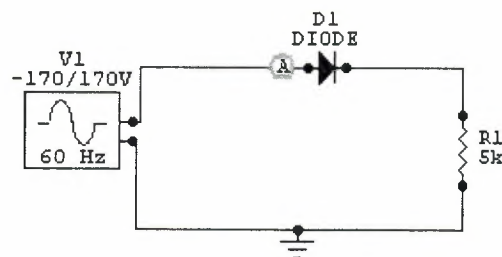


Figure 3.10 half wave diode rectifier

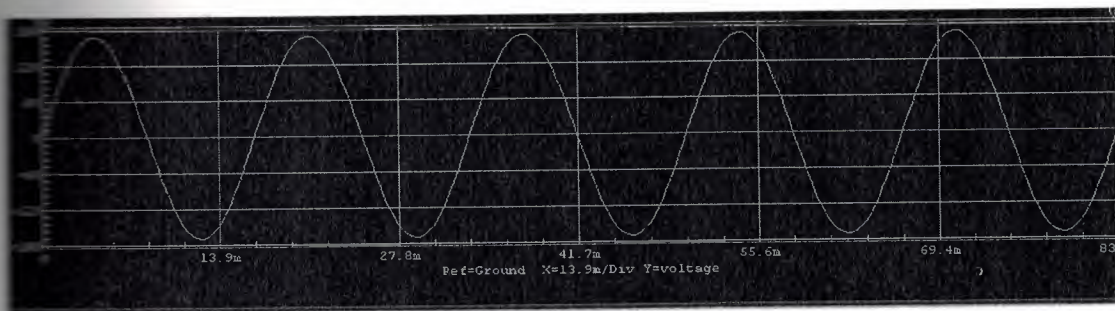


Figure 3.11 *input voltage* half wave rectifier

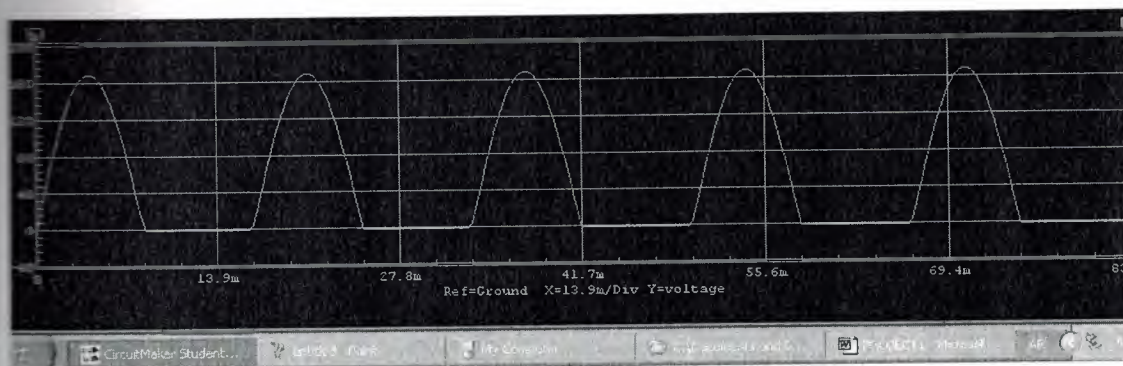


Figure 3.12 the output of half wave rectifier

3.4.1.3 Mathematical Analysis

An expression for the current through the diode can be obtained as shown below. It is assumed that the current flows for $0 < \omega t < \beta$, where $\beta > 0$. When the diode conducts, the driving function for the differential equation is the sinusoidal function defining the source voltage. During the period defined by $\beta < \omega t < 2\pi$, the diode blocks current and acts as an open switch. For this period, there is no equation defining the behaviour of the circuit. For $0 < \omega t < \beta$, the equation (2) defined below applies.

$$L \frac{di}{dt} + R * i = E * \sin (\theta) , \text{ where } 0 \leq \theta \leq \beta \quad (2)$$

$$L \frac{di}{dt} + R * i = 0 \quad (3)$$

$$wL \frac{di}{d\theta} + R * i = 0 \quad (4)$$

$$i(\theta) = A * e^{-\frac{R\theta}{wL}} \quad (5)$$

Given a linear differential equation, the solution is found out in two parts. The homogeneous equation is defined by equation (3). It is preferable to express the equation in terms of the angle θ instead of 't'. Since $\theta = wt$, we get that $d\theta = w.dt$. Then equation (3) then gets converted to equation (4). Equation (5) shown above is the solution to this homogeneous equation and is called the complementary integral.

The value of constant A in the complimentary solution is to be evaluated later.

The particular solution is the steady-state response and equation (6) expresses the particular solution. The steady-state response is the current that would flow in steady-state in a circuit that contains only the source, the resistor and the inductor shown in the circuit above, the only element missing being the diode. This response can be obtained using the differential equation or the Laplace transform or the ac sinusoidal circuit analysis. The total solution is the sum of both the complimentary and the particular solution and it is shown as equation (7). The value of A is obtained using the initial condition. Since the diode starts conducting at $wt = 0$ and the current starts building up from zero, $i(0) = 0$. The value of A is expressed by equation (8).

Once the value of A is known, the expression for current is known after evaluating

A current can be evaluated at different values of wt , starting from $wt = \pi$. As wt increases, the current would keep decreasing. For some value of wt , say β , the current

would be zero. If $\omega t > \beta$, the current would evaluate to a negative value. Since the diode blocks current in the reverse direction, the diode stops conducting when ωt reaches β . Then an expression for the average output voltage can be obtained. Since the average voltage across the inductor has to be zero, the average voltage across the resistor and the average voltage at the cathode of the diode are the same. This average value can be obtained as shown in equation (9).

$$i(\theta) = \left[\frac{E}{Z} \right] * \sin(\omega t - a), \text{ where } a = \tan^{-1} \left(\frac{\omega L}{R} \right) \text{ and } Z^2 = R^2 + (\omega L)^2 \quad (6)$$

$$i(\theta) = A * e^{\left(\frac{-R\theta}{\omega L} \right)} + \frac{E}{Z} * \sin(\theta - a) \quad (7)$$

$$A = \left[\frac{E}{Z} \right] \sin(a) \quad (8)$$

$$V_{\text{avg}} = \frac{E}{2\pi} \int_0^\beta \sin \theta \cdot d\theta = \frac{E}{2\pi} * [1 - \cos \beta] \quad (9)$$

3.4.2 Half-wave bridge thyristor (SCR) rectifier

3.4.2.1 Circuit operation

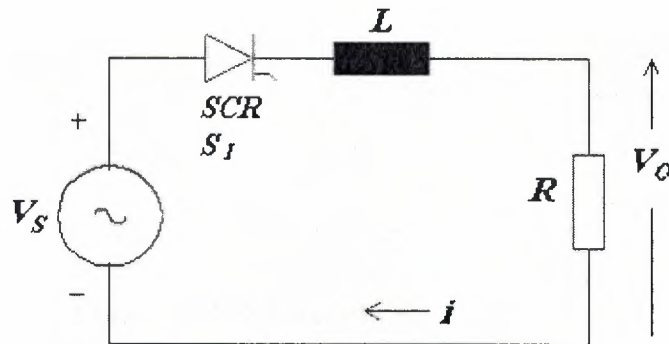


Figure 3.13 SCR circuit

A circuit with a single SCR and an RL load is shown above. The source v_s is an alternating sinusoidal source. If $v_s = E \sin(\omega t)$, v_s is positive when $0 < \omega t < \pi$, and v_s is negative when $\pi < \omega t < 2\pi$. When v_s starts becoming positive, the SCR is forward-biased but remains in the blocking state till it is triggered. If the SCR is triggered at when $\omega t = \alpha$, then α is called the firing angle. When the SCR is triggered in the forward-bias state, it starts conducting and the positive source keeps the SCR in conduction till ωt reaches radians. At that instant, the current through the circuit is not zero and there is some energy stored in the inductor at $\omega t = \pi$ radians. The voltage across an inductor is positive when the current through it is increasing and it becomes negative when the current through the inductor tends to fall. When the voltage across the inductor is negative, it is in such a direction as to forward-bias the SCR.

There is current through the load at the instant $\omega t =$ radians and the SCR continues to conduct till the energy stored in the inductor becomes zero. After that the current tends to flow in the reverse direction and the SCR blocks conduction. The entire applied voltage now appears across the diode.

