UNIVERSITY OF NAIROBI

SCHOOL OF ENGINEERING

DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING

DESIGN A THREE PHASE CONTROLLED RECTIFIER FOR USE IN THE LABORATORY

PROJECT INDEX: 116

SUBMITTED BY

MWONGA BRIAN MATOLO

F17/39946/2011

SUPERVISOR: MR. S. L. OGABA

EXAMINER: MR OMBURA

PROJECT REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENT FOR THE AWARD OF THE DEGREE

OF

BACHELOR OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING OF THE

UNIVERSITY OF NAIROBI

DATE SUBMITTED: 17^{TH} MAY 2016

DECLARATION OF ORIGINALITY

NAME OF STUDENT: MWONGA BRIAN MATOLO

REGISTRATION NUMBER: F17/39946/2011

COLLEGE: Architecture and Engineering

FACULTY/SCHOOL/INSTITUTE: Engineering

DEPARTMENT: Electrical and Information Engineering

COURSE NAME: Bachelor of Science in Electrical and Electronic Engineering

TITLE OF WORK: Three Phase Controlled Rectifier For Use In The Laboratory

1) I understand what plagiarism is and I am aware of the university policy in this regard

2) I declare that this final year project report is my original work and has not been submitted elsewhere for examination, award of a degree or publication. Where other people's work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.

3) I have not sought or used the services of any professional agencies to produce this work.

4) I have not allowed, and shall not allow anyone to copy my work with the intention of passing it off as his/her own work.

5) I understand that any false claim in respect of this work shall result in disciplinary action, in accordance with University anti-plagiarism policy.

Signature……………………………………………………………………..

Date……………………………………………………………………………..

CERTIFICATION

The report has been submitted to the Department of Electrical and Information Engineering, University of Nairobi with my approval as supervisor:

Mr. S. L. Ogaba.

Date: ……………………………..

DEDICATION

I dedicate this project to my parents and family for always believing in me and to my friends for their encouragement and support.

ACKNOWLEDGEMENT

I wish to appreciate the Almighty God for His amazing grace throughout my life. His love and guidance has brought me this far to complete my final year project entitled “Three phase controlled rectifier for use in the lab”.

I would also like to take this opportunity to thank all the people who had assisted me directly and indirectly in completing the project. My first gratitude goes to Mr. S.L Ogaba my supervisor for the project whom had given support, advice and Guidance. I am indebted to him for always being there to help me shape the problem and provide insights towards the solution. The progress I have made now would have been impossible without his guidance. I also appreciate the teaching staff and non-teaching staff at the University of Nairobi, Department of Electrical and Information Engineering for their selfless effort that enabled me to achieve my academic goals during the entire course of my studies.

I would also like to thank my friends for their constant encouragement and helpful discussions throughout the course of this work.

Last but not least, I would like to thank my beloved parents who had given me a lot of moral support while I was doing this project.

Once again to all, thank you very much.

ABSTRACT

Three phase AC to DC conversion of electric power is widely employed in adjustable speed drives (ASDs), uninterruptible power supply (UPSs), HVDC systems and utility interfaces with non-conventional energy sources such as electroplating welding units etc, battery charging for electric vehicles and power supplies for telecommunication systems.

The purpose of this project is to successfully convert three phase ac to dc conversion of electric power using SCRs. AC to DC line commutated converters are used as the most usual choice for application. This is due to simplicity of the circuits requiring a minimum number of active and passive components. Thyristors or SCRs are the main line commutated power switches. In this project is built on thyristors and a control or firing system using ATmega328p microcontroller which is used to trigger the three phase full-controlled bridge rectifier.it adopts three synchronization signals; 6-channels trigger pulses from it are very symmetrical and the pulses can be shifted within a cycle of a sine wave from 0 degree to 162 degrees

Its structure of this circuit is simple and consists of the rectifier circuit consisting of the 6-SCRs and the isolation circuit with the protection system, a microcontroller a LCD screen ,synchronization circuits and the control voltage circuit.; its performance is high stable and reliable; Its anti-interference ability is strong and its operation is easy.

A zero crossing circuit attached to the AC lines produces a digital signal to the processor (based on signal zero crossings) that is captured and used to predict the next zero crossing capture time and fire the SCR's based on this prediction. For accuracy and precision, a phase locked loop algorithm is implemented in software that works to improve the accuracy of the next predicted zero crossing and locks to produce the desired output voltage.

Table of Contents

TABLE OF FIGURES

LIST OF ABBREVIATIONS

AC - Alternate Current

DC - Direct Current

SCR - Silicon Control Rectifier

BJT – Bipolar junction transistors

GTO - Gate Turn-Off Thyristors

VCD - Variable speed drive

THDI - Total Harmonic Distortion Current

MOSFET - Metal–Oxide–Semiconductor Field-Effect Transistor

HPF - High Power Factor

ADC – **Analog Digital Converter**

IC - Integrated Circuit

***RF* - Ripple Factor**

***TUF*- Transformer Utilization Factor**

ISR -interrupt service routine

PCINT- Pin change interrupt

MCU-Microcontroller

LCD-Liquid Crystal Display

CHAPTER 1
INTRODUCTION

1.1 Overview

Power electronics refers to control and conversion of electrical power by power semiconductor devices wherein these devices operate as switches Power electronics circuits convert electric power from one form to another using electronic devices. Power electronics circuits function by using semiconductor devices as switches, thereby controlling or modifying a voltage or current. [3]

Power electronics started with the development of the mercury arc rectifier. Invented by peter cooper 1902, it was used to convert alternating current (AC) into direct current (DC).From the 1920's on Uno Lamm developed a mercury valve with grading electrodes making them suitable for high voltage direct current power transmission. . By late 1940 Shockley's invention of the bipolar junction transistor (BJT) improved the stability and performance of transistors, and reduced costs and higher power semiconductor diodes became available and started replacing vacuum tubes.

The invention of the integrated circuit(IC) by J.Kibly from "Texas Instruments" in 1958 followed by the planar process of "Fairchild Semiconductor" in 1959 that became the key solid state electronics. The period of power semiconductors began in 1956, when the silicon controlled rectifier (SCR) was invented by General Electric, greatly increasing the range of power electronics applications.

The introduction of SCRs resulted into significant improvements in semiconductor fabrication technology and physical operation were made and many different types of power semiconductor devices appeared. The growth in power electronics in the last 15 years application has been remarkable because of this introduction of very fast and high-power switching devices, like the metal-oxide semiconductor field-effect transistors (MOSFET), bipolar NPN and PNP transistors, junction transistors and gate turn-off (GTO) thyristors were developed. Later the microprocessors, specified integral circuits and power integral circuits were produced.

In the last 20 years, the growth in power electronics application has been remarkable because of this introduction of very fast and high-power switching devices, coupled with the utilization of state-of –the –art control algorithms. An electric power can be converted from one form to another form by using power electronics devices .The function of power electronics circuits by using semiconductor devices as switch is modifying or controlling a voltage. The goal of power electronics circuits are to convert electrical energy from one form to another, from source to load with highest efficiency, high availability and high reliability with the lowest cost, smallest size and weight and are hence called converters. They serve as interface between source and load. Converters are classified by the relationship between input and output.

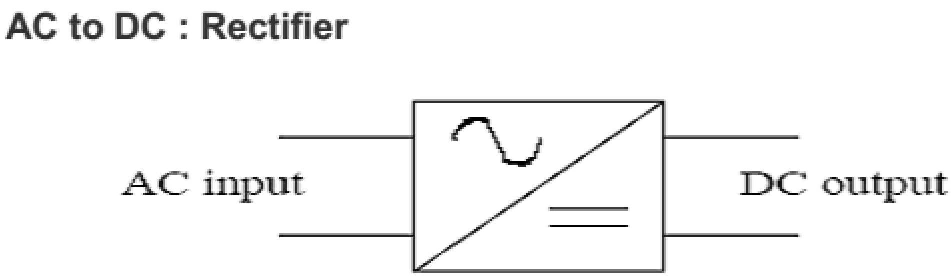


Figure 1: Rectifier

AC to DC converters- Rectifiers that transform ac to DC with adjustment of voltage and current

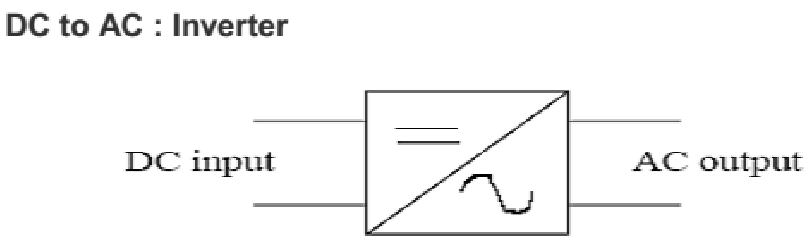


Figure 2: inverter

DC to AC converters- inverters that produce AC of controllable magnitude and frequency, particularly with galvanic isolation via a transformer

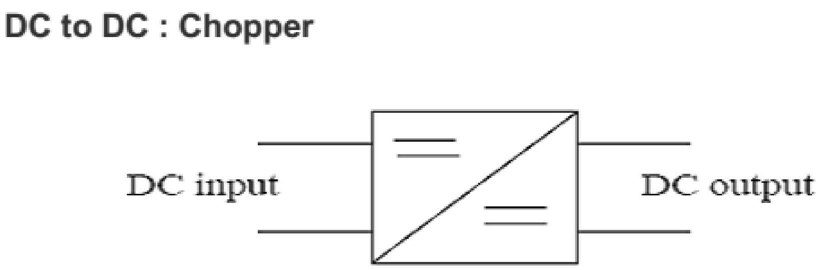


Figure 3: Chopper

DC to DC converters -conversion of an unregulated dc voltage to a regulated dc voltage, linear regulators and switching choppers.

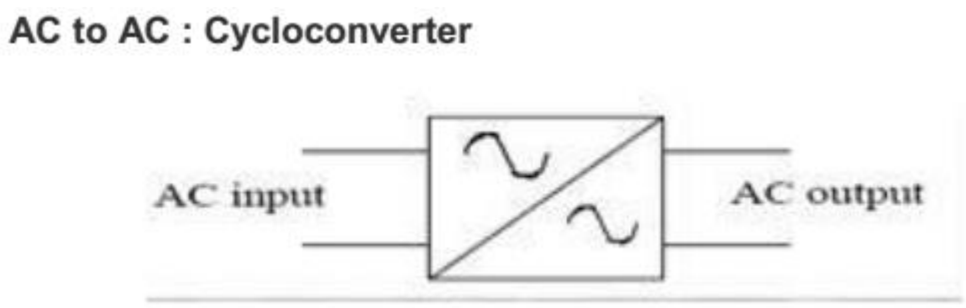


Figure 4 cycloconverter

AC to AC converters-conversion of an AC power source from one amplitude and frequency to another amplitude and frequency

1.2 background

Power electronic converters can be found wherever there is a need to modify a form of electrical energy (i.e. change its voltage, current or frequency). The power range of these converters is from some milliwatts (as in a mobile phone) to hundreds of megawatts (e.g. in a HVDC transmission system). With classical electronics, electrical currents and voltage are used to carry information, whereas with power electronics, they carry power. Thus, the main metric of power electronics becomes the efficiency. The first very high power electronic devices were mercury arc valves. In modern systems the conversion is performed with semiconductor switching devices such as diodes, thyristors and transistors. In contrast to electronic systems concerned with transmission and processing of signals and data, in power electronics substantial amounts of electrical energy are processed. An AC/DC converter (rectifier) is the most typical power electronics device found in many consumer electronic devices, e.g. television sets, personal computers, battery chargers, etc. The power range is typically from tens of watts to several hundred watts. In industry the most common application is the variable speed drive (VSD) that is used to control an induction motor. The power range of VSDs start from a few hundred watts and end at tens of megawatts. Power electronics refers to control and conversion of electrical power by power semiconductor devices wherein these devices operate as switches. Advent of silicon-controlled rectifiers, abbreviated as SCRs, led to the development of a new area of application called the power electronics. Prior to the introduction of SCRs, mercury-arc rectifiers were used for controlling electrical power, but such rectifier circuits were part of industrial electronics and the scope for applications of mercury arc rectifiers was limited. Once the SCRs were available, the application area spread too many fields such as drives, power supplies, aviation electronics, high frequency inverters and power electronics originated.

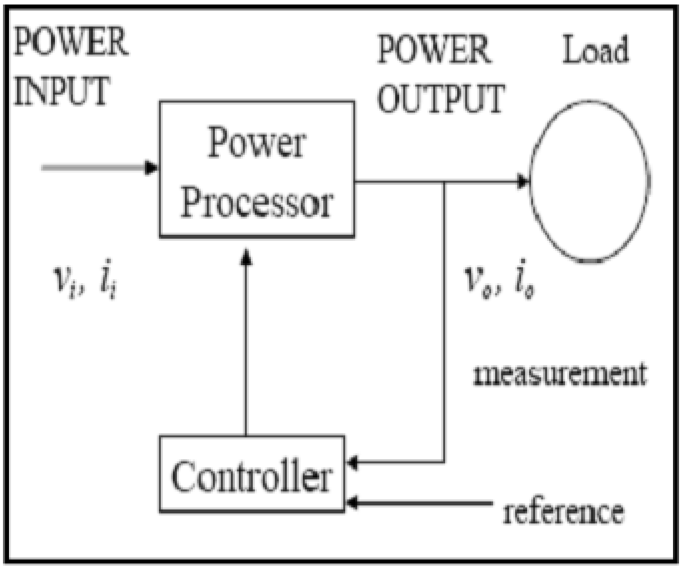


Figure 5 :power electronics interface between the power processor and controller

1.3 Objectives

The first objective of this project is to design a three phase controlled rectifier circuit to convert three phase 110V AC input voltage to DC output voltage.

The second objective is to develop a hardware of three phase controlled rectifier with line input voltage of 110v using six SCRs to convert AC input to a DC output depending on the firing angle of the SCRs and a control circuit for firing angle to range between 0 ̊ to 160 ̊ degrees varying the DC output voltage and can be used by students in the lab to study.

1.4 Scope

This project concentrates on design of circuit and development of hardware to get a DC output at a three phase AC input. The three phase controlled rectifier uses six SCRs with protective circuits and filter circuits in the rectifier circuit and AVR Atmega328p microcontroller and a synchronizing circuit (zero crossing detector circuit) in the control circuit. Besides the scope is to program a microcontroller to control delay angle alpha 0 ̊ to 160 ̊ to rectifier AC voltage DC voltage.

To develop the whole project, it consists of three methods which are the concept of switching, electrical structure, and the software programming.

After designing and building completely the rectifier circuit, the driver circuit should be able to control the delay angle α. The delay angle will be adjusted by using microcontroller AVR Atmega328p. It will involve the programming development to control the ON state of the SCRs and adjust the phase angle. Here, the trigger angle of SCRs will be programmed in certain time sequence to ensure the input voltage goes from low to full voltage on which the circuit is to be connected to different loads or supply dc voltage.

1.5 problem statement

A rectifier is a power electronic circuit converter that converts bidirectional AC voltage to unidirectional DC voltage by using power diodes or by controlling the firing angle of thyristors or controllable switches. Rectification is of two forms uncontrolled rectification where there is use of power diodes and controlled rectification by use of thyristors or controllable switches.it can be either single phase or three phase and this depends on the input. A diode is the simplest electronic switch. It is uncontrollable in that the on and off conditions are determined by voltages and currents in the circuit. The diode is forward-biased (on) and reverse-biased (off).

AC to DC converter is mostly used in industries and also in domestic equipment.ac voltage from generators are variable hence provide variable dc if uncontrolled AC-DC converter is used, this variable DC is not suitable to be used in the lab for voltage supply purposes .

To overcome this problem the output of the voltage of the rectifier need to be controlled. In the design of the three phase rectifier thyristors or SCRs (Silicon Control Rectifier) are connected in full wave rectifier. Thyristors are electronic switches used in power electronic circuits where control of switch turn-on is required and controlled by a control system for which the output voltage can be varied by the user to desired voltage. Power converter system was designed using modern technology and methods to implement a three phase fully-controlled rectifier.

1.6 Project Report outline

This project report is structured into five chapters and every chapter elaborates into details more about this chapter.

Chapter one is the introduction of this project which gives the overview of this project. Converters of power by providing background information. The three phase controlled rectifier ac to dc converter is discussed including the objectives, scope and problem statement as a guide to develop the three phase controlled rectifier.

The second chapter is composed of the literature review of the three phase controlled rectifier.it discusses the previous research done by others and the comparison with the relevance the research. Discussion of the books and papers that are used in the reference and the shortcomings of the previous research.

Chapter three explains and discusses on the methodologies of the three phase controlled rectifier that has been used and applied in the design and development of the hardware.it also consists of block diagram, flow charts and circuit diagrams which are explain the process of implementation and how the three phase AC voltage converts to DC voltage then connected to the different loads.it also discusses how the outputs voltage can be varied.

The fourth chapter is discussing and displaying all the results obtained, the analysis of the results and the limitations encountered in the project.

Chapter five will discuss on the conclusion and summary of the development of the three phase controlled rectifier project. In this chapter also discusses on the recommendation for this project development or modification.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents an overview of rectifier, the projects that have been made from various sources like journals, books, articles and others. From the literature review the input that has been collected is useful for better understanding of this project. It is because for nearly a century, rectifier circuits have been the most common power electronics circuits used to convert AC to DC. The AC-DC converter produces a DC output from an AC input while the average power transferred from an AC source to a DC load.

