# SIMULATION OF 6 PULSE GTO THYRISTOR CONVERTER AND HARMONICS ANALYSIS

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## BORANG PENGESAHAN STATUS TESIS♦

JUDUL: **SIMULATION OF 6 PULSE GTO THYRISTOR CONVERTER AND HARMONICS ANALYSIS**

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# SIMULATION OF 6 PULSE GTO THYRISTOR CONVERTER AND HARMONICS ANALYSIS

NURUL DIYANA BT MOHAMED

A thesis submitted in partially fulfillment of the requirement for the award of the degree of Bachelor of Electrical Engineering (Power System)

Faculty of Electrical & Electronics Engineering

Universiti Malaysia Pahang

NOVEMBER 2009

# DECLARATION

I declare that this thesis entitled “Simulation of 6 Pulse GTO Thyristor Converter and Harmonics Analysis” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : …………………………….

Name : Nurul Diyana Bt Mohamed

Date : November 19th , 2009

**For My Lovely Mother and**

**In Loving Memory of My Late Father**

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## ABSTRACT

This project is about the simulation of 6 pulse GTO thyristor converter circuit and their harmonics analysis when the LC filter circuit is added to the system. Gate turn-off thyristor (GTO) are four-layer PNPN devices that act as switches, rectifiers, and voltage regulators. It is a fully controllable switches which can be turned on and off by their third lead, the GATE lead. Besides that, it is also high-power semiconductor device which make it suitable to be used in High-voltage Direct Current (HVDC) systems. The 6 pulse converter is also known as 3 phase fully controlled Full Wave Bridge Converter and can be functioned as a rectifier or an inverter. This project used OrCAD PSpice simulator to simulate the results for the analysis purpose. Computer simulation is a very economical and time effective approach to design the circuit since it is an attempt to model a real-life or hypothetical situation on a computer so that it can be studied to see how the system works and if the simulation is successful, further action can be taken to prepare the hardware. It is also can be used in large scale system such as HVDC. The GTO thyristor model must be create since it is not included in the library of OrCAD PSpice. Using the GTO thyristor model, the 6 pulse GTO thyristor converter circuit will be created in OrCAD PSpice simulator. The evaluation and analysis of performance of simulation studies for a 6 pulse converter using PSPICE simulators with GTO thyristor as a control element is continue by adding the LC filter circuit to improve the performance of the converter circuit by reducing the harmful effects of the harmonics current. The harmonic for the circuit before and after adding the LC filter circuit is analyse and compared. The simulation results of DC output voltage is also will be compared to the mathematical calculation results by using graph. This contribution can be very useful particularly for the operation and maintenance personnel who can perform better with greater insight into the functioning of the complex system obtained through the model as developed.

# ABSTRAK

Projek ini adalah mengenai simulasi litar penukar “6 pulse GTO thyristor” dan analisis harmonik mereka apabila litar penapis LC ditambah untuk sistem itu. “GTO thyristor” adalah empat lapisan PNPN yang boleh menjadi suis-suis, pelurus, dan pengatur-pengatur voltan. Ia adalah suis-suis terkawal sepenuhnya yang boleh dihidupkan dan dimatikan oleh kaki ketiga mereka, kaki GATE. Selain itu, ia peranti semikonduktor yang berkuasa tinggi dan membolehkan ia sesuai digunakan dalam sistem arus terus voltan tinggi (HVDC). Litar penukar “6 pulse” adalah turut dikenali sebagai 3 fasa “Full Wave Bridge Converter” terkawal sepenuhnya dan boleh berfungsi seperti satu pelurus atau satu penyongsang. Projek ini menggunakan pensimulasi OrCAD PSpice untuk mensimulasikan litar-litar untuk tujuan analisis. Simulasi berkomputer adalah satu kaedah yang sangat ekonomi dan pendekatan berkesan yang menjimatkan masa untuk merekabentuk litar kerana ia adalah satu cara memodelkan satu situasi sebenar atau secara hipotetikal menggunakan komputer supaya ia boleh dikaji untuk melihat bagaimana sistem itu bekerja dan sekiranya simulasi berjaya, tindakan lanjut boleh diambil untuk menyediakan perkakasan bagi menghasilkan produk sebenar. Ia juga boleh digunakan dalam sistem berskala besar seperti HVDC. Model “GTO thyristor” mesti dicipta terlebih dahulu kerana ia tidak terdapat dalam perpustakaan bagi perisian komputer OrCAD PSpice. Menggunakan model “GTO thyristor” yang dihasilkan, litar penukar “6 pulse GTO thyristor” akan dicipta dalam pensimulasi OrCAD PSpice. Penilaian dan analisis prestasi kajian simulasi untuk “6 pulse GTO thyristor” menggunakan simulator PSPICE yang menggunakan “GTO thyristor” sebagai satu unsur kawalan diteruskan dengan menambahkan litar penapis LC untuk meningkatkan prestasi bagi litar penukar dengan mengurangkan kesan-kesan berbahaya arus elektrik harmonik. Hasil simulasi bagi voltan output DC akan dibandingkan dengan pengiraan matematik menggunakan graf. Sumbangan ini sangat berguna terutama untuk kakitangan operasi dan penyelenggaraan yang boleh memajukan model ini dengan lebih baik.

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# LIST OF SYMBOLS

| | | |
|---|---|---|
| *W* | - | Watt |
| *I* | - | Current |
| *P* | - | Power |
| *V* | - | Voltage |
| Ω | - | Ohm |
| *H* | - | Henry |
| *F* | - | Frequency |
| *F* | - | Farads |
| ° | - | Degree |
| *U* | - | Commutation Overlap |
| *A* | - | Firing Angle |

# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| GTO | - | Gate-Turn-Off |
| SCR | - | Silicon Controlled Rectifier |
| HVDC | - | High Voltage Direct Current |
| AC | - | Alternating Current |
| DC | - | Direct Current |
| G1 | - | Gate Circuit 1 |
| G6 | - | Gate Circuit 6 |
| VSD | - | Variable Speed Drive |
| PFC | - | Power Factor Correction |
| UPS | - | Un-interruptible power supply |
| PS | - | Power System |
| PQ | - | Power Quality |
| TD | - | Time Delay |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

In general, the electrical engineering field may be divided into three areas of specialization which is electronics, power and control. In the electronics, there is the study of semiconductor devices and circuits for the processing of information at low power level. For the power field, it deals with both rotating and static equipments for the generation, transmission and distribution systems to the loads. But the Control study is about the stability and response characteristics of the closed loop systems using feedback. This feedback can be used on either a continuous or sampled data basis to analyse the output of a system and make sure the system is stable.

The combination of power and electronics is called power electronics. This power electronics deals with the used of electronics for the control and conversion of large amounts electrical power. The power electronics equipment design involves the interactions between the sources, loads, utilities small signal electronic control circuits and power semiconductor devices.

Thyristor is the general named given to a family of power semiconductor switching devices. All of them is characterised by a bistable switching action depending upon PNPN regenerative feedback. The thyristor is normally has four or more layers and three or more junctions. They have similar characteristics to thyratron gas tube, see Figure 1.1. Thyratron is a type of gas filled tube used as a high energy electrical switch and controlled rectifier.

Figure 1.1 Thyratron gas tube.

The conventional thyristor known as Silicon Controlled Rectifier (SCR) is proposed by William Shockley in 1950 and championed by Moll and others at Bell Labs. It was developed in 1956 by power engineers led by Gordon Hall at General Electric (G.E.) and commercialized by G.E.'s Frank W. "Bill" Gutzwiller.

A gate turn-off thyristor (GTO) is a unique type of thyristor, a high-power semiconductor device. It is actually the replacement for the conventional thyristor, SCRs that are widely used in high power control circuits. SCRs are not fully controllable switches which are can only be turned ON and cannot be turned OFF. It can be switched ON by a gate signal, but even after the gate signal is not present, the thyristor remains in the ON-state until any turn-off condition occurs which can be the application of a reverse voltage to the terminals, or when the forward current falls below a certain threshold value known as the holding current. GTOs, as opposed to SCRs, are fully controllable switches which can be turned on and off by their third lead, the GATE lead. This improvement of the thyristor family and their development has made it possible to manufacture a self commutated converter using the GTO thyristor for power electronics applications.

## 1.2 Background

This project is about the simulation of 6 pulse GTO thyristor converter circuit and their harmonics analysis after the LC filter circuit is added to the system. Gate turn-off thyristor (GTO) are four-layer PNPN devices that act as switches, rectifiers, and voltage regulators. It is a fully controllable switches which can be turned on and off by their third lead, the GATE lead. Besides that, it is also high-power semiconductor device which make it suitable to be used in High-voltage Direct Current (HVDC) systems. They are the most suitable for high-current, high speed switching applications, such as inverters and chopper circuits.

This GTO thyristor is used to overcome the disadvantage of the SCRs that has being used in various applications such as in power converter of HVDC transmission system and DC speed controller for DC motor application. The disadvantage of the SCR compared to the GTO thyristor is it can only be turn on with two conditions, that is by forward blocking state of the device or when positive gate current is applied to the gate. Besides that, it cannot be turned off automatically but only with natural commutation or forced commutation which means it is not self commutated compared to the GTO thyristor which is self commutated and can be used to supply power to the weak AC system and load only system while at the same time it is able to control reactive power from lead to lag to keep an ac bus voltage constant [1].

In Cambridge Advanced Learner's Dictionary, converter is defined as a machine or device that changes something into a different form. In engineering form, the electrical converter can be defined as converter that converts alternating current into direct current or vice versa. For this project, the 6 pulse converter is used. The 6 pulse converter is also known as 3 phase fully controlled Full Wave Bridge Converter and can be functioned as a rectifier or an inverter. In this project, the 6 pulse GTO thyristor consist of 6 GTO thyristor triggered by the gate circuit G1 until G6.

The LC filter circuit consists of an inductor represented by the letter L, and a capacitor, represented by the letter C. It is an Electronic circuits which perform signal processing functions, specifically intended to remove unwanted signal components or enhance wanted ones. LC filter is normally used in the application circuit to reduce the harmful effects of the harmonics current.

This project used OrCAD PSpice simulator to simulate the results for the analysis purpose. Computer simulation is a very economical and time effective approach to design the circuit since it is an attempt to model a real-life or hypothetical situation on a computer so that it can be studied to see how the system works and if the simulation is successful, further action can be taken to prepare the hardware.

In this project, the GTO thyristor model with its operation circuit and gate circuit is created and simulate at different anode current using OrCAD PSpice simulator to analyse their switching characteristic. It is because there is no GTO thyristor model is included in the library of OrCAD PSpice. After that, this GTO thyristor model is implemented in designing the 6 pulse GTO thyristor converter circuit. The LC filter is used to reduce the harmful effects of the harmonics current to improve the circuit performance. Finally, the comparison of the simulation results of the DC output between before and after the LC filter circuit is added to the system is conducted for the harmonics analysis.

### 1.3 Objective

There are few objectives for this project; the first objective is to design the GTO thyristor model. The GTO thyristor model need to be design in this project since there is no GTO thyristor model is included in the library of OrCAD PSpice and this model will be simulate at different anode current using OrCAD PSpice simulator to analyse their switching characteristic. Besides that, the turn off time of the GTO thyristor also being analyse to proof that the higher percentage of the anode current used can improve the turn off time.

The second objective for this project is to design 6 pulse GTO thyristor converter circuit. In this stage, the GTO thyristor model that has been designed earlier is used to design the 6 pulse GTO thyristor converter circuit. The 6 pulse GTO thyristor consist of 6 GTO thyristor model triggered by the gate circuit G1 until G6. This 6 pulse GTO thyristor converter circuit is then simulate again at different firing angle using OrCAD PSpice simulator to analyse their function either as a rectifier or an inverter.

The third objective is to improve the design using LC filter circuit. The LC filter circuit is used to reduce the harmful effects of the harmonics current to improve the circuit performance of the 6 pulse GTO thyristor converter circuit. The Simulation using OrCAD PSpice simulator is again conducted to analyse their harmonics.

The fourth and the last objective is to do the harmonics analysis between before and after the LC filter circuit is added to the system. In this stage, all the simulation data from each of the design will be collected and compared for the analysis.

## 1.4 Scopes

Generally, this project concentrates on the development the circuit from the designing of the GTO thyristor model and their application circuit, 6 pulse GTO thyristor converter circuit until 6 pulse GTO thyristor converter with LC filter circuit. There are several simulations conducted for each of the circuit development for the analysis.

To make sure the development of the circuit and the analysis is completed, there is two scope or method used in this project which is the software and the analysis and comparison.

For the software, this project used **PSPICE – OrCAD Release 9.1** to design and simulate the circuit for the GTO thyristor model, 6 pulse GTO thyristor converter and 6 pulse GTO thyristor converter with LC filter.

For the analysis and comparison, the process started with the simulation results from all the circuit that being simulates using software is gathered and compared. Then, some of the mathematical calculation is conducted and compare with the simulation results. Lastly, the graph is prepared using all the data gathered from before for easy comparison and analysis.

## 1.5 Problem Statement

The advantage of high voltage direct current (HVDC) is the ability to transmit large amounts of power over long distances with lower capital costs and with lower losses than AC. Depending on voltage level and construction details, losses are quoted as about 3% per 1,000 kilometers. High-voltage direct current transmission allows efficient use of energy sources remote from load centers. The disadvantages of HVDC are in conversion, switching and control. The required static inverters are expensive and have limited overload capacity. At smaller transmission distances the losses in the static inverters may be bigger than in an AC transmission line. The cost of the inverters may not be offset by reductions in line construction cost and lower line loss.

This disadvantage can be overcome by replacing all former mercury rectifiers worldwide with the GTO thyristor units. This is when the 6 pulse GTO thyristor converter with LC filter circuit can be used to make the HVDC transmission over short distance can be possible.

## 1.6 Thesis Organization

This thesis generally consists of five main chapters and each chapter will explain in details about this project. The first chapter is about the introduction of the project, it will elaborate on the overview, background, objective, scopes, problem statement and this thesis organization sub chapter.

The second main chapter is about the literature review related to this project. It will elaborate on the few paper of the previous researcher that the contents is related to this project. It can be used as information to conduct this project and to add more knowledge about the project.

The third chapter elaborates on the methodology for the simulation of 6 pulse GTO thyristor converter and harmonics analysis. It gives the review on how the GTO thyristor model is designed and analyse until the final circuit for 6 pulse GTO thyristor converter with LC filter is designed and analyse.

The fourth chapter will be displaying all the circuits and the simulation results obtained from the project. The discussion will be concentrate on the harmonics analysis before and after the LC filter circuit is added to the system.

The fifth chapter is the last chapter of this thesis. It will give overall conclusion from all the chapters for the simulation of 6 pulse GTO thyristor converter and harmonics analysis project. This chapter also discussed about the applications, the problems and recommendation for the development or improvement.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Overview

Several papers have been published in the area of assessing the reliability of the 6 pulse GTO thyristor converter system. The papers are by H. Yamada M**.** Sampei, H. Kashiwazaki C. Tanaka, and T. Takahashi T. Horiuchi [1], Rajiv Kumar, Thomas Leibfried [2], Muhamad Zahim Sujod [3] and Johan Setr´eus, Lina Bertling [5].

Advancement in power electronics is making High Voltage Direct Current (HVDC) more attractive and reliable. Developing countries like China and India with their ambitious capacity enhancement program are installing more HVDC system for long distance transmission.

In the Analytical Modelling of HVDC Transmission System Converter using MATLAB/Simulink paper [2], it is explained that deeper insight into functioning of the complex HVDC system converter can be obtained by analytical modeling. They said that it is easy to comprehend analytical model using universal software like MATLAB/Simulink. The MATLAB is the acronym for Matrix Laboratory but PSpice is stands for Personal Simulation Program with Integrated Circuit Emphasis. Using MATLAB/Simulink, the schematic of the 6 pulse converter is much more complex and hard to understand since its only used block diagram for the modelling. Besides that, this method also used complex equation that must be inserted to perform the simulation. But by using Pspice/Simulink, the circuit is much simpler and used real component model such as R, L and C components that much more easy to understand and do not need any complex equation for the simulation. Through this review, it can be conclude that when using MATLAB/Simulink, the modeling of the HVDC transmission system converter is much more complicated compare to PSpice/Simulink. So, the PSpice/Simulink is the right method for this project. Besides that, the improvement also can be made compared to the paper by conducting the simulation on both rectifier and inverter.

## 2.2 Power Electronics Devices

Power electronic devices are the electronic devices that can be directly used in the power processing circuits to convert or control electric power by supplying voltages and currents in a form that is optimally suited for user loads. Figure 2.1 shows the basic block diagram of power electronics.

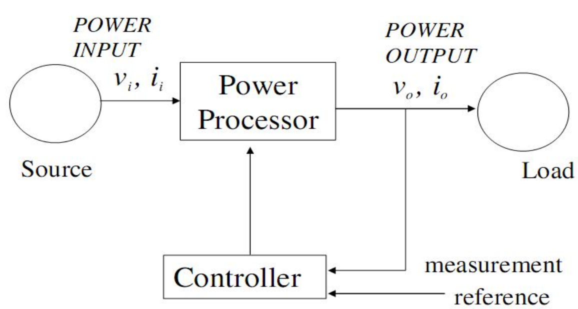


Figure 2.1 Basic block diagram of power electronics.

Power electronic converters can be found wherever there is a need to modify the electrical energy form such as to modify voltage, current or frequency. The range of power is from some milliwatts to hundreds of megawatts. Normally, the minimum power is used in a mobile phone but in a HVDC transmission system the power can be up to hundreds of megawatts.

In power electronics, the electrical currents and voltage are used to carry power compare to the conventional electronics which the electrical currents and voltage are used to carry information. Therefore, the main metric of power electronics becomes more efficient. The first very high power electronic devices were mercury arc valves.

Nowadays, the modern systems conversion is performed using 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.

Normally, the AC or DC converter such as rectifier is the most typical power electronics device used in the consumer electronic devices, for the example in the television sets, personal computers, battery chargers and others. The power range is typically from tens of watts to several hundred watts but in industry the most common application is the variable speed drive (VSD) that is used to control an induction motor. The power ranges of VSDs start from a few hundred watts and end at tens of megawatts which is higher. The power conversion systems can be classified according to the type of the input and output power. The four types of conversion is the AC to DC which is known as rectifier, the DC to AC which is an inverter, the DC to DC which is known as chopper and lastly the AC to AC which is known as cycloconverter. A converter uses a matrix of power semiconductor switches to convert electrical power at high efficiency.

### 2.2.1 Phase Controlled Rectifiers (AC to DC Converters)

AC to DC converter is the converters which convert the alternating current (AC) from the mains to a direct current (DC) are used in a great variety of applications, such as controlling DC motors for household or industrial use, see Figure 2.2. For example it is used in washing machines, refrigerators, dishwashers, industrial machines. This converter is also known as Switch Mode Power Supply (SMPS). AC to DC converters generally comprise a rectifier bridge to rectify the AC current of the input line and a regulating device supplying on output of one or more regulated DC voltages.

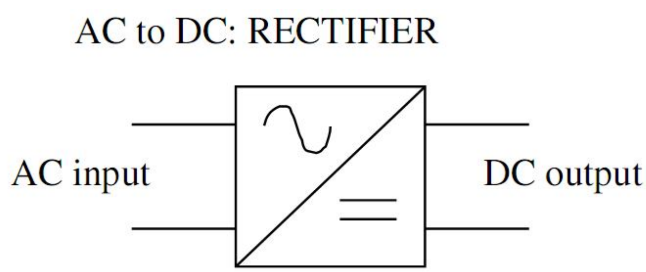


Figure 2.2 Block diagram of AC to DC conversion.

In converters without isolation between the input and output, a neutral conductor of the input line can be placed directly on the output, and will act as voltage a reference for the whole converter. AC to DC converters which receive power from AC power mains often rectify the sinewave of the AC mains voltage and store energy in a capacitor. The capacitor generally charges to the peak mains voltage such that current only flows into the power supply around the peaks of the input voltage.

Many conventional AC to DC power converters employ power factor correction. This is often accomplished with two stages in series, a boost converter input stage and a buck converter second stage. The power factor correction (PFC) techniques can be used to reduce the harmonic content of the input current by reforming the input current into what approximates a sinewave. Such power factor circuits are, however, generally complex. AC to DC converters need power factor correction in order to fulfill international standards of low input harmonic current content. The front end boost PFC converter is one way to obtain good input harmonic current to meet these international standards. Another DC to DC converter is generally cascaded from the front-end boost PFC converter to provide a steady output voltage.

Regarding the complexity of the PFC, in this project the power factor correction (PFC) functions to reduce the harmonics current will be replaced with the LC filter. This 6 pulse GTO thyristor converter with LC filter can be used to improve the disadvantage of the PFC techniques.

#### 2.2.1.1 Applications

This type of converter can be used for the application of high voltage dc transmission systems, DC motor drives, regulated dc power supplies, static VAR compensator, wind generator converters, or battery charger circuits.

### 2.2.2 Inverters (DC to AC Converter)

This DC to AC converter converts DC to AC power by switching the DC input voltage or current in a predetermined sequence so as to generate AC voltage or current output. Normally, this type of converter is used in an un-interruptible power supply (UPS), industrial induction motor drives, traction, and HVDC transmission lines. Figure 2.3 shows the block diagram of DC to AC conversion.

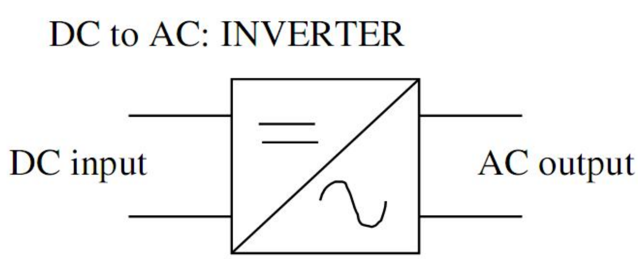


Figure 2.3 Block diagram of DC to AC conversion.

This type of converter is also known as the inverter. The static inverters have no moving parts and are used in a wide range of applications, from small switching power supplies in computers until the large electric utility high voltage direct current (HVDC) applications that transport bulk power. Inverters are commonly used to supply AC power from DC sources such as solar panels or batteries.

In HVDC power transmission, AC power is rectified and high voltage DC power is transmitted to another location. At the receiving location, an inverter in a static inverter plant converts the power back to AC.

The electrical inverter is a high-power electronic oscillator and it is named as an inverter because early mechanical AC to DC converters was made to work in reverse, and thus was "inverted", to convert DC to AC. This inverter performs the opposite function of a rectifier.

#### 2.2.2.1 Applications

This type of converter can be used for the application of uninterruptible power supply (UPS), aircraft and space power supplies, induction and synchronous motor drives, high voltage DC transmission systems, or induction heating supplies.

### 2.2.3 Choppers (DC to DC Converter)

The definition of the chopper is converting the unregulated DC input to a controlled DC output with a desired voltage level. In electronic engineering, a DC to DC converter is an electronic circuit which converts a source of direct current (DC) from one voltage level to another and it is a class of power converter. Figure 2.4 shows the block diagram of the DC to DC conversion.