3.4.2.2 Simulate output Using circuit maker

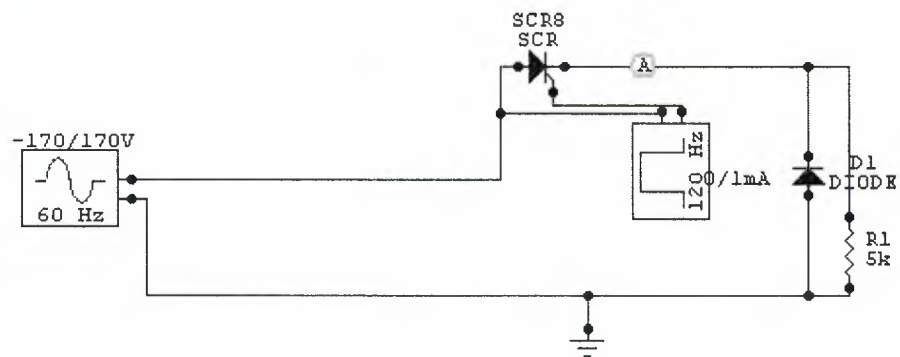


Figure 3.14 half wave SCR

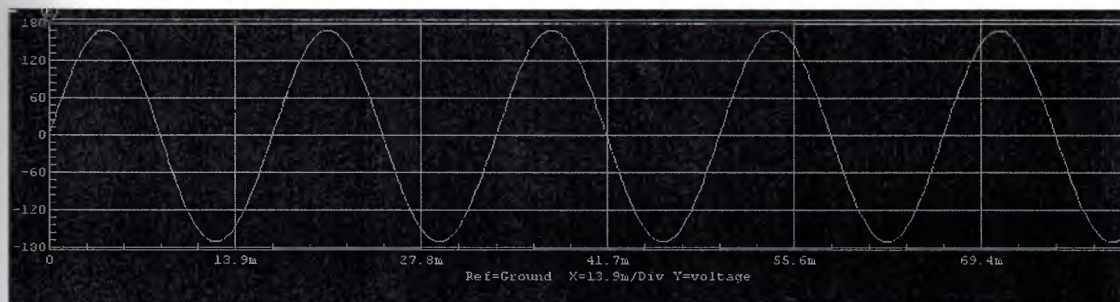


Figure 3.15 *input voltage* half wave rectifier

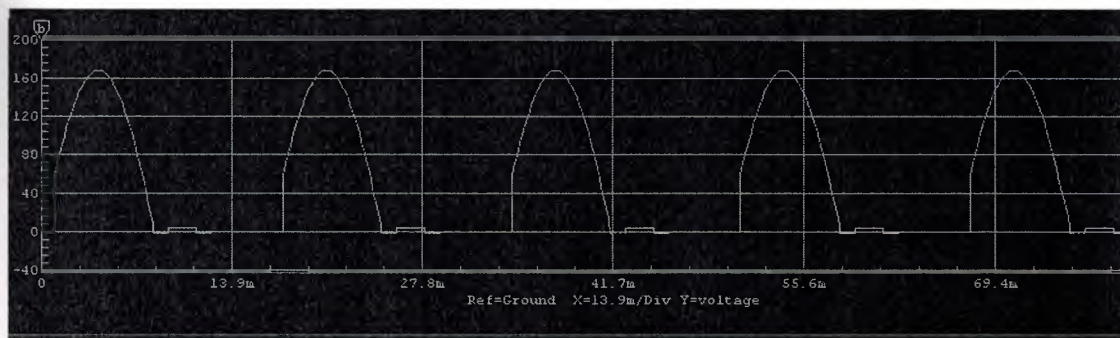


Figure 3.16 *output voltage* half wave rectifier

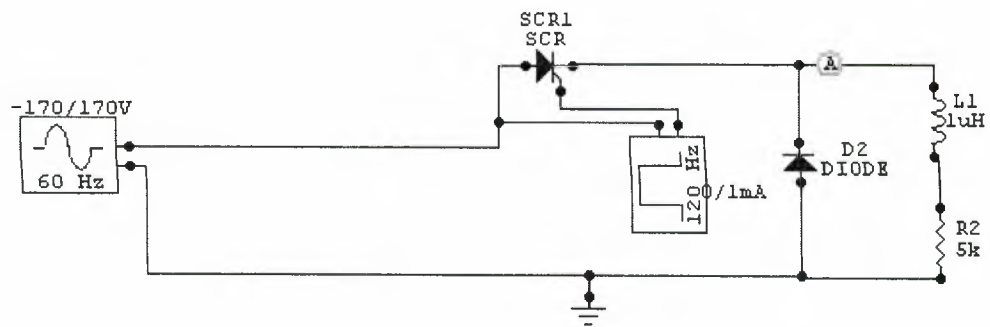


Figure 3.17 half wave thyristor rectifier with RL Load

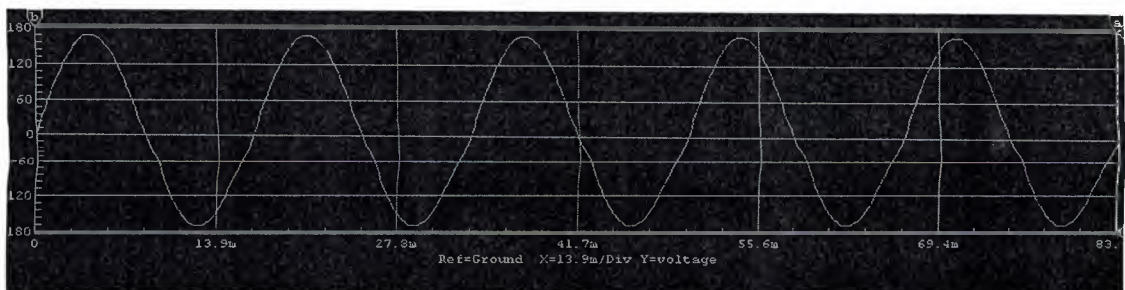


Figure 3.18 *input voltage* half wave thyristor rectifier

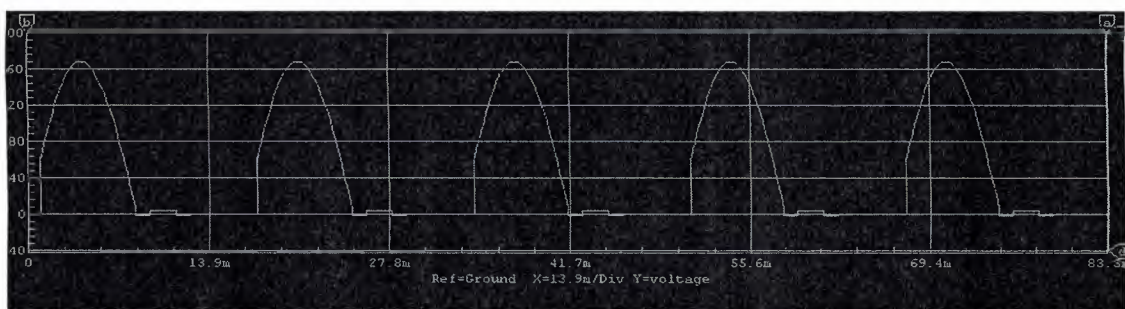


Figure 3.19 *output voltage* half wave thyristor rectifier

3.4.2.3 Mathematical Analysis

An expression for the current through the SCR can be obtained as shown below. It is assumed that the current flows for $\alpha < \omega t < \delta$, where $\delta > \alpha$. When the SCR conducts, the driving function for the differential equation is the sinusoidal function defining the source voltage. Outside this period, the SCR blocks current and acts as an open switch. For this period, there is no equation defining the behaviour of the circuit. For $\alpha < \omega t < \delta$, equation (10) applies. Given a linear differential equation, the solution is found out in two parts. The homogeneous equation is given by equation (11), where α is the firing angle. The value of constant A in the complimentary solution is to be evaluated later. The particular solution is the steady-state response and is displayed as equation (12). The total solution is the sum of both the complimentary and the particular solution and is presented as equation (13). The value of A is obtained using the initial condition. Since the SCR starts conducting at $\omega t = \alpha$ and the current starts building up from zero, $i(\alpha) = 0$. In the expression above $\tau = \omega L/R$. Then A can be expressed as in equation (14).