A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction to direct current (DC). The word rectification is used not because these circuits produce DC but rather because the current flows in one direction. Rectifiers have many uses including as components of power supplies and as detectors of radio signals. Rectifiers may be made of solid state diodes, vacuum tube diodes, mercury arc valves, and other components.

Rectifiers are used as stand-alone units feeding single and multiple dc loads and as input stages of ac systems because of their virtually unlimited output electromechanical transients occurring in motor drives and power suppliers.AC/DC line –commutated converters or called natural commutation or passive rectifiers, are the most usual choice for applications, where a single phase and three phase supply is available. This is due to circuits requiring a minimum number of active and passive components. Thyristors are the main line-commutated power switches. Line commutation is the transfer of current from one conduction element to the next, as a function of the mains voltage .to turn on a thyristors an injection of a current pulse into its gate is required.

In low power applications, vehicle, medicine and household devices where there is no ac supply or where reactive current and harmonics caused by line commutation would be unreachable we employ forced commutated converters having a more complex circuitry and involving higher losses sometimes. For this purpose active rectifiers are developed.

Three-phase controlled rectifiers have a wide range of applications, from small rectifiers to large High Voltage Direct Current (HVDC) transmission systems. They are used for electro-chemical process, many kinds of motor drives and speed control, traction equipment, controlled power supplies, and many other applications.

From the point of view of the commutation process rectifier circuits are divided broadly into two types of AC-DC converters which are half-wave rectifiers and full-wave rectifiers, half-wave describes the current in each a.c line is unidirectional .The full-wave circuits are which are in effect two half-wave circuits in series, one feeding into the load the other returning load current directly to the a.c lines eliminating the need of a.c neutral, the full-wave are commonly called bridge circuits alternatively double-way circuits. Which then are further subdivided into uncontrolled, semi-controlled and fully controlled. The input of these converters can be single phase or multi-phase (3 phase). The systems built on diodes are the uncontrolled rectifiers since the output cannot be changed while the controlled rectifiers are those built on thyristors and power transistors their dc output can be changed. The fully-controlled are referred as bidirectional converters as it permits power flow in either direction between supply and load. The semi-controlled rectifiers contain a mixture of thyristors and diodes which prevent a reversal of load voltage but do allow adjustment of the direct (mean) voltage level. The semi-controlled and uncontrolled (diodes only) are called unidirectional converters as they permit power flow only from a.c supply to d.c load.

They are further divided according to their inputs either single –phase or multiple (three) phase. Pulse-number is a manner of describing the outputs characteristics of a given circuit and defines the repetition rate in the direct voltage waveform over one cycle of the a.c supply.

2.2 Theory of rectifiers

- **Half-wave rectifier**
    - Uncontrolled rectifiers
        - Single phase uncontrolled rectifiers
        - Three phase controlled rectifiers
    - Controlled rectifiers
        - Single phase controlled rectifiers
        - Three phase controlled rectifiers
- **Full-wave rectifier**
    - Uncontrolled rectifiers
        - Single phase uncontrolled rectifiers
        - Three phase controlled rectifiers
    - Controlled rectifiers
        - Single phase controlled rectifiers
        - Three phase controlled rectifiers

Assumption made is all voltages at the input of the rectifiers have sinusoidal waveforms with period *T*mains = 20 ms (corresponding to *f*mains = 50 Hz). With the usual definition

$\omega = 2\pi f = \frac{2\pi}{T}$

Uncontrolled rectifiers can be classified based on the type of input power supply as
• Single phase uncontrolled Rectifiers which operate from single phase ac input power supply and they are further subdivided into different types

• Half wave uncontrolled rectifier which uses a single diode device

• Full wave uncontrolled rectifiers

Half wave uncontrolled rectifier which uses a single diode device (which provides output one half cycle of input ac supply, and it provides low dc output).Full wave uncontrolled rectifiers (which provide higher dc output).
Full wave controlled rectifier using a center tapped transformer (which requires two diode).

• Single phase controlled Rectifiers which operate from single phase ac input power supply and they are further subdivided into different types

• Half wave controlled rectifier which uses a single diode device

• Full wave controlled rectifiers

Half wave controlled rectifier which uses a single thyristor device (which provides output control only in one half cycle of input ac supply, and it provides low dc output).Full wave controlled rectifiers which provide higher dc output.

Single phase semi-converter (half controlled bridge converter, using two SCR's and two diodes, to provide single quadrant operation).Single phase full converter (fully controlled bridge converter which requires four SCR's, to provide two quadrant operation. Full wave controlled rectifiers which provide higher dc output.
Full wave controlled rectifier using a center tapped transformer which requires two thyristors.

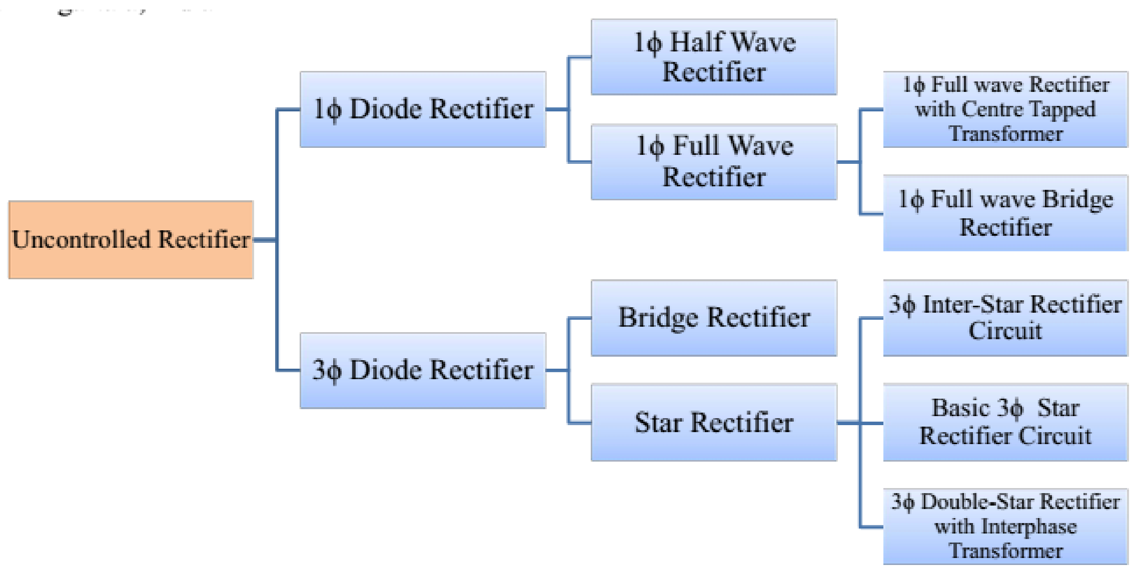


Figure 6:uncontrolled rectifier and sub divisions

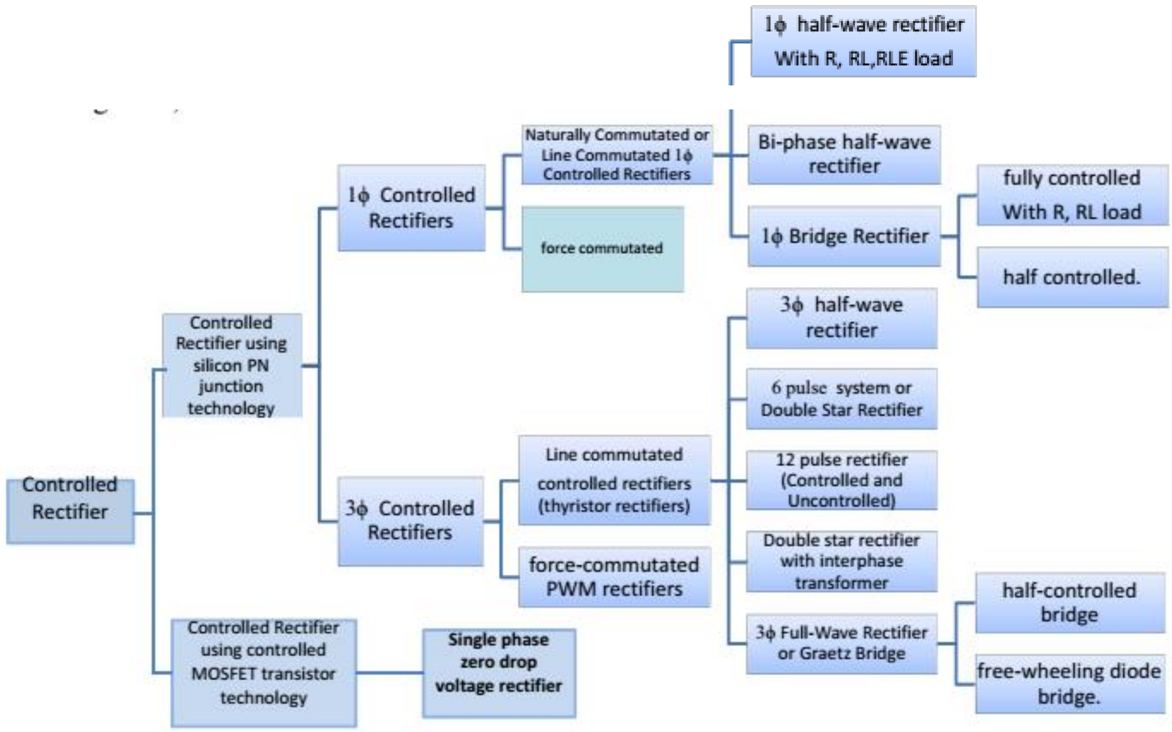


Figure 7 : controlled rectifier and sub divisions

2.2.1 Single-Phase Rectifiers

In applications, the DC voltage from the rectifier is connected to a DC bus for distribution to several different circuit systems, subsystems and other converters as loads. In other applications, the rectifiers also supply power to inductive-resistive (motors) and capacitive-resistive (power supplies) loads.

2.2.1.1 Single-Phase uncontrolled Half-Wave Rectifiers

A single-phase uncontrolled half-wave rectifier consists of a single diode .It produces an output waveform that is half of the incoming AC voltage waveform. The positive pulse output waveform shown in Figure.8 occurs because of the forward-bias condition of the diode. Over the negative portion of the input waveform, the diode is reverse biased ideally so no current flows. Thus, the output waveform is zero or nearly zero during this portion of the input waveform. By using diode, the DC level of the output and the power transferred to the load are fixed when the source and load parameters are established. It produces an output waveform that is half of the incoming AC voltage waveform as shown im

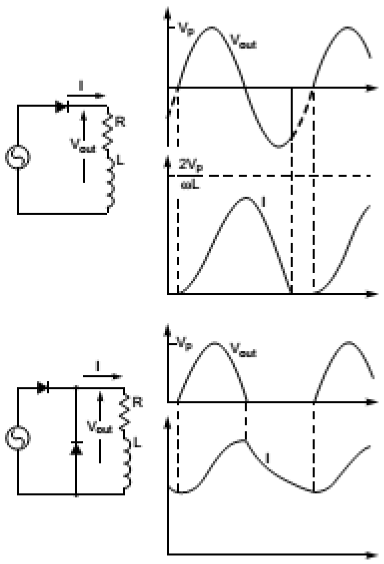


Figure 8: Single-phase half wave diode rectifier-R/L Load

$$V_{ave} = \frac{\omega}{2\pi}\int_0^{\frac{\pi}{\omega}} V_p \sin \omega t \, dt = \frac{V_p}{\pi}$$

(2.1)

$$I_{ave} = \frac{V_p}{\pi R}$$

(2.2)

2.2.1.2 Single-Phase controlled Half-Wave Rectifiers

Unlike the diode, the silicon controlled rectifier (SCR) will not to begin to conduct as soon as the source becomes positive . Gate trigger current is the minimum current required to switch silicon controlled rectifiers from the off-state to the on-state at the specified off-state voltage and temperature. Once the SCR is conducting, the gate current can be removed and the SCR remains on until the current goes to zero . Figure 9 shows a basic controlled half-wave rectifier.

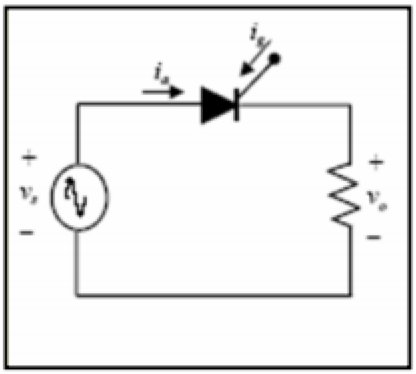


Figure 9: A basic half wave controlled rectifier

2.2.1.3: Single Phase Full-Wave Rectifiers

A single-phase full-wave rectifier consists of four diodes arranged as shown in figure 10 and figure 11 are a bridge rectifier and the center-tapped rectifier. This rectifier circuit produces an output waveform that is the positive half of the incoming AC voltage waveform and the inverted negative half.

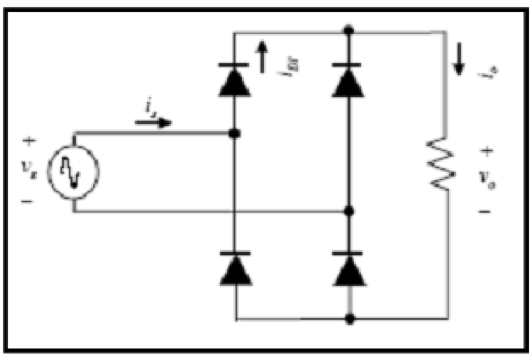


Figure10 a: The Bridge Rectifier

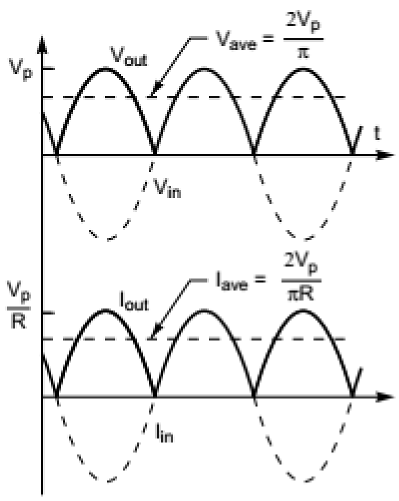


Figure 10 b: single diode rectifier waveforms

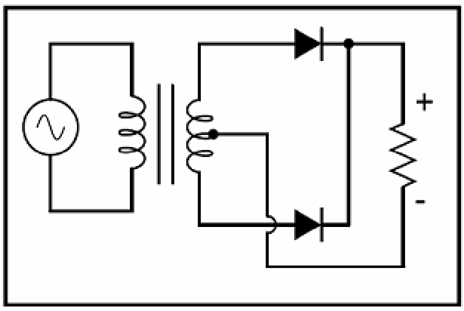


Figure 10 c: The center-Tapped Transformer rectifier

The output voltage of single phase uncontrolled rectifier in eqn(2.3)

$$RI_{ave} = V_{ave} = \frac{\omega}{\pi}\int_{0}^{\frac{\pi}{\omega}} V_p \sin \omega t \, dt = \frac{2}{\pi} V_p \tag{2.3}$$

The lower peak diode voltage in the bridge rectifier which consists of four diodes arranged makes it more suitable for high-voltage applications. Thus, the center-tapped transformer rectifier in addition to including electrical isolation has only one diode voltage drop between the source and load making it desirable for low-voltage and high current applications.

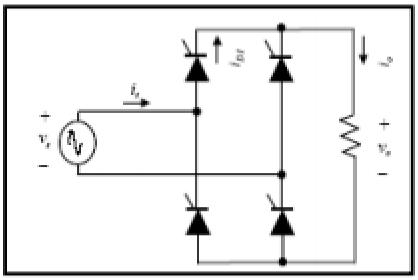


Figure 11: a full wave controlled bridge rectifier

Similar to the diode bridge rectifier topology, a versatile method of controlling the output of a full-wave rectifier is to substitute controlled switches such as SCRs for the diode. Because of their unique ability to be controlled, the output voltage and hence the power can be controlled to desire levels. The triggering of the thyristor has to be synchronized with the input sinusoidal voltage in an AC to DC rectifier circuit. The delay angle α is the angle interval between the forward biasing of the SCR and the gate signal application Otherwise, if the delay angle is zero, the rectifiers behave exactly like uncontrolled rectifiers with diodes. Figure 11 shows a basic controlled full-wave rectifier.

$$V_d(\alpha) = \frac{2V_p}{\pi} cos\alpha \tag{2.4}$$

2.2.2 Three Phase Rectifiers

Three phase rectifiers are commonly used in industry to produce a DC voltage and current for large loads.In industrial applications, where three-phase AC voltages are available, three phase rectifiers are favorable. At the output of this type of rectifier compared to the single-phase rectifiers, the DC component is higher, the ripple of the output voltage is lower, and the output power is higher. Like single phase rectifiers, three phase rectifiers also have two types that are uncontrolled and controlled.

Three phase rectifiers are more commonly used because of the following reasons:

i. Three phase AC power is readily available.
ii. It is economical to provide DC supply to DC motors of capacity 20kW and more from a three phase rectifier rather than single phase.
iii. The ripple frequency of the output current of the three phase rectifiers is higher than that for single phase ones.

2.2.2.1 Three phase half-wave uncontrolled rectifiers

The use of single-way configurations one diode per phase, each diode is conducting while the others are blocked becomes more convenient as the number of phases increases. The figure 2.8 shows a single way configuration.