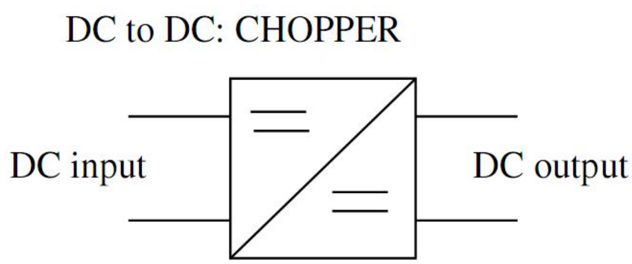


Figure 2.4 Block diagram of DC to DC conversion.

The used of the DC to DC converters are important in portable electronic devices such as cellular phones and laptop computers, which are the primary supply is from the battery power. Such electronic devices often contain several sub-circuits, each with its own voltage level requirement different than that supplied by the battery or an external supply. It is sometimes higher or lower than the supply voltage, and possibly even negative voltage. Additionally, the battery voltage declines as its stored power is drained. Switched DC to DC converters offer a method to increase voltage from a partially lowered battery voltage thereby saving space instead of using multiple batteries to accomplish the same thing.

**2.2.3.1 Applications**

This type of converter can be used for the application of DC drives, subway cars, battery driven vehicles, electric traction or switch mode power supplies.

### 2.2.4 Cycloconverters (AC to AC Conveters)

The cycloconverter converts an AC waveform such as the mains supply to another AC waveform at the lower frequency. It is synthesizing the output waveform from segments of the AC supply without an intermediate direct current link. This type of the converter is most commonly used in three phase applications. Figure 2.5 shows the block diagram of the cycloconverter.

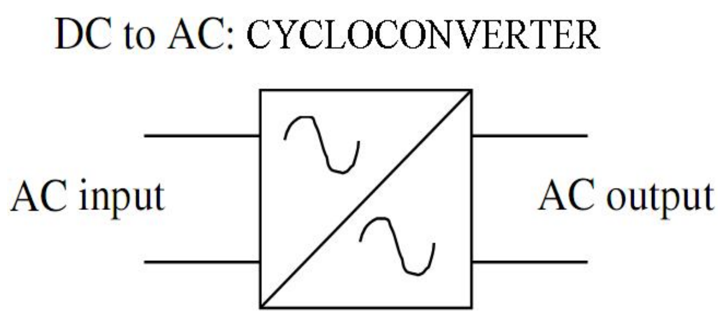


Figure 2.5 Block diagram of AC to AC conversion.

In the most power systems, 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. The output frequency of a three-phase cycloconverter must be less than about one-third to one-half of the input frequency. The quality of the output waveform improves if more switching devices are used for the example the 6 pulse converter. Cycloverters are used in very large variable frequency drives, with ratings of several megawatts.

A typical application of a cycloconverter is for use in controlling the speed of an AC traction motor and starting of synchronous motor. Most of these cycloconverters have a high power output, in a few megawatts. Normally silicon-controlled rectifiers (SCRs) are used in these circuits. By contrast, low cost, low-power cycloconverters for low-power AC motors are also in use, and many such circuits 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, but 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. However, it is common in very high power applications such as for ball mills in ore processing and for cement kilns.

The switching of the AC waveform creates noise, or harmonics, in the systems that depend mostly on the frequency of the input waveform. These harmonics can damage sensitive electronic equipment. If the relative difference between the input and output waveforms are small, then the converter can produce subharmonics. Subharmonic noise occurs at a frequency below the output frequency, and cannot be filtered by load inductance. This limits the output frequency relative to the input. These limitations make cycloconverters often inferior to a DC link converter system for most applications. The filter can be used to reduce the harmonics and subharmonics and improve the limitation of the cycloconverter so the use of the cycloconverter in any applications is possible.

#### 2.2.4.1 Applications

This type of converter can be used for the application of lighting control, speed control of large fans and pumps or electronic tap changers.

## 2.3 GTO Thyristor

Nowadays, the Gate Turn Off (GTO) thyristor is develop with large capacity that make it possible to manufacture self commutated converter using GTO thyristor for the power applications. The design and simulation must be conducted to make sure the circuit proposed is functioning and can be manufactured. The OrCAD Pspice simulator can be used for the design and simulation but before further design can be conducted, we must design the GTO thyristor model because there is no GTO thyristor model in OrCAD Pspice library. Two transistor models can be used to design GTO thyristor model in PSpice. Figure 2.6 shows the GTO thyristor symbol and *v-i* characteristics.

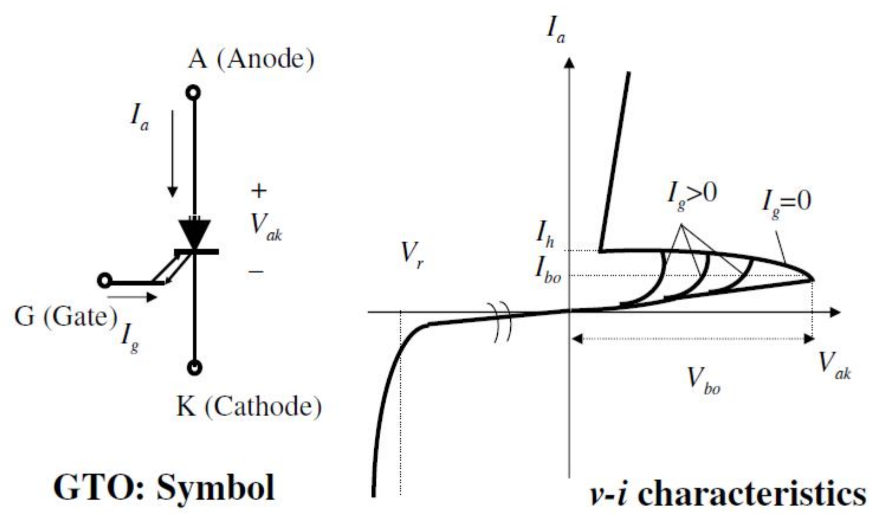


Figure 2.6 GTO thyristor symbol and *v-i* characteristic

The monolithic PNPN structure of GTO thyristor can be conceptualized as comprising an NPN transistor and a PNP transistor, interconnected as shown in Figure 2.7. Here, the collector of the NPN transistor provides base-drive to the PNP, while the collector of the PNP, along with any externally supplied gate current, furnishes base current to the NPN. In this positive feedback arrangement, regeneration occurs once the loop gain exceeds one, when each transistor drives its "mate" into saturation [3]. The simulation of the GTO thyristor model with its operation circuit and gate circuit for the different anode current is conducted to analyse and find the suitable range of current for turn on and turn off characteristics. The GTO thyristor is easy to turn on and turn off, only by using positive and negative gate current signal respectively. Small gate pulse current is enough for turn on process; normally about 5% of the anode current is acceptable. Normally, the gate required about 20% of the anode current for the turn off process but about 60% of the anode current is used to consider the turn off time which is smaller when used 60% of the anode current compared to 20% of the anode current. For the 6 pulse GTO thyristor converter circuit, the design used the GTO thyristor model from before and simulate at different firing angle using OrCAD Pspice simulator to analyse their function either as a rectifier or an inverter [3]. To improve this paper, the Simulation of 6 pulse GTO Thyristor Converter and Harmonics analysis project is conducted. In this project, the LC filter circuit is used to reduce the harmful effects of the harmonics current to improve the circuit performance.

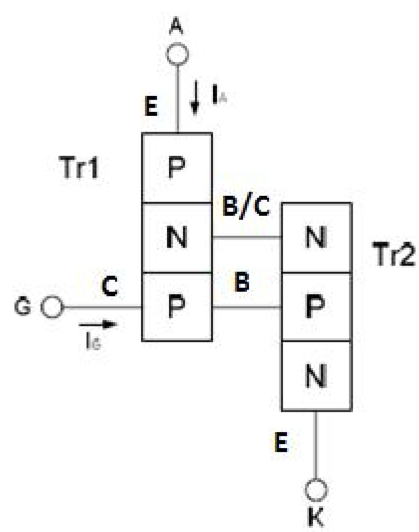


Figure 2.7 Two transistor model for GTO thyristor design.

## 2.4 High Voltage Direct Current (HVDC)

From Wikipedia [4] it is explained that a high-voltage, direct current (HVDC) electric power transmission system uses direct current for the bulk transmission of electrical power, in contrast with the more common alternating current systems. For long-distance distribution, HVDC systems are less expensive and suffer lower electrical losses. For shorter distances, the higher cost of DC conversion equipment compared to an AC system may be warranted where other benefits of direct current links are useful [4].

The 6 pulse GTO thyristor converter can be used to improve this disadvantage because by using the GTO thyristor, the turn on and turn off of the converter can be controlled which can reduced the losses. The reliability block diagram of the HVDC single line diagram is shown in Figure 2.8. The HVDC technology is used in transmission systems to transmit electric bulk power over long distances by cable or overhead lines. It is also used to interconnect asynchronous AC systems having the same or different frequency [5].

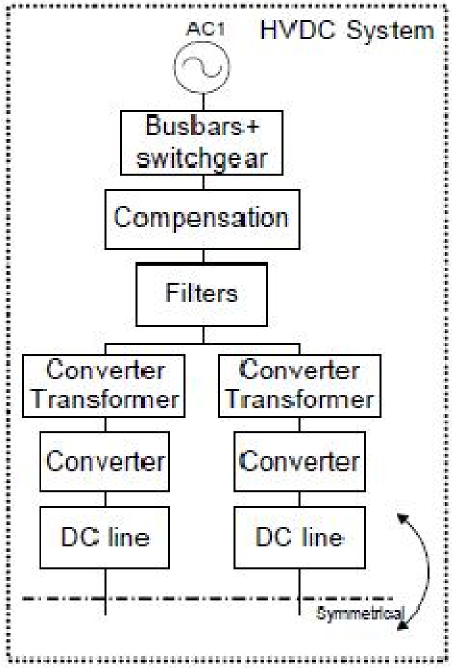


Figure 2.8 Example of a reliability model for an HVDC system [5].

## 2.5 Multipulse Converters

The multipulse converters are defined as diode or thyristor converters where the pulse number is bigger than six (6). The normal three-pulse converter is not very popular since they require special types of converter transformer to prevent DC magnetisation. Therefore, a three phase converter with higher pulse number is developed to provide large-output and least ripple content. Six pulse and twelve pulse converters have been developed. Above 12-pulse connections, that is, 18-pulse and 24-pulse connections are rarely used. The most frequently used for industrial applications nowadays is six pulse, the ones that we have looked at so far for this project but for transmission lines, 12-pulse connections are preferred. Generally the pulse number is a multiple of 6 by assuming 3 phase system; so 12, 18, 24-pulse circuits and so on are possible to be used. The 6 pulse converter is also known as 3-phase fully controlled full wave bridge converter. Refer to Table 2.1 for the simplified table of multipulse converters.

Table 2.1 The simplified table of multipulse converters.

| Pulse Number | Harmonics in input current (K=1,2,3,4...) | Ripple frequency on DC side |
|---|---|---|
| 6 | 6K±1 | 6*supply |
| 12 | 12K±1 | 12*supply |
| 18 | 18K±1 | 18*supply |
| 24 | 24K±1 | 24*supply |

A 12 pulse converter, for example, consists of two 6 pulse converters fed from a 6 phase supply and connected in series or parallel on the DC side. The 18 pulse has three 6 pulse circuits and so on. Since a 6 phase supply is not normally available, it is generated from the 3 phase supply using a phase shifting transformer. The 6 phase source is equivalent to two 3 phase sources with 30º phase shift between them.

The advantage of using the multipules circuit like this, rather than just connecting them in parallel or series is that harmonic cancellation takes place and the power quality at the input and output is improved. Besides that, higher pulse number means fewer input harmonics that can cause a better power factor, and smoother output or smaller smoothing components [7].

The six-pulse connections have the following advantages compared to three-pulse converters;

i. Commutation is made very easier.
ii. Distortion in the AC side is reduced due to the reduction in lower-order harmonics.
iii. Inductance required in series is considerably reduced.

The six-pulse converters can be realised in the following forms:

i. Simple six-pulse converter
ii. Six-pulse mid-point converter with interphase-transformers.
iii. Six-pulse bridge-converter.

## 2.6 Power Quality

Power quality is a set of boundaries that allows electrical systems to function in their intended manner without significant loss of performance or life. The term is used to describe electric power that drives an electrical load and the load's ability to function properly with that electric power. Without the proper power, an electrical device or load may malfunction, fail prematurely or not operate at all [8].

There are many ways in which electric power can be of poor quality and many more causes of such poor quality power [8]. Power Quality problem manifested in voltage, current or frequency deviations that result in failure or misoperation of customer equipment. Power quality is a consumer driven issue and the end user’s point of reference usually takes into account.

In the beginning of the introduction of power electronics devices, electrical machines and devices were conservatively designed. This early device consumed large amount of electricity but at the same time highly robust. Nowadays, the industrial age has led to more economical and competitive products that cause the machines and devices becoming smaller and more sensitive.

There are four major reasons that led to the power quality concerns. Firstly is the newer generation of load equipment, secondly is the increasing demand on power system (PS) efficiency, thirdly is the consumer’s awareness of power quality (PQ) issues and lastly are the things that is interconnected in a network.

Problems, such as harmonics, arise within the customer’s own installation and may or may not propagate onto the network and so affect other customers. Harmonic problems can be dealt with by a combination of good design practice and well proven reduction equipment. Therefore, the 6 pulse GTO thyristor converter can be used to improve the power quality of the power system.

## 2.7 Harmonic Distortion

Harmonics distortion is the change in the waveform of the supply voltage from the ideal sinusoidal waveform that can be refer in Figure 2.9. It can be caused by the interaction of distorting customer loads with the impedance of the supply network. The ideal low voltage single phase supply is 240 Vrms, at a frequency of 50 Hz and with sinusoidal waveshape as shown in Figure 2.9. Until the 1960s, most customer loads drew a current waveform which was also sinusoidal. Such loads include induction motor, incandescent lights, stoves and most of the household appliances [9].

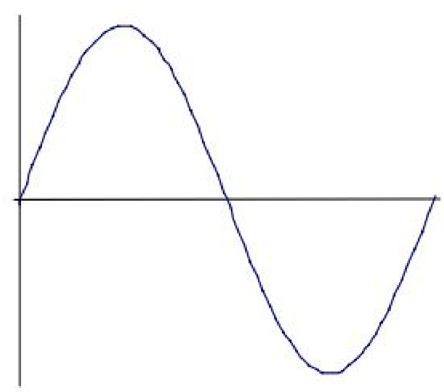

Figure 2.9 Ideal sinewave [9].

Harmonic distortion is found in both the voltage and the current waveform. Most current distortion is generated by electronic loads, also called non-linear loads. These non-linear loads might be single phase loads such as point-of-sale terminals, or three-phase as in variable speed drives.

As the current distortion is conducted through the normal system wiring, it creates voltage distortion according to Ohm's Law. While current distortion travels only along the power path of the non-linear load, voltage distortion affects all loads connected to that particular bus or phase.

Current distortion affects the power system and distribution equipment. It may directly or indirectly cause the destruction of loads or loss of product. From the direct perspective, current distortion may cause transformers to overheat and fail even though they are not fully loaded. Conductors and conduit systems can also overheat leading to open circuits and downtime [10]. The simple harmonic distortion that happens is shown in Figure 2.10.

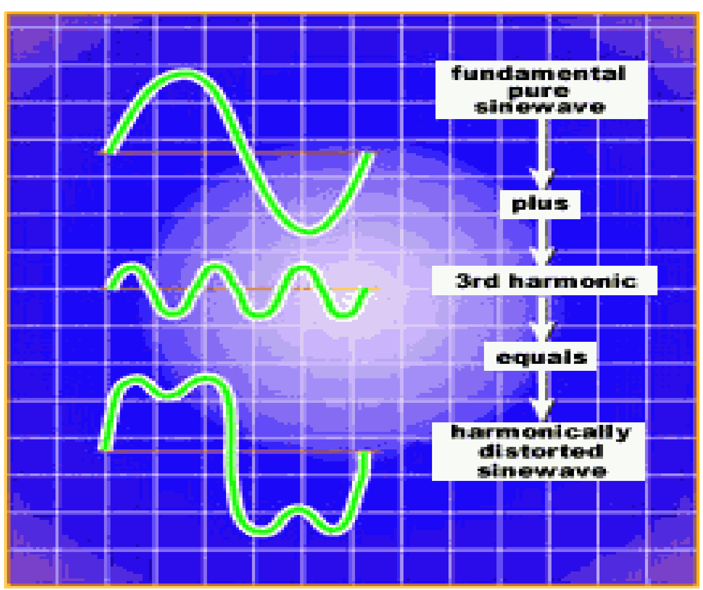


Figure 2.10 Harmonic distortions [10].

The growth in harmonic distortion is inevitable but only can be reduced. The actual power system voltage can depart from the ideal sinewave in several respects. Harmonics distortion is the name for a departure in which every cycle of the waveform is distorted equally. Figure 2.11(a) shows a distortion which appears on one cycle occasionally due to the switching of power factor correction capacitors on the power system and this is not harmonics distortion. However the distortion in the Figure 2.11(b) and (c) are forms of harmonics distortion, giving flat-topped and notching effect respectively.

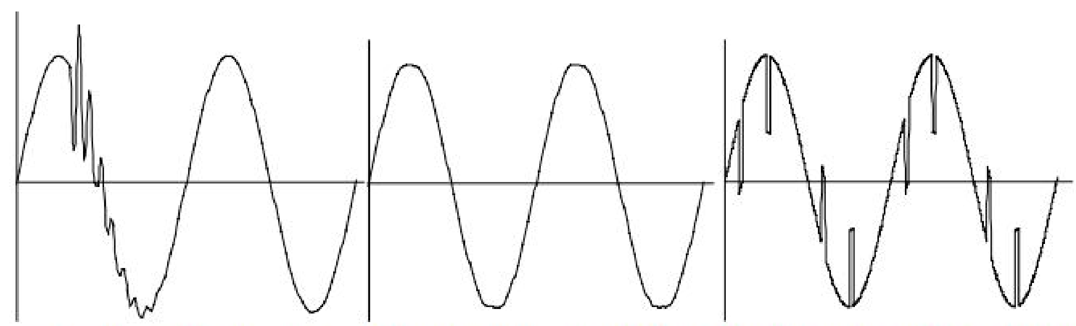


Figure 2.11 Types of voltage distortions.

The major adverse effects of the harmonics distortion are the heating of induction motors, transformers and capacitors and the overloading of neutrals. Therefore, it is important for us to overcome this harmonics distortion especially in the 6 pulse GTO thyristor converter project. In the 6 pulse GTO thyristor converter, the LC filter is used to reduce the harmonics distortion in the circuit.

## 2.8 Filters

Electronic filters are electronic circuits which perform signal processing functions, specifically to remove unwanted frequency components from the signal, to enhance wanted ones, or both. Electronic filters can be:

1. Passive or active
2. Analog or digital
3. High-pass, low-pass, bandpass, band-reject (band reject; notch), or all-pass.
4. Discrete-time (sampled) or continuous-time
5. Linear or non-linear
6. Infinite impulse response (IIR type) or finite impulse response (FIR type)

The most common types of electronic filters are linear filters, regardless of other aspects of their design [11].

From Figure 2.8, we could see that the filters are needed in the transmission line to improve the transmission line performance by removing unwanted signal components or enhance wanted ones.

### 2.8.1 LC Filter

In some applications such as UPS, the smooth sine wave output is required and this is when the filter is important. The combinations of L and C will tend to resonate, and this property can be exploited in designing band-pass and band-stop filter circuits. The series LC circuits give minimum impedance at resonance, while parallel LC circuits give maximum impedance at their resonant frequency. Knowing this, we have two basic strategies for designing either band-pass or band-stop filters.

For band-pass filters, the two basic resonant strategies are series LC to pass a signal in Figure 2.12 or parallel LC in Figure 2.14 to short a signal.

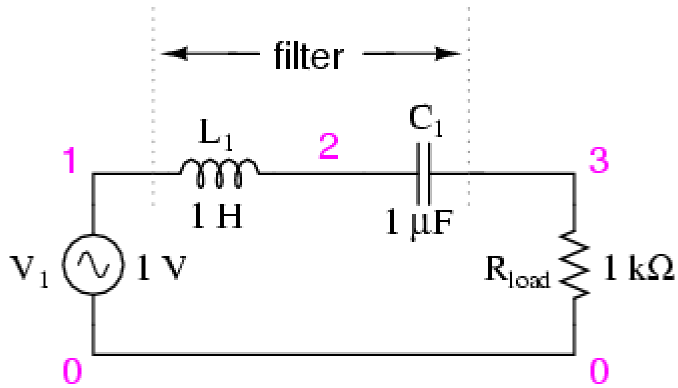


Figure 2.12 Series resonant LC band-pass filter.

The series LC components pass signal at resonance, and block signals of any other frequencies from getting to the load. This can be seen in Figure 2.13 below. Since this filter works on the principle of series LC resonance, the resonant frequency of which is unaffected by circuit resistance, the value of the load resistor will not skew the peak frequency. However, different values for the load resistor will change the "steepness" of the Bode plot and this is called the "selectivity" of the filter.

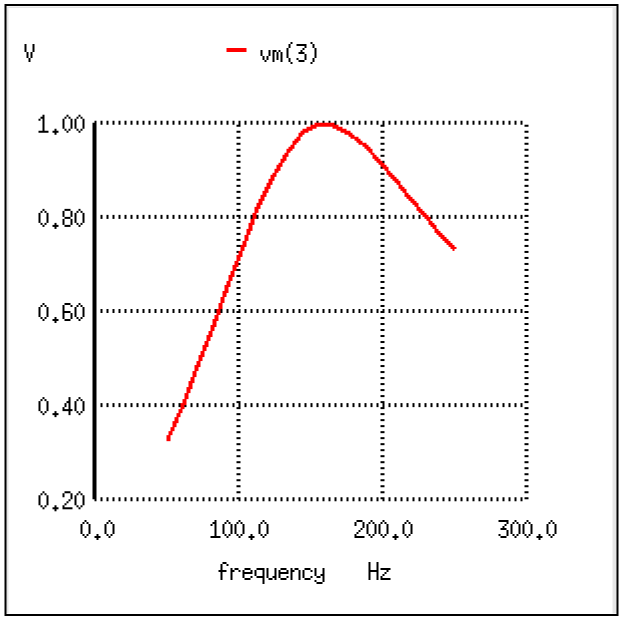


Figure 2.13 Series resonant band-pass filter waveform.

The other basic style of resonant band-pass filters employs a tank circuit or parallel LC combination to short out signals too high or too low in frequency from getting to the load. This can be seen in Figure 2.14 below.

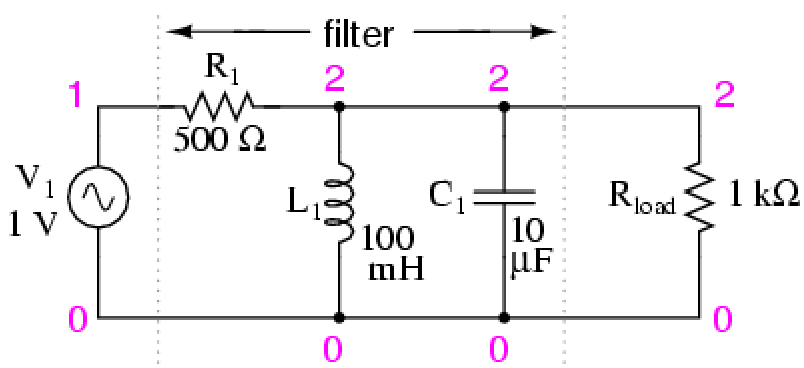


Figure 2.14 Parallel resonant LC band-pass filters.