Once the value of A is known, the expression for current is known. When the firing angle α and the extinction angle δ are known, the average output voltage at the cathode of the SCR can be evaluated as shown in equation (15)

$$L \frac{di}{dt} + R * i = E * \sin(\theta), \text{ where } \theta = \omega t \quad (10)$$

$$i(\omega t) = A * e^{\left(-\frac{\omega t - \alpha}{\tau}\right)} \quad (11)$$

$$i(\theta) = \frac{E}{Z} * \sin(\omega t - \beta), \text{ where } \beta = \alpha \tan\left(\frac{\omega L}{R}\right) \text{ and } Z = \sqrt{R^2 + (\omega L)^2} \quad (12)$$

$$i(\theta) = \frac{E}{Z} * \sin(\theta - \beta) + A * e^{\left(\frac{\theta - a}{\tau}\right)} \quad (13)$$

$$A = \frac{E}{Z} * \sin(\beta - a) \quad (14)$$

$$V_{\text{avg}} = \frac{E}{2\pi} \int_{\alpha}^{\delta} \sin \theta \cdot d\theta = \frac{E}{2\pi} * [\cos \alpha - \cos \delta] \quad (15)$$

The average load current can be obtained by dividing the average load voltage by the load resistance, since the average voltage across the inductor is zero.

3.4.3 Fully Controlled 3 - PH Bridge SCR Rectifier

3.4.3.1 Circuit Operation:

The operation of a 3-phase fully-controlled bridge rectifier circuit is described in this page. A three-phase fully-controlled bridge rectifier can be constructed using six SCRs as shown below.

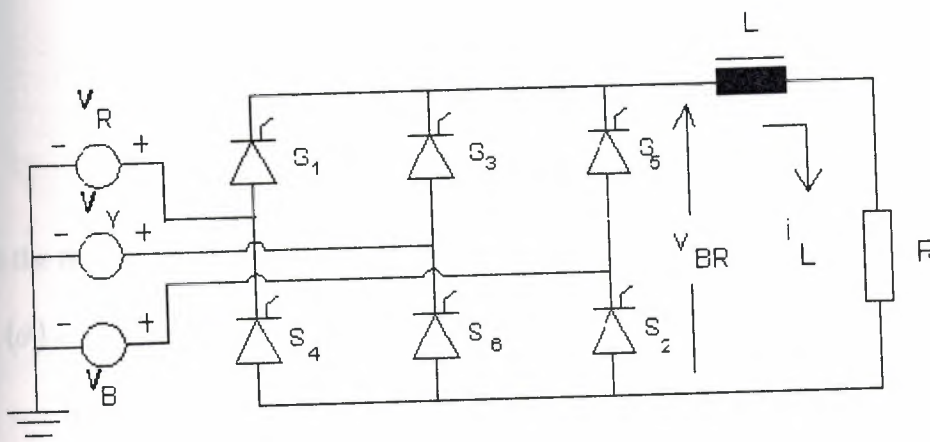


Figure 3.20 three-phase fully-controlled bridge rectifier

The three-phase bridge rectifier circuit has three-legs, each phase connected to one of the three phase voltages. Alternatively, it can be seen that the bridge circuit has two halves, the positive half consisting of the SCRs S_1 , S_3 and S_5 and the negative half consisting of the SCRs S_2 , S_4 and S_6 . At any time when there is current flow, one SCR from each half conducts. If the phase sequence of the source be RYB, the SCRs are triggered in the sequence S_1 , S_2 , S_3 , S_4 , S_5 , S_6 and S_1 and so on.

The operation of the circuit is first explained with the assumption that diodes are used in place of the SCRs. The three-phase voltages vary as shown below.

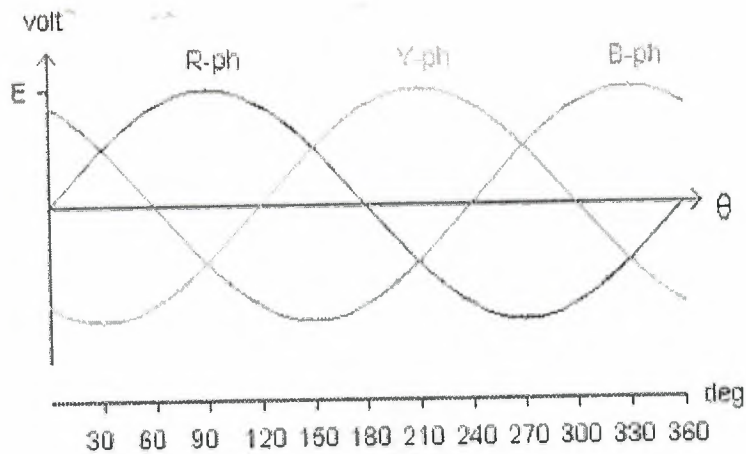


Figure 3.21 three-phase voltages

Let the three-phase voltages be defined as shown below.

$$v_R(\theta) = E * \sin(\theta), \quad v_Y(\theta) = E * \sin(\theta - 120^\circ), \quad \text{and} \quad v_B(\theta) = E * \sin(\theta + 120^\circ)$$

It can be seen that the R-phase voltage is the highest of the three-phase voltages when θ is in the range from 30° to 150° . It can also be seen that Y-phase voltage is the highest of the three-phase voltages when θ is in the range from 150° to 270° and that B-phase voltage is the highest of the three-phase voltages when θ is in the range from 270° to 390° or 30° in the next cycle. We also find that R-phase voltage is the lowest of the three-phase voltages when θ is in the range from 210° to 330° . It can also be seen that Y-phase voltage is the lowest of the three-phase voltages when θ is in the range from 330° to 450° or 90° in the next cycle, and that B-phase voltage is the lowest when θ is in the range from 90° to 210° . If diodes are used, diode D_1 in place of S_1 would conduct from 30° to 150° , diode D_3 would conduct from 150° to 270° and diode D_5 from 270° to 390° or 30° in the next cycle. In the same way, diode D_4 would conduct from 210° to 330° , diode D_6 from 330° to 450° or 90° in the next cycle, and diode D_2 would conduct from 90° to 210° . The positive rail of output voltage of the bridge is connected to the topmost segments of the envelope of three-phase voltages and the negative rail of the output voltage to the lowest segments of the envelope.

At any instant barring the change-over periods when current flow gets transferred from diode to another, only one of the following pairs conducts at any time.

Period, range of θ	Diode Pair in conduction
30° to 90°	D_1 and D_6
90° to 150°	D_1 and D_2
150° to 210°	D_2 and D_3
210° to 270°	D_3 and D_4
270° to 330°	D_4 and D_5
330° to 360° and 0° to 30°	D_5 and D_6

Table 3.1 diode Periodic conduction

If SCRs are used, their conduction can be delayed by choosing the desired firing angle. When the SCRs are fired at 0° firing angle, the output of the bridge rectifier would be the same as that of the circuit with diodes. For instance, it is seen that D_1 starts conducting only after $\theta = 30^\circ$. In fact, it can start conducting only after $\theta = 30^\circ$, since it is reverse-biased before $\theta = 30^\circ$. The bias across D_1 becomes zero when $\theta = 30^\circ$ and diode D_1 starts getting forward-biased only after $\theta = 30^\circ$. When $v_R(\theta) = E \sin(\theta)$, diode D_1 is reverse-biased before $\theta = 30^\circ$ and it is forward-biased when $\theta > 30^\circ$. When firing angle to SCRs is zero degree, S_1 is triggered when $\theta = 30^\circ$. This means that if a synchronizing signal is needed for triggering S_1 , that signal voltage would lag $v_R(\theta)$ by 30° and if the firing angle is α , SCR S_1 is triggered when $\theta = \alpha + 30^\circ$. Given that the conduction is continuous, the following table presents the SCR pair in conduction at any instant.