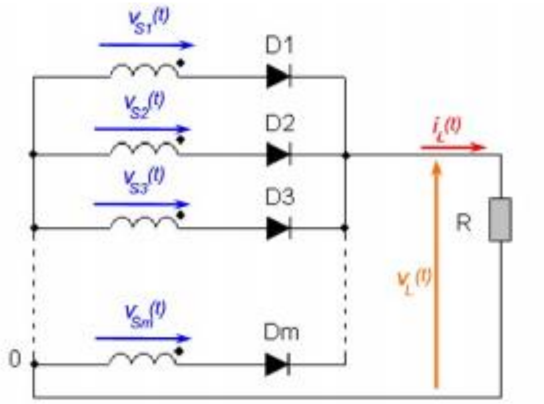


Figure 12: single way rectifier

Figure 13 shows the waveforms of the phase voltages (in this example m = 3) and of the current in the load. Each phase voltage has the same amplitude (VS) and the same frequency. There is a phase displacement of $2\pi/m$ electrical radians between one voltage and the next. In one period there is a specific number of peaks (usually called pulses), depending on the number of phases and on the structure of the rectifier. The number of pulses in a period is indicated by p.

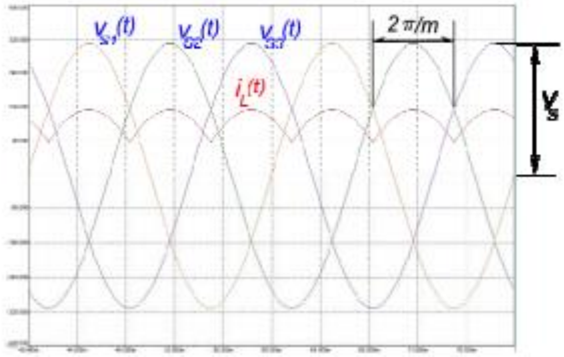


Figure 13: waveforms for the number of pulses of single way rectifier

2.2.2.2 Three phase full wave uncontrolled rectifiers

Three phase full-bridge rectifier use diodes as switch. A simplified circuit by assuming an idealized drive and by replacing a real load by a current generator. Due to neglecting the series inductances of the driving generators, three phase rectifier divides into two groups which are top group and bottom group. For top group, diode with its anode at the highest potential will conduct at one time. The other two will be reversed. Thus for bottom group, diode with its cathode at the lowest potential will conduct. The other two will be reversed. Figure 2.15 a shows the phase voltage and the resulting combinations of line-to-line voltages from a balanced three phase source. The output voltage is equal to the difference of the voltages at the points P and N compared to the neutral point n,

$$Vo = Vpn - VNn \qquad (2.5)$$

Since one diode of the upper group and one diode of the lower group are always conducting, the voltages VPn and VNn are equal to one of the AC voltages Van,Vbn or Vcn . So, the output voltage follows in turn six sinusoidal voltage during one cycle as shown in Figure 14 b these been $Va - Vb, Va - Vc, Vb - Vc, Vb - Va, Vc - Va, Vc - Vb$ all having the maximum value of the line voltage that is √3 times the phase voltage and for this reason, these rectifiers are often called the six-pulse rectifiers. The output voltage during one cycle practically consists of six sinusoidal peaks thus its ripple is small and the average value is close to the amplitude of the line voltages. The phase currents are determined by

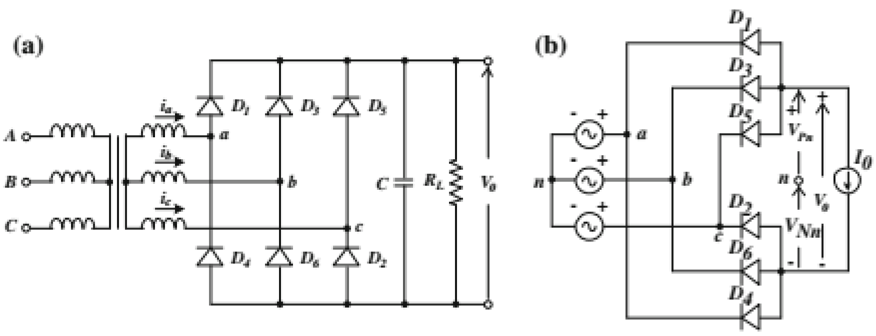


Figure 14: Three - phase bridge rectifier (a) and (b) it's ideal equivalent circuit

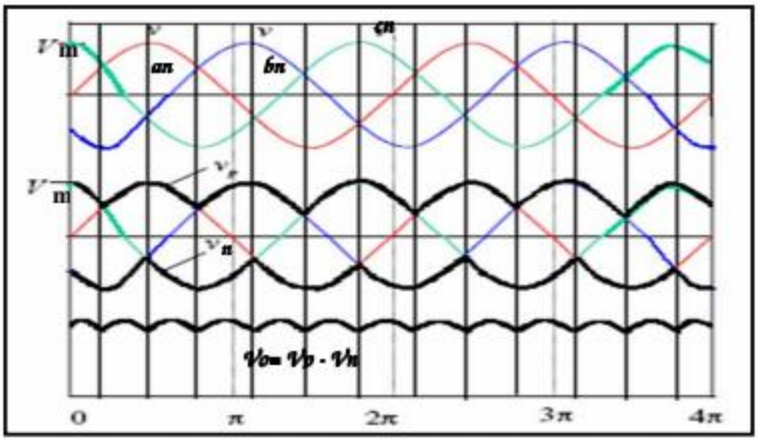


Figure 15(a): source and output voltage

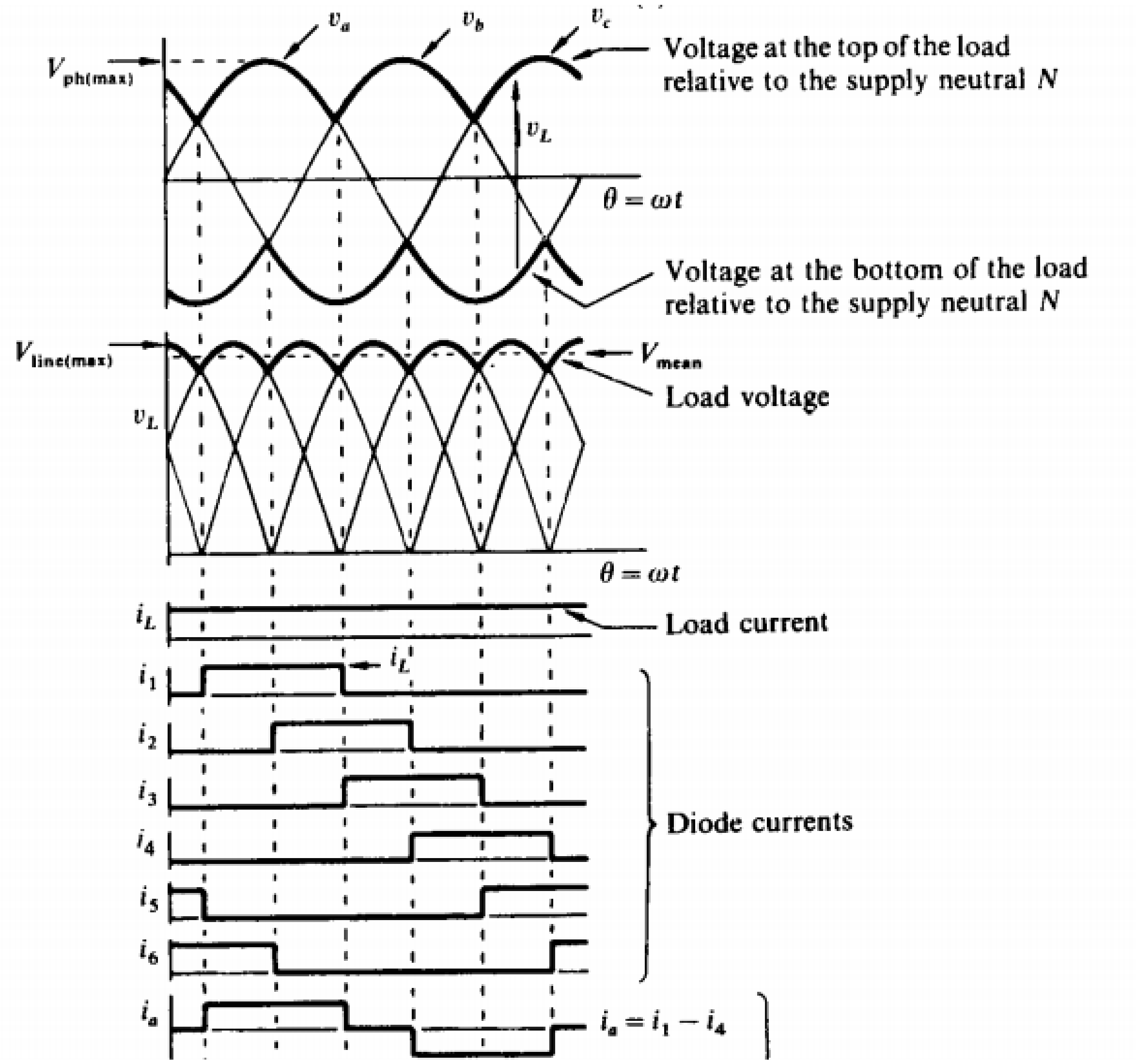


Figure 16 b: waveforms of voltages and current of a three phase rectifier operating in the constant load current mode

The maximum reverse voltage of a diode is equal to the amplitude of the line voltage. The output voltage is cyclic with the cycle π/3. The corresponding Fourier series is

$$v_o(t) = V_0 + \sum_{n=6,12,18}^{\infty} V_n \cos(n\omega_0 t + \pi), \tag{2.6}$$

Where the average value is

$$Vavr = 2 \times \frac{3\sqrt{3}}{2\pi} \text{ Vph (max)} \tag{2.7}$$

Or calculated from the six-pulse load voltage waveform which is

$$Vmean = \frac{3}{\pi} Vline(max) \tag{2.8}$$

Therefore, the average value of the output voltage is approximately equal to the amplitude of the line voltage, $Vline(max)$

The diode current waveforms shown in figure 2.11b reveal that each diode conducts the full-load currents for one third of a cycle that is $\frac{\pi}{3}$ *of the cycle*, the order of commutation determining the numbering of the diodes in circuit. Each diode conducts during 120°. They conduct in pairs (6, 1), (1, 2), (2, 3), (3, 4), (4, 5), (5, 6), and (6, 1). Diodes turn on in the sequence 1, 2, 3, 4, 5, 6, 1…

2.2.2.3 Three phase Controlled Rectifiers

Similar to single phase controlled rectifier, the output of the three phase rectifier can be controlled by replacing the diodes with thyristors (SCRs). Figure. 17 a shows the controlled six-pulse three phase rectifier. Thyristor is a device whose transition from the blocking to the conducting state depends not only on the polarity of the anode–cathode voltage as for diodes, which are naturally commutating devices but is also controlled via the application of an adequate current pulse at the gate terminal. Thyristors have three terminals the trigger pulse is applied to the gate while the anode–cathode voltage is positive. The difference in the principle of operation is that the diodes are conducting when forward biased and the thyristors conducts if a triggering pulse is present in the gate circuit together with the forward bias, this is the way of controlling the angle of conduction and consequently the average value of the output voltage. Thus, the transition of the output voltage to the maximum instantaneous line-to-line source voltage can be delayed. The delay angle α is the interval between when the SCR becomes forward-biased and when the gate signal is applied.

In this circuit there is a problem which is the one of starting .when connected to the three phase a.c. supply firing gate pulses will be delivered to the thyristors and it must be in the correct sequence but if only a single firing gate pulse is used no current will flow as the other thyristor in the current path will be in the off-state. In order to start the circuit functioning two thyristors must be fired at the same time in order to commence current flow. From the supply of three phase when Va is at its peak value or its more positive the next firing pulse will be to thyristor T2 however thyristor T2 will not conduct unless at the same time T1 is pulsed. Reference to the waveforms shown in fig.17 b this shows that there are two thyristors conducting at that instance. Hence for starting purposes the firing circuit must produce a firing pulse 60° after its first pulse .Once the circuit is running normally the second pulse will have no effect as the thyristor will already be in the on-state.

The starting pulse can be fed to the thyristors by two methods;

i. Each firing circuit having two isolated outputs one to its own thyristor and the other to the previous thyristor.
ii. The circuit can be electronically linked so that when each firing circuit initiates a pulse to its own thyristor it also does likewise to the previous firing circuit.

A large firing delay causes the load voltage to have negative periods as shown in figure 17 .c and makes it difficult to visualize the load voltage waveform from the two three-phase pictures hence the six-line voltages $Va - Vb, Va - Vc, Vb - Vc, Vb - Va, Vc - Va, Vc - Vb$ gives a direct picture of the load voltage waveforms and clearly shows that zero mean voltage is reached when firing delay angle is 90°. Equation (2.4) is valid when the condition of continuous conduction that is the instantaneous voltage at the DC terminals is at all times positive is satisfied. For delay angles beyond 60 degrees the instantaneous voltage at the DC terminals goes to zero and negative if the load has an inductive component and the current does not flow continuously anymore.

The average output voltage is determined by

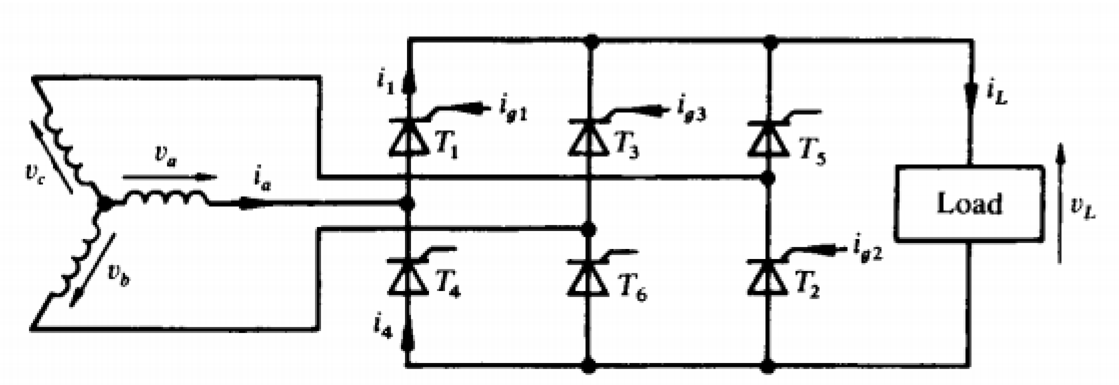
$$\boxed{V_o = \frac{1}{\pi/3}\int_{\pi/3+\alpha}^{2\pi/3+\alpha} V_{m,L-L}\sin(\omega t)\, d(\omega t) = \frac{3V_{m,L-L}}{\pi}\cos\alpha} \quad \boldsymbol{for\ 0 < \propto < \pi/3} \qquad (2.9)$$

Equation (2.4) shows that the average output voltage is reduced as the delay angle increases.