The tank circuit will have a lot of impedance at resonance, allowing the signal to get to the load with minimal attenuation. Under or over resonant frequency, however, the tank circuit will have low impedance, shorting out the signal and dropping most of it across series resistor $R_1$. The waveform can be see in Figure 2.15.

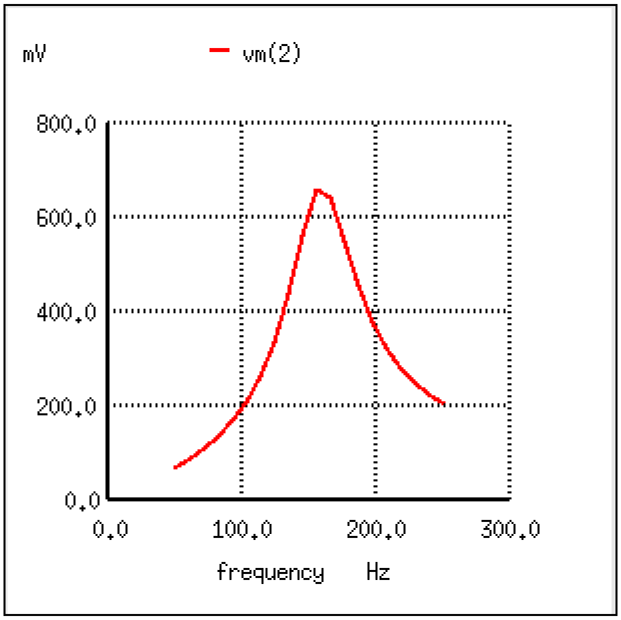


Figure 2.15 Parallel resonant band-pass filter waveform.

Just like the low-pass and high-pass filter designs relying on a series resistance and a parallel “shorting” component to attenuate unwanted frequencies, this resonant circuit can never provide full input (source) voltage to the load. That series resistance will always be dropping some amount of voltage so long as there is a load resistance connected to the output of the filter.

It should be noted that this form of band-pass filter circuit is very popular in analog radio tuning circuitry, for selecting a particular radio frequency from the multitudes of frequencies available from the antenna. In most analog radio tuner circuits, the rotating dial for station selection moves a variable capacitor in a tank circuit.

The power factor correction (PFC) can be used together with the LC filter but for this project, only the LC filter is used to improve the harmonics distortion of the 6 pulse GTO thyristor converter circuit.

## 2.9 Conclusion

One conclusion from this review is that a large number of reliability assessments of the HVDC system and GTO thyristor have been published, but very few in the area of its impact on the composite power system reliability. Choosing the suitable method for the simulation and analysis is important because different method may give different results and unsuitable method or technique can gives less accurate results or hard to perform. Today the computer resources are more sufficient for the inclusion of such methods in the reliability calculations. The growth in harmonic distortion is inevitable but only can be reduced and the power factor correction (PFC) can be used together with the LC filter to reduce the harmonic distortion but for this project, only the LC filter is used to improve the harmonics distortion of the 6 pulse GTO thyristor converter circuit.

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

Methodology can be defined as the analysis of the principles of methods, rules, and postulates employed by a discipline or a particular procedure or set of procedures. This chapter will be discussed about all the procedures that are being used in this project. The aim of all the method used is to archive the objective for this project. There are two types of the method used in this project, which is the first one is the simulation and the another one is the analysis. The simulation for this project used **PSPICE – OrCAD Release 9.1** simulator to design and simulate the GTO thyristor model, 6 pulse GTO thyristor converter and 6 pulse GTO thyristor with LC filter. To do the analysis method, all the data from the previous simulation will be gathered and mathematical calculations is conducted to prove the results. Then all the simulation and calculation data will be compile in a graph for the easy comparison for the analysis purpose. The comparison between the 6 pulse GTO thyristor converter and 6 pulse GTO thyristor with LC filter is also conducted for the harmonics analysis.

## 3.2 Project Planning

For the work progress planning, can refer to the gantt chart in Appendix A. Figure 3.1 shows the general work flow for the Simulation of 6 Pulse GTO Thyristor Converter and Harmonics Analysis project;

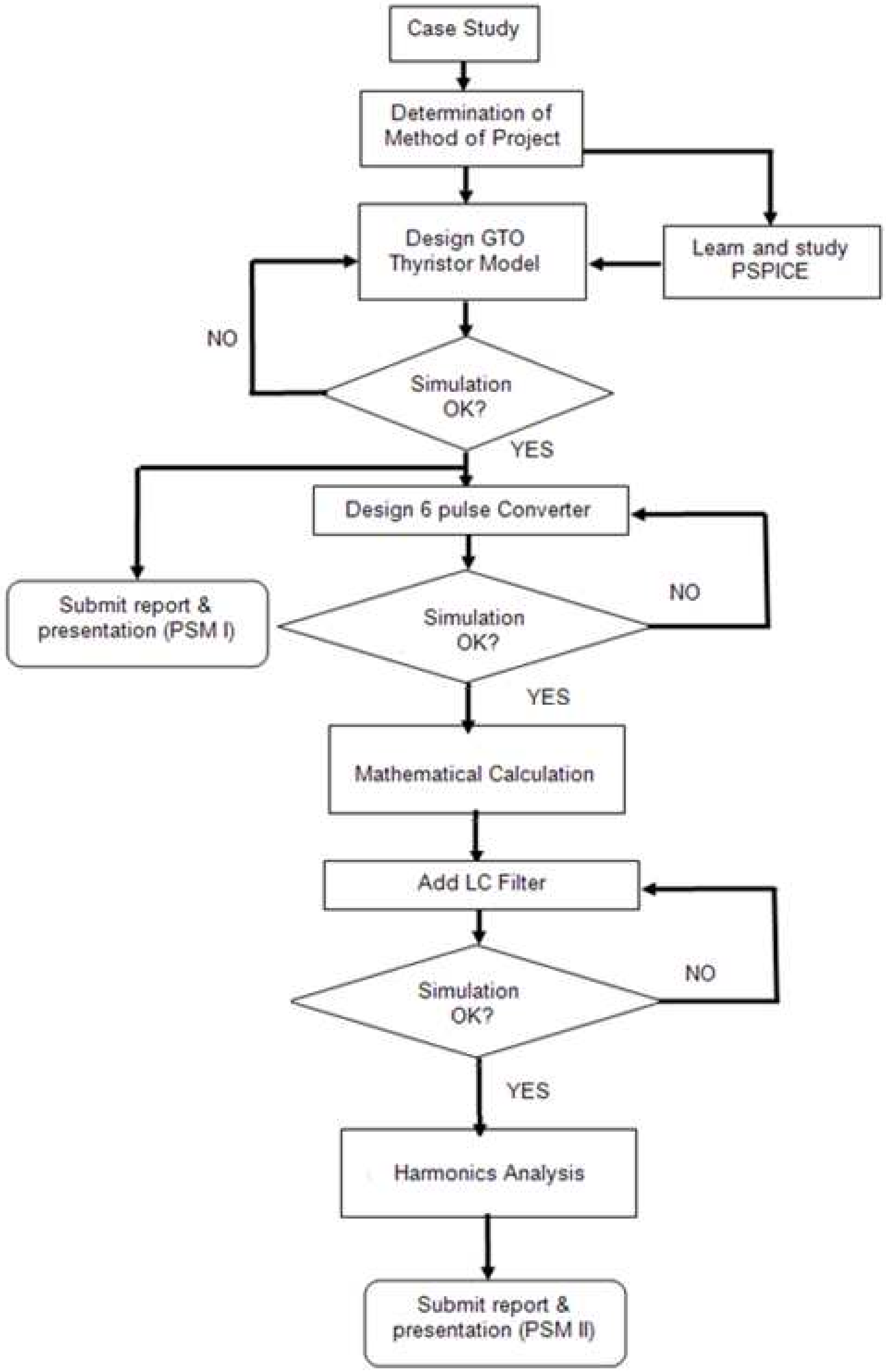


Figure 3.1 Project work flow for the Simulation of 6 Pulse GTO Thyristor Converter and Harmonics Analysis.

### 3.3 GTO Thyristor Simulations

Below in Figure 3.2 are the GTO thyristor model and its operation circuit proposed design that has being simulated and analyse using OrCAD PSpice.

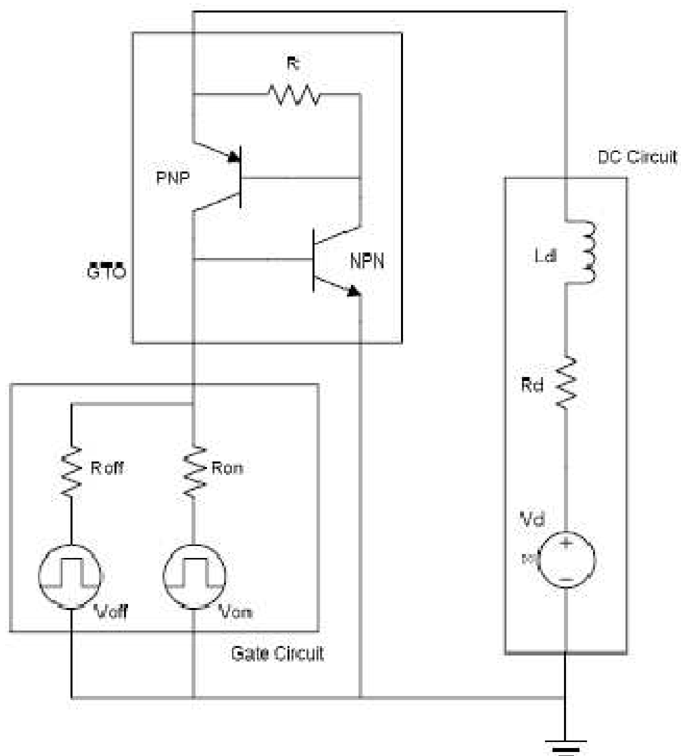


Figure 3.2 GTO thyristor model and its operation circuit.

For this simulation, the SMBTA06 and SMBT3906 is used for the NPN and PNP transistors respectively. This device can be found in the EBIPOLAR library for SMBTA06 and EPWRBJT for SMBT3906. The turn-on and turn-off of the GTO thyristor model are controlled by connecting the gate terminal to the gate circuit. The gate pulse current is set for about 5% of the anode current (positive pulse) for the turn-on process and about 60% of the anode current (negative pulse) is used to turn it off. Normally, 20% of anode current is enough to turn it off but 60% of the anode current is used considering the turn-off time where 60% of anode current is smaller than 20% of the anode current. Besides that, this decision is taken to consider the voltage loss. To simulate the circuit, the gate circuit turn-on time delay is set to the value of 2.0µs and the turn-off time delay is set at 10µs. This settings is very important in the switching operation of the GTO thyristor model and its operation circuit. The suitable simulation settings is also important in the PSPICE simulation because the schematic output waveform for the simultion will be displayed based on this settings. The simulation settings is compulsory in PSPICE simulation. The simulation settings for GTO thyristor model is 20us for the TSTOP and 0.1us for the maximum step size under Time Domain (Transient) in the Analysis tab.

The anode current, $I_a$ is calculated using the fomula in Equation 3.1 below;

$$I_a = \frac{V_d}{R_d} \quad \text{..................Equation 3.1}$$

Equation in 3.2 below is used to calculate the 5% of the turn-on time for the simulation and Equation 3.3 is used to calculate the turn-on resistance, $R_{on}$ that must be used for the simulation setting.

$$I_{on} = \frac{5}{100} x \, I_a \quad \text{.........Equation 3.2}$$

$$R_{on} = \frac{V_{on}}{I_{on}} \quad \text{..............Equation 3.3}$$

For the turn-off setting, basically the same formula is used but this time the value calculated is for the turn-off setting. For the turn-off setting, 60% of the anode current is used. The formula in equation 3.4 and 3.5 is used for this purpose.

$$I_{off} = \frac{60}{100} x \, I_a \quad \text{......Equation 3.4}$$

$$R_{off} = \frac{V_{off}}{I_{off}} \quad \text{...........Equation 3.5}$$

To prove the theory that higher percentage of the anode current can improve the turn-off time. The comparison for the 60% and 80% of the anode current is taken into consideration. The equation 3.6 and 3.5 is used to calculate the turn-off current, $I_{off}$ and turn-off resistance, $R_{off}$ respectively.

$$I_{off} = \frac{80}{100} x\, I_a \quad \text{.........Equation 3.6}$$

Table 3.1 below shows the GTO thyristor model operation circuit parameters that has been used in the simulation;

Table 3.1 Operation circuit parameters of the GTO thyristor model

| | | |
|---|---|---|
| Operation Circuit | $L_d$ | 1μH |
| | $R_d$ | 20Ω, 10Ω, 5Ω |
| | $V_d$ | 300V |
| GTO Thyristor | PNP | SMBT3906 |
| | NPN | SMBTA06 |
| | R | 1Ω |
| Gate Circuit | $V_{on}$ | 30V |
| | $V_{off}$ | -180V |
| | $R_{on}$ | 40Ω, 20Ω, 10Ω |
| | $R_{off}$ (60%) | 20Ω, 10Ω, 5Ω |
| | $R_{off}$ (80%) | 15Ω, 7.5Ω, 3.75Ω |

From the simulation, the total turn-off time which is composed from three distinct times; storage time, fall time and tail time, must be measured from each output graph. For the measurement, can refer to the GTO thyristor turn-on and turn-off characteristic and their definition in Appendix B and C.

### 3.4 6 pulse GTO Thyristor Converter Simulations

The 6 pulse converter is also known as 3-phase fully controlled full wave bridge converter. The 6 pulse GTO thyristor converter is supplied by 3 phase AC supply. The 6 pulse GTO thyristor converter supplies power to the load. Each three single phase power supply, Va, Vb and Vc fed 50V and 50Hz of the AC voltage and frequency respectively. For the Va, Vb and Vc, the VSIN from the SOURCE OrCAD PSpice library is used. To make sure the supply is three phase, the PHASE setting under property editor for each supply is made, the PHASE setting is 0°, -120º and 120° for Va, Vb and Vc respectively. Basically, the GTO thyristor model data from the simulations before is used in this 6 pulse GTO thyristor converter simulations.

The parameters for the AC side are shown in Table 3.2. The 6 pulse GTO thyristor converter circuit consists of 6 GTO thyristors that are triggered by the gate circuit G1 until G6. The gate circuit parameters for this simulation are the same as in Table 3.1, explained in the GTO thyristor simulations subtopic. At the DC side, the load is composed of a DC voltage, $V_d$ and a variable resistor $R_d$ in series with a smoothing inductor $L_d$. The parameters of these components are also shown in Table 3.2.

In 6 pulse converter circuits, the thyristor can be turned ON by the gate at any firing angle, with respect to the applied voltage. This firing angle is measured with respect to the given reference, at which the firing pulses are applied to the thyristor gates. The reference point is the point at which the applications of the gate pulses results in the maximum mean positive DC terminal voltage of which the converter is capable.

In the other words, a firing angle of 0° corresponds to the conditions when each thyristor in the circuit is fired at the instant its anode voltage first becomes positive in each cycle, under this condition, therefore, the converter operates in exactly the same manner as if it was an uncontrollable circuit. The 'α' is the symbol of the firing angle. Hence, the most efficient method to control the turning ON of a thyristor is archived by varying the firing angle of the GTO thyristor. Such method of control is called as phase-angle control.

The value of the variable resistor and DC voltage is varying to get the most suitable output for each firing angle. The 6 pulse GTO thyristor converter can be functioned as a rectifier and an inverter depend on the firing angle, α. It is function as a rectifier when the firing angle is in the range of 0º until 90º which converts AC to DC. When the firing angle is more than 90º, the converter will be function as an inverter which converts DC to AC. Therefore, DC voltage, $V_d$ is required during the inverter operation. So, the DC voltage value is varying in the range of 1µV ~ 200V for this simulation.

Table 3.2 Parameters of the 6 pulse GTO thyristor converter circuit

| | | |
|---|---|---|
| 3 Phase Circuit (AC Side) | Ra, Rb, Rc | 0.1mΩ |
| | Va, Vb, Vc | 50V, 50Hz |
| 6 pulse GTO Thyristor Converter | G1~G6 | Gate Circuit |
| DC Side | Rd | variable |
| | Ld | 1mH |
| | Vd | 1µV~ 100V |

The different firing angles are set using the formula in the Equation 3.7. The time delays are setting depend on the required firing angle. For example, if we want to turn-on GTO thyristor with gate circuit G1 at firing angle, α = 15°, we need to fired a positive gate current at time delay, TD=2.5ms but for the firing angle, α = 60°, the time delay for G1 is 5ms.

$$TD = \frac{\alpha + 30°}{360°}\ x\ \frac{1}{f}$$ ………Equation 3.7

Where, $f$ is the supply frequency.

For the simulation of the 6 pulse GTO thyristor converter, the firing angle, α used for the simulation is for 0°, 15°, 30°, 60°, 90°, 120°, 165°. The time taken for one cycle of sinusoidal wave can be calculated using the Equation 3.8 below;

$$T = \frac{1}{f}$$ ………..Equation 3.8

And because of this simulation using 6 GTO thyristor circuit G1 until G6, the value of the time, T is divided by 6. To get the value for other GTO settings except for G1, the value is added by this value. Since the frequency used for supply is 50Hz, the value of time need to add one after another is about 3.3333333ms. For example, this value is added with G1 time delay to get G2 time delay and so on. But when the value exceeded the value of the time for one cycle, T, the time delay value for that GTO thyristor circuit must be minus by T.

Figure 3.3 below shows the block diagram for the design of 6 pulse GTO converter circuit;

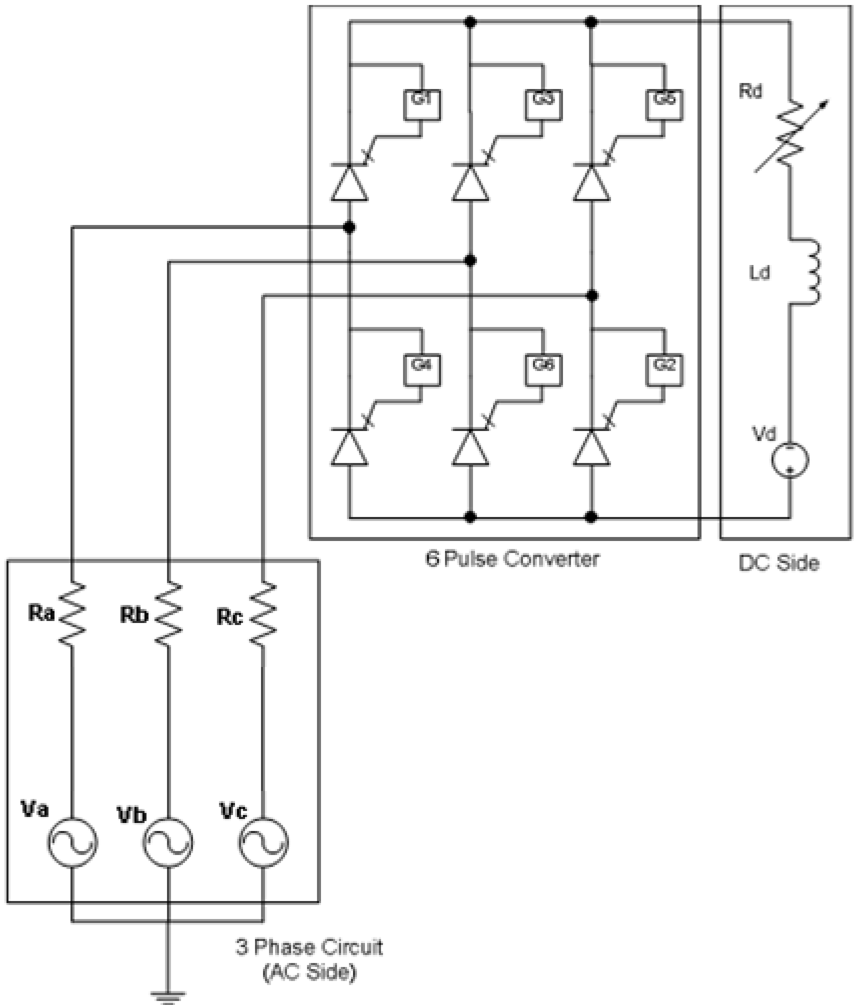


Figure 3.3 The block diagram of 6 pulse GTO thyristor converter circuit.

### 3.5 Mathematical Analysis

To do the analysis, all the data from the simulation of 6-pulse GTO thyristor converter will be gathered and mathematical calculations is conducted to prove the results. Then all the simulation and calculation data will be compile in a graph for the easy comparison for the analysis purpose. During calculations, Equation 3.9 will be used to find DC output voltage.

$$E_{dc} = \frac{3\sqrt{3}}{2\pi} E_m (\cos\alpha + \cos(\alpha + u))$$ ..... ………Equation 3.9

The value of the Em is the maximum AC voltage taken from the AC side which is 50V, α is the firing angle used and u is the commutation overlap. To find α + u, Equation 3.10 is used;

$$\alpha + u = \phi - \frac{\pi}{2} + \cos^{-1}\left(\cos\left(\alpha + \frac{\pi}{2} - \phi\right) - \frac{2I_d\sqrt{R^2 + (\omega L)^2}}{\sqrt{3}E_m}\right)$$ …Equation 3.10

The value of R and L is taken from the AC side and $I_d$ is the DC output current that is found from varying the value of $R_d$. To find Φ, Equation 3.11 is used;

$$\phi = \tan^{-1}\frac{\omega L_d}{R_d}$$ ……..Equation 3.11

### 3.6 6 pulse GTO Thyristor Converter With LC Filter Simulations

The LC filter is added to the 6 pulse GTO thyristor converter circuit to reduce the harmful affects of the harmonics current in the output. The harmonics currents are displayed as the distortion in the output waveforms. The type of LC filter used is the series resonant LC band-pass filter. This filter is inserted in each phase of the 3-phase power supply. Figure 3.4 below shows the block diagram for the design of 6 pulse GTO converter circuit with LC filter.