Period, range of θ	SCR Pair in conduction
$\alpha + 30^\circ$ to $\alpha + 90^\circ$	S_1 and S_6
$\alpha + 90^\circ$ to $\alpha + 150^\circ$	S_1 and S_2
$\alpha + 150^\circ$ to $\alpha + 210^\circ$	S_2 and S_3
$\alpha + 210^\circ$ to $\alpha + 270^\circ$	S_3 and S_4
$\alpha + 270^\circ$ to $\alpha + 330^\circ$	S_4 and S_5
$\alpha + 330^\circ$ to $\alpha + 360^\circ$ and $\alpha + 0^\circ$ to $\alpha + 30^\circ$	S_5 and S_6

Table 3.2 SCR Periodic conduction

The operation of the bridge-rectifier is illustrated with the help of an applet that follows this line. You can set the firing angle in the range $0^\circ < \text{firing angle} < 180^\circ$ and the instantaneous angle. The applet displays the SCR pair in conduction at the chosen instant. The current flow path is shown in red colour in the circuit diagram. The instantaneous angle can be either set in its text-field or varied by dragging the scroll-bar button. The rotating phasor diagram is quite useful to illustrate how the circuit operates. Once the firing angle is set, the phasor position for firing angle is fixed. Then as the instantaneous angle changes, the pair that conducts is connected to the thick orange arcs. One way to visualize is to imagine two brushes which are 120° wide and the device in the phase connected to the brush conducts. The brush that has "Firing angle " written beside it acts as the brush connected to the positive rail and the other acts as if it is connected to the negative rail. This diagram illustrates how the rectifier circuit acts as a commutator and converts ac to dc. The output voltage is specified with the amplitude of phase voltage being assigned unity value.

3.4.3.2 Synchronizing Signals

To vary the output voltage, it is necessary to vary the firing angle. In order to vary the firing angle, one commonly used technique is to establish a synchronizing signal for each SCR. It has been seen that zero degree firing angle occurs 30° degrees after the zero-crossing of the respective phase voltage. If the synchronizing signal is to be a sinusoidal signal, it should lag the respective phase by 30° and then the circuitry needed to generate a firing signal can be similar to that described for single-phase. Instead of a single such circuit for a single phase rectifier, we would need three such circuits.

When the 3-phase source supply connected to the rectifier is star-connected, the line voltages and the phase voltages have a 30° phase angle difference between them, as shown below.

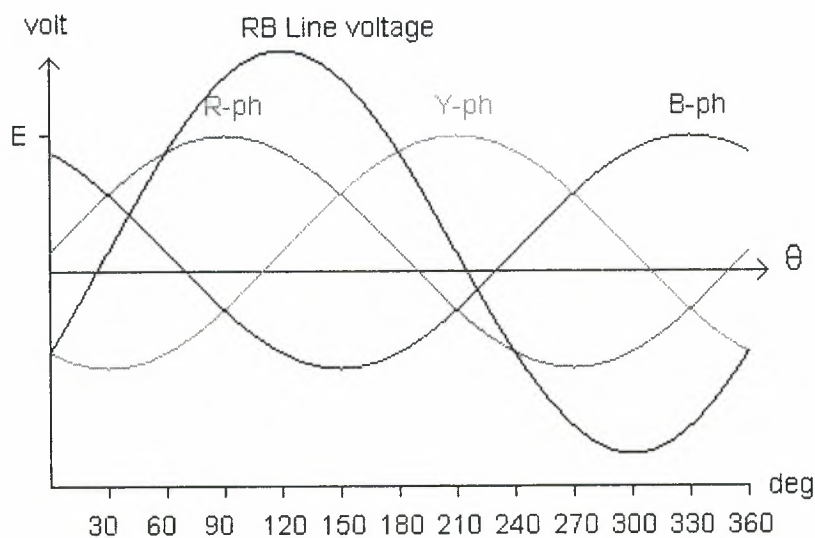


Figure 3.22a phase angle difference between line voltages and the phase voltages(www.introduction power supply.com)

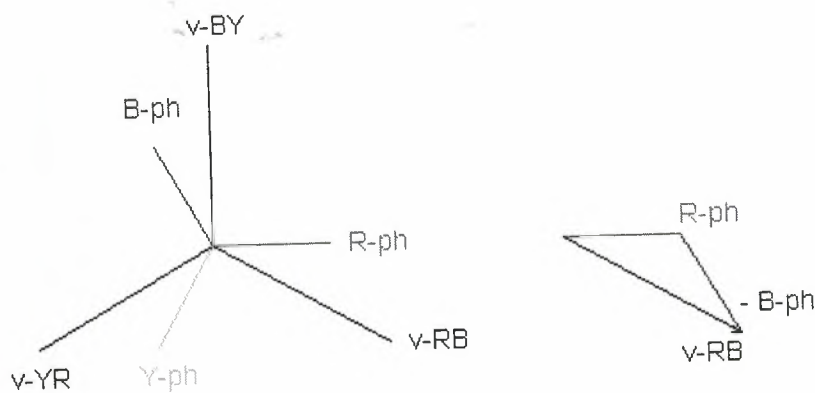


Figure 3.23b phase angle difference between line voltages and the phase voltages

The line voltage can also be obtained as:

$$\begin{aligned}
 v_{RB}(\theta) &= v_R(\theta) - v_B(\theta) \\
 &= E \sin(\theta) - E \sin(\theta + 120^\circ) \\
 &= E \sin(\theta) + \frac{E}{2} \sin(\theta) - \frac{\sqrt{3}E}{2} \cos(\theta) \\
 &= \sqrt{3}E \sin(\theta - 30^\circ) \quad (17)
 \end{aligned}$$

This line voltage lags the R-phase voltage by 30° and has an amplitude which is 1.732 times the amplitude of the phase voltage. The synchronizing signal for SCR S_1 can be obtained based on v_{RB} line voltage. The synchronizing signals for the other SCRs can be obtained in a similar manner.

To get the synchronizing signals, three control transformers can be used, with the primaries connected in delta and the secondaries in star, as shown below.

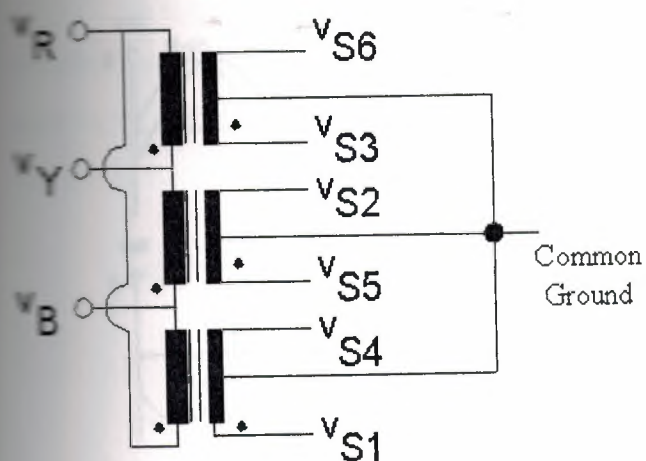


Figure 3.24 three control transformers

For S_1 , voltage v_{S1} is used as the synchronizing signal. Voltage v_{S2} is used as the synchronizing signal for SCR S_2 and so on. The waveforms presented by the synchronizing signals are as shown below. The waveforms do not show the effect of turns ratio, since any instantaneous value has been normalized with respect to its peak value. For example, let the primary phase voltage be 240 V and then its peak value is 339.4 V. The primary voltage is normalized with respect to 339. V. If the peak voltage of each half of secondary is 10 V, the secondary voltage are normalized with respect to 10 v.