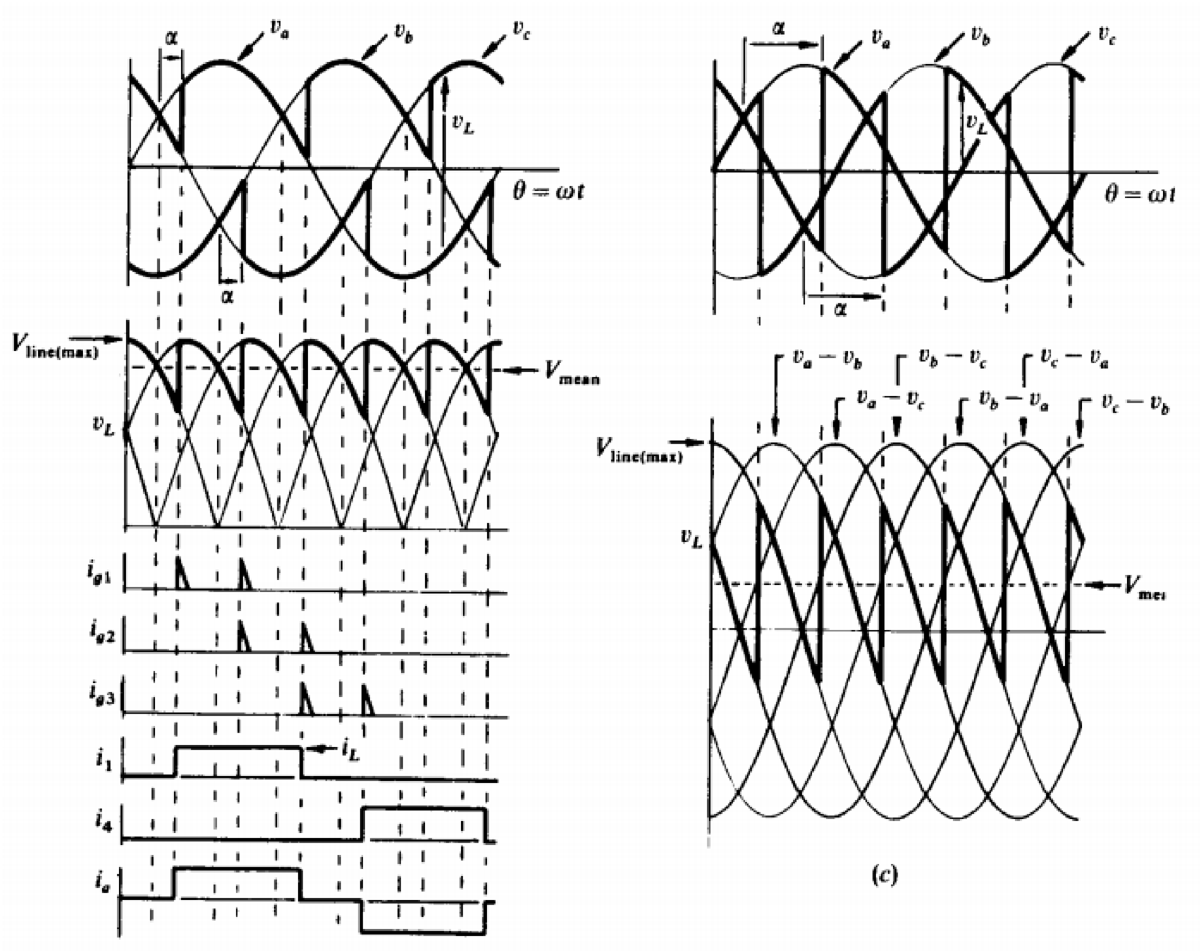
Compared to Vo of the three-phase diode rectifier the factor cosα is present here. If the angle of triggering is greater than π/3 (α > π/3), the rectifier operates in the discontinuous mode of the load current. Then the average value of the output voltage is determined by

$$V_o = \frac{1}{\pi/3}\int_{\pi/3+\alpha}^{\pi} V_{LLM}\sin(\omega t)\mathrm{d}(\omega t) = \frac{3V_{LLM}}{\pi}[1+\cos(\pi/3+\alpha)].$$

$$\boldsymbol{for\ \pi/3 < \propto < 2\pi/3} \qquad (2.10)$$



(a)



(b)

Figure 17: (a) fully-controlled three phase bridge ciruit, (b) the output voltage waveforms with small fring angle and (c) with large firing angle

2.3 Thyristor commutation — effect of the AC input reactance

The commutation of real devices is not instantaneous. Turning on and off a diode or a thyristor takes a finite time. Taking into consideration the thyristors only, turning off occurs when the anode current goes below holding current *I*h. In addition to the finite turn off time, the inductance of the line and of the secondary of the transformer plays an important role in rectifier operation. The commutation between the phases takes a finite time, during which the two phases involved are almost shorted. This time (electrical angle) is called commutating or overlapping time (angle) and it is usually indicated as μ□□during the transition from phase B to phase A, both thyristors T2 (which is turning off) and T1 (which is turning on) are conducting at the same time. The current *i*sc is limited, in practice, by the impedance seen at the AC input of the rectifier, here indicated as LS.

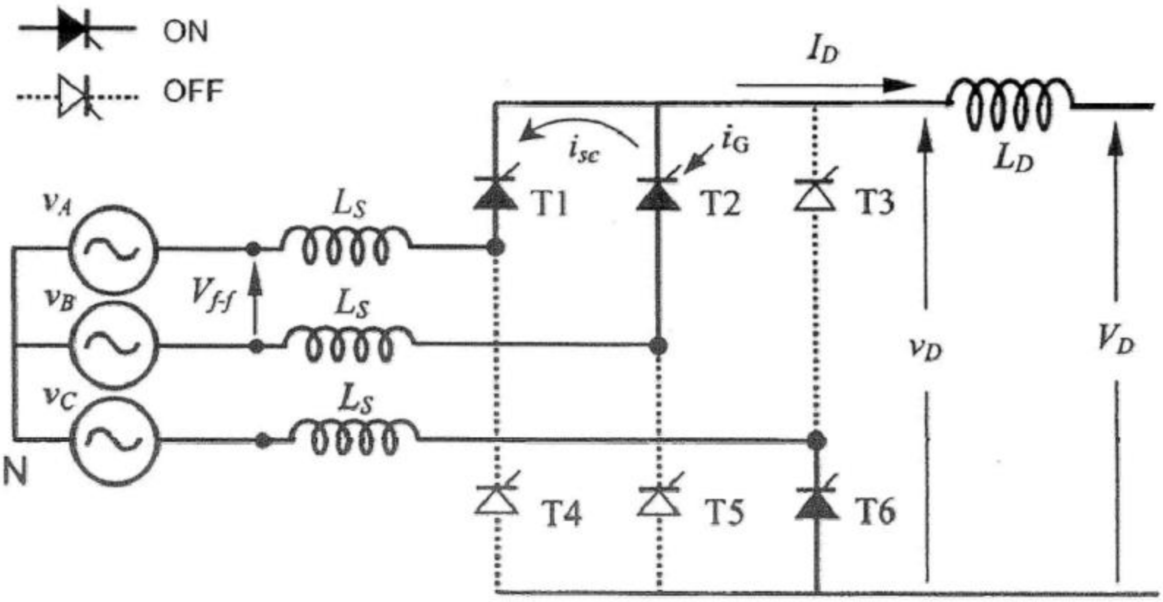


Figure 18: Commutation of thyristor from one phase to another

Assuming the *dc* current *ID* to be smooth, and with the help of figure 18, the following relation is deducted:

$$2L_S \cdot \frac{di_{sc}}{dt} = \sqrt{2} \cdot V_{f-f} \sin\omega t = v_A - v_B \qquad (2.20)$$

where *isc* is the current in the valve being fired during the commutation process (thyristor T2 in figure 18). This current can be evaluated, and it yields:

$$Isc = \frac{\sqrt{2}}{2Ls}.Vf - f\frac{cos\omega t}{\omega} + C \qquad (2.11)$$

The constant "C" is evaluated through initial conditions at the instant when T2 is ignited. In terms of angle, when wt=α:

Where wt=α, $Isc = 0$

Therefore

$$C = \frac{Vf-f}{2Ls}.cos\ \alpha \qquad (2.12)$$

During the commutation time, the load current *ID* remains constant, *isc* returns through T1, and T1 is automatically switched-off when the current *isc* reaches the value of *ID*. This happens because thyristors cannot conduct in reverse direction. At this moment, the overlap time lasts µ, and the current *ID* is then conducted by T2. In terms of angle:

$\omega\, t=\alpha+\mu, \quad i_{sc}=I_D$

For a given direct current ID and the corresponding delay angle □ it can be calculated from the following equation:

$$I_D = \frac{V_{f\text{-}f}}{\sqrt{2}\cdot\omega\cdot L_S} \cdot [\cos(\alpha) - \cos(\alpha+\mu)]$$
(2.13)

The fact that during the commutation time two switches are conducting at the same time creates short circuit and a reduction in the rectified voltage (vD) and in its average (VD). The reduction in
the DC voltage by an amount ΔVmed in Figure. 2.15.

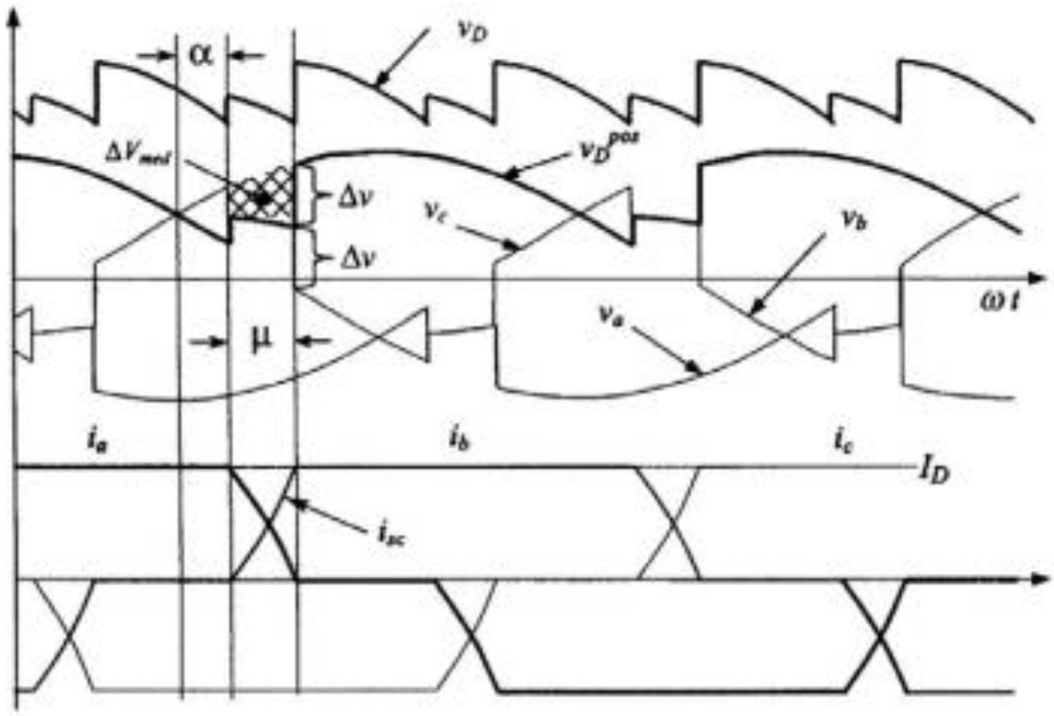


Figure 19: Effect of the overlap angle on the voltage and currents

The area $\Delta Vmed$ showed in figure 19 represents the loss of voltage that affects the average voltage VC, and can be evaluated through the integration of Δv during the overlap angle μ. The voltage drop Δv can be expressed as:

$$\Delta v = \left(\frac{v_A - v_B}{2}\right) = \frac{\sqrt{2}\cdot V_{f-f}^{sec}\sin\omega t}{2}$$
(2.14)

Integrating eq. (2.14) into the corresponding period (60°) and interval (μ), at the instant when the commutation begins (α):

$$\Delta V_{med} = \frac{3}{\pi}\cdot\frac{1}{2}\int_{\alpha}^{\alpha+\mu}\sqrt{2}\cdot V_{f-f}^{sec}\sin\omega t\cdot d\omega t$$
(2.15)

$$\Delta V_{med} = \frac{3\cdot V_{f\text{-}f}}{\pi\cdot\sqrt{2}} \cdot [\cos(\alpha) - \cos(\alpha+\mu)]$$
(2.16)

As can be seen in Figure 2.15, the waveform of the rectified voltage *v*D is additionally distorted during the overlapping angle, worsening the output ripple of the rectifier.

$$V_D = \frac{3 \cdot \sqrt{2} \cdot V_{f-f}^{sec}}{\pi} \cos\alpha - \Delta V_{med} \tag{2.17}$$

$$V_D = \frac{3 \cdot \sqrt{2} \cdot V_{f-f}^{sec}}{2\pi} \left[\cos\alpha + \cos(\alpha + \mu)\right] \tag{2.18}$$

The load current can be written as a function of the primary winding of the transformer, if any.

$$I_D = \frac{a \cdot V_{f-f}^{prim}}{\sqrt{2} \cdot \omega L_S} \cdot \left[\cos\alpha - \cos(\alpha + \mu)\right] \tag{2.19}$$

$$V_D = \frac{3 \cdot \sqrt{2} \cdot a \cdot V_{f-f}^{prim}}{2\pi} \left[\cos\alpha + \cos(\alpha + \mu)\right] \tag{2.20}$$

Where *a=Vf-fsec/Vf-fprim*.

2.4 Power displacement factor and Power factor

The angular displacement between the fundamental components of the.AC line current and the associated line to neutral voltage.The Displacement Power Factor is defined as

$$\text{DPF} = \cos\Phi 1 \tag{2.21}$$

$$\cos \Phi = cos\alpha$$

In the case of non-sinusoidal current, the active power delivered per phase by the sinusoidal supply is

$$P = \frac{1}{T}\int_0^T va(t)ia(t)dt = V_a^{rms} I_a^{rms} \cos\Phi 1 \tag{2.22}$$

Where *Vrms* is the *rms* value of the voltage *va*, and *Ia 1rms* the *rms* value of *ia1* (fundamental component of *ia*). Analog relations can be obtained for *vb* and *vc*.

The apparent power per phase is given by:

$$S = V_a^{rms} I_a^{rms} \tag{2.23}$$

The power factor is defined by:

$$PF = \frac{P}{S} \tag{2.24}$$

Where PF becomes:

$$PF = \frac{I_{a1}^{rms}}{I_{a}^{rms}} \cos\alpha \tag{2.25}$$

This equation shows clearly that due to the non-sinusoidal waveform of the currents, the power factor of the rectifier is negatively affected both by the firing angle α and by the distortion of the input current. In effect, an increase in the distortion of the current produces an increase in the value of *Iarms* in equation (2.24), which deteriorates the power factor.

Considering now the r.m.s. value of the distortion component in the line current,

$$I_{\mathrm{Dis}} = \sqrt{I_{\mathrm{R}}^2 - I_{\mathrm{R1}}^2}\,, \tag{2.26}$$

The total harmonic distortion is given as

$$THD = \frac{I_{\mathrm{Dis}}}{I_{\mathrm{R1}}} = \frac{\sqrt{I_{\mathrm{R}}^2 - I_{\mathrm{R1}}^2}}{I_{\mathrm{R1}}}\,. \tag{2.27}$$

2.5 Effects on the AC mains voltage

During the commutation of the thyristors the two phases involved are almost shorted through the line/transformer secondary reactance. This causes notches on the AC voltage. It can be demonstrated that these notches have a maximum depth and width depending on the delay angle α ,the line/transformer secondary reactance *L*S, the phase-to-phase voltage *V*f-f, and the average value of the rectified current *I*D.

$$Notch\_Depth \equiv \sqrt{2} \cdot V_{\mathrm{f\text{-}f}} \cdot \sin(\alpha)$$
$$Notch\_Width \equiv \frac{2 \cdot \pi \cdot f \cdot 2 \cdot L_{\mathrm{S}} \cdot I_{\mathrm{D}}}{\sqrt{2} \cdot V_{\mathrm{f\text{-}f}} \cdot \sin(\alpha)}\,. \tag{2.28}$$

The total harmonic distortion of the mains AC voltage can be calculated from the impedance of the AC source the line feeding the primary of the rectifier's transformer *L*Sline and the harmonics of the converter's input current. The THD can thus be given by

$$THD_{\mathrm{V}} = \frac{\sqrt{\sum_{k=1}^{\infty} \left(I_{\mathrm{Rn}} \cdot n \cdot 2 \cdot \pi \cdot f \cdot L_{\mathrm{Sline}}\right)^2}}{V_{\mathrm{phase}}}\,. \tag{2.29}$$

2.6 How to reduce the harmonics on the AC mains

Various techniques of improving the input current waveform are discussed below. The intent of all techniques is to make the input current more continuous so as to reduce the overall current harmonic distortion. The different techniques can be classified into four broad categories:

i. Introduction of line reactors and/or DC link chokes
ii. Passive filters (series, shunt, and low pass broadband filters)
iii. Phase multiplication (12-pulse, 18-pulse rectifier systems)
iv. Active harmonic compensation

The term three-phase line reactor or just reactor is used in the following paragraphs to denote three-phase line inductors.

2.6.1 Three-Phase Line Reactors

Line reactors offer a significant magnitude of inductance that can alter the way the current is drawn by a nonlinear load such as a rectifier bridge. The reactor makes the current waveform less discontinuous, resulting in lower current harmonics. Since the reactor impedance increases with frequency, it offers larger impedance to the flow of higher order harmonic currents. Therefore, it is instrumental in impeding higher frequency current components while allowing the fundamental frequency component to pass through with relative ease. On knowing the input reactance value, one can estimate the expected current harmonic distortion. A table illustrating the typically expected input current harmonics for various amounts of input reactance is shown in Table 1.
Input reactance is determined by the accumulated impedance of the AC reactor, DC link choke (if used), input transformer, and cable impedance. To maximize the input reactance while minimizing AC

Table 1: percent Harmonics vs Total line impedances

Harmonic	Total Input Impedance 3%	4%	5%	6%	7%	8%	9%	10%
5th	40	34	32	30	28	26	24	23
7th	16	13	12	11	10	9	8.3	7.5
11th	7.3	6.3	5.8	5.2	5	4.3	4.2	4
13th	4.9	4.2	3.9	3.6	3.3	3.15	3	2.8
17th	3	2.4	2.2	2.1	0.9	0.7	0.5	0.4
19th	2.2	2	0.8	0.7	0.4	0.3	0.25	0.2
%THID	44	37	35	33	30	28	26	25
True rms	1.09	1.07	1.06	1.05	1.05	1.04	1.03	1.03

Voltage drop, one can combine the use of both AC-input reactors and DC link chokes. One can approximate the total effective reactance and view the expected harmonic current distortion from Table 1. The effective impedance value in percent is based on the actual loading and is:

$$Z_{\text{eff}} = \frac{\sqrt{3} \times 2 \times \pi \times f \times L \times I_{\text{act (fnd.)}}}{V_{L-L}} \times 100 \qquad (2.30)$$

Where Iact (fnd.) is the fundamental value of the actual load current and $VL-L$ is the line-line voltage. The effective impedance of the transformer as seen from the nonlinear load is:

$$Z_{\text{eff},x\text{-mer}} = \frac{Z_{\text{eff},x\text{-mer}} \times I_{\text{act (fnd.)}}}{I_r} \qquad (2.31)$$

Where *Z*eff,*x*-mer is the effective impedance of the transformer as viewed from the nonlinear load end; *Zx*-mer is the nameplate impedance of the transformer; and *Ir* is the nameplate rated current of the transformer

2.6.2 DC-Link Choke

Based on the above discussion, it can be noted that any inductor of adequate value placed between the AC source and the DC bus capacitor of the ASD will help in improving the current waveform. These observations lead to the introduction of a DC-link choke, which is electrically present after the thyristor rectifier and before the DC bus capacitor. The DC-link choke performs very similar to the three-phase line inductance. The ripple frequency that the DC-link choke has to handle is six times the input AC frequency for a six-pulse ASD. However, the magnitude of the ripple current is small. One can show that the effective impedance offered by a DC-link choke is approximately half of that offered by a three-phase AC inductor. In other words, a 6% DC-link choke is equivalent to a 3% AC inductor from an impedance viewpoint. This can be mathematically derived equating AC side power flow to DC side power flow as follows:

$$Pac = 3 \times \frac{V_{L-N}^2}{R_{ac}}; \quad Pac = P_{dc} \qquad (2.32)$$

VL −N is the line-neutral voltage at the input to the three-phase rectifier.

$$Pdc = \frac{V_{DC}^2}{Rdc}; \qquad (2.33)$$

$$Vo = \frac{3\times\sqrt{2}\times VL-L\times COS(\alpha)}{\pi} = \frac{3\times\sqrt{2}\times VL-N\times COS(\alpha)}{\pi} \qquad (2.34)$$

Hence $Rdc = 2(\frac{9}{\pi^2})Rac$ (2.35)

2.6.3 Passive Filters

Passive filters consist of passive components like inductors, capacitors, and resistors arranged in a predetermined fashion either to attenuate the flow of harmonic components through them or to shunt the harmonic component into them. Passive filters can be of many types. Some popular ones are series passive filters, shunt passive filters, and low-pass broadband passive filters. Series and shunt passive filters are effective only in the narrow proximity of the frequency at which they are tuned. Low-pass broadband passive filters have a broader bandwidth and attenuate almost all harmonics above their cutoff frequency.passive filter components can interact with existing transformers and power factor correcting capacitors and could create electrical instability by introducing resonance into the system. Some forms of low-pass broadband passive filters do not contribute to resonance but they are bulky, expensive, and occupy space. A typical low-pass broadband filter structure popularly employed by users of ASDs .