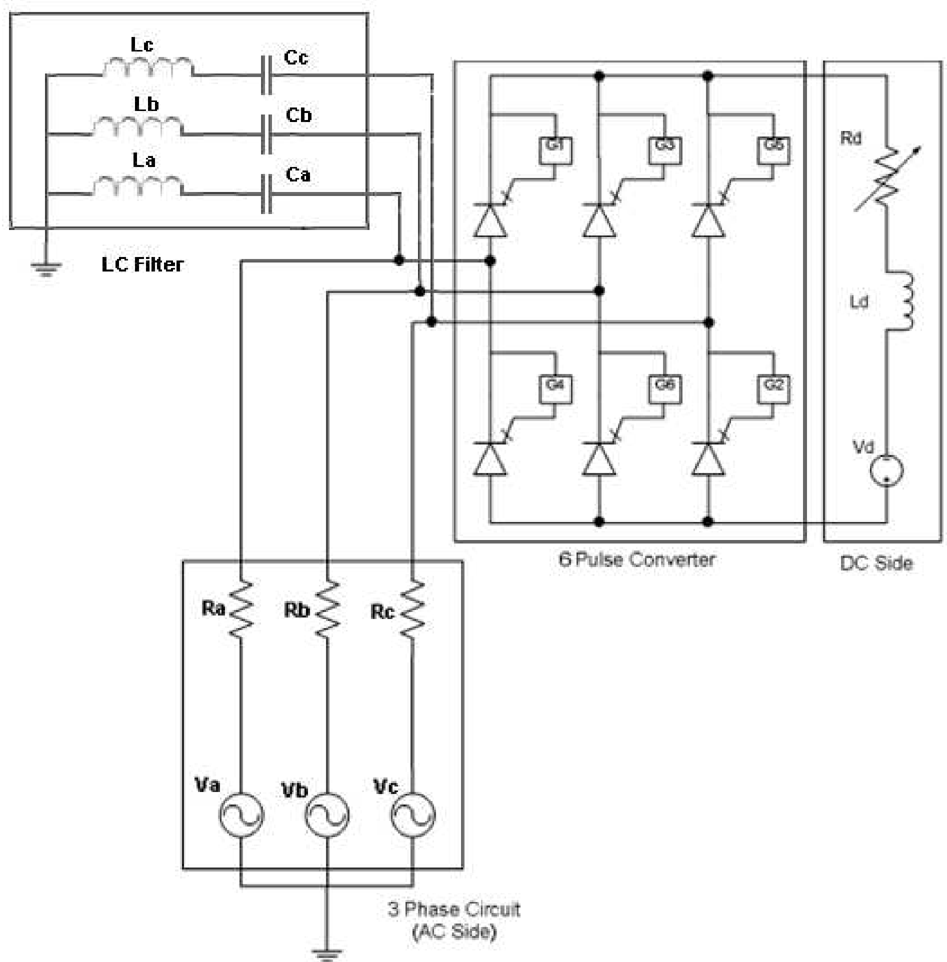


Figure 3.4 6 pulse GTO converter circuit with LC filter.

The series resonant LC band-pass filter, also called a resonant circuit or tuned circuit consists of an inductor, represented by the letter L, and a capacitor, represented by the letter C. When connected together, an electrical current can alternate between them at the circuit's resonant frequency. The resonant frequency can be calculated using Equation 3.9 below.

$$f = \frac{1}{2\pi\sqrt{LC}}$$ …..Equation 3.12

Where L is the inductance in henries, and C is the capacitance in farads. The angular frequency has units of radians per second. LC circuits are used either for generating signals at a particular frequency, or picking a signal at a particular frequency from a more complex signal. They are key components in many applications such as oscillators, filters, tuners and frequency mixers. An LC circuit is an idealized model since it assumes there is no dissipation of energy due to resistance

## 3.7 Harmonics Analysis

Harmonics current are created by non-linear loads that generate non-sinusoidal current on distribution power system. However, because of the increased popularity of electronic and other non-linear loads, the current waveform quite often became distorted. To understand the distortion phenomena, it is necessary to analyze the distorted waveform by a process called harmonic analysis. It allows us to express the distorted waveform as a sum of dc component, fundamental sine wave of the distorted waveform and a series of pure sine wave. For this analysis, the fourier circuit analysis is conducted for 6-pulse GTO thyristor converter and 6 pulse GTO thyristor with LC filter in OrCAD PSpice to get the fourier transform waveform that explains the harmonics in both circuits. The comparison between the 6 pulse GTO thyristor converter and 6 pulse GTO thyristor with LC filter circuits is conducted using the harmonics output waveform from the fourier circuit analysis.

# CHAPTER 4

# RESULTS AND ANALYSIS

## 4.1 Introduction

This chapter will briefly discuss on the results and analysis of the project. This project has been successful in achieving the objective. The GTO thyristor model is successfully designed in OrCAD PSpice, then it is applied in the 6 pulse GTO thyristor converter circuit and lastly the converter is improved using LC filter. The methodology is already discussed in the previous chapter.

## 4.2 GTO Thyristor Model

The turn-on and turn-off of the GTO thyristor model are controlled by connecting the gate terminal to the gate circuit. The gate pulse current is set for about 5% of the anode current (positive pulse) for the turn-on process and about 60% of the anode current (negative pulse) is used to turn it-off. Normally, 20% of anode current is enough to turn it off but 60% of the anode current is used considering the turn-off time where 60% of anode current is smaller than 20% of the anode current. To prove the theory that higher percentage of the anode current can improve the turn-off time, the comparison between 60% and 80% of the anode current is prepared.

### 4.2.1 The 60% of Anode Current

Simulation has been done with PSpice simulator using the parameters in Table 3.1 from previous chapter. For the anode current, $I_A = 15$ A, the simulation circuit and turn-on and turn-off characteristics of the GTO thyristor output waveform characteristic is shown in Figure 4.1 and Figure 4.2.

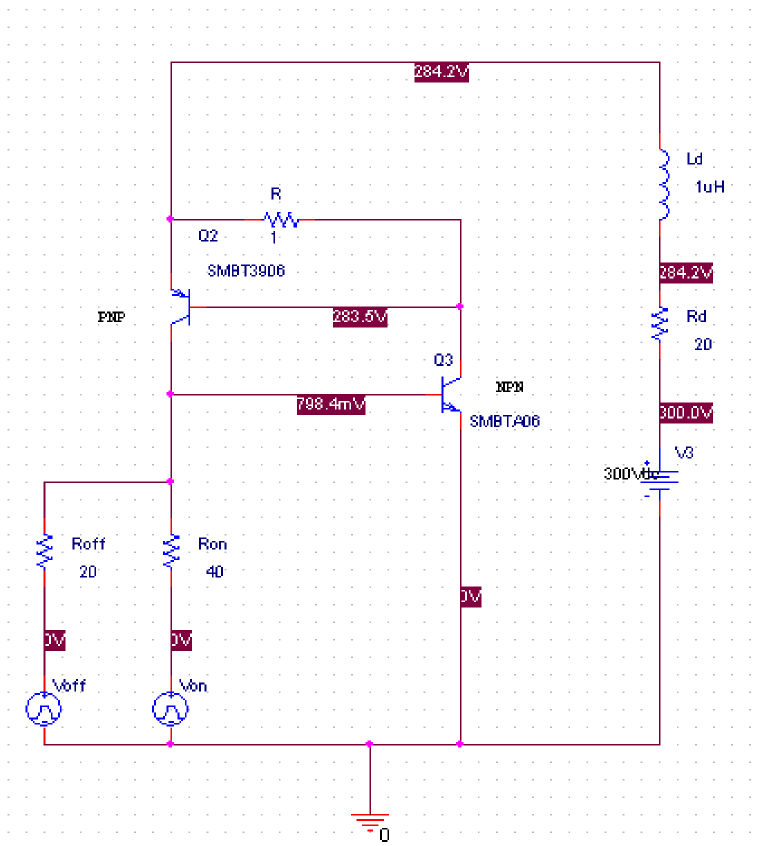


Figure 4.1 Simulation circuit for anode current 15A (60%).

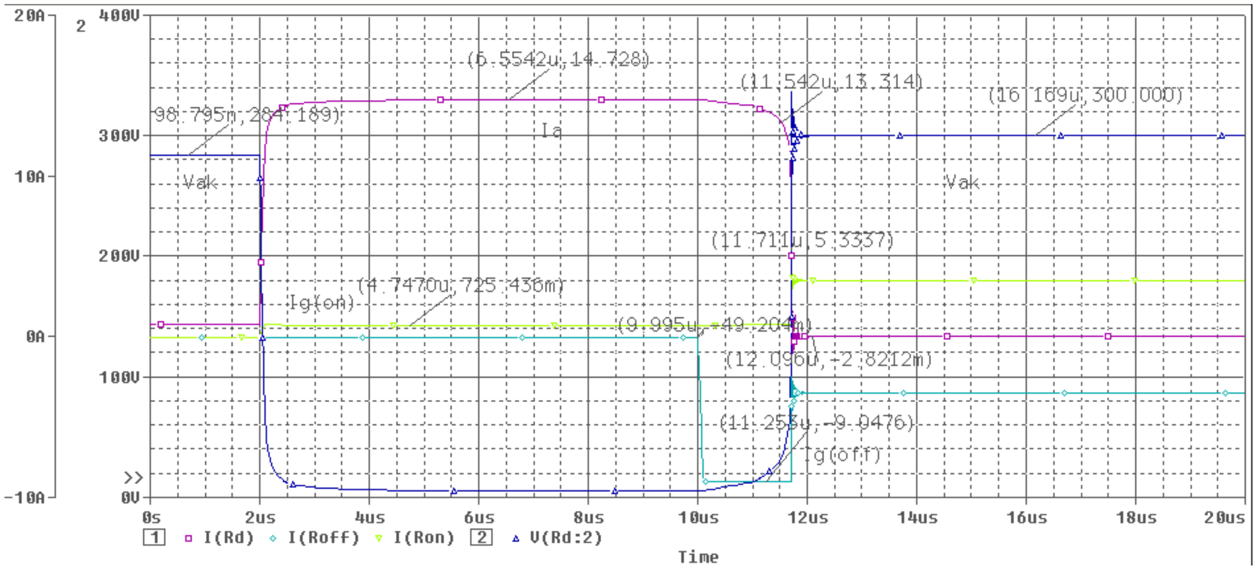


Figure 4.2 Turn-on and turn-off characteristic of GTO thyristor for $I_A$=15A (60%).

For the anode current, $I_A$ = 30 A, the simulation circuit and turn-on and turn-off characteristics of the GTO thyristor output waveform characteristic is shown in Figure 4.3 and Figure 4.4 respectively.

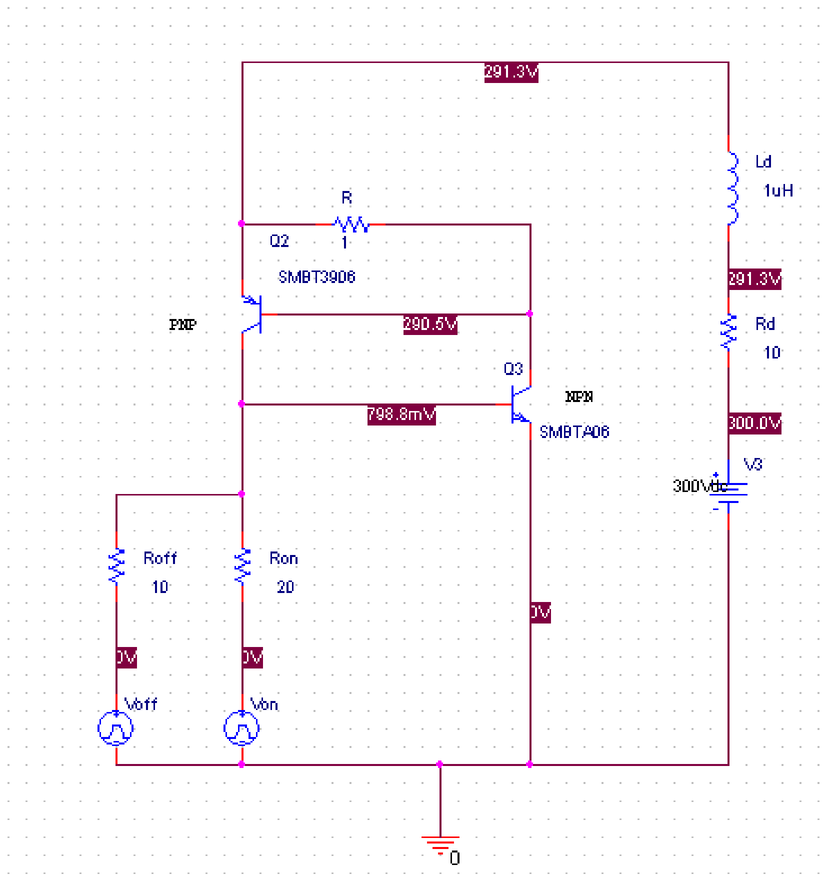


Figure 4.3 Simulation circuit for anode current 30A (60%).

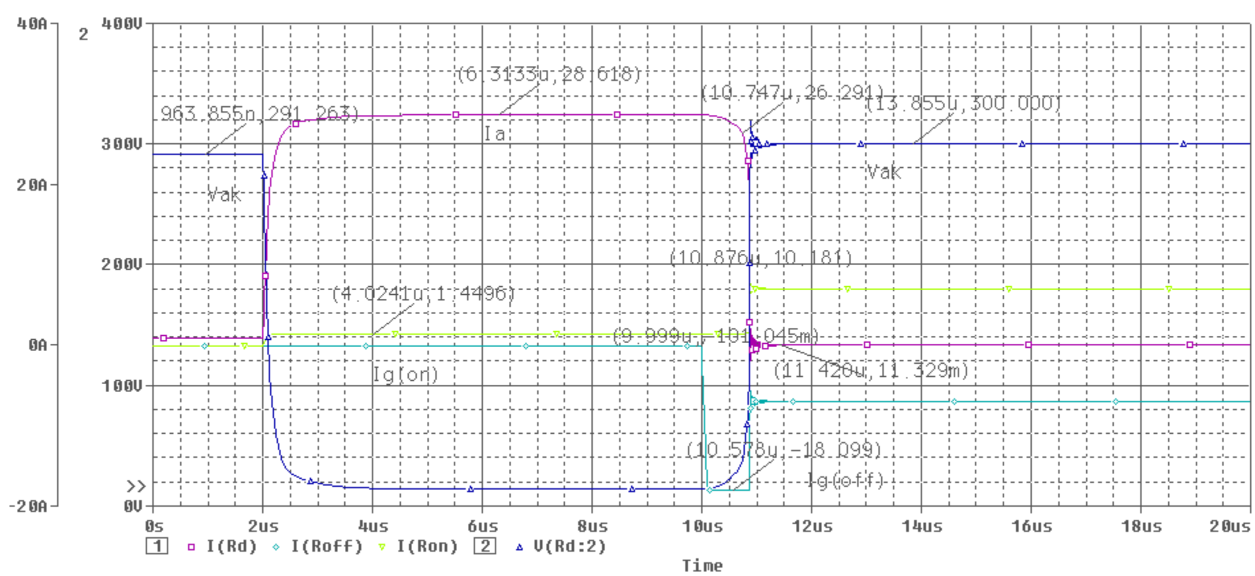


Figure 4.4 Turn-on and turn-off characteristic of GTO thyristor for $I_A$=30A (60%).

For the anode current, $I_A = 60$ A, the simulation circuit and turn-on and turn-off characteristics of the GTO thyristor output waveform characteristic is shown in Figure 4.5 and Figure 4.6.

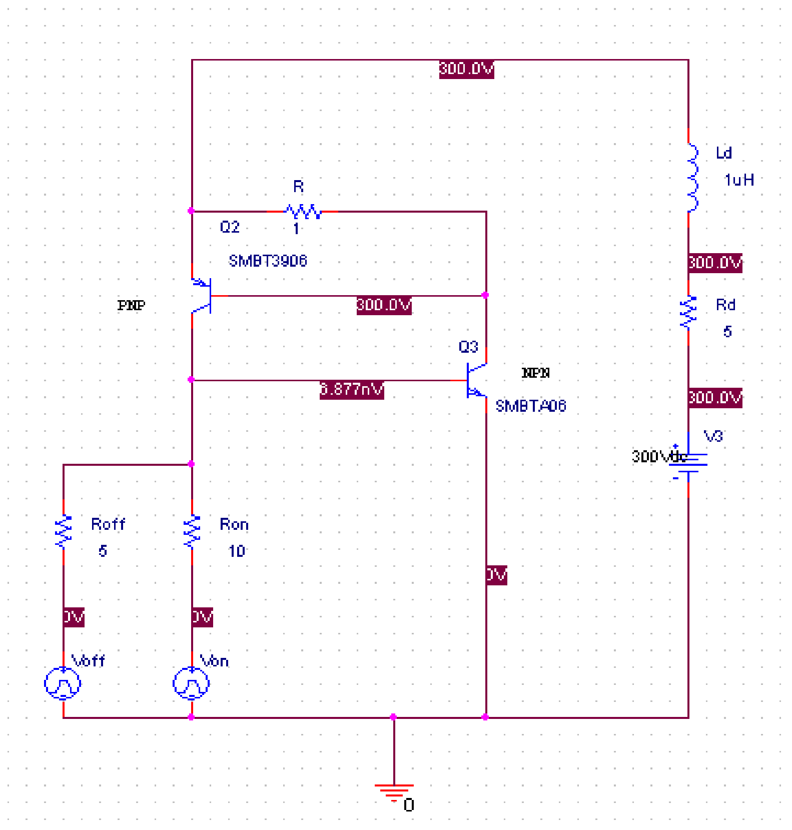


Figure 4.5 Simulation circuit for anode current 60A (60%).

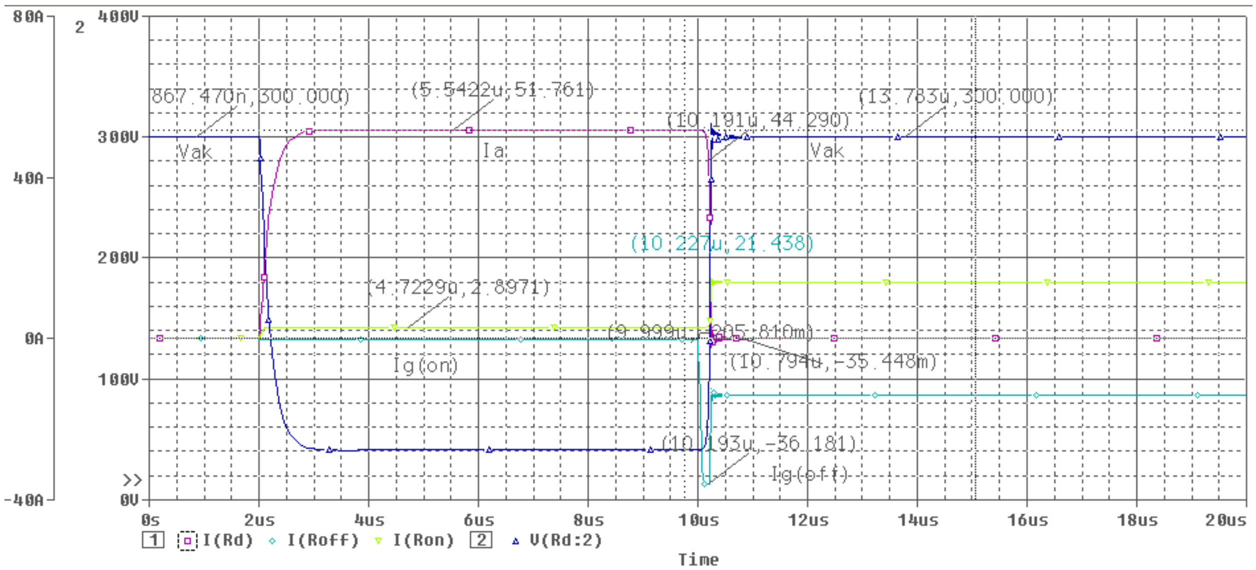


Figure 4.6 Turn-on and turn-off characteristic of GTO thyristor for $I_A$=60A (60%).

### 4.2.2 The 80% of Anode Current

The simulation of 80% of the anode current for $I_{off}$ is conducted to prove the theory that higher percentage of the anode current can improve the turn off time. The simulation conducted using the parameters in Table 3.1 from previous chapter. For the anode current, $I_A$ = 15A, the simulation circuit in Figure 4.7 is designed in OrCAD PSpice, the output simulation results is as shown in Figure 4.8.

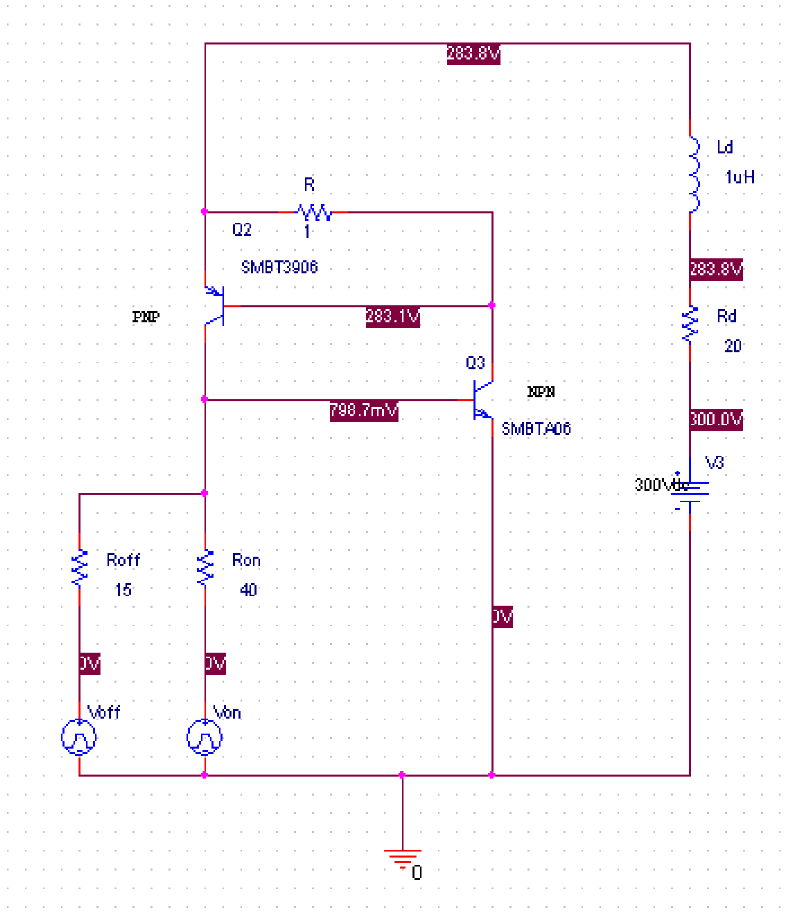


Figure 4.7 Simulation circuit for anode current 15A (80%).

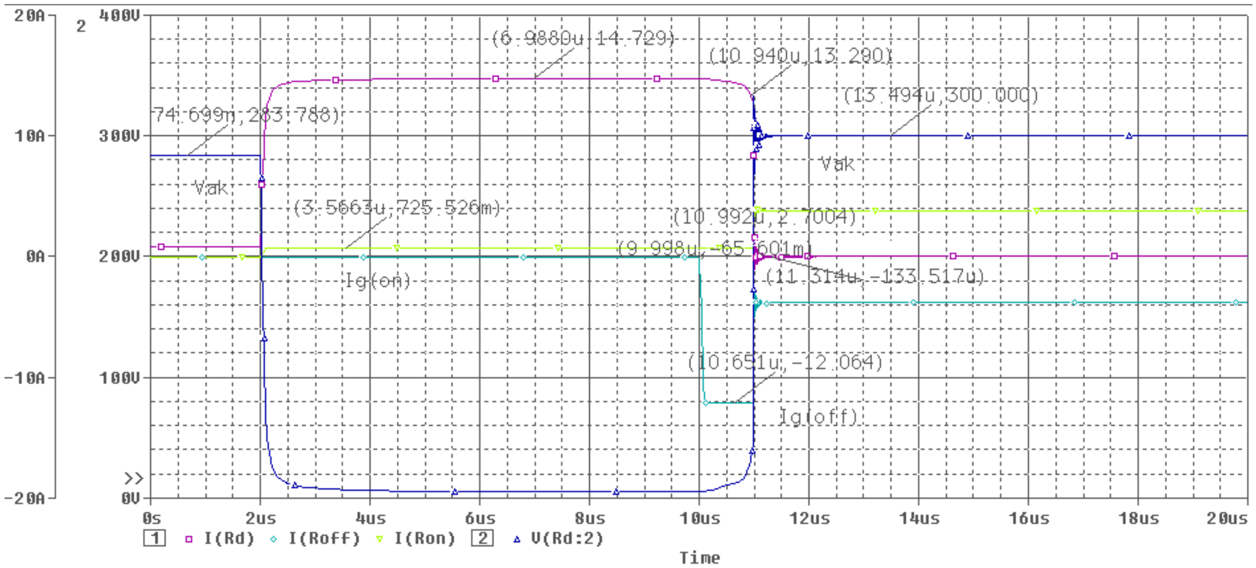


Figure 4.8 Turn-on and turn-off characteristic of GTO thyristor for $I_A$=15A (80%).