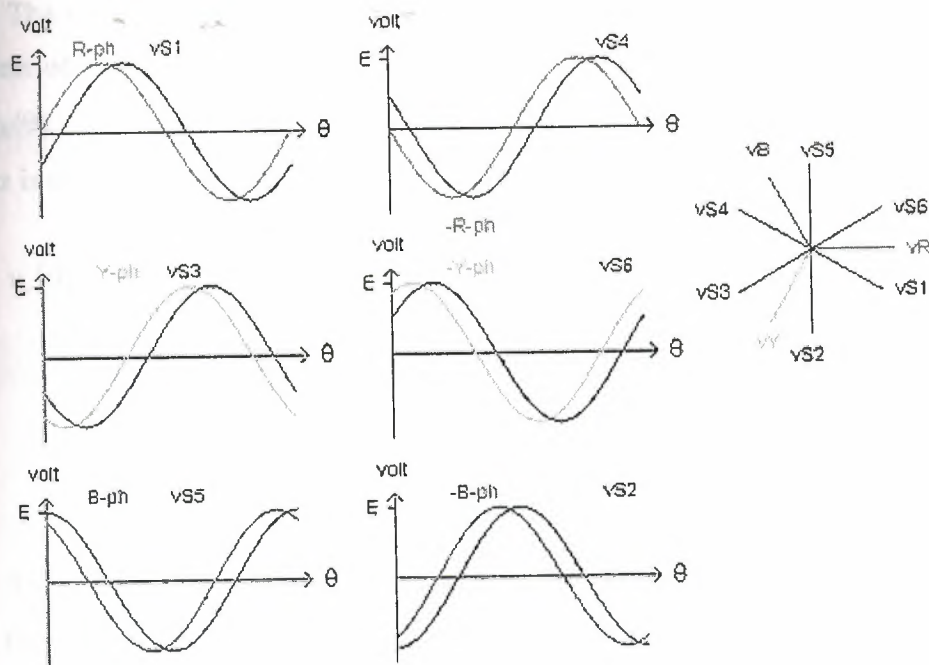


Figure 3.25 analysis phase-thyristor voltages

3.4.3.3 Mathematical Analysis

Analysis of this three-phase controlled rectifier is in many ways similar to the analysis of single-phase bridge rectifier circuit. We are interested in output voltage and the source current. The average output voltage, the rms output voltage, the ripple content in output voltage, the total rms line current, the fundamental rms current, THD in line current, the displacement power factor and the apparent power factor are to be determined. In this section, the analysis is carried out assuming that the load current is a steady dc value.

3.4.3.3.1 Average Output Voltage

Before getting an expression for the output voltage, it is preferable to find out how the output voltage waveform varies as the firing angle is varied. In one cycle of source voltage, six pairs conduct, each pair for 60° . This means that the period for output waveform is one-sixth of the period of line voltage.

The output waveform repeats itself six times in one cycle of input voltage. The waveform of output voltage can be determined by considering one pair. It is seen that when $v_R(\theta) = E \sin(\theta)$, SCR S1 and S6 conduct when θ varies from $30^\circ + \alpha$ to $90^\circ + \alpha$, where α is the firing angle. Then

$$\begin{aligned} v_o(\theta) &= v_R(\theta) - v_Y(\theta) \\ &= E \sin(\theta) - E \sin(\theta - 120^\circ) \\ &= \sqrt{3}E \sin(\theta + 30^\circ), \text{ for } (\alpha + 30^\circ) < \theta < (\alpha + 90^\circ). \quad (18) \end{aligned}$$

The waveform of output can be plotted for different firing angles. The applet below takes in the firing angle as an input and plots the output. The peak line-to-line voltage is marked as 'U' and the applet starts with the instant an SCR is fired and displays the output waveform for one input cycle period.

The average output voltage of the bridge circuit is calculated as follows, with a change in variable, where $\theta = \alpha + 60^\circ$.

$$V_{avg}(\alpha) = \frac{\sqrt{3}E}{\pi/3} \int \sin(\theta) \cdot d\theta = \frac{3}{\pi} U \cos(\alpha) \quad (19)$$

In the expression above, U is the peak line-to-line voltage, whereas E is the amplitude of phase voltage of 3-phase supply.

3.4.3.3.2 RMS Output Voltage

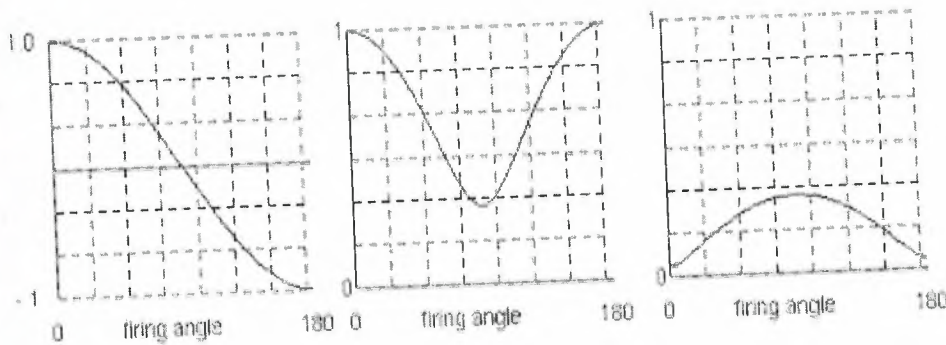
The rms output voltage is calculated as follows:

$$V_{rms}(\alpha) = \sqrt{\frac{3}{\pi} \int \sin^2\left(\theta + \frac{\pi}{3} + \alpha\right) \cdot d\alpha} = U \sqrt{\frac{1}{2} + \frac{3\sqrt{3}}{4\pi} \cos(2\alpha)}. \quad (20)$$

The ripple factor of the output voltage is then:

$$RF(\alpha) = \frac{1}{V_{avg}(0^\circ)} * \sqrt{(V_{svg}(\alpha))^2 - (V_{avg}(\alpha))^2} \quad (21)$$

The applet below displays the average output voltage, the rms output voltage and the ripple factor for the case of continuous conduction through the load.



3.26a average output voltage **3.26b** rms output voltage **3.26c** ripple factor

Figure 3.26 effect of continuous conduction through the load.

(www.introduction power electronic.com)

It is seen that the average output voltage is negative when firing angle exceeds 90° . It means that power flow is from the dc side to the ac source. When the firing angle is kept in the region $0^\circ < \alpha < 90^\circ$, this circuit is said to be operating in the **rectifier region**. When the firing angle is kept in the region $90^\circ < \alpha < 180^\circ$, this circuit is said to be operating in the **inverter region**. When the circuit operates in the rectifier region, the net power flow is from the ac source to the dc link. In the inverter region, the net power flow is in the reverse direction. To operate in the inverter region, it is necessary to have a dc source present in the dc link which can provide the power that is fed back to the ac source.

3.4.3.3 RMS Line Current

The rms line current is relatively easy to find out if the dc current is ripple-free and steady. The load current is ripple-free if the inductance in the dc link is relatively large. To maintain load current at any firing angle, it is necessary that the dc link should contain a voltage source. Given that the resistance of the load circuit is zero, the voltage source should equal the average output voltage of the bridge circuit. The waveforms shown below are based on the assumption that these conditions are met. It has been shown that if $v_R(\theta) = E \sin(\theta)$, SCR S_1 conducts when θ varies from $\alpha + 30^\circ$ to $\alpha + 90^\circ$ and that SCR S_4 conducts when θ varies from $\alpha + 210^\circ$ to $\alpha + 270^\circ$. If the amplitude of dc load current is assigned to be unity, the line current waveform is then a rectangular pulse, remaining at + 1 from $\alpha + 30^\circ$ to $\alpha + 150^\circ$, at - 1 from $\alpha + 210^\circ$ to $\alpha + 330^\circ$, and zero elsewhere. The amplitude of the fundamental in line current is then $3.464/\pi$ (which evaluates to nearly 0.78) and the amplitude of other odd harmonics is $3.464/n\pi$, where n is the odd harmonic number. When the dc load current is steady and has a magnitude of unity, the rms line current is obtained as shown in equation (22). The rms value of the fundamental is obtained as shown in equation (23). Equation (23) is based on how trigonometric Fourier coefficients are defined for waveforms with quarter-wave symmetry. When the line current is a rectangular and symmetric, the phase current is the same as the line current and the fundamental component of the phase current lags the phase voltage by an angle equal to the firing angle. Hence the displacement power factor is expressed as shown by equation (24). Since the line current is not sinusoidal, the apparent power factor, usually referred to just as the power factor in most of the texts, is less than DPF and is represented by equation (25). Since the line current is not sinusoidal, the distortion component in the line current has to be computed. This component, called the THD(Total Harmonic Distortion), is calculated as shown in equation (26).

$$I_{rms} = \sqrt{\frac{1}{\pi} * \int_{\pi/6}^{5\pi/6} d\theta} = 0.816 \quad (22)$$

$$I_{1,rms} = \frac{4}{\sqrt{2\pi}} * \int_{\pi/6}^{\pi/2} \sin(\theta) \cdot d\theta = 0.7797 \quad (23)$$

$$DPF = \cos(\alpha) \quad (24)$$

$$\text{Apparent } PF = \frac{I_{1,rms}}{I_{rms}} * DPF = 0.955 * \cos(\alpha). \quad (25)$$

$$THD = \sqrt{\frac{(I_{rms})^2}{(I_{1,rms})^2} - 1} = 0.311 \quad (26)$$

3.4.4 UnControlled 3 - PH Bridge Diode Rectifier:

(Practical Project)