2.6.4 DC side harmonic filtering

The fundamental ripple frequency is given by;

$$f_r = p \cdot f_{\text{mains}} , \qquad (2.36)$$

where *p* is the number of pulses.

The ripple voltage at the output of the rectifier can be represented as an independent time varying voltage over/imposed on the average value of the rectified voltage (*V*DC). In order to reduce the ripple amplitude, a passive *LC* filter is usually connected between the rectifier and the load. The time-varying voltage can thus be interpreted as a composition of harmonics that are individually weakened by the filter.

passive *LC* filters are used to reduce the harmonics content on the output
of the rectifiers: "a combination of *L* and *C* produces a lower ripple with normal components values than is possible with either *L* or *C* alone" . The inductance smoothens the oscillations in the current and the capacitance those in the voltage. The resonance frequency is given by

$$f_0 = \frac{1}{2 \cdot \pi \cdot \sqrt{LC}}$$

(2.37)

and it has to be chosen so as to satisfy the condition *f*0 << *f*r*;* furthermore, for a given *f*0, a degree of freedom remains in the choice of *L* or *C*.

The critical inductance is calculated with the condition that the peak of the fundamental harmonics of the current ripple through the filter inductance is equal to the minimum *IDC* in the load.

$$I_{\text{DC min}} = \frac{V_{\text{ripple\_1}}}{2 \cdot \pi \cdot f_{\text{r\_1}} \cdot L_c} \quad \Rightarrow \quad L_c = \frac{V_{\text{ripple\_1}}}{2 \cdot \pi \cdot f_{\text{r\_1}} \cdot I_{\text{DCmin}}}$$

(2.38)

where *V* ripple_1 is the amplitude of the fundamental harmonic of the ripple at frequency *f*r_1. In order to avoid resonances, a damping resistor is normally added in the filter structure. A typical scheme for a damped *LC* filter is given in Fig. .

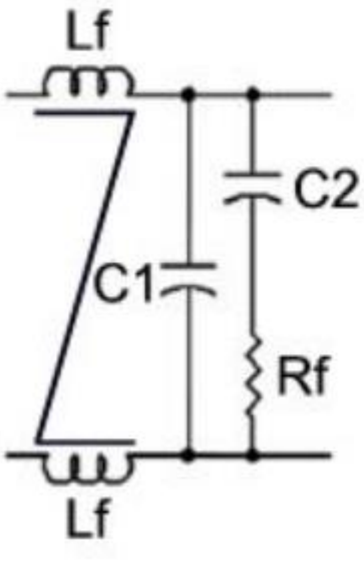


Figure 20: passive filter

The resistance is chosen so as to limit the overshoot in the step response of the filter. From the equation of the systems of the second order, with an overshoot equal to 1.5, the equations for this type of filter are reported in (eqn 2.39)

$$
\begin{aligned}
& f_0 = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot (C_1 + C_2)}} \\
& L > L_c \qquad C_1 = 4 \cdot C_2 \qquad (\text{or } C_1 = 5 \cdot C_2) \\
& \delta = \frac{R}{2\sqrt{\dfrac{L}{C_1 + C_2}}} \\
& \delta = 0.2 \quad \Rightarrow \quad R = 0.4 \cdot \sqrt{\frac{L}{C_1 + C_2}}\ .
\end{aligned}
\tag{2.39}
$$

2.7 Silicon Controlled Rectifier

The thyristor is a solid-state semiconductor device with four layers of alternating N and P-type material. They act as a switch, conducting when their gate receives a current pulse, and continue to conduct for as long as they are forward biased (that is, as long as the voltage across the device has not reversed).

Some sources define silicon controlled rectifiers and thyristors as synonymous; others define SCRs as a subset of thyristors, along with gate turn-off thyristor (GTO), triode ac switch (triac), static induction transistor (SIT), static induction thyristor (SITH) and MOS-controlled thyristor (MCT). Among the latter, the International Electro technical Commission 60747-6 standard stands out. Non-SCR thyristors include devices with more than four layers, such as triacs and DBGTOs.

The thyristor is a four-layer semiconducting device, with each layer consisting of alternately N-type or P-type material, for example P-N-P-N. The main terminals, labeled anode and cathode, are across the full four layers, and the control terminal, called the gate, is attached to p-type material near to the cathode. (A variant called an SCS Silicon Controlled Switch brings all four layers out to terminals.) The operation of a thyristor can be understood in terms of a pair of tightly coupled Bipolar Junction Transistors, arranged to cause the self-latching action:

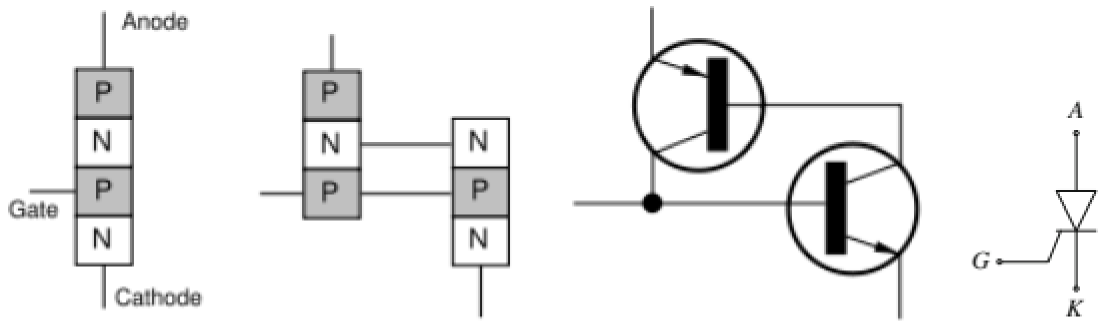


Figure 21: two- transistor model of the thyristor (SCR) (a and b) and its symbol

2.7.1 Working of SCR

Thyristor act in three states:

Reverse blocking mode -- Voltage applied in the direction that would be blocked by a diode .

Forward blocking mode -- Voltage applied in the direction that would cause a diode to conduct, but the thyristor has not yet been triggered into conduction.

Forward conducting mode -- The thyristor has been triggered into conduction and will remain conducting until the forward current drops below a threshold value known as the "holding current"

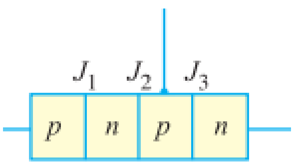


Figure 22: layer diagram of thyristor

When the anode is at a positive potential VAK with respect to the cathode with no voltage applied at the gate, junctions J1 and J3 are forward biased, while junction J2 is reverse biased. As J2 is reverse biased, no conduction takes place (Off state). Two ways of switching On SCR.

If VAK is increased beyond the breakdown voltage VBO of the thyristor, avalanche breakdown of J2 takes place and the thyristor starts conducting (On state).

If a positive potential VG is applied at the gate terminal with respect to the cathode, the breakdown of the junction J2 occurs at a lower value of VAK. By selecting an appropriate value of VG, the thyristor can be switched into the on state immediately. It should be noted that once avalanche breakdown has occurred, the thyristor continues to conduct, irrespective of the gate voltage, until either: (a) the potential VG is removed or (b) the current through the device (anode−cathode) is less than the holding current specified by the manufacturer. Hence VG can be a voltage pulse, such as the voltage output from a UJT relaxation oscillator.[6]

These gate pulses are characterized in terms of gate trigger voltage (VGT) and gate trigger current (IGT). Gate trigger current varies inversely with gate pulse width in such a way that it is evident that there is a minimum gate charge required to trigger the thyristor.[2,6]

2.7.2 Switching Characteristics of SCR

In a conventional thyristor, once it has been switched on by the gate terminal, the device remains latched in the on-state (i.e. does not need a continuous supply of gate current to conduct), providing the anode current has exceeded the latching current (IL). The thyristor will remain in the on state (the region of low resistance) as long as the anode current is higher than the holding current, *IH* . The holding current is the lowest anode current maintaining the thyristor in the state of conduction with the gate open (*IG* = 0) [6, 5].

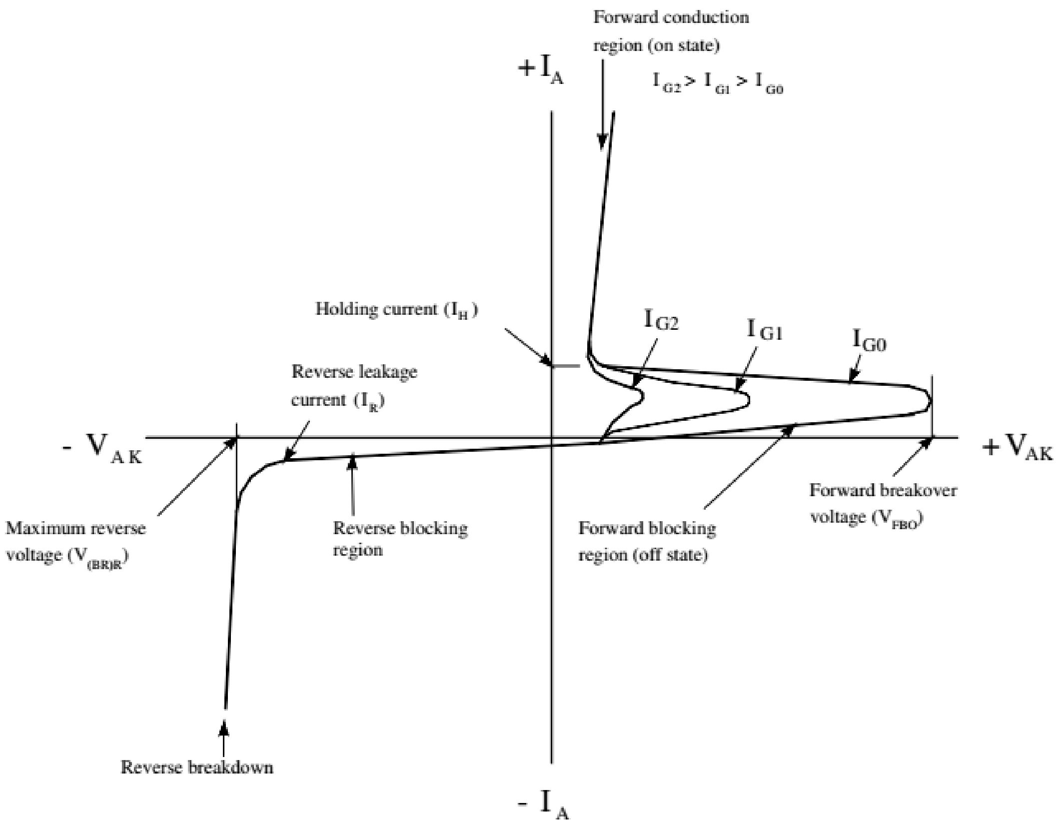


Figure 23: The static V-I characteristic of an SCR

A thyristor can be switched off if the external circuit causes the anode to become negatively biased. In some applications this is done by switching a second thyristor to discharge a capacitor into the cathode of the first thyristor. This method is called forced commutation. After a thyristor has been switched off by forced commutation, a finite time delay must have elapsed before the anode can be positively biased in the off-state. This minimum delay is called the circuit commutated turn off time (tQ). Attempting to positively bias the anode within this time causes the thyristor to be self-triggered by the remaining charge carriers (holes and electrons) that have not yet recombined [6].

For applications with frequencies higher than the domestic AC mains supply (e.g. 50 Hz or 60 Hz), thyristors with lower values of tQ are required. Such fast thyristors are made by diffusing into the silicon heavy metals ions such as gold or platinum which act as charge combination centers. Alternatively, fast thyristors may be made by neutron irradiation of the silicon [6, 7].

2.7.3 SCR Ratings

A data sheet for a typical thyristor follows this section and includes the following information:

Surge Current Rating (*I*FM)—The surge current rating (*I*FM) of an SCR is the peak anode current a SCR can handle for a short duration.

Latching Current (*IL*) — a minimum anode current must flow through the SCR in order for it to stay ON initially after the gate signal is removed. This current is called the latching current (*IL*).

Holding Current (*IH*) — After the SCR is latched on, a certain minimum value of anode current is needed to maintain conduction. If the anode current is reduced below this minimum value, the SCR will turn OFF.

Peak Repetitive Reverse Voltage (*V*RRM)—the maximum instantaneous voltage that an SCR can withstand, without breakdown, in the reverse direction.

Peak Repetitive Forward Blocking Voltage (*V*DRM)—the maximum instantaneous voltage that the SCR can block in the forward direction. If the *V*DRM rating is exceeded, the SCR will conduct without a gate voltage.

Non-repetitive Peak Reverse Voltage (*V*RSM) — the maximum transient reverse voltage that the SCR can withstand.

Maximum Gate Trigger Current (*I*GTM) — the maximum DC gate current allowed to turn the SCR ON.

Minimum Gate Trigger Voltage (*V*GT) — The minimum DC gate-to-cathode voltage required to trigger the SCR.

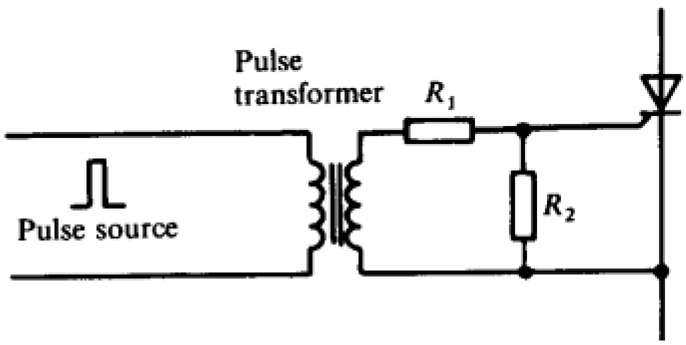
Minimum Gate Trigger Current (*I*GT) — The minimum DC gate current necessary to turn the SCR ON .

2.7.4 Gate Circuit Requirements.

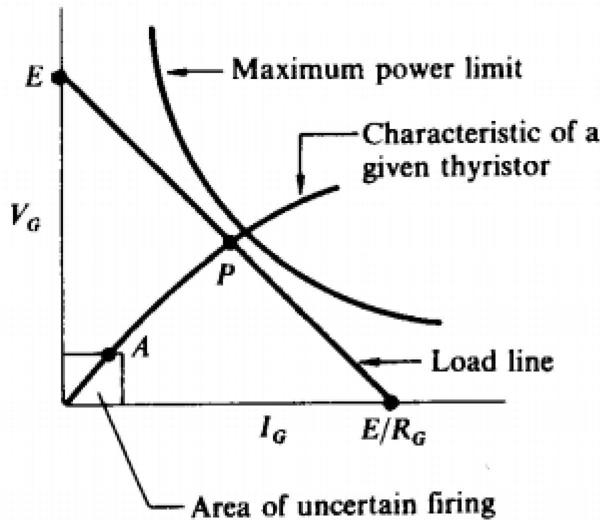
The trigger signal should have voltage amplitude greater than the minimum gate trigger voltage of the thyristor being turned ON. It should not be greater than the maximum gate trigger voltage, either. The gate current should likewise be in between the minimum and maximum values specified by the thyristor manufacturer. Low gate current driver circuits can fail to turn ON the thyristor [7].