For the anode current, $I_A$ = 30 A, the simulation circuit and turn-on and turn-off characteristics of the GTO thyristor output waveform characteristic is shown in Figure 4.9 and Figure 4.10.

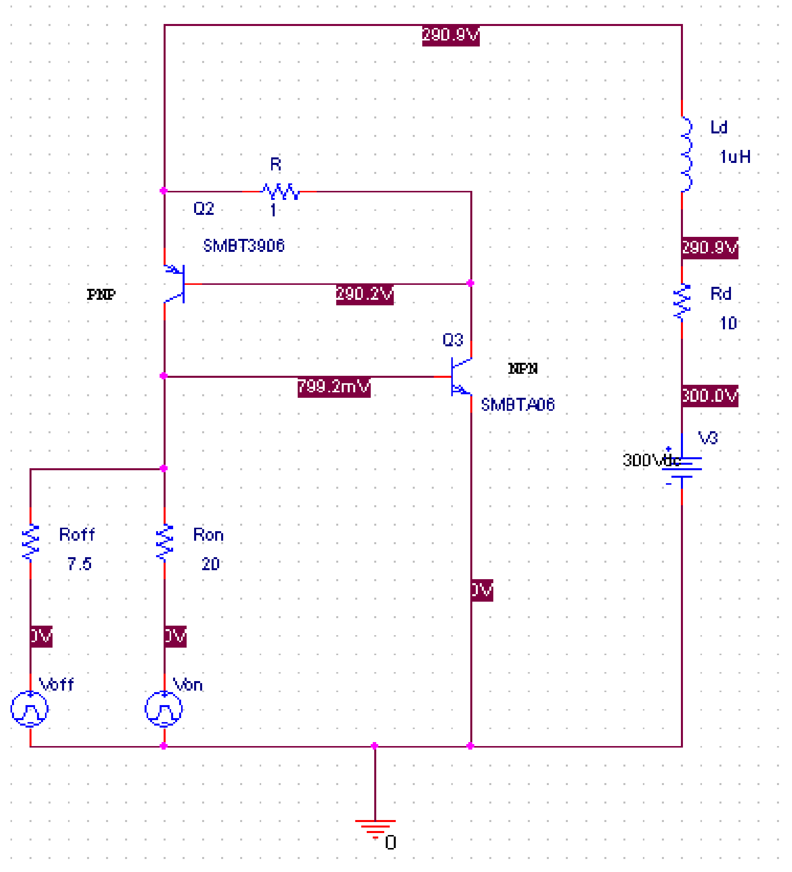


Figure 4.9 Simulation circuit for anode current 30A (80%).

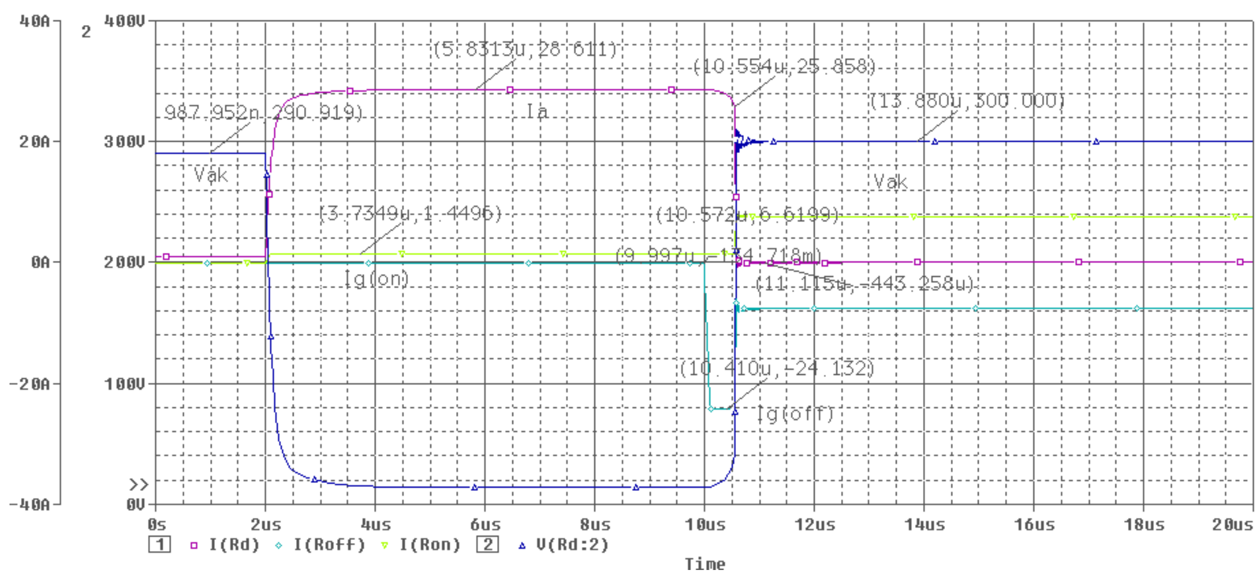


Figure 4.10 Turn-on and turn-off characteristic of GTO thyristor for $I_A$=30A (80%).

For the anode current, $I_A$ = 60A, the simulation circuit in Figure 4.11 is designed in OrCAD PSpice, the output simulation results is as shown in Figure 4.12.

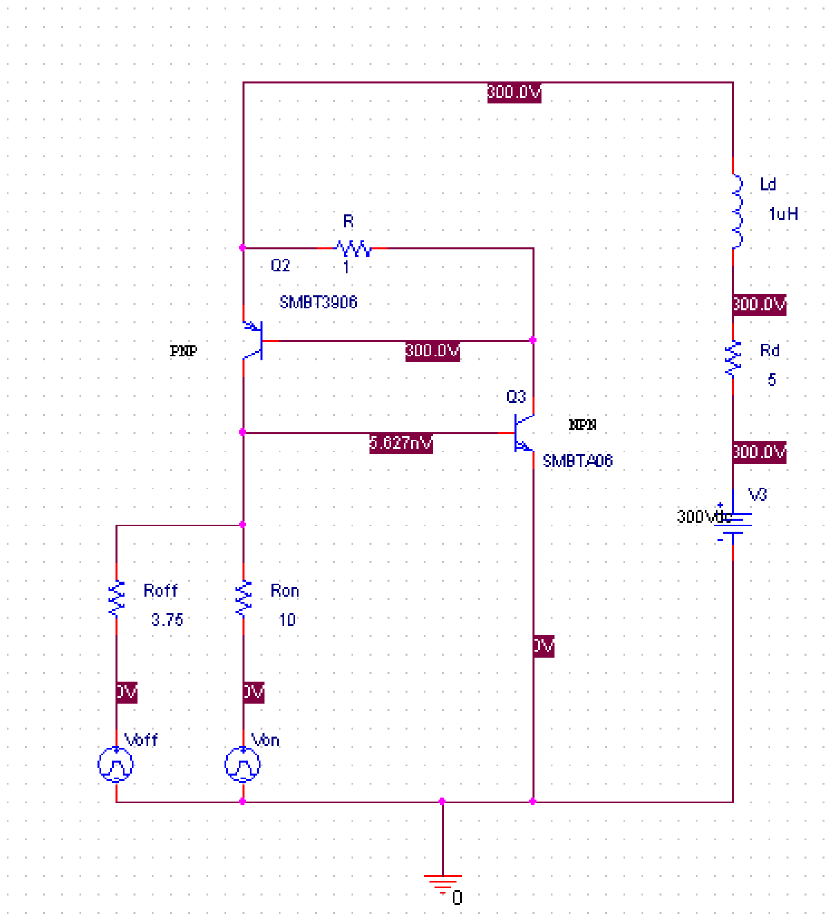


Figure 4.11 Simulation circuit for anode current 60A (80%).

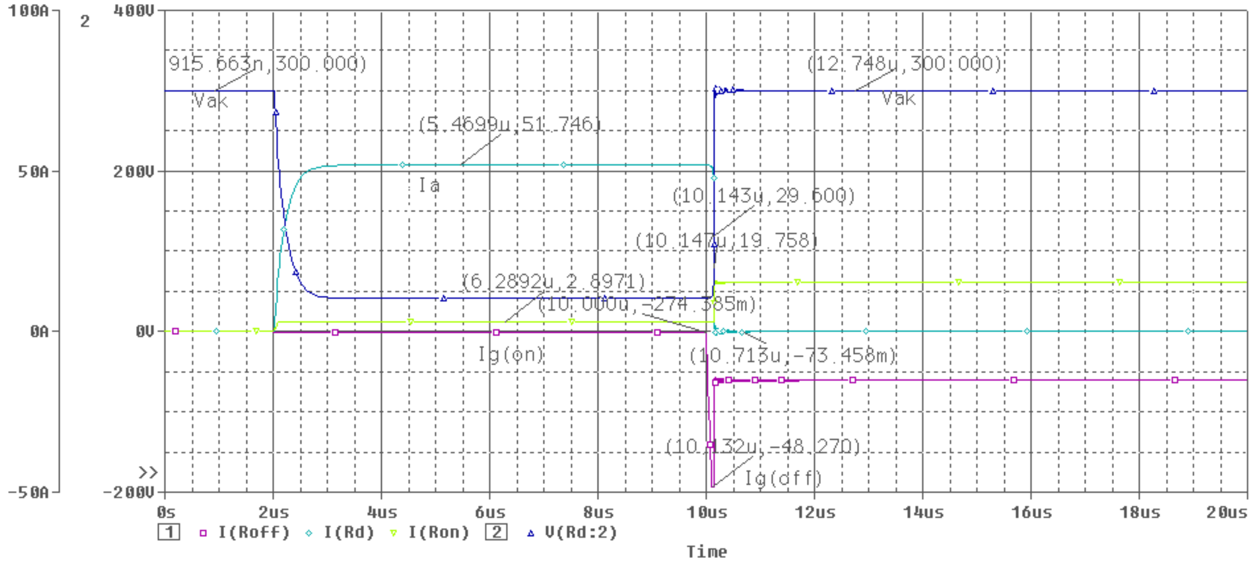


Figure 4.12 Turn-on and turn-off characteristic of GTO thyristor for $I_A$=60A (80%).

### 4.2.3 Turn-off Time Comparison

When a positive signal is applied, GTO thyristor starts conducting. Before positive gate current is applied, the initial condition of anode current, $I_A$ is zero and anode-cathode voltage $V_{AK}$ is the peak reverse voltage. When positive gate current applied, conduction starts and anode current, $I_A$ rise to full value and the $V_{AK}$ becomes very small. When a negative gate signal is applied, the anode current becomes zero and the $V_{AK}$ rises to peak reverse voltage.

The total turn-off time is composed of three distinct times, storage time, fall time and tail time. Initiation of turn off process starts immediately on the application of negative gate signal. The time elapsing between applications of negative gate current till this current reaches its negative peak value known as storage time. During this period, the excess charges are removed by the negative gate current and GTO thyristor gets ready to turn-off. During fall time, the anode current decreases rapidly and anode cathode voltage rises. After fall time is over, the current falls slowly to zero value during tail time. At the end of the tail time, the anode current $I_A$ becomes zero and $V_{AK}$ becomes equal to peak reverse voltage.

Table 4.1 and Table 4.2 shows the storage time, fall time, tail time and turn-off time for different anode current for $I_{off}$ 60% of the anode current and $I_{off}$ 80% of the anode current respectively.

Table 4.1 Storage Time, Fall Time, Tail Time and Turn-off Time for different anode current for $I_{off}$ 60% of the anode current.

| Anode Current [A] | Storage Time [μs] | Fall Time [μs] | Tail Time [μs] | Turn-off Time [μs] |
|---|---|---|---|---|
| 15 | 1.547 | 0.169 | 0.385 | 2.101 |
| 30 | 0.748 | 0.129 | 0.544 | 1.421 |
| 60 | 0.192 | 0.036 | 0.567 | 0.795 |

Table 4.2 Storage Time, Fall Time, Tail Time and Turn-off Time for different anode current for $I_{off}$ 80% of the anode current.

| Anode Current [A] | Storage Time [μs] | Fall Time [μs] | Tail Time [μs] | Turn-off Time [μs] |
|---|---|---|---|---|
| 15 | 0.942 | 0.052 | 0.322 | 1.316 |
| 30 | 0.557 | 0.018 | 0.543 | 1.118 |
| 60 | 0.143 | 0.004 | 0.570 | 0.717 |

From this simulation results, it is known that this GTO thyristor model can be turn-on and turn-off in the range of anode current of 15A to 60A. The theory that higher percentage of the anode current can improve the turn off time is also proven as we can see in the tables that the $I_{off}$ 80% of the anode current has smaller turn-off time compare to the $I_{off}$ 60% of the anode current.

## 4.3 The 6 Pulse GTO Thyristor Converter

A six-pulse converter operating from a 50Hz supply produces a 300Hz (6 x 50) ripple in the output DC voltage waveform. For high powers, above 20kW, three phase circuit are used. Current pulses are required for triggering GTOs. The output voltage in all the configurations is controlled by delaying the firing angle, α of the thyristor. The setting of firing angle, α can bee refer to Appendix D. The calculation for the firing angle has been explained in Chapter 3 before. The simulations for 6 pulse GTO thyristor converter for this project has been conducted for the firing angle 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 150° and 165°. Since there is too many simulations conducted, only a simulation for firing angle 0°, 15°, 30°, 75°, and 105° will be showing in this part and the other is used for the analysis part. This simulations is done for DC currents, $I_d$=1A. Below in Figure 4.13 and Figure 4.14 is the simulation circuit for firing angle 0° and the simulation output respectively;

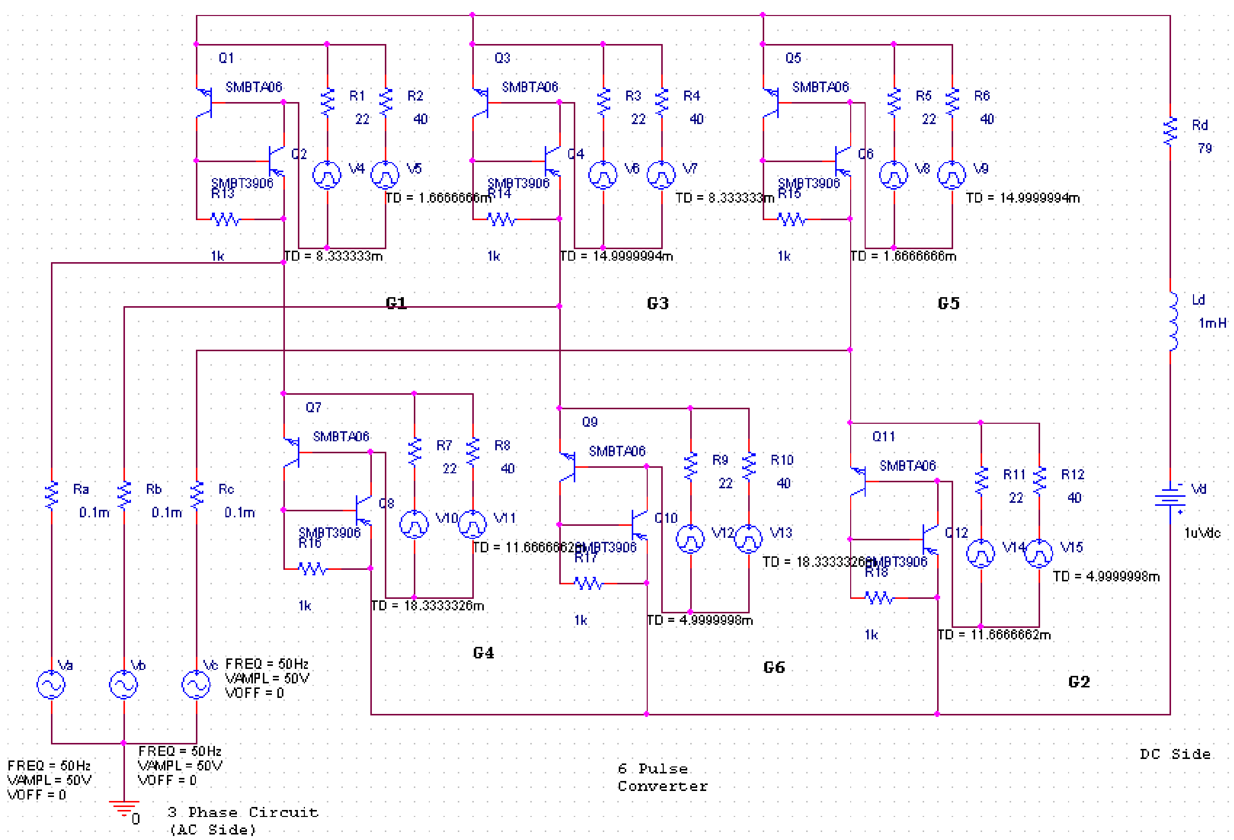


Figure 4.13 Simulation circuit for α=0°.

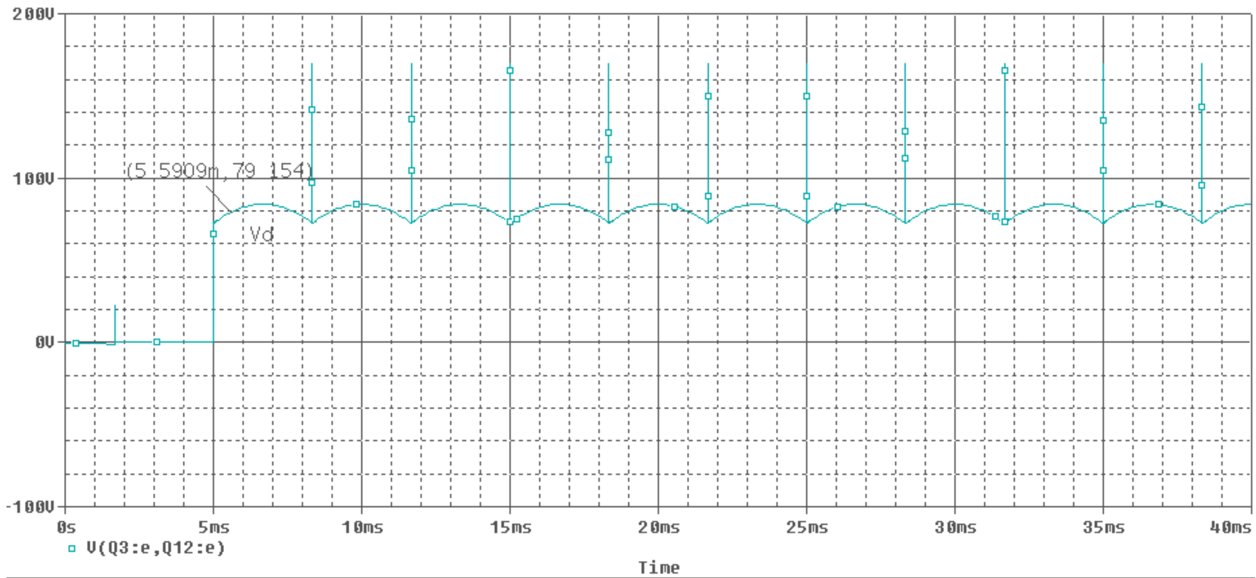


Figure 4.14 Simulation output for α=0°.

Below in Figure 4.15 and Figure 4.16 is the simulation circuit for firing angle 15° and the simulation output respectively;

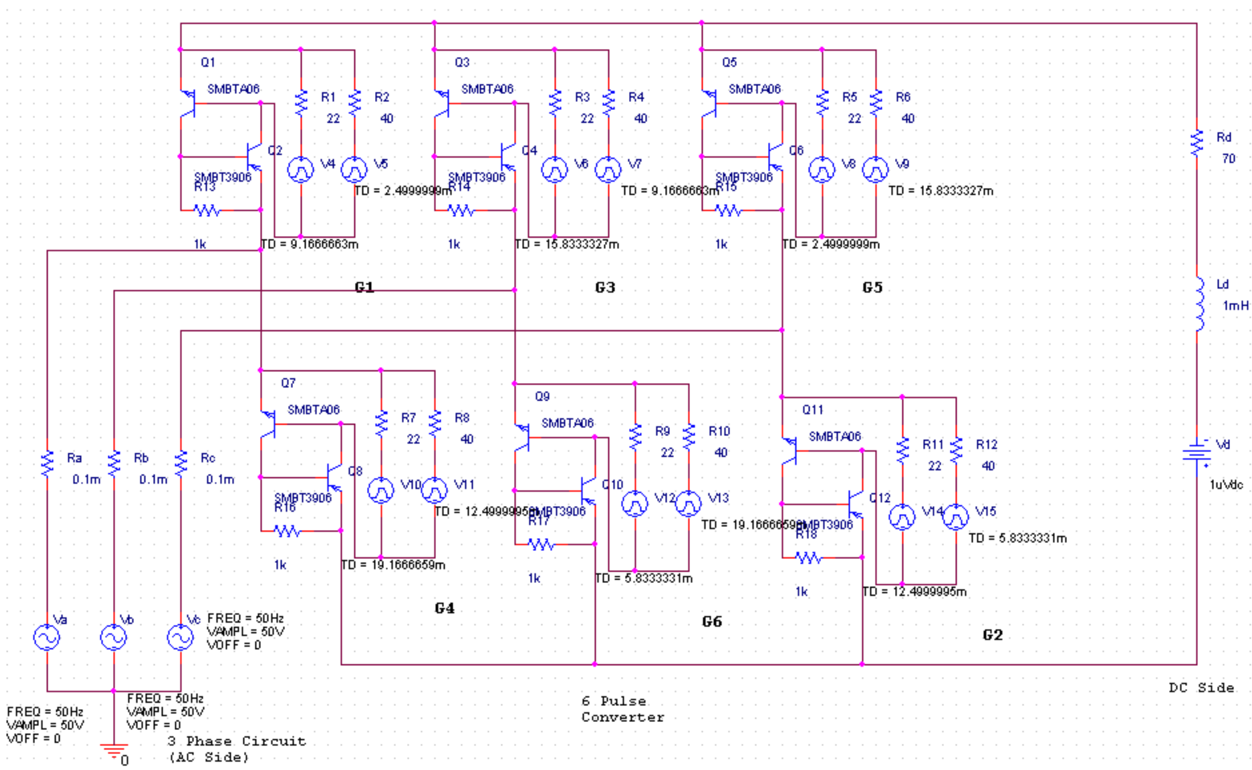


Figure 4.15 Simulation circuit for α=15°.