3.4.4.1 Circuit operation

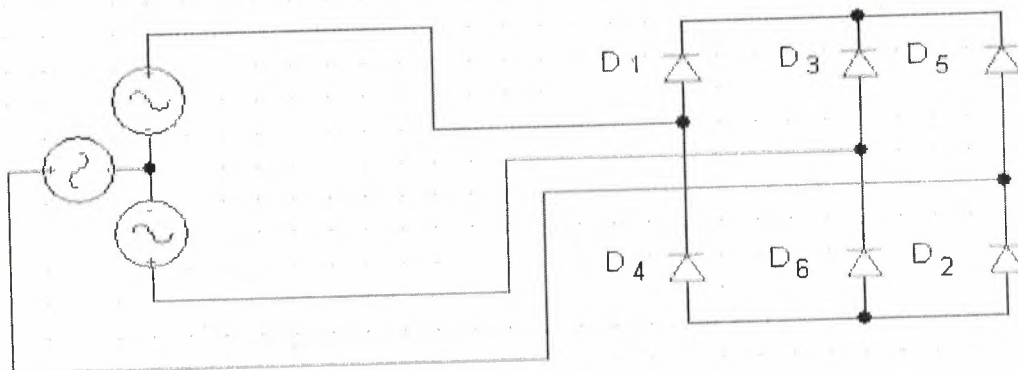


Figure 3.27 UnControlled 3 - PH Bridge Diode Rectifier

The three-phase bridge rectifier circuit has three-legs, each phase connected to one of the three phase voltages. Alternatively, it can be seen that the bridge circuit has two halves, the positive half consisting of the Diodes D₁, D₃ and D₅ and the negative half consisting of the Diodes D₂, D₄ and D₆. At any time when there is current flow, one Diode from each half conducts. If the phase sequence of the source be A B C, the Diodes are triggered in the sequence D₁,D₂,D₃,D₄,D₅,D₆ and D₁ and so on.

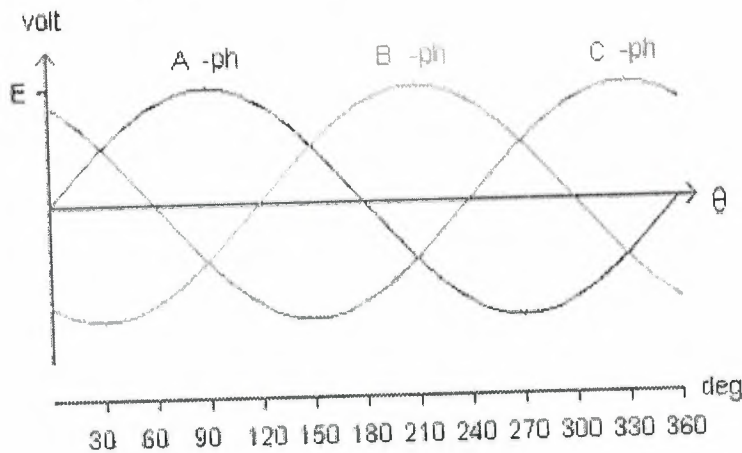


Figure 3.28 three-phase voltages

Let the three-phase voltages be defined as shown below.

$$v_A(\theta) = E * \sin(\theta), \quad v_B(\theta) = E * \sin(\theta - 120^\circ), \quad \text{and} \quad v_C(\theta) = E * \sin(\theta + 120^\circ)$$

It can be seen that the A-phase voltage is the highest of the three-phase voltages when θ is in the range from 30° to 150° . It can also be seen that B-phase voltage is the highest of the three-phase voltages when θ is in the range from 150° to 270° and that C-phase voltage is the highest of the three-phase voltages when θ is in the range from 270° to 390° or 30° in the next cycle. We also find that A-phase voltage is the lowest of the three-phase voltages when θ is in the range from 210° to 330° . It can also be seen that B-phase voltage is the lowest of the three-phase voltages when θ is in the range from 330° to 450° or 90° in the next cycle, and that C-phase voltage is the lowest when θ is in the range from 90° to 210° . If diodes are used, diode D_1 would conduct from 30° to 150° , diode D_3 would conduct from 150° to 270° and diode D_5 from 270° to 390° or 30° in the next cycle. In the same way, diode D_4 would conduct from 210° to 330° , diode D_6 from 330° to 450° or 90° in the next cycle, and diode D_2 would conduct from 90° to 210° . The positive rail of output voltage of the bridge is connected to the topmost segments of the envelope of three-phase voltages and the negative rail of the output voltage to the lowest segments of the envelope.

At any instant barring the change-over periods when current flow gets transferred from diode to another, only one of the following pairs conducts at any time.

Period, range of θ	Diode Pair in conduction
30° to 90°	D_1 and D_6
90° to 150°	D_1 and D_2
150° to 210°	D_2 and D_3
210° to 270°	D_3 and D_4
270° to 330°	D_4 and D_5
330° to 360° and 0° to 30°	D_5 and D_6

Table 3.3 diode Periodic conduction

3.4.4.2 Mathematics analysis

As we said before three Lines voltage equals,

$$v_A = E * \sin(\theta), \quad v_B = E * \sin(\theta - 120^\circ), \quad \text{and} \quad v_C = E * \sin(\theta + 120^\circ)$$

To find v output we should find inter section points between three Lines which equals ,

$$\text{Between LA -LC} = \frac{\pi}{6}, \quad \text{Between LA -LB} = \frac{5\pi}{6}, \quad \text{Between LB -LC} = \frac{3\pi}{2}$$

Then take integration $\sin(\omega t)$ as follows formula,

$$\begin{aligned}
 v_{out} &= \frac{3}{2\pi} \int_{\pi/6}^{5\pi/6} V_m * \sin(\omega t) dt \\
 &= \frac{3 * V_m}{2\pi} \int_{\pi/6}^{5\pi/6} \sin(\omega t) dt
 \end{aligned}$$

$$V_{out} = \frac{3 * \sqrt{3} V_m}{2\pi} \quad (27)$$

3.4.4.3 Project experiment

We will be built the circuit as figure (3.29), then takes variables values of the AC inputs voltage by three phase transformer, then takes measured values of DC outputs voltage by Oscilloscope instrument.