The thyristor is a current controlled switch and so the gate circuit should be able to provide the needed turn ON gate current into the thyristor. Sufficient gate trigger current will turn ON the thyristor and current will flow from the anode to the cathode provided that the thyristor is favorably biased and the load is such that the current flowing is higher than the latching current of the thyristor. The gate trigger will turn ON the thyristor only if it occurs during the positive part of the AC .Any trigger signal during the negative part of the AC cycle will not turn ON the thyristor and the thyristor will remain in blocking state. Keeping the gate signal ON during the negative part of the AC cycle does not typically damage a thyristor [7].

The current into and the voltage at, the gate are both subject to maximum values, but turn-on requirements demands they also exceed certain minimum levels. The product of gate and current gives a power level to which a maximum is set.in figure 2.19 shows the limits imposed on the gate cathode characteristic, giving the area into which must be fitted the gate firing signal for certain firing into the on-state to take place. Final stage of gate triggering network consist of a pulse transformer for isolation ,a resistor (R1) to limit the gate current and R2 to limit the gate voltage when the thyristor is in the off state.[1]



(a)



(b)

Figure 24: (a) Firing network desirable network connection,(b) firing network load line

2.7.5 SCR protection

2.7.5.1 Overcurrent

The current rating of a device is the current which raises the temperature of the junction to its top limit (normally around 125°C). An overcurrent will raise the temperature of the junction excessively and cause malfunctions or the destruction of the device.

The simplest way to protect a thyristor is using adequate fuses. They must be fast acting fuses preventing the rise to high arc voltages (less than 1.5 times the peak voltage in circuit). The $I2t$ parameter normally characterizes fuses: this value must be lower than the $I2t$ that would damage the thyristor (the semiconductor manufacturer usually indicates the maximum $I2t$ for the protection fuses).

2.7.5.2 Overvoltage

Withstanding the estimated reverse voltage for the application where it is used is one of the main parameters for the design of the converter. If the thyristor is submitted to a reverse voltage greater than its rated value, it will break down. Choosing oversized devices (VRRM 30% or 50% higher than that one expected) is a solution in this case.

2.7.5.3 Transients/ surges

Voltage transients or voltage surges, i.e., an excessive slew rate of voltage (dv/dt) are another source of overvoltage that may damage the thyristors. Transients may originate from sources that are either internal or external to the device.

The general approach to protect thyristors from voltage surges is to quickly store the surge energy in a capacitor, and then to dissipate it slowly in a resistor. Each thyristor commutation causes some transient voltage peaks, in particular at turn off. Owing to the presence of an inductance (line, transformer winding, etc.) in series during its conduction phase, a high peak reverse voltage is generated when the thyristor is turned off. In order to mitigate this voltage surge, a *RC* combination, called snubber circuit, is connected in parallel to each device.

Capacitor C1 suppresses the voltage surge dv/dt that appears when the thyristor Th goes into the blocking state. Resistor *R* (R1) is used to damp possible oscillations in the *LC* circuit (*L* is the inductance of the AC connection seen by the thyristor). The same resistance *R* (or, in the circuit on the right, R2) has to limit the discharge current from the capacitor through the thyristor when it starts to conduct again.

Typical values for *C* are 0.1–1 μF and for *R* are 10–1000 Ω

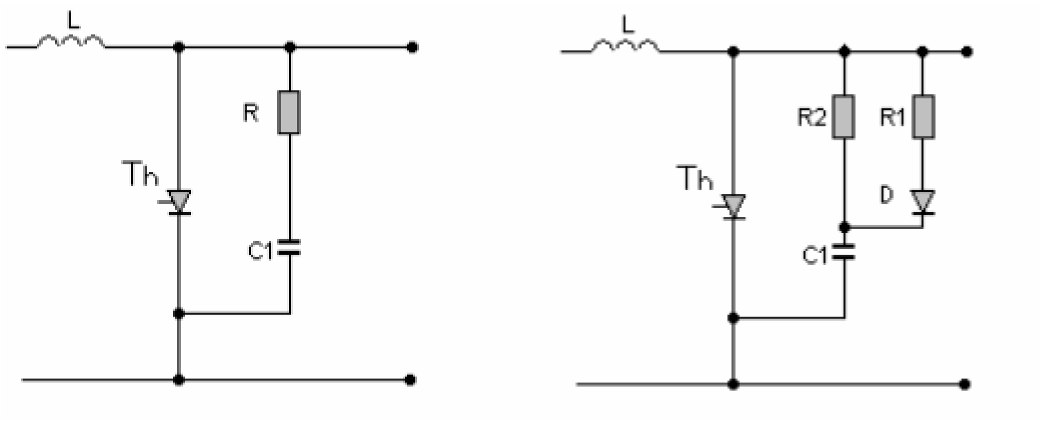


Figure 25: protecting thyristors from internal surges using snubber circuit

External transients come from the AC supply line. The main cause is the action of the power converter's main contactor; when it opens, it interrupts the magnetizing current at the primary of the transformer. The energy stored in the secondary windings of the transformer is then dissipated throughthe thyristors and the load. When the contactor closes, a voltage overshoot may occur in the oscillating circuit constituted by the inductance of the secondary windings and a capacitance, either stray or physically present. Also in this case a *RC* combination is used. The capacitance must be able to store the energy of the transformer. Sometimes the *RC* groups are connected directly between the phases immediately before the rectifier. In order to decouple the capacitance from the inductance of the connection, a bucket circuit is often preferred. In practice the *RC* group is connected to the line through a diode rectifier (Fig. 26). Resistance R1 is the damping resistance, calculated from the inductance of the line and of the transformer and the capacitance *C*. Resistance R2 is the discharge resistor of the capacitor; it is sized in order to have a time constant of about 100 ms.

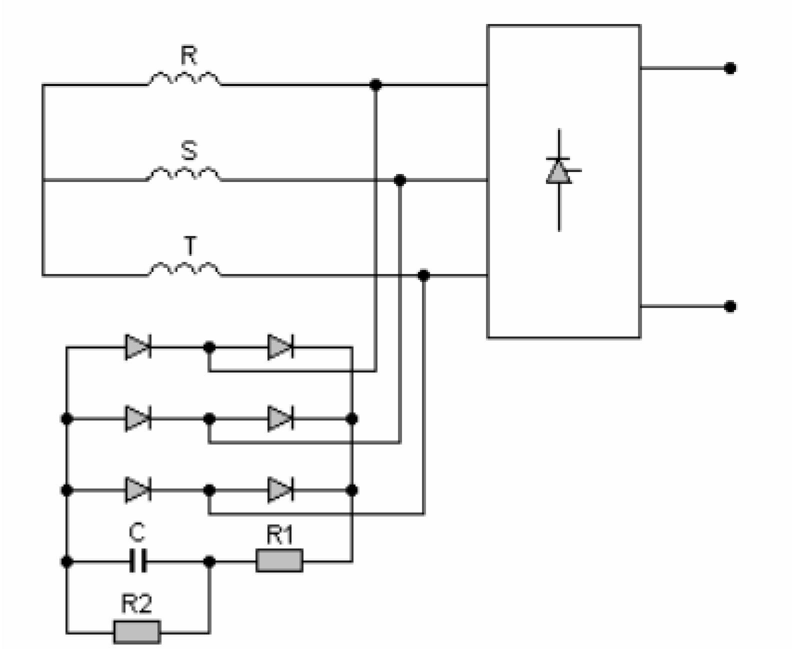


Figure 26:protecting thyristor from external voltage souces using bucket circuit ***CHAPTER 3***

METHODOLOGY

3.1 introduction

This project deals with the design, development and control of a 3-phase controlled rectifier whose power circuit is shown in Fig. 3.1 it is the most widely rectifier circuit. It consists of a three phase transformer in star / delta connection, six thyristor bridge connected, load , CLC filter , synchronization circuits , the trigger control and isolation circuit.

This three phase rectifier circuit must be double-pulse triggered or trigger pulse width to ensure that at every moment it has two thyristors in same turn or triggered at same time. The three phase transformer is connected in star / delta connection so as to reduce a multiple a multiple of 3 harmonic currents impacting on the power and have three phase inputs which have a phase difference of 120°.

It is a common cathode connection and is made of the three-phase half-wave phase controlled rectifier circuits and a common anode connection of the three phase half-wave phase controlled in series circuit.

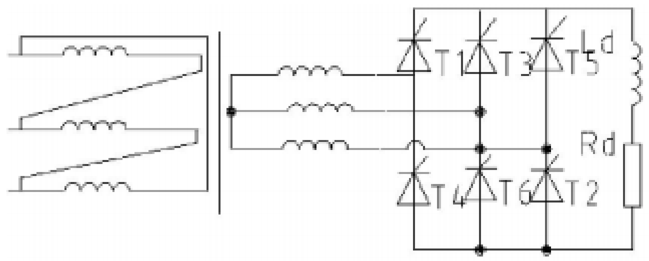


Figure 27: Three phase controlled rectifier circuits

The trigger circuit used in this paper is that of digital triggering and the trigger circuit is controlled by a microcontroller unit belonging to the Atmel which is an Atmega328p microcontroller. Its main feature includes generation of 6 channel trigger pulses whose time interval is 60 degree; only needing a synchronization signal; shift phase range of 0 degrees to 160 degree; inputting shift phase angle by variation of a potentiometer which is displayed on a LCD display.

Each thyristor requires a trigger pulse, so this trigger circuit needs to generate 6 trigger pulses in all and a time interval of between the trigger pulses is 60 degrees.

A block diagram of the trigger circuit is shown in Figure 1. There is a microcontroller unit (MCU) – ATMEGA 328P from ATMEL corporation- which controls the trigger circuit to normally run and there are also other peripheral module circuits of the MCU including LCD display, Zero crossing detector signals and trigger pulses output.

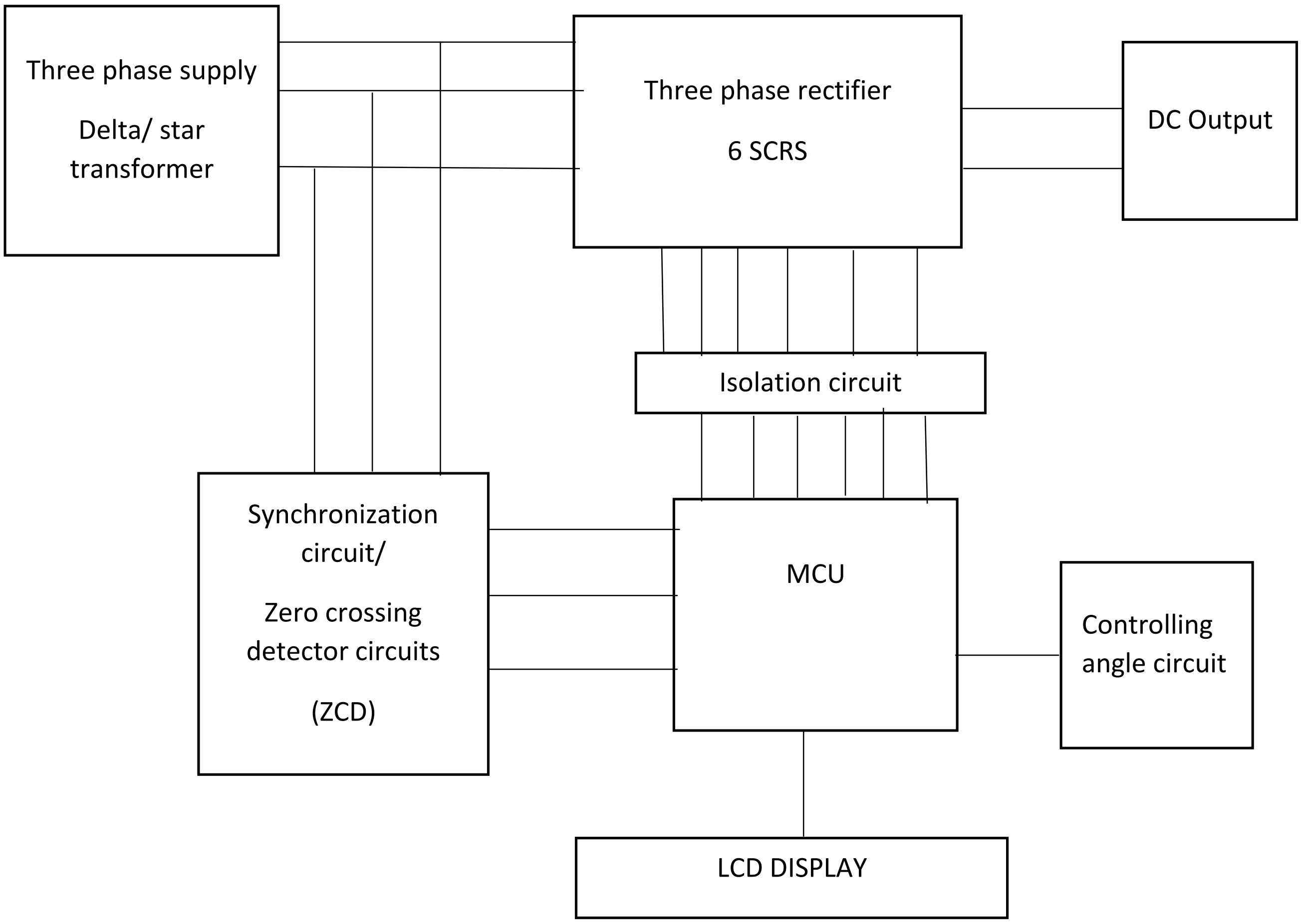


Figure 28: Tri-phase control rectifier block diagram

A point on AC wave, after which it starts repeating its cycle again from 0 degrees, is called "zero crossing point". In order to have a full control over the entire cycle, it is necessary to precisely find out zero crossing point. The digital controller used in this proposed design is in the form of a microcontroller unit (MCU). MCUs, being inexpensive, fulfill one of the primary purposes of this design that is the economy. The controller selected for this is the ATMEL ATmega328p.

3.2 Design

3.2.1 Input

The input to be rectified is an A.C 110V supplied. Its connected to the secondary side of three transformers connected in delta connection on the primary side and star connected on the secondary side. For safety purpose there is a switch and fuses of 13A on every line from the star connection.

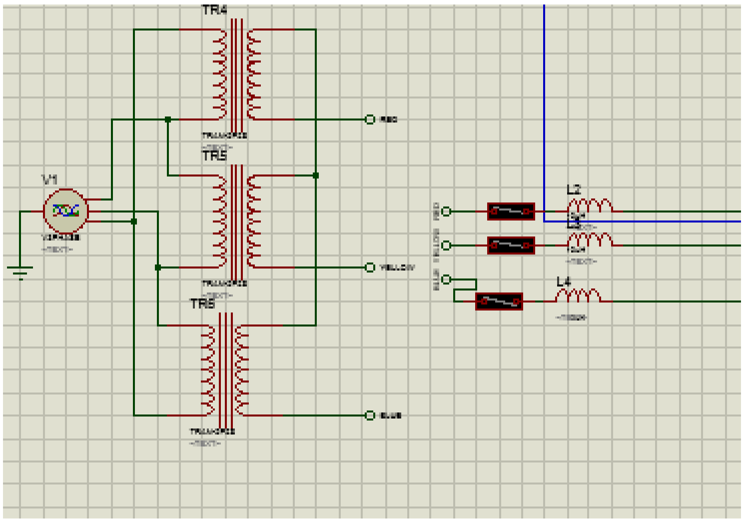


Figure 29: The input circuit to rectifier

The transformers specifications were;

Primary inductance = 1H

Secondary inductance = 0.1H

Coupling factor=1.0

The virtual source connected to the primary side specifications;

Amplitude volts = 78v Vrms and frequency of 50Hz.

Fuse =13A rating

$$\text{Vrms} = \frac{\text{Vm}}{\sqrt{2}} \qquad (3.1)$$

$$\text{The Vm} = 78\text{v} \times \sqrt{2} = 110.30\text{v} \qquad (3.2)$$

3.2.2 The rectifier circuit

The circuit below shows the connection of both rectifier connection, the snubber circuit, isolation circuit and the filter of the dc at the output which is connected to a resistive load.