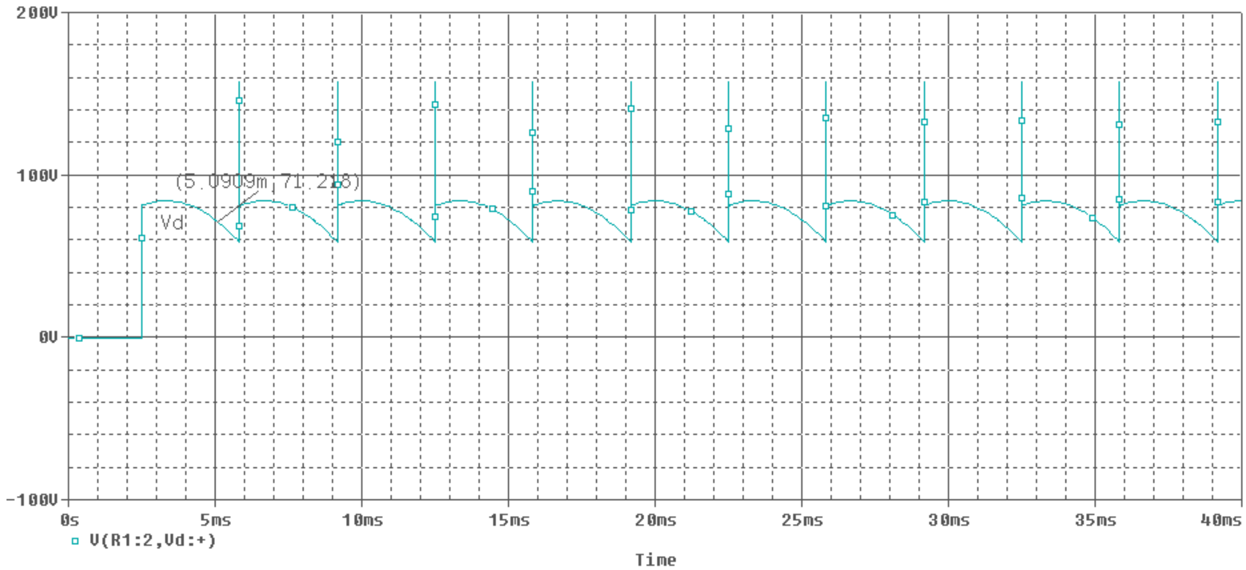


Figure 4.16 Simulation output for α=15°.

Below in Figure 4.17 and Figure 4.18 is the simulation circuit for firing angle 30° and the simulation output respectively;

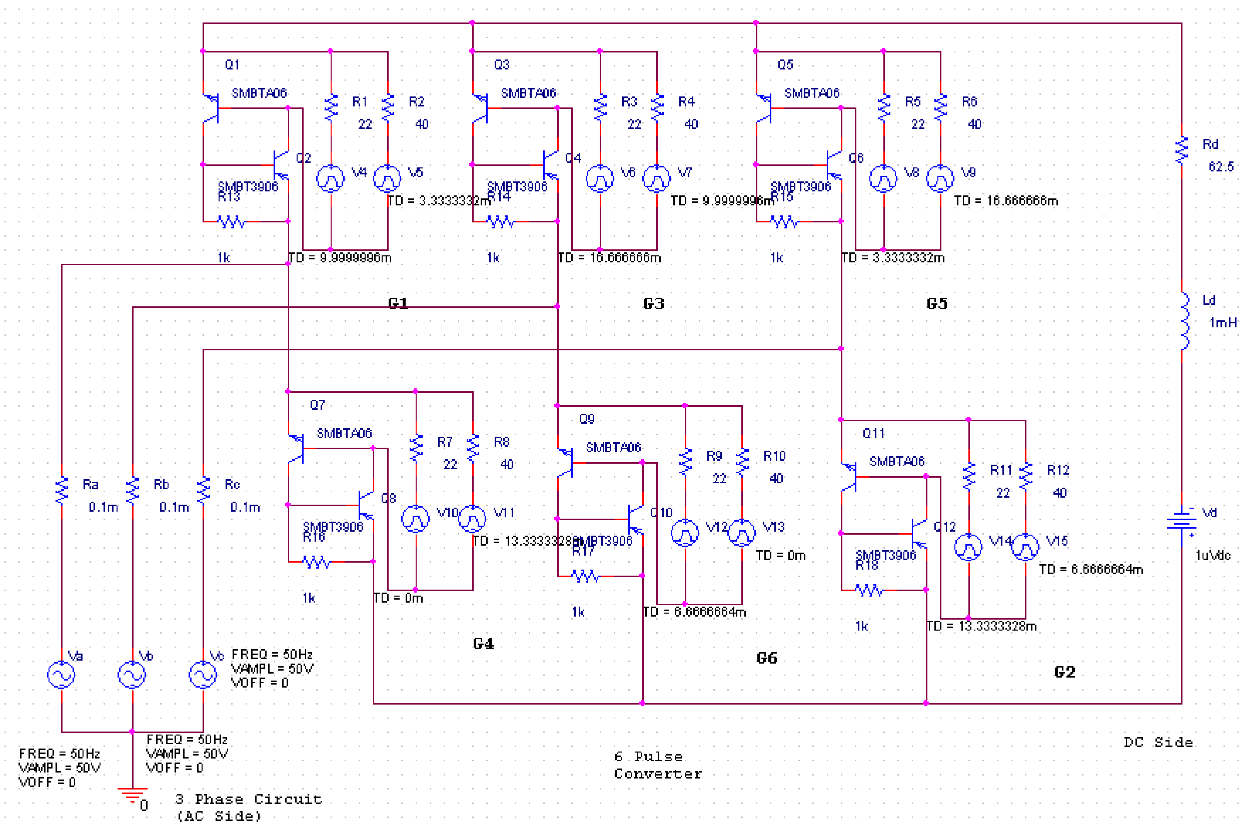


Figure 4.17 Simulation circuit for α=30°.

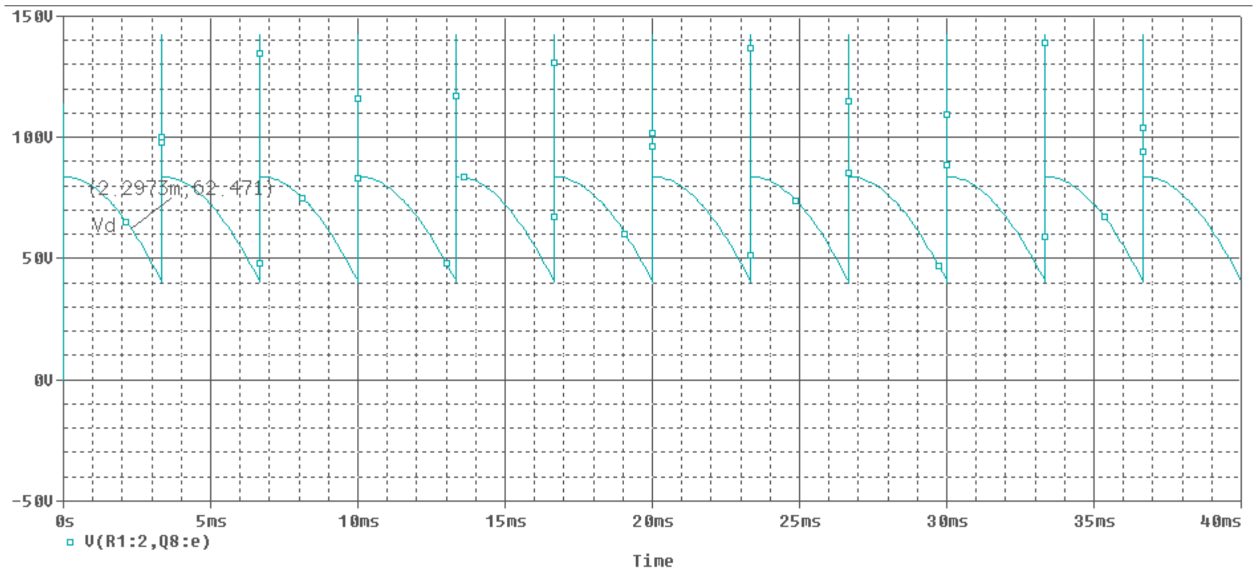


Figure 4.18 Simulation output for α=30°.

Below in Figure 4.19 and Figure 4.20 is the simulation circuit for firing angle 75° and the simulation output respectively;

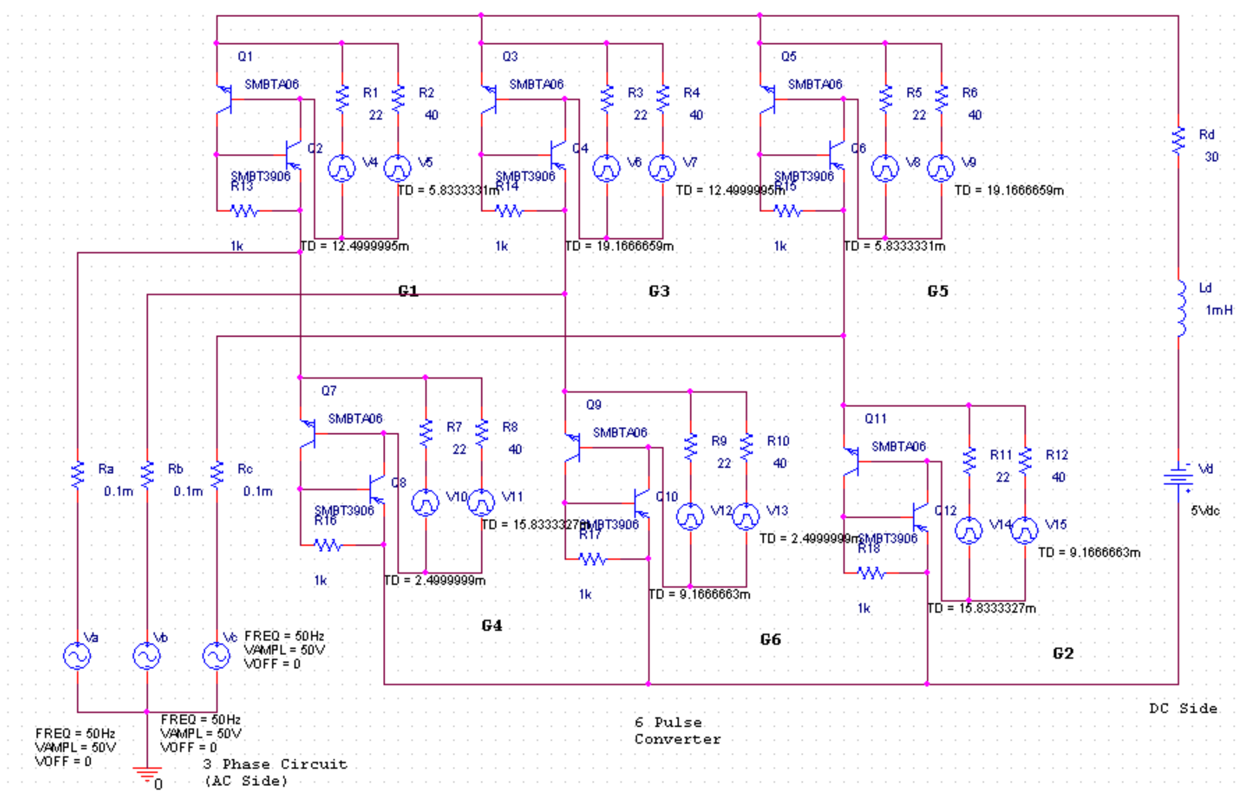


Figure 4.19 Simulation circuit for α=75°.

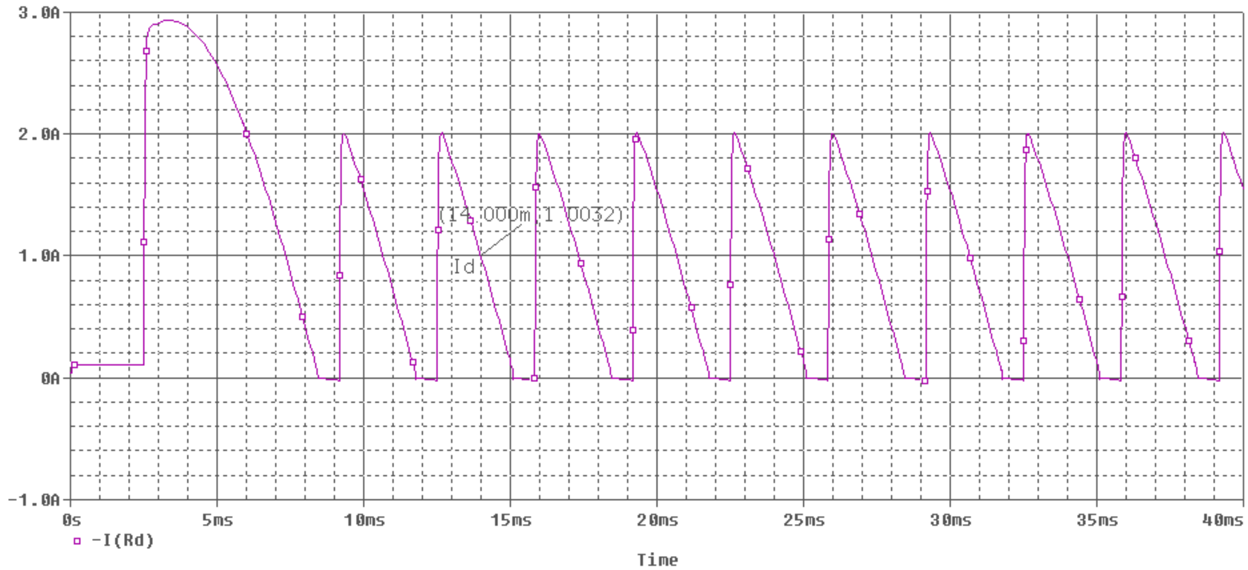


Figure 4.20 Simulation output for α=75°.

Below in Figure 4.21 and Figure 4.22 is the simulation circuit for firing angle 105° and the simulation output respectively;

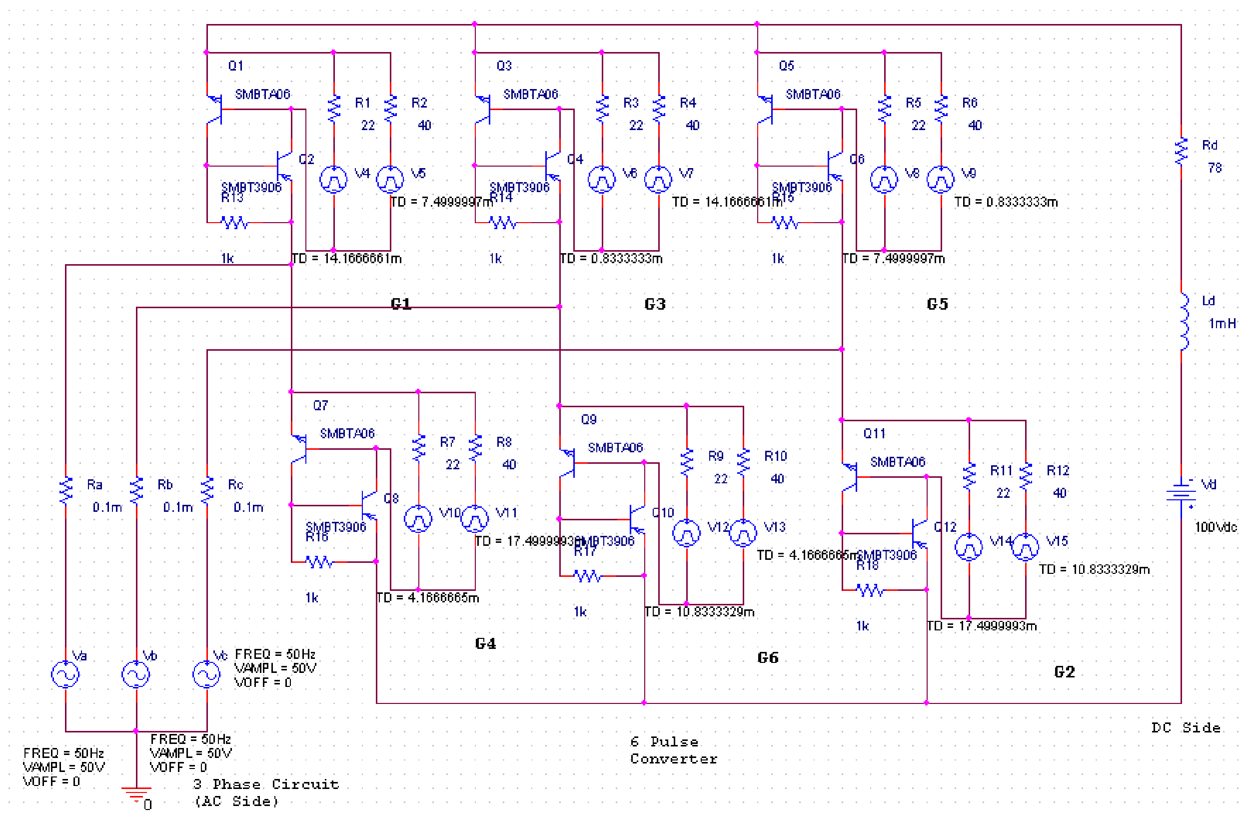


Figure 4.21 Simulation circuit for α=105°.

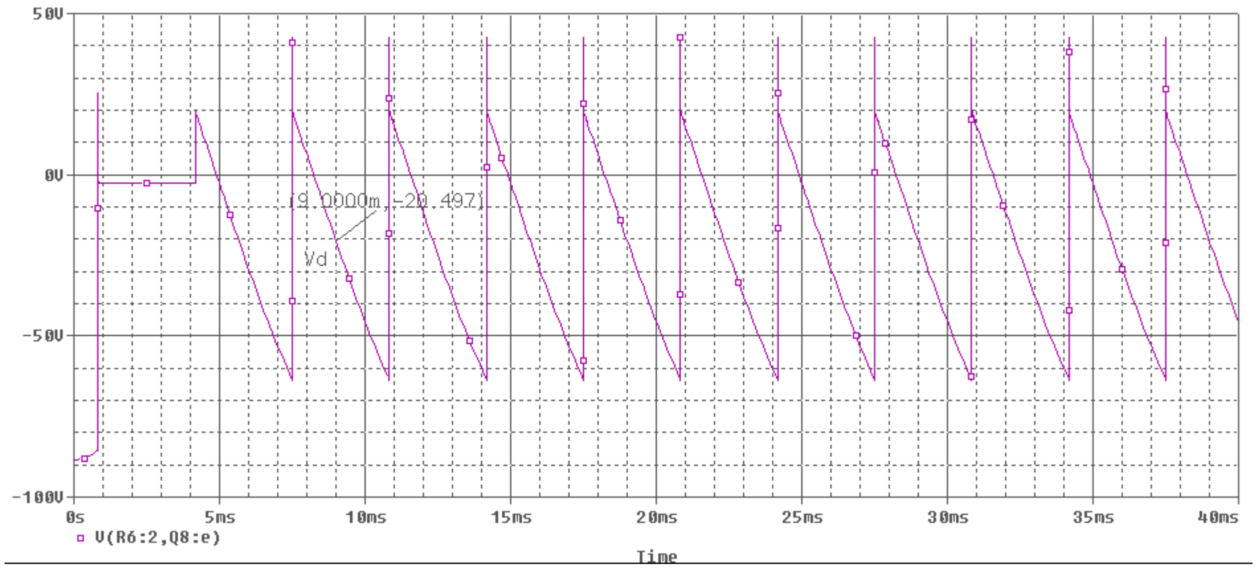


Figure 4.22 Simulation output for α=105°.

### 4.3.1 Analysis for the 6 Pulse GTO Thyristor Converter

The 6 pulse GTO thyristor converter can be functioned as the rectifier and inverter depends on the firing angle settings. It can function as a rectifier when the firing angle is in the range of 0° until 90° but when the firing angle is in the range of 90° and above, the converter will function as an inverter. This can be seen from the simulation before that for the firing angle of 105°, the DC output voltage is dropped to the negative but for the simulation from the 0° until 90°, the DC output voltage is positive. Figure 4.23, Figure 4.24 and Figure 4.25 also explains that after the firing angle reached 90° the DC output voltages becomes negative.

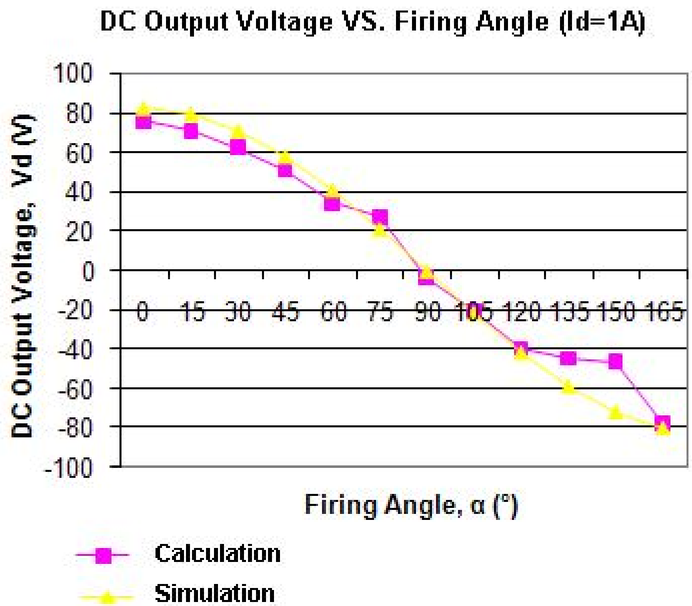


Figure 4.23 DC output voltage vs. firing angle ($I_d$=1A).

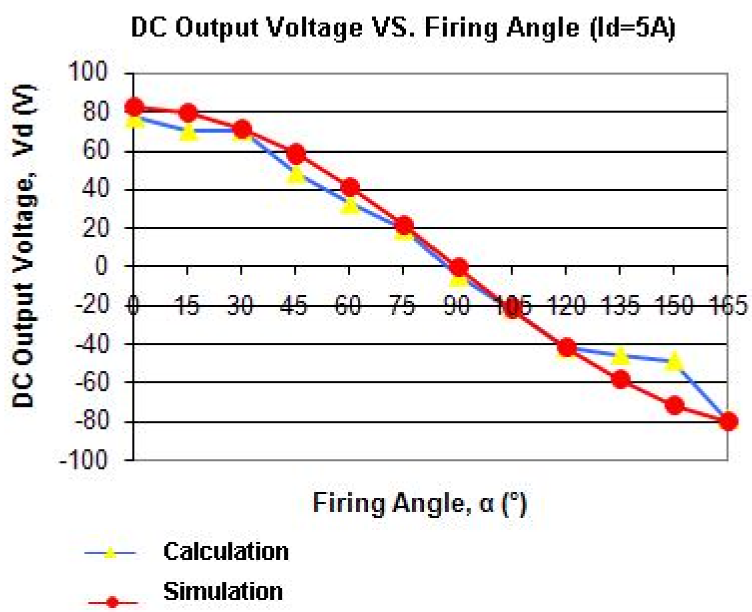


Figure 4.24 DC output voltage vs. firing angle ($I_d$=5A).