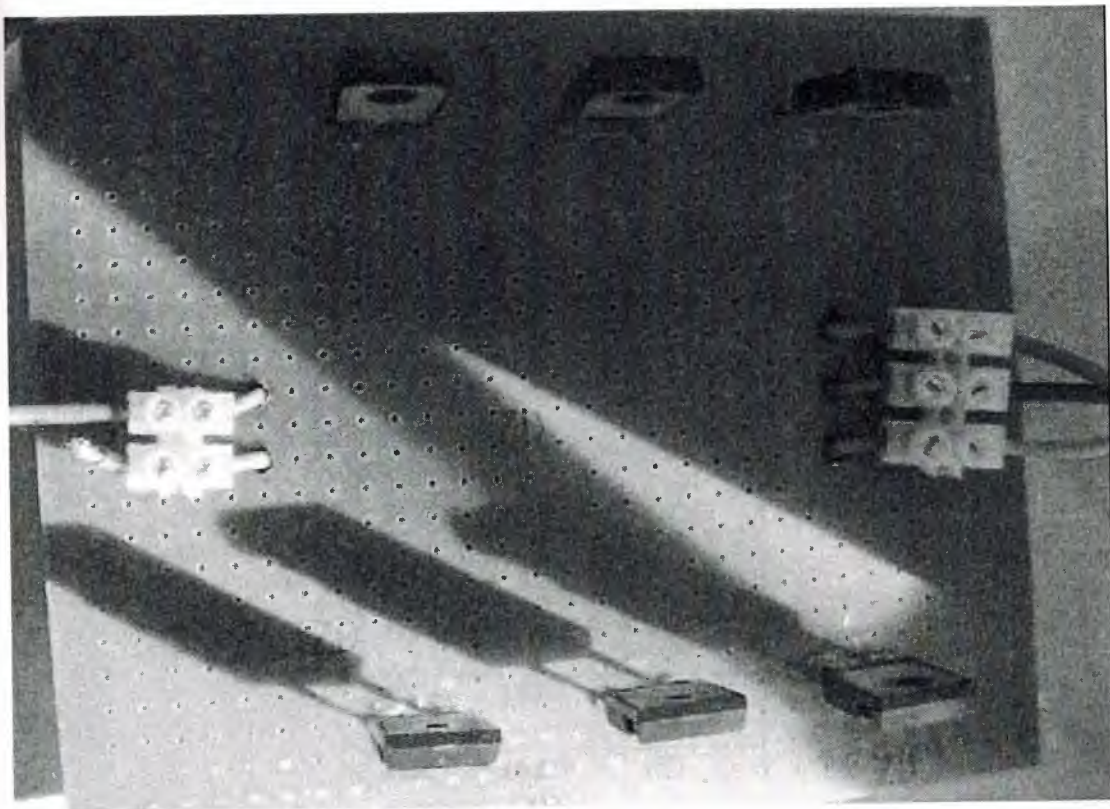


Figure 3.29 practical circuit of Uncontrolled 3 - PH Bridge Diode Rectifier

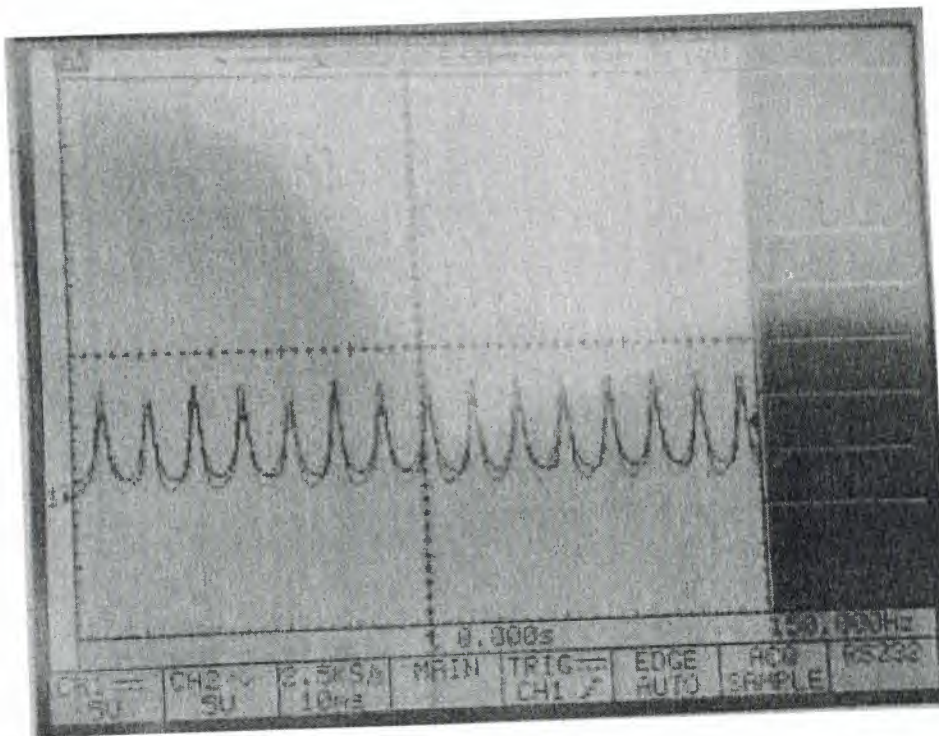


Figure 3.30 output DC voltage experimentally

The measured DC outputs voltages without loads,

V_{in} RMS	V_{in} PEAK	V_{out} DC
80	113	107
93	131	124
107	151	143
115	162.5	157
131	185	174
145	205	191

TABLE 3.4 Results of experiment

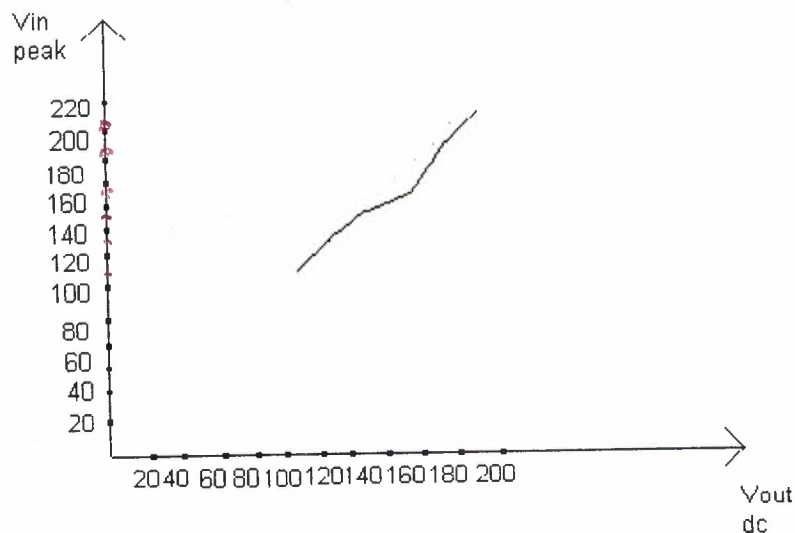


Figure 3.31 relations between in-out voltages

From the figure 3.30 we can see the relation between V_{in} peak and V_{out} ; it is linear by means direct relation if V_{ac} input increased the V_{dc} output will increased also. And from this we can says the value of output dc voltage depend on the how much value of Ac input voltage will supplied.

To gives correct judgment on our experiment we should find the mathematical values then comparing it with measurements values.

V_{in} RMS	V_{in} PEAK	V_{out} DC
80	113	93.5
93	131	108
107	151	125
115	162.5	134
131	185	153
145	205	170

TABLE 3.5 Mathematics results

From tables (3.4 -3.5) we can observe there are some differences in both values, and it is normal case for the following reasons;

- The human reading mistakes
- The instruments measured mistakes
- The losses in circuit

3.4.4.4 Simulate output Using circuit maker

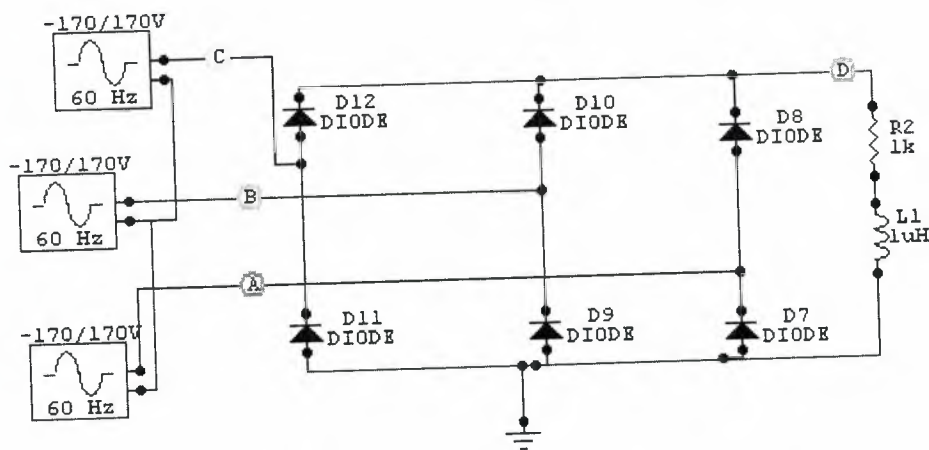


Figure 3.32 simulation UnControlled 3 - PH Bridge Diode Rectifier

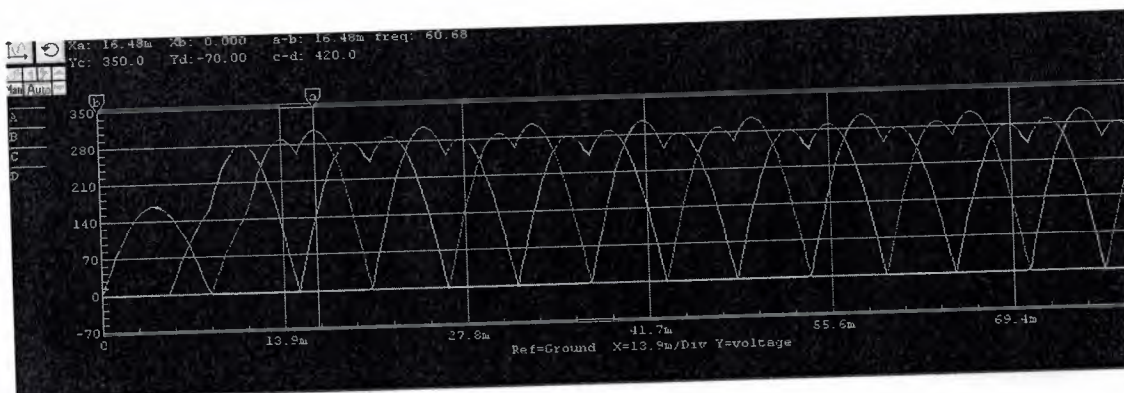


Figure 3.33 simulation output of Uncontrolled 3 - PH Bridge Diode Rectifier

3.5 Rectification efficiency

Rectification efficiency measures how efficiently a rectifier converts AC to DC. It is defined as the ratio of the DC output power to AC input power, where DC output power is a product of the average current and voltage. A simpler way to calculate efficiency is