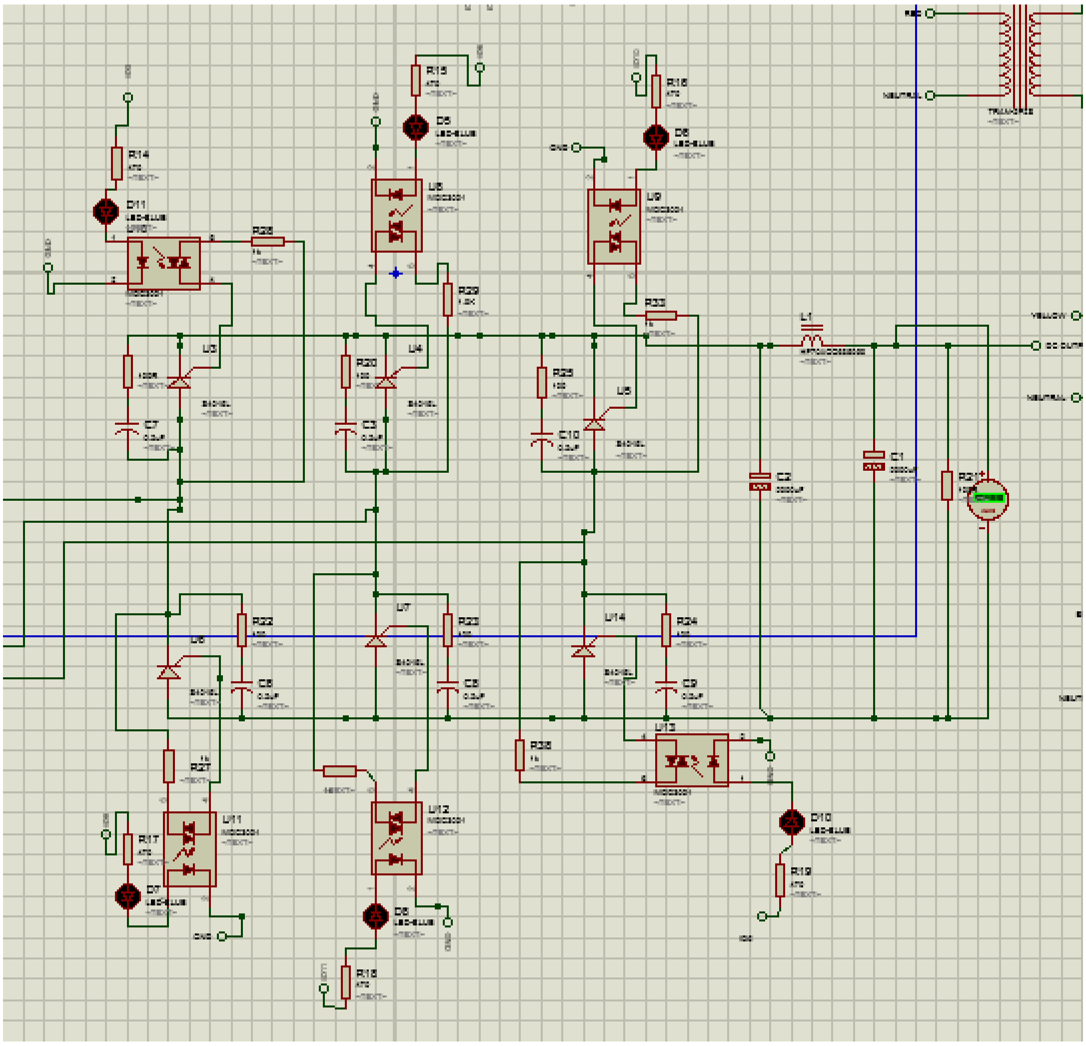


Figure 30: three phase connected to the supply with the snubber circuits and isolation circuit

Scr S4015L ratings

Vrmm/Vdrr = 200v (min)

Ig = 1 mA (min) and 20 mA (max) –the gate current

Vgt = 1.5 V max the dc gate trigger voltage

Ih = 30 mA the dc holding current;gate open

The SCR in this paper are gate triggered. Using the manufacturer ratings the calculations of the gate voltage and currents and the components specified.

3.2.2.1 Snubber circuit.

The circuit is used for high $\frac{\mathrm{dVD}}{\mathrm{dt}}$ protection of SCR the critical rate of rise of off- voltage. Leakage current though the scr increases with the increase in $\frac{dv}{dt}$ that is the rate of change of applied voltage across the thyristor. This current can turn on the device even when the gate signal is absent which is called the $\frac{dv}{dt}$ and is avoided by using a Snubber circuit which consists of a capacitor in series with a resistor applied parallel with the SCR.

C= 0.2 u F / 250V

R =100R /2W

3.3.2.2 Opto-coupler MOC3021

If= 60mA forward current

Vr = 3V reverse voltage Vdrm = 400V

Ih = 100uA holding current.

Idrm = 100nA .

Vtm = 3V.

The function of the opto-isolator is;

- Monitor high voltage
- Output voltage sampling for regulation
- System control micro for power ON/OFF
- Ground isolating

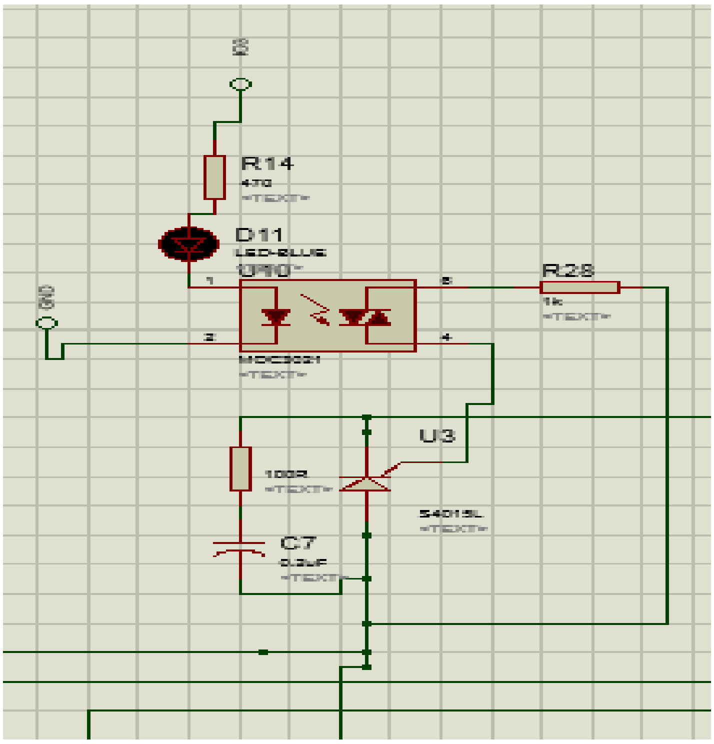


Figure 31: MOC3021 isolator connection to SCR and interface with ATmega328p microcontroller

Opto-isolators are made up of a light emitting devices and a light sensitivity device all wrapped up in one packet, but with no electrical connection between the two just beams of light. They allow two circuits to exchange signals yet remain electrically isolated.

As seen in the figure 3.2 terminal IO3 is to a pin of the microcontroller interfaced with MOC3021 ic pin 1 led in series, which glows to indicate a logic high pulse from the MCU through a current limiting resistor so to that a current is flowing in internal led of the opto-ic. Current flows from pin 1 to 2 and LED light falls on the DIAC causing pin 6 and 4 to close.

During each half cycles of the AC source current flows through gate , series resistor and through opto-diac to the main SCR to trigger for the load to operate .

Ohms law;

$$V = IR \qquad (3.3)$$

$$R = \frac{V}{I} \qquad (3.4)$$

The series resistor for current limiting is;

The LED must have 15mA and 1.2 V to light on the output voltage of the mcu is 5V.

$$R = \frac{5V - 1.2V}{0.015} = 250\text{R} \qquad (3.5)$$

R= 250R

3.2.3 Synchronization circuit/ Zero crossing detector circuits.

To have full control over the firing angle of the SCRs (from 0 to π radians), it is necessary to precisely detect the zero crossing of the sinusoidal input. Schematic of the zero crossing circuit that was implemented is shown in fig 3.4

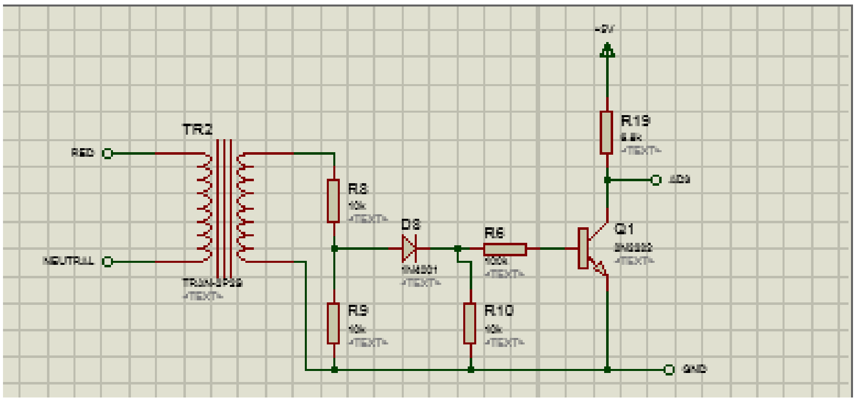


Figure 32: zero crossing circuit with input transformer

Since the rectifier has three phase supply three of this circuits are used so as to detect the zero points of the three ac supply helping to trigger the SCRs in the correct sequence.

Transformer used is at the input side is used for two purposes. Firstly it scales down the mains alternating voltage to a lower and safer value up to the 6 to 9 volts rms. This gives peak voltage of 8.46 = √2*6 volts up to 12.728 = √2*9 volts, respectively. Secondly it provides the galvanic isolation between mains and zero crossing detection circuitry that is another key goal of the proposed design.

This scaled down and isolated AC input is then scaled down further by using a resistor consisting on R8 and R9 and they are of equal values.

$$\text{Vout} = (\text{R8}/\text{R9}) \times \text{Vsec} \qquad (3.6)$$

R11 and R12 = 10k

The transformer steps down the voltage = 10.5V

The 50Hz sine wave synchronization shift voltage from a power grid is transformed to square-wave signal with same frequency as the sine and then the square-wave signal is sent to the interrupt pin of the MCU which can received external interrupt.

controller circuit is required to sense the zero crossing instant of the input voltage and from thereof generates six equidistant trigger pulses in each cycle (one time period or 20 ms) for switching of SCR of three phase converter.

The maximum voltage that the zero crossing is 4.88 v which is applicable for the mcu .

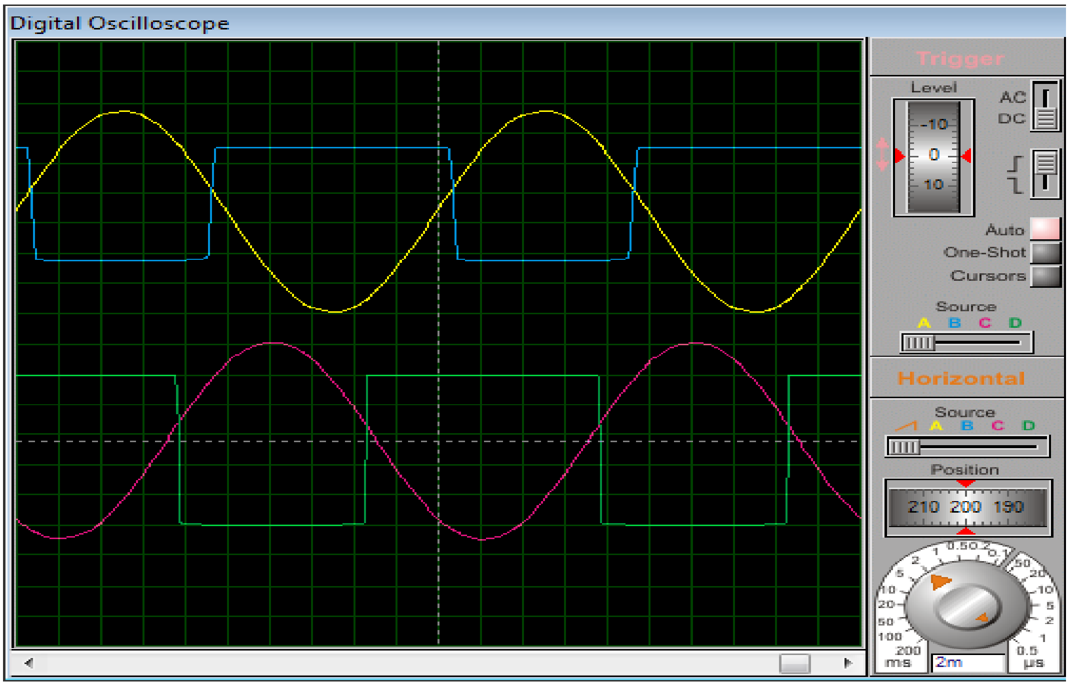


Figure 33: square wave zero crossing signals of the two phases

3.3.3 Controlling voltage

Analog Voltage (0-5 V) is used for controlling the converter power, ADC of Atmega-328 microcontroller is 10 bit resolution. Analog Voltage (0-5 V) is converted in to (0-1023) count. Analog voltage is provided to one of the channel of ADC port. As per variation in the analog voltage there is change of digital value. ADC conversion takes around 250 micro second. PWM is achieved with the help of variable controlling voltage.

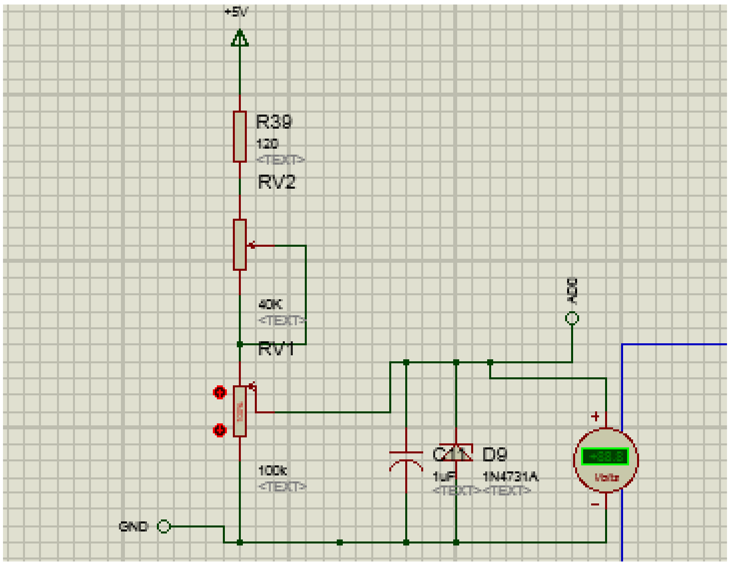


Figure 34: Controlling Voltage circuit

3.3.4 Generating of the firing pulses

A supply of 5v dc is used in this the specification of this paper was to trigger the SCRs the controlling analog circuit varies the input from 0v to 5v.

ADC of ATmega328p is of 10-bit resolution hence the maximum value from the ADC WITH +5 volts reference will be of 0-5 V are 0-1023 counts therefore a scaling down factor of 5.68 is used.

The 0-5v range controls the firing angle 0° to 180°

The presented results were drawn by operating the system in 50 Hz mode due to the national standard of power transmission in Kenya.

$$f = \frac{1}{T} \qquad (3.7)$$

So the period of the supply is;

$$T = \frac{1}{f} \qquad (3.8)$$

$$T = \frac{1}{50} = 0.02 = 20msec \qquad (3.9)$$

Half cycle time the period is 10ms the delay angle can thus be calculated as ;

$$\alpha = ADC/5.68 \qquad (3.10)$$

Where ;

ADC = the output of the ADC converter/ the counts

α =is the firing angle

The ADC reading is converted into a delay after which firing pulse is to be generated. using equation(3.11)

$$d = (adc * 5) * 1.955 \qquad (3.11)$$

d - delay in microseconds

adc is the output of the ADC

1.955- value is a scaling up factor for the ADC reading

5 -is the reference value

In the circuit a 4.7V zener diode is used so as to clump the voltage not to exceed 4.3 V due to the specifications of this paper was for the firing angle not to exceed 163° firing angle

Table 2: the delay angle calculated table

Voltage value (V)	**ADC counts**	**Angle (α)**	**Delay (d) ms**
0	0	0	0
1	204.6	36.02	1.9999
1.5	306.9	53.87	2.9999
3	613.8	108.06	5.9999
4.3	879.78	154.48	8.5998
4.5	920.7	162.09	8.9998

The output of ATmega328p is 4.8V and a current of 10miliampers each pin. The current is enough to trigger the SCR used which is has a maximum of gate current 20mA.

The triggering of the 6 scrs are in sequencial form.each of the 6 SCRs are switched at an interval of 60° sequentially,from T1,T2,T3,T4,T5,T6,and the sequence repeats again after a complete cycle. 60° translate to a delay of 3331.32 microseconds .

From the theory part for the flow of the current two SCRs must be conducting at the same time forming a pair of SCRs conducting.as shown in the table

Table 3: The algorith of triggering the SCR

SCR pair conducting	Angle in degrees	Extracted line voltage
T6 , T1	∝+30 to ∝+90	Vab
T1 , T2	∝+90 to ∝+150	Vac
T2,T3	∝+150 to ∝+210	Vbc
T3,T4	∝+210 to ∝+270	Vba
T4,T5	∝+270to ∝+330	Vca
T5 ,T6	∝+330 to ∝+30	Vcb
T6,T1	∝+30 to ∝+90	Vab

The firing angle = ∝, a phase shift of 60°

Using table 3.2 helped In the programming of the microcontroller.

ATmega328p has been programmed for triggering the power circuit. The execution of the program in step by step process is explained using a flowchart. Which is show the flowchart below.

From the output of the zero crossing circuit which is a square wave on which shows where the AC wave crosses the zero is an input to the ATmega328p and INT01 and INT1 from the three synchronization circuits using the Pin-change interrupts of the microcontroller causes an interrupt showing that a phase has crossed the zero point from figure 3.5 show that at the rising edge of the square wave that is when the phase is on the positive half.