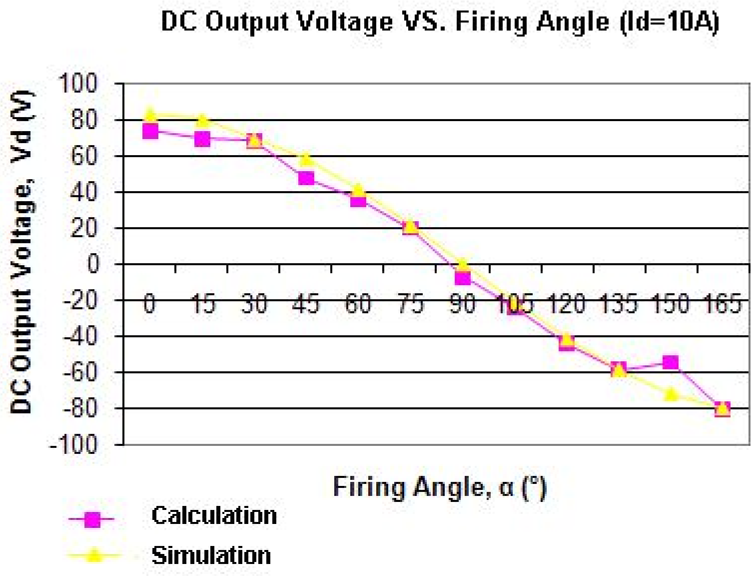


Figure 4.25 DC output voltage vs. firing angle ($I_d$=10A).

Figure 4.23, Figure 4.24 and Figure 4.25 is prepared for the analysis for the relation between firing angle and dc output voltage. In this figures, the simulation results are compared with mathematical calculation results. The calculation results are calculated using the equations that have been explained in the methodology chapter before. From these figures, it can be seen that the the curves of the simulations results and the mathematical results are almost the same. The value have some variations because of some reasons such as the voltage drop during the turn-on and turn-off operation of the GTO thyristors, power loss due to commutation overlap and measurement error in maintaining the same level of DC output current during simulation. Therefore, we could conclude that the simulations for the 6 pulse GTO thyristor converter is succesfully conducted since has been determine by the mathematical calculations.

## 4.4 The 6 Pulse GTO Thyristor Converter with LC Filter

The simulations for the 6 pulse GTO thyristor converter with LC filter are conducted to improve the 6 pulse GTO thyristor converter. For the first simulation, we prepare the simulation for firing angle 0° at Id=5A. Below in Figure 4.26 is the simulation for the firing angle 0° at 5A before LC filter is added to the system.

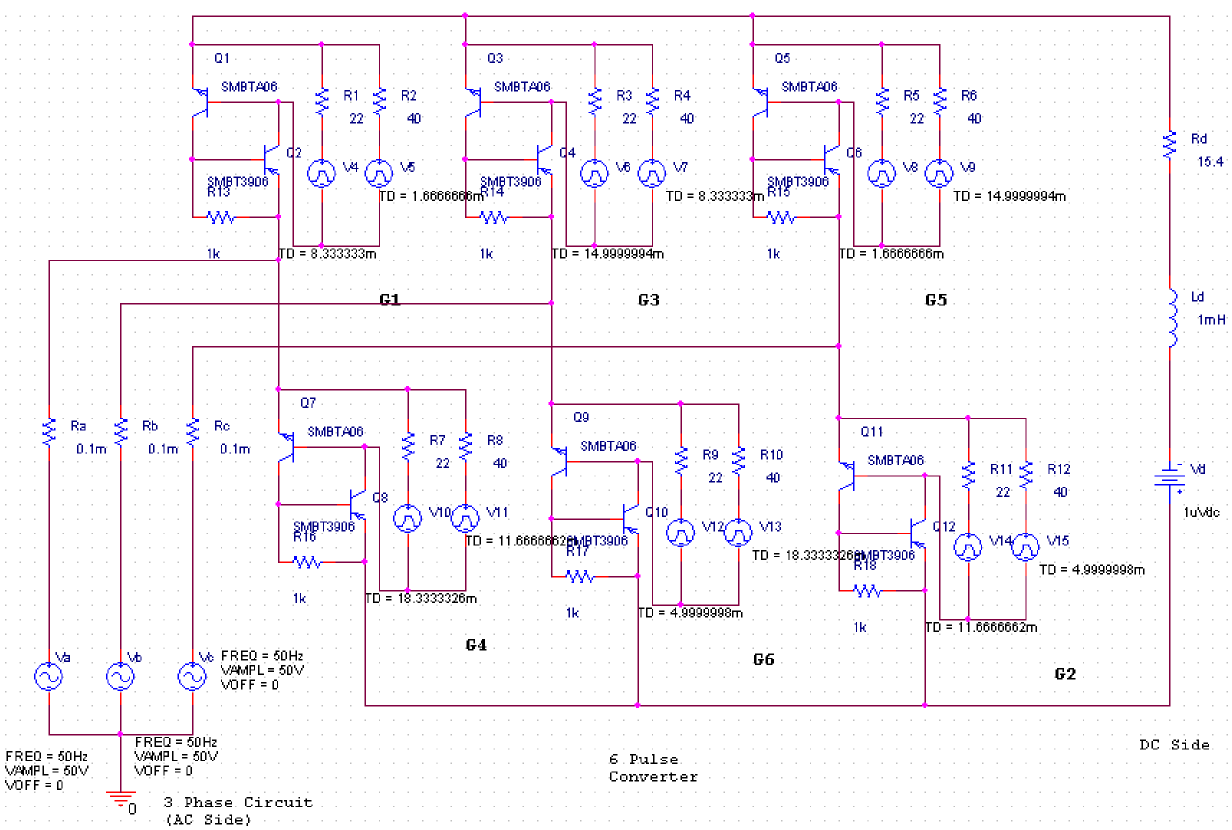


Figure 4.26 The simulation for the firing angle 0° without LC filter (Id=5A).

Below in Figure 4.27 and Figure 4.28 is the harmonics output current and voltage for the firing angle 0° without LC filter at Id=5A respectively.

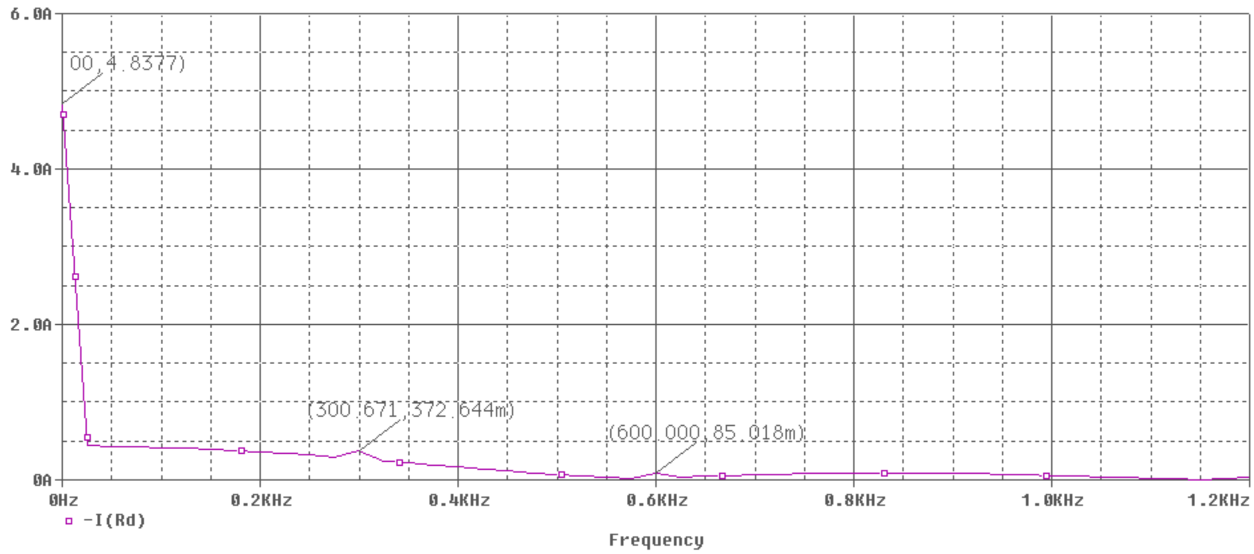


Figure 4.27 The harmonics output current for the firing angle 0° without LC filter (Id=5A).

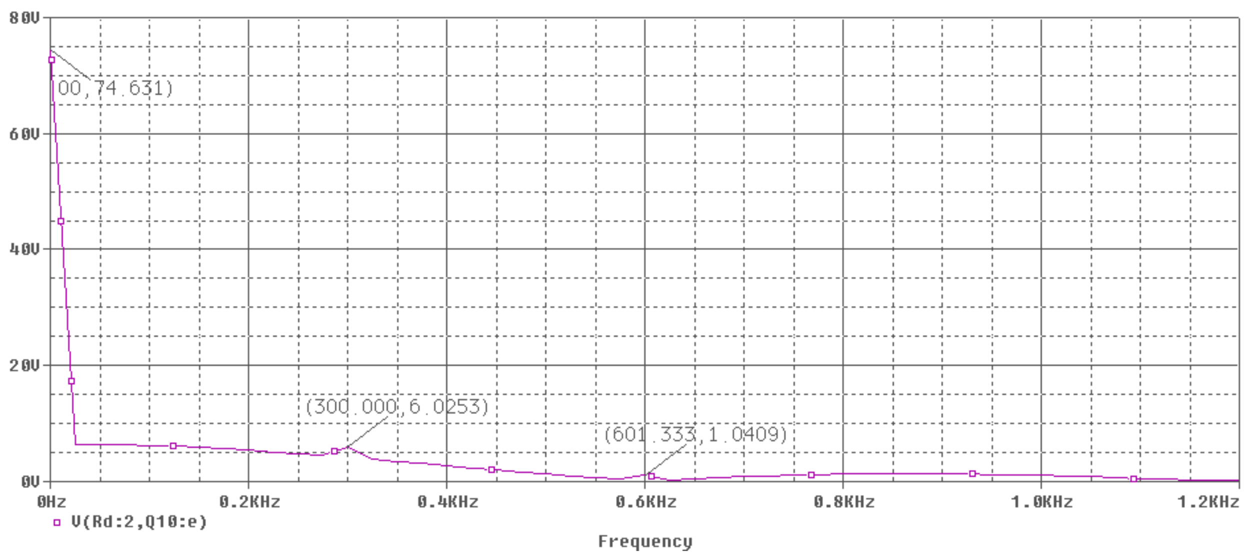


Figure 4.28 The harmonics output voltage for the firing angle 0° without LC filter (Id=5A).

Below in Figure 4.29 is the simulation for the firing angle 0° at 5A after LC filter is added to the system. The cut-off frequency used for this simulation is 600.38Hz for value of inductance, L is 23.04mH and capacitance, C is 3.05μF. The series LC filter is designed at every phase of the system.

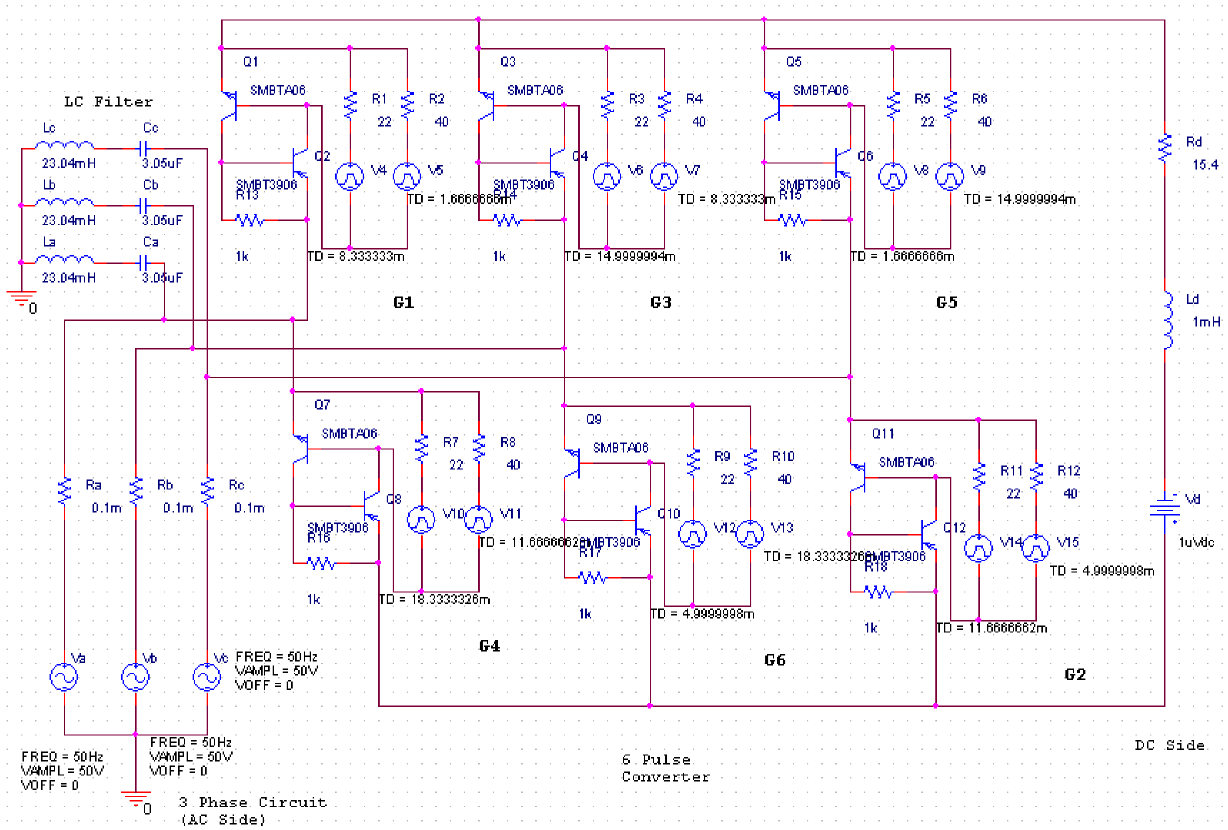


Figure 4.29 The simulation for the firing angle 0° with LC filter (Id=5A).

Figure 4.30 and Figure 4.31 shows the harmonics output current and voltage for the firing angle 0° after LC filter is added to the system at Id=5A respectively.

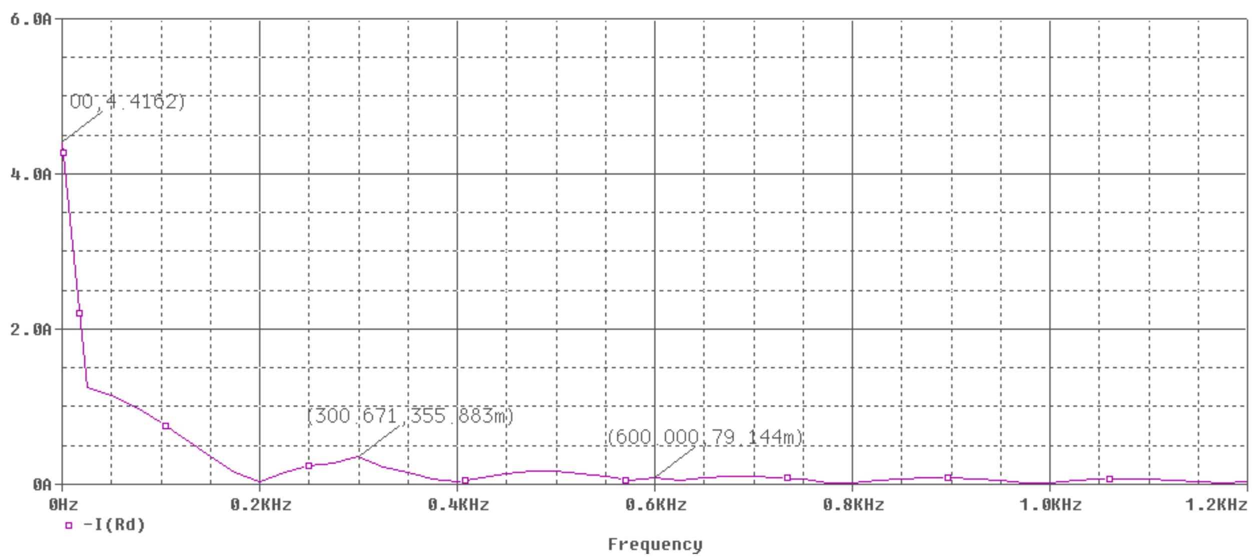


Figure 4.30 The harmonics output current for the firing angle 0° with LC filter (Id=5A).

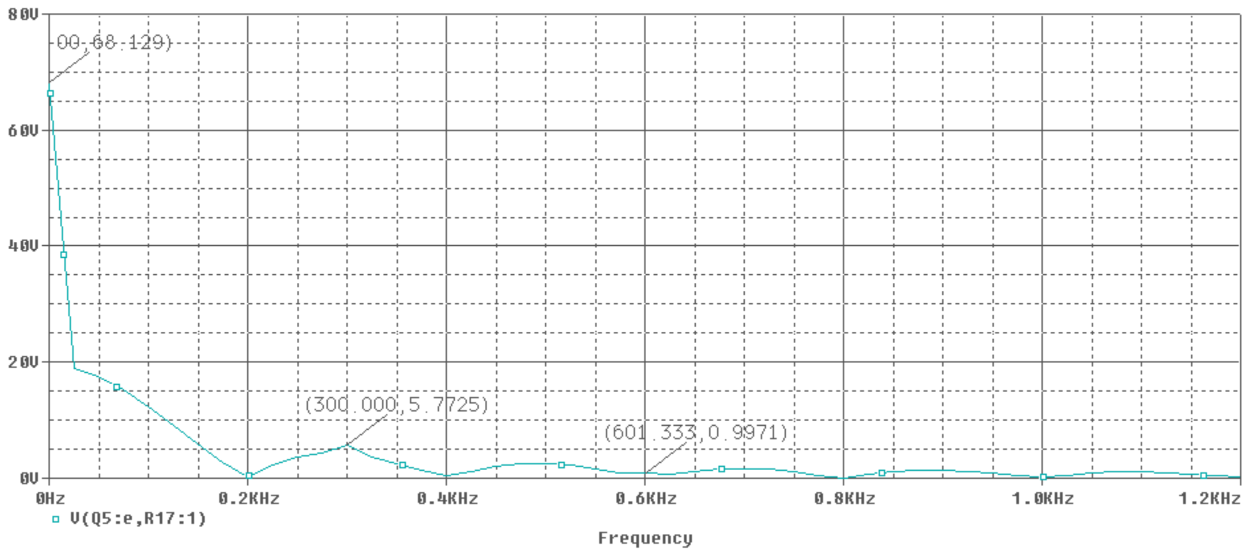


Figure 4.31 The harmonics output voltage for the firing angle 0° with LC filter (Id=5A).

It can be seen that the harmonics voltage and current output is decreased after the LC filter is added to the system. Below in Figure 4.32 is the simulation for the firing angle 15° at Id=5A before LC filter is added to the system.

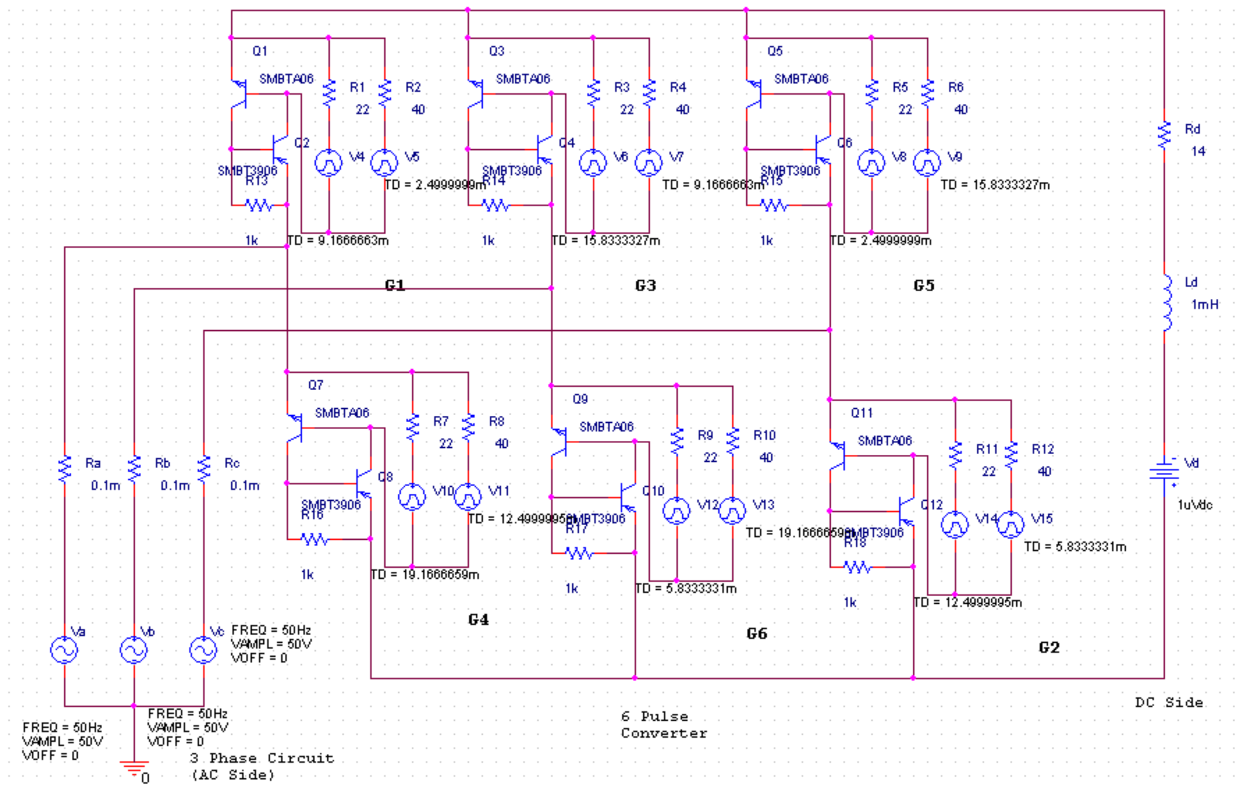


Figure 4.32 The simulation for the firing angle 15° without LC filter (Id=5A).

Figure 4.33 and Figure 4.34 shows the harmonics output current and voltage for the firing angle 15° before LC filter is added to the system at Id=5A respectively.

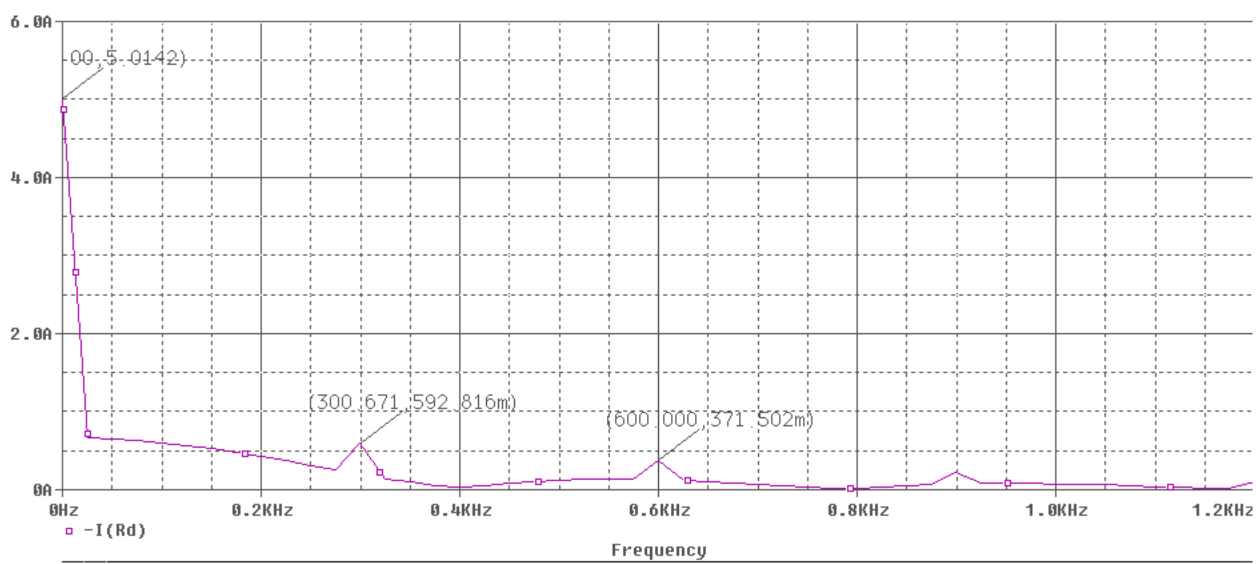


Figure 4.33 The harmonics output current for the firing angle 15° without LC filter (Id=5A).