$$\frac{V_{DC}^2}{V_{AC}^2} \quad (28)$$

Without smoothing, full-wave rectifiers have $\frac{8}{\pi^2}$ or 81% efficiency. Half-wave rectifiers have $\frac{4}{\pi^2}$ or 40.5% efficiency.

And now we can know what efficiency of our circuit by using Rectification efficiency formula (28) as following;

V_{in} peak	DC V_{out}	Rectification efficiency
113	107	0.89
131	124	0.89
151	143	0.89
162.5	157	0.93
185	174	0.88
205	191	0.88

Table 3.6 Rectification efficiency of experiment

From table (3.5) we can consider the Rectification efficiency of experiment equal $\cong 0.89$, it is a good ratio.

3.6 Rectifier output smoothing

While half- and full-wave rectification suffices to deliver a form of DC output, neither produces steady DC. In order to produce steady DC from a rectified AC supply, a smoothing circuit is required. In its simplest form this can be what is known as a reservoir capacitor or smoothing capacitor, placed at the DC output of the rectifier. There will still remain an amount of AC ripple voltage where the voltage is not completely smoothed.

To further reduce this ripple, a capacitor-input filter can be used. This complements the reservoir capacitor with a choke and a second filter capacitor, so that a steady DC output can be obtained across the terminals of the filter capacitor. The choke effectively presents a high impedance to the ripple current.

As the rectifier voltage increases, it charges the capacitor and also supplies current to the load. At the end of the quarter cycle the capacitor is charged to its peak value V_m of the rectifier voltage. Following this the rectifier voltage starts to decrease as it enters the next quarter cycle. This initiates the discharge of the capacitor through the load.

The term 'filter capacitor' usually refers to a capacitor specifically intended to smooth the ripple voltage present in the pulsating DC voltage output of a power supply rectifier.

Sometimes the term merely refers to a capacitor that is part of an electrical or electronic filter circuit.

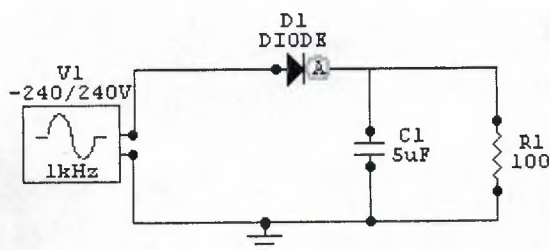


Figure 3.34 half wave diode rectifier with capacitor

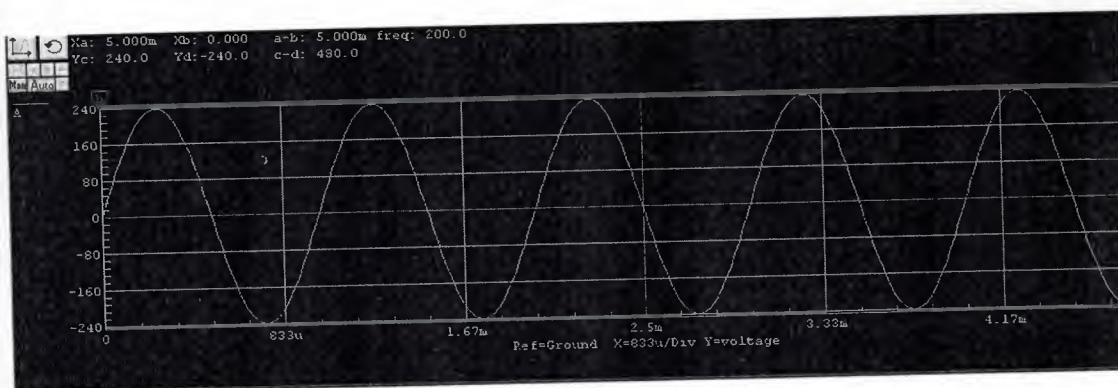


Figure 3.35 input voltage half wave rectifier

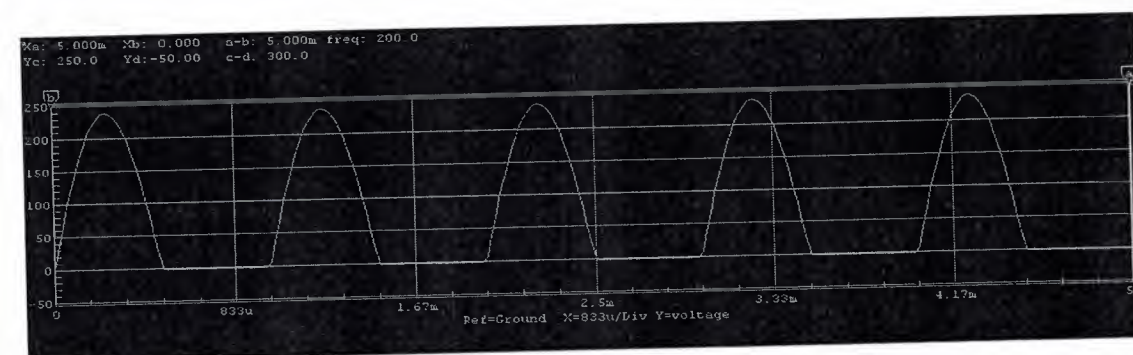


Figure 3.36 output voltage half wave rectifier without capacitor

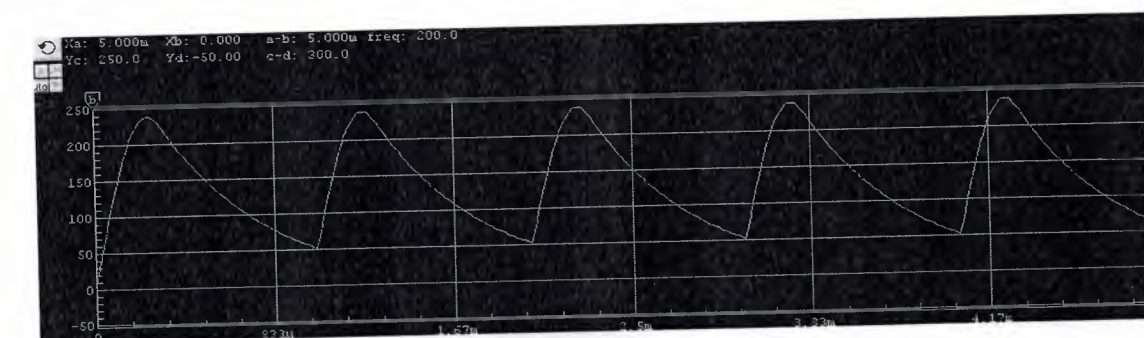


Figure 3.37 output voltage half wave rectifier with capacitor

Conclusions

1. The main task of power electronics is to control and convert electrical power from one form to another.
2. There is different between Diode and Thyristor components in operation which means, diode starts operation directly (switch) but thyristor not directly operation it is wait to take external trigger via gate so we called it controlled device and called un-controlled device for diode.
3. In rectifier operation we should be care for the following;
 - Ripple voltage
 - Rectification efficiency
 - Rectifier output smoothing
4. There are many operations to power electronics in industrial life for example,
 - Frequency converter
 - AC variable speed drives
5. Many power electronic circuits have an electrical machine as their load. In ac variable speed drive, it may be a reluctance motor, an induction motor or a synchronous motor. In a dc variable speed drive, it is usually a dc shunt motor.

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