The MCU executes its interrupt service routine (ISR).the function of the ISR is to determine how to generate rising edge of the first trigger pulse which for elimination of the starting problem of the rectifier and it initializes Timer 1 in the MCU to start counting from 0 and counts up until it hits the 'TOP' value which the 'TOP' value is from the varied voltage which gives the desired delay divided by a factor and it fires an interrupt which then T1 is fired at 30° approximately 1.667sec the first pulse is generated.by setting PORT D , bit-3 high and a delay of 1 millisecond and then timer runs the second time when the timer overflows the MCU executes ISR of the timer.In this routine PORTD,bit-5 is cleared this pin is connected to T1 since the time interval between the first pulse and the second pulse is 60° which is approximately 3.334 millisecond which means the time interval between the falling edge of the first pulse and the rising edge of the second pulse is t1=3.334-1=2.334ms,the timer runs the third time and when it hits the 'TOP' value it overflows and the MCU executes the timer ISR in the routine PORT D,bit-5 high connected to T2 and a second pulse to T1 both pins are set to high to start the second trigger pulse and the following steps reapeat the generation process of the first pulse until the other pulses are outputted at this point the zero-crossing wave of phase two has caused an interrupt. The length of time of the timer is determined by shift angle $\propto$ inputted though varying the potentiometer.

Here timer 1 is as a 16-bit timer and operates in mode 1. The MCU has an external 16 MHz oscillator and fuses are set to use the external crystal clock. Fuses are used to control things like which oscillator to use and what speed to run , blowout detection and the size of the boot flash.

The trigger pulses are outputted in a way that each thyristor is triggered twice that is a main pulse and secondary pulse at 60° shift from the main pulse. pin PD3 outputs a main pulse to thyristor 1 and at the same time PB3 outputs a secondary pulse to thyristor 6;pin PD5 outputs main pulse to thyristor 2 at the same time pin PD3 outputs the secondary pulse to thyristor 1;pin PD6 outputs the main pulse to thyristor 3 and at the same time pin PD5 outputs the secondary pulse to thyristor 2;pin PB1 outputs a main pulse to thyristor 4 and at the same time pin PD6 a secondary pulse to thyristor3;pin PB2 outputs a main pulse to thyristor 5 and at same time pin PB1 a secondary pulse to thyristor 4;pin PB3 outputs a main pulse to thyristor 6 and at the same time pin PB2 outputs a secondary pulse to thyristor 5. And this process repeats its self in the cycles.

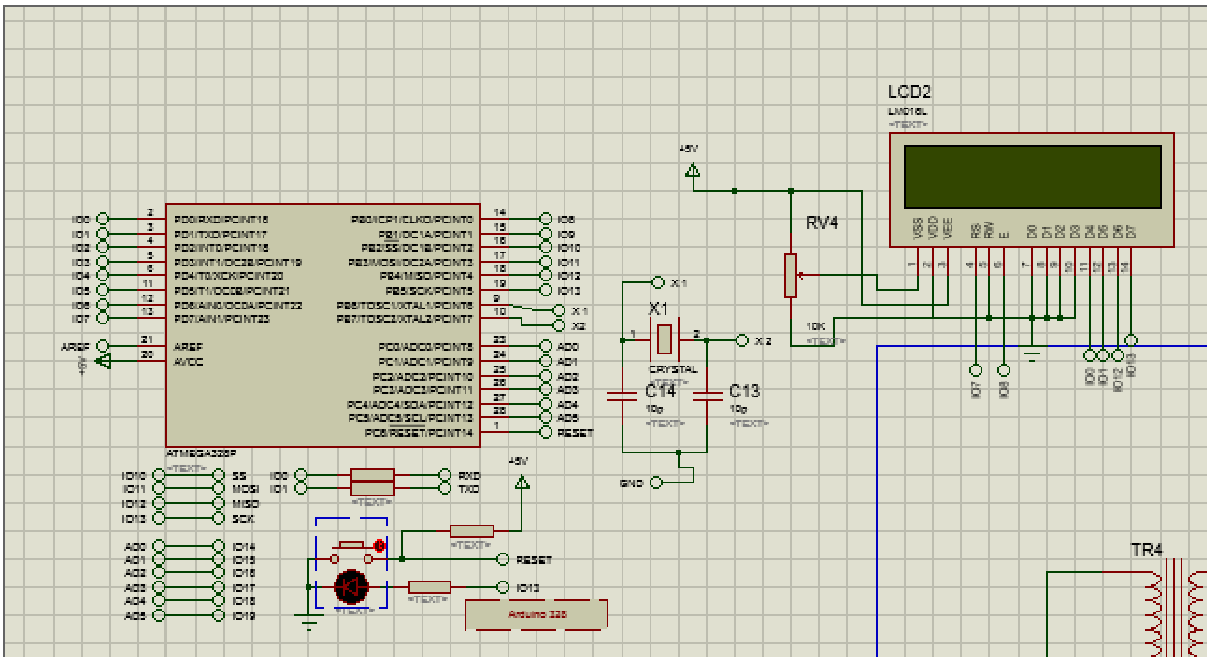


Figure 35: MCU and LCD display

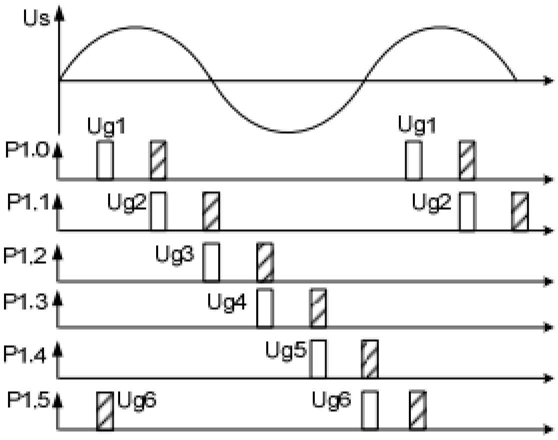


Figure 36: waveform of the output pulse

3.4 Software Design

the software design includes the main program,the display subroutine and the analog voltage varied that is the ADC conversion,the external interrupt service routine and the timer interrupt service routine.

3.4.1 Main Program

In this program it initializes the pins which input and the output pins; that is the analog pin(PC0) from the controlling voltage circuit and the ADC handling initialization, three interrupt pins (PCINT8,PCINT10,PCINT11) from the three zero crossing detector , the output of the trigger pulses pins with their corresponding thyristor (PD3-T1, PD5-T2, PD6-T3, PB1-T4, PB2-T5, PB3-T6) and the display subroutine.

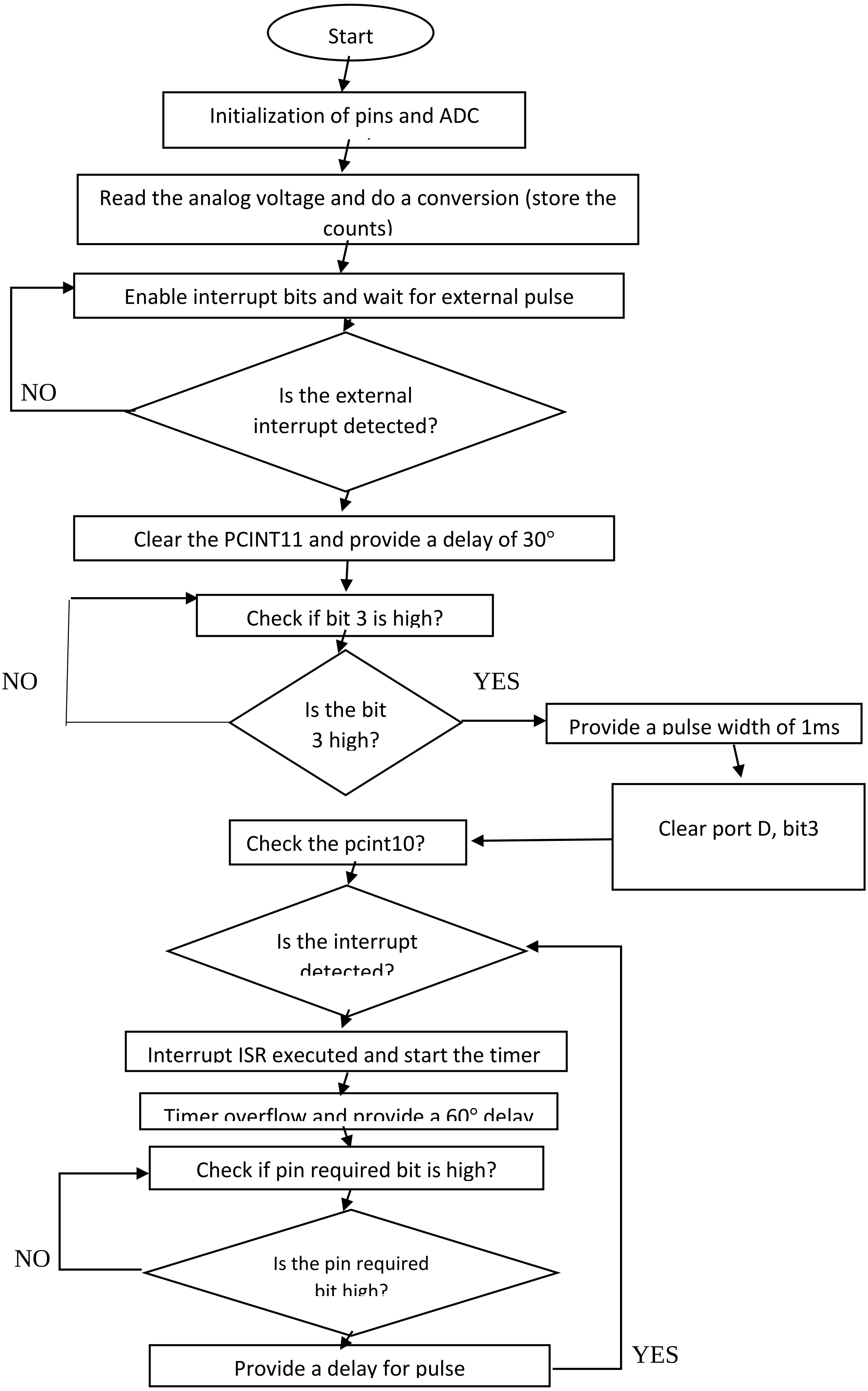


Figure3.9 flow chart for six-pulse generation

3.4.2 ADC program for delay

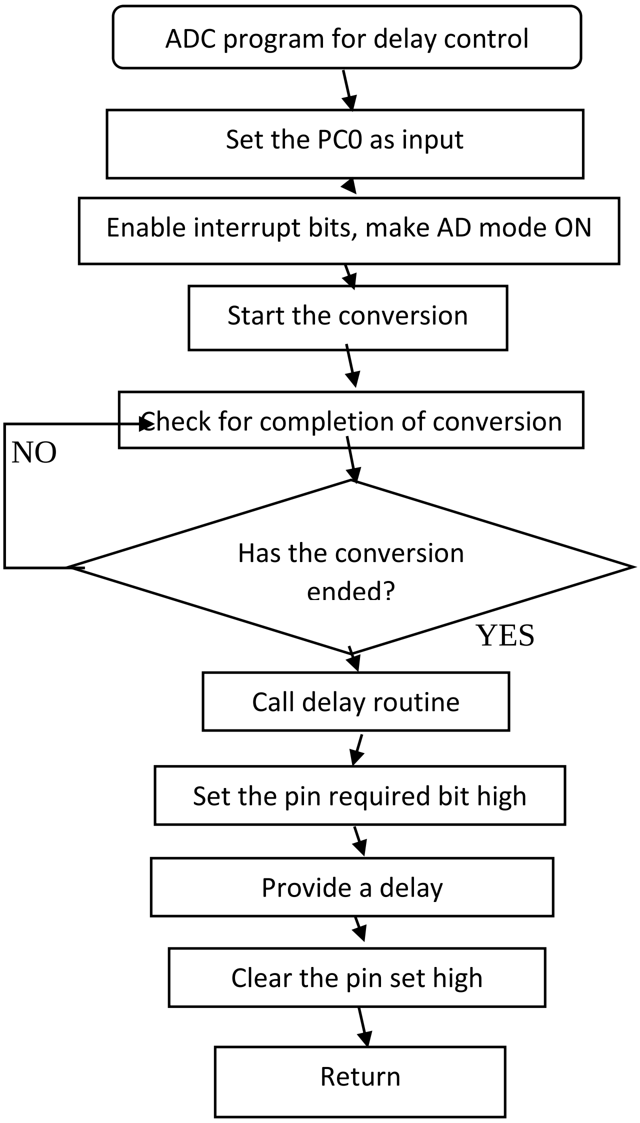


Figure 37: flow chart ADC subroutine and delay control

CHAPTER 4:

RESULTS AND ANALYSIS

4.1 Theoretical Results

This are on ideal case basis from the equation (4.1);

$$Vdc = \frac{3\sqrt{2}}{\pi} Vl \times \cos\alpha \qquad \text{for } 0 < \propto < 60° \qquad (4.1)$$

$$Vo = \frac{1}{\pi/3} \int_{\pi/3+\propto}^{\pi} Vllm \sin(\omega t)\, d(\omega t) = \frac{3Vllm}{\pi}\{1 + \cos(\pi/3 + \alpha)\}$$

$$for\ 60° < \propto < 120°$$

$$Vl = RMS\ Value\ of\ the\ line - line\ voltage = \frac{110v}{\sqrt{2}} = 77.78v$$

Table 4: ideal results

Firing angle	Dc Voltage
0°	181.93V
30°	157.56V
70°	62.23V
130°	64.99V

Table 5 Simulated results

Firing angle	Dc voltage

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The project the software to trigger six thyristor or SCRs used in the power circuit of three-phase, six pulse, and controlled rectifier has been discussed. Three fully controlled rectifiers are very popular in many industrial applications particular in situations where power regeneration from dc side is essential.in this the rectifier implemented was for use in the lab.

The design is isolated from electronic interference at input and output side. Power control is possible by varying $\propto the\ firing\ angle$ with controlling voltage with the use of ATmega328p microcontroller and by programming the analog voltage given it controls the firing angle and controls the dc voltage output.

The configuration used lends itself to easy series and parallel connection for increasing voltage and current rating or improvement in harmonic behavior. Since three phase fully controlled rectifier are obtained at the cost of increased circuit complexity due to the use of six SCRs and their associated control circuit. This complexity can be reduced by using this software for easily triggering the six SCRs. Moreover the trigger pulses generated by this software are controllable.

5.2 Recommendations for Further Work

Following are areas of future study which can be considered for further research work.

1. Speed Control Of Motors
2. Transmission of HVDC

REFFERENCES

[1] R. Simard and V. Rajagopalan, "Economical equidistant pulse Firing scheme for Thyristorized D.C. drives," IEEE Trans. Ind. Electron. Contr. Instrum., vol. IECI-22, No.3, pp. 425-429, 1975

[2] Gangul M.R, G.P Jain, "Design and Implementation of AT Mega 328 microcontroller based firing control for a tri-phase thyristor control rectifier," International Journal of Engineering Research & Technology (IJERT), 2013.

[3] R. Visintini, "Rectifiers," Elettra Synchrotron Light Laboratory, Trieste, Italy

[4] Juan Dixon (Ph.D.). "Three phase controlled rectifiers," Pontifical Universidad Católica de Chile. Vicuña Mackenna 4860

[5] Branko Dokic, Branko Blanusa, "Power Electronics Converters and Regulators."

[6] Mohd Helmi. "Control Rectifier for Variable Speed Single Phase DC Motor," University Malaysia Pahang.

[7] J. David Irwin, "The power electronics hand book," Auburn University

[8] XU Wuxiong, "Design of Thyristor Digital Trigger Circuit Based on Microcontroller Unit," The 1st International Conference on Information Science and Engineering (ICISE2009)

[9] Daniel W. Hart, "power electronics," mc craw-hill

[10] Suhel Mustajab, Mohd. Kashif Adhami, "Software based approach for Triggering 3-phase, 6-pulse, AC to DC Controlled Converter," International Journal of Advanced Research in Computer Engineering & Technology (IJARCET) ,Volume 1, Issue 9, 2014.

[11] Shashikant V. Lahade1 and S. R. Hirekhan2, "Microcontroller based Digital Trigger Circuit for Converter, Proc. of Int. Conf. on Advances in Power Electronics and Instrumentation Engineering, PEIEs

[12] R. Arockiasamy and S. Doraipandy, "A novel trigger scheme for Thyristor operating under variable frequency anode supply," IEEE Trans. Ind. Electron. Contr .Instrum., vol. IECI-22, No. 1, pp. 83-85, Feb.1975.

[13] Cyril W. Lander, "power electronics,"

[14] S. Murugesan and C.Kameswara, "Simple adaptive analog and Digital trigger circuits for thyristors working under wide range of Supply frequency," IEEE Trans. Ind. Electron. Contr. Instrum., vol. IECI-24, No. 1, pp.46-49, 1977.

[15] L.H.Hoang ,"A digitally controlled thyristor trigger circuit," Proc. IEEE, vol. 66, No.1, pp. 89-91, Jan. 1978.

[16] B. Ilango, R. Krishman, R. Subramanian, and S. Sadasivam, "Firing circuit for three-phase thyristor rectifier IEEE Trans. Ind. Electron. Contr. Instrum., vol. IECI-25, no. 1, pp. 45-49, 1978.

[17] S.C.Gupta, K.Venkatesan, and K.Eape Generalized Firing Angle Controller Using Phase Loop for Thyrist Control," IEEE Transactions On Industrial Electronics And Control Instrumentation, vol. IECI-28, No. 1, February 1981

[18] John William,"introduction to solid state power electronics," POWEREX, Inc. 200 Hillis Street Youngwood, PA 15697-1800

[19] A.W. Kelley and W.F. Yadusky, Rectifier design for minimum line-current harmonics and maximum power factor, *IEEE Trans. Power Electron.* **7** (1992) 332.