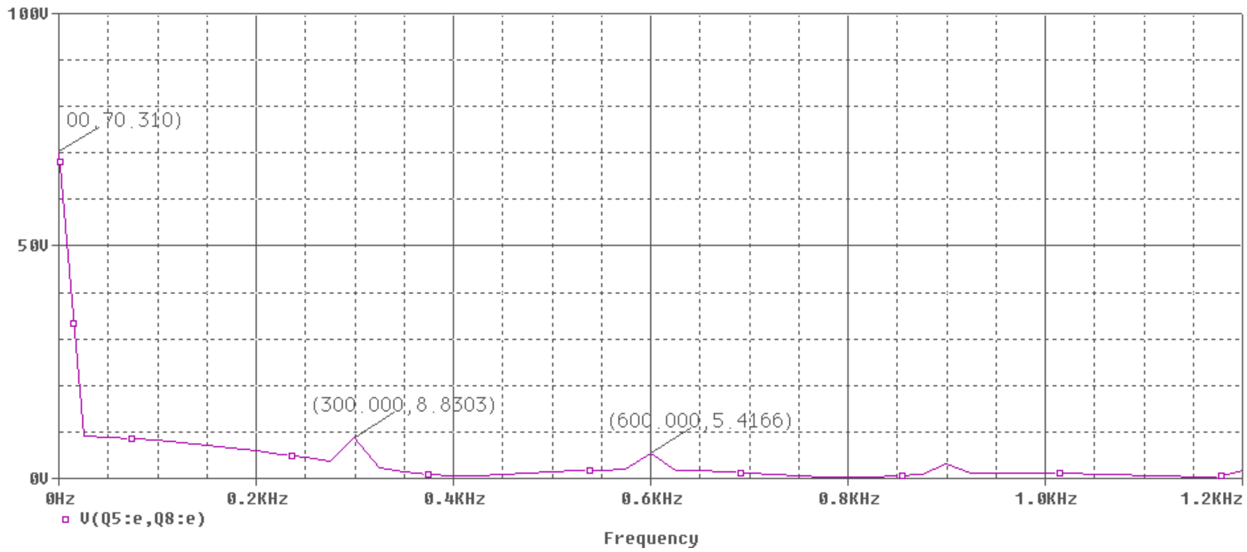


Figure 4.34 The harmonics output voltage for the firing angle 15° without LC filter (Id=5A).

Below in Figure 4.35 is the simulation for the firing angle 15° at 5A after LC filter is added to the system. The cut-off frequency used for this simulation is 10 kHz for value of inductance, L is 23.08mH and capacitance, C is 0.01µF.

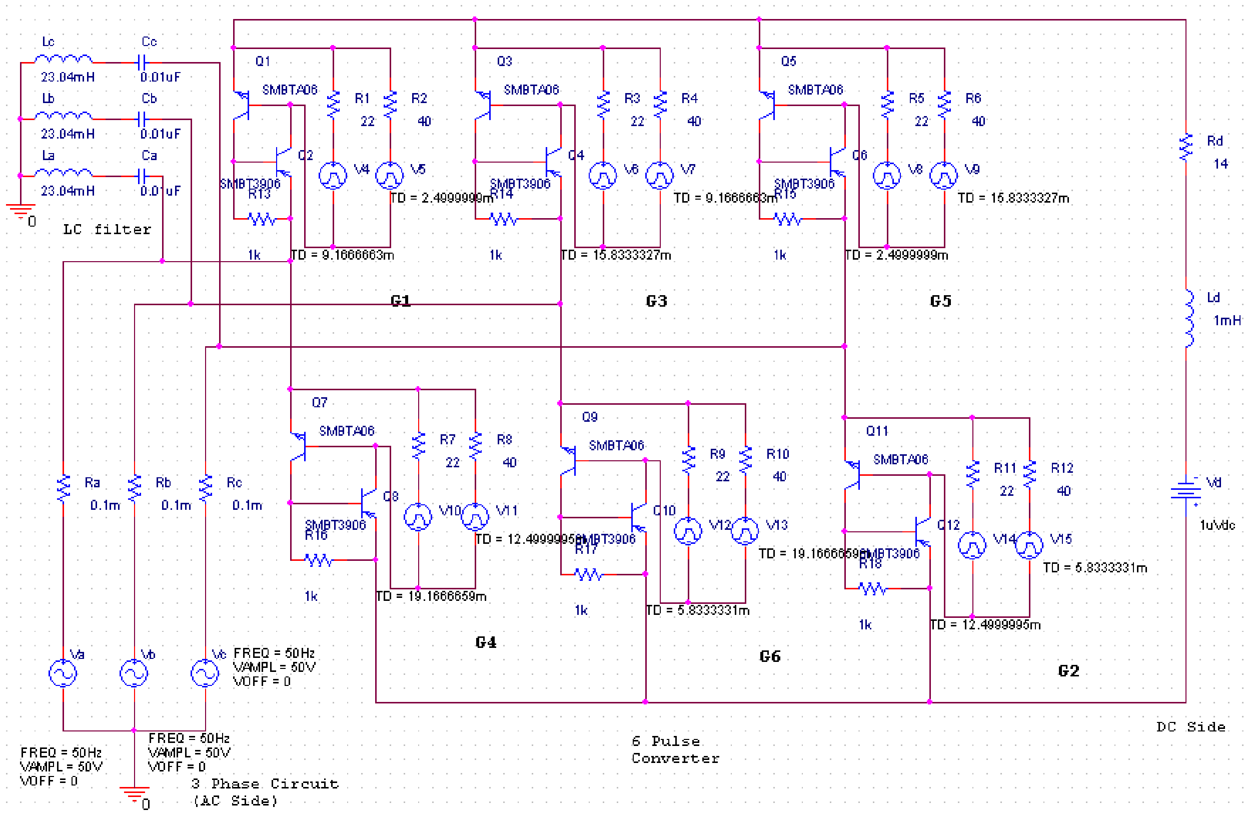


Figure 4.35 The simulation for the firing angle 15° with LC filter (Id=5A).

Figure 4.36 and Figure 4.37 shows the harmonics output current and voltage for the firing angle 15° after LC filter is added to the system at Id=5A respectively.

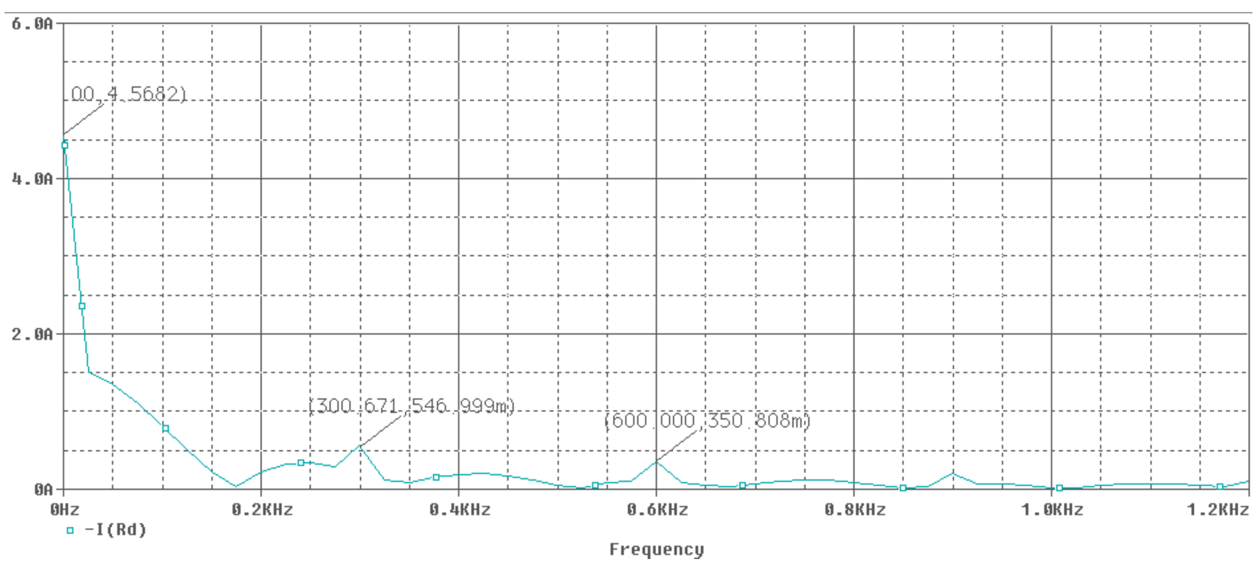


Figure 4.36 The harmonics output current for the firing angle 15° with LC filter (Id=5A).

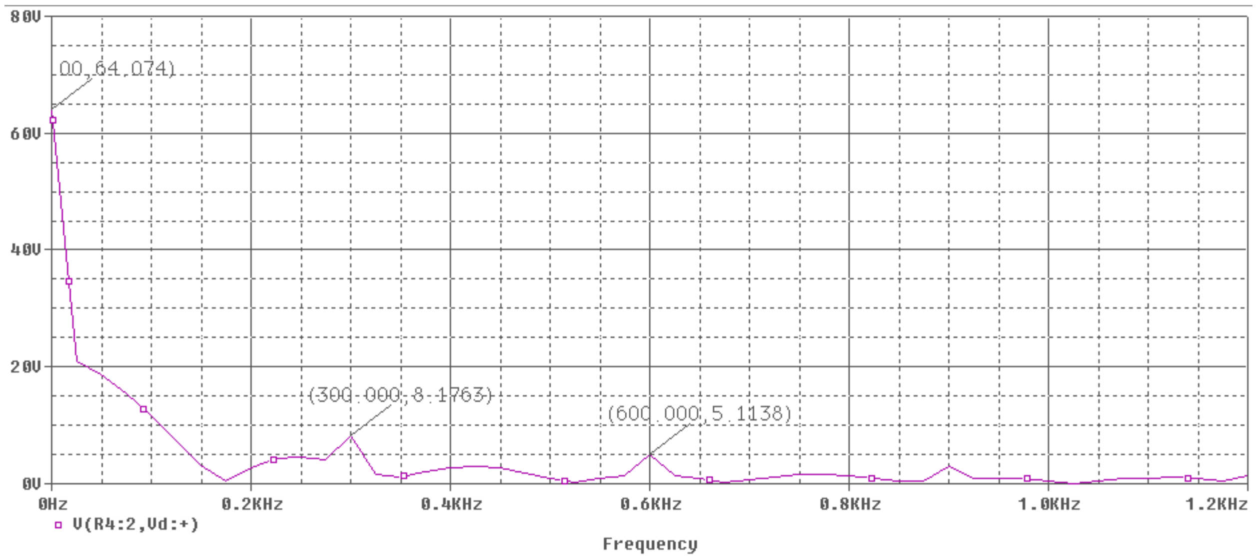


Figure 4.37 The harmonics output voltage for the firing angle 15° with LC filter (Id=5A).

Below in Figure 4.38 is the simulation for the firing angle 75° at Id=5A before LC filter is added to the system.

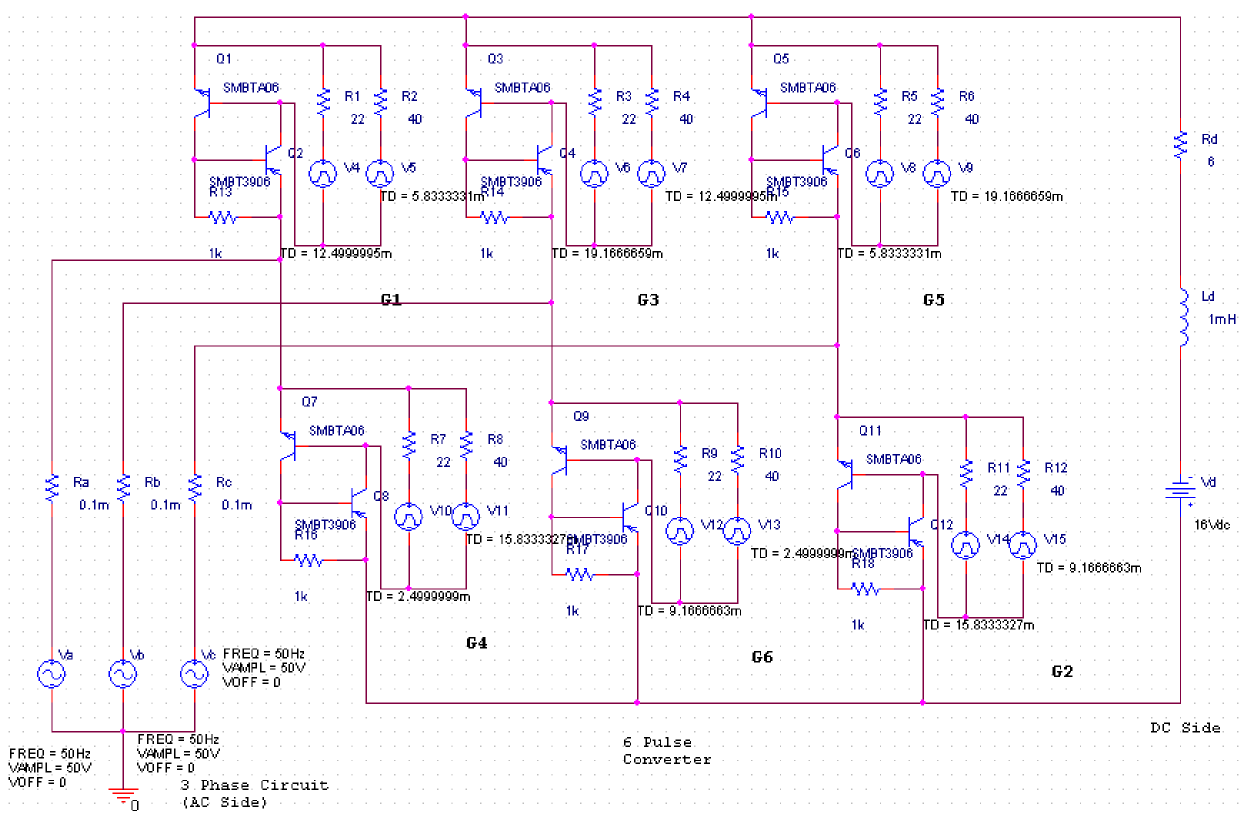


Figure 4.38 The simulation for the firing angle 75° without LC filter (Id=5A).

Figure 4.39 and Figure 4.40 shows the harmonics output current and voltage for the firing angle 75° after LC filter is added to the system at Id=5A respectively.

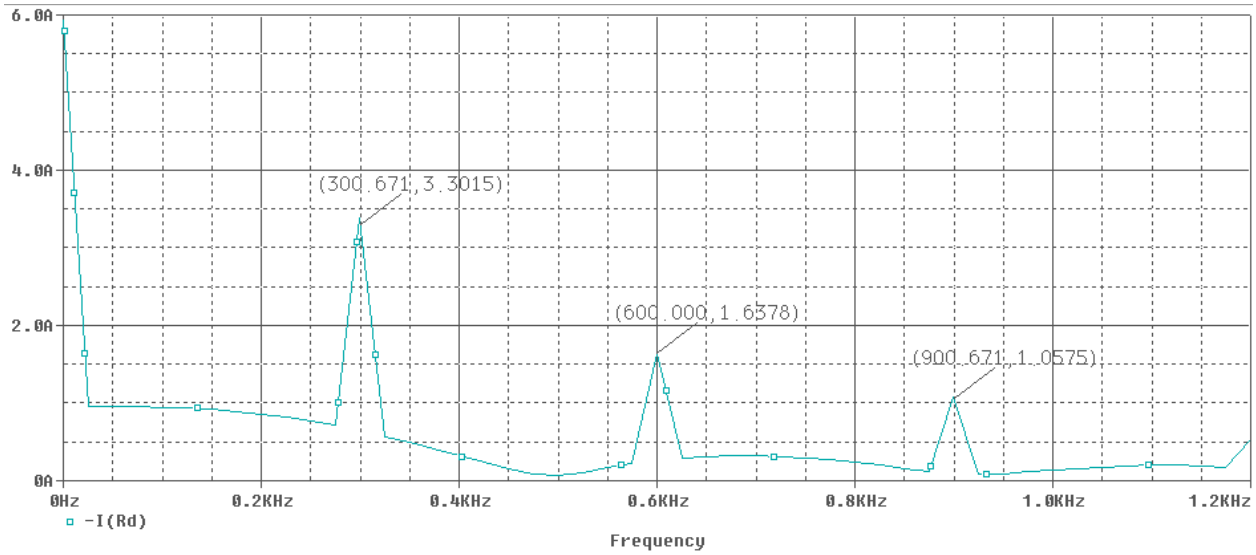


Figure 4.39 The harmonics output current for the firing angle 75° without LC filter (Id=5A).

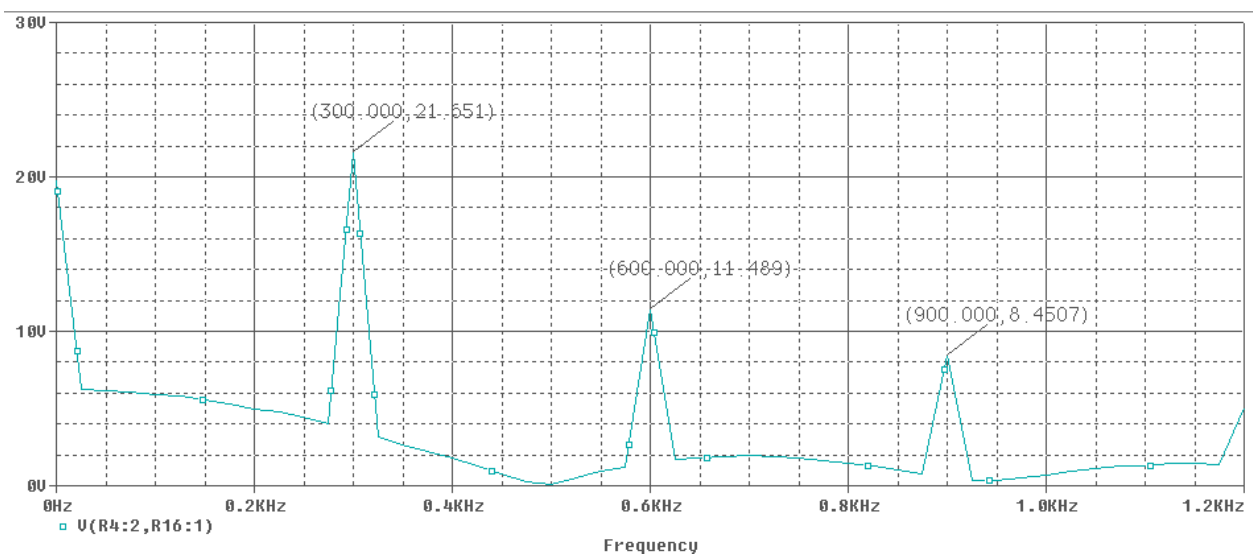


Figure 4.40 The harmonics output voltage for the firing angle 75° without LC filter (Id=5A).

Below in Figure 4.41 is the simulation for the firing angle 75° at 5A after LC filter is added to the system. The cut-off frequency used for this simulation is 40 kHz for value of inductance, L is 1.58mH and capacitance, C is 0.01μF.

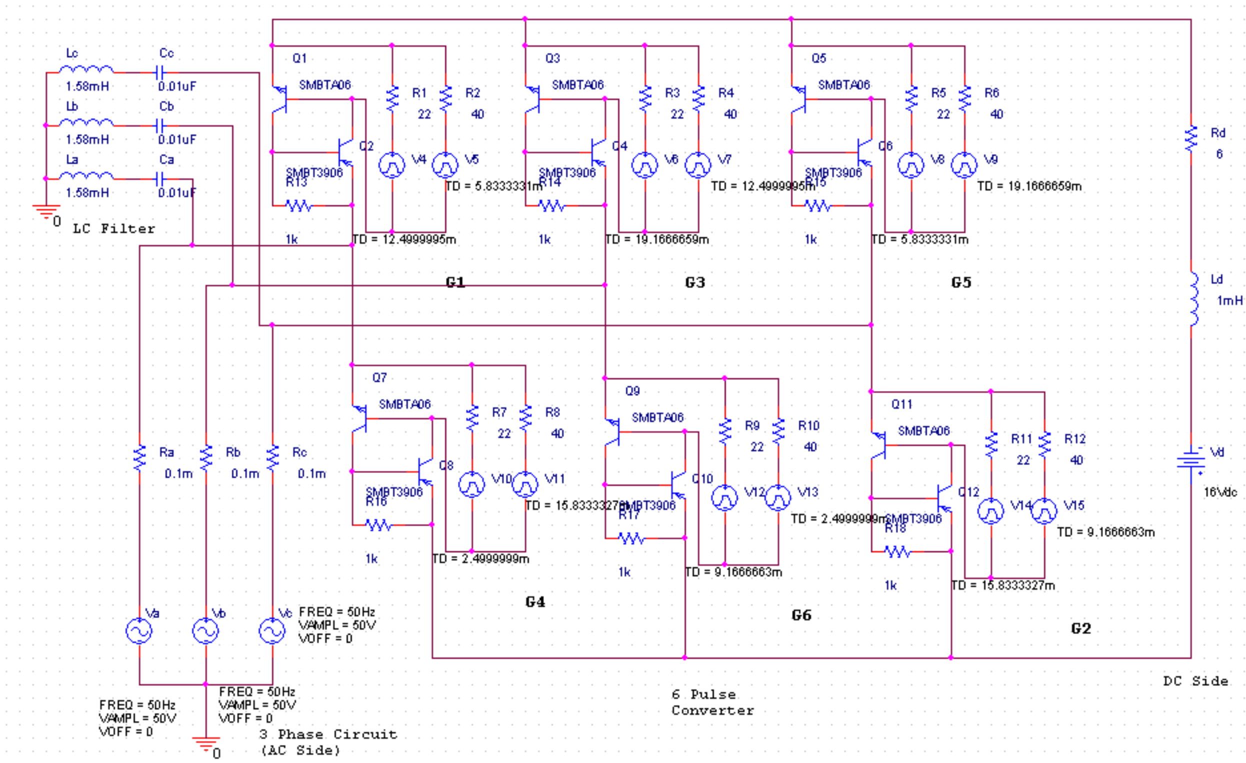


Figure 4.41 The simulation for the firing angle 75° with LC filter (Id=5A).

Figure 4.42 and Figure 4.43 shows the harmonics output current and voltage for the firing angle 75° after LC filter is added to the system at Id=5A respectively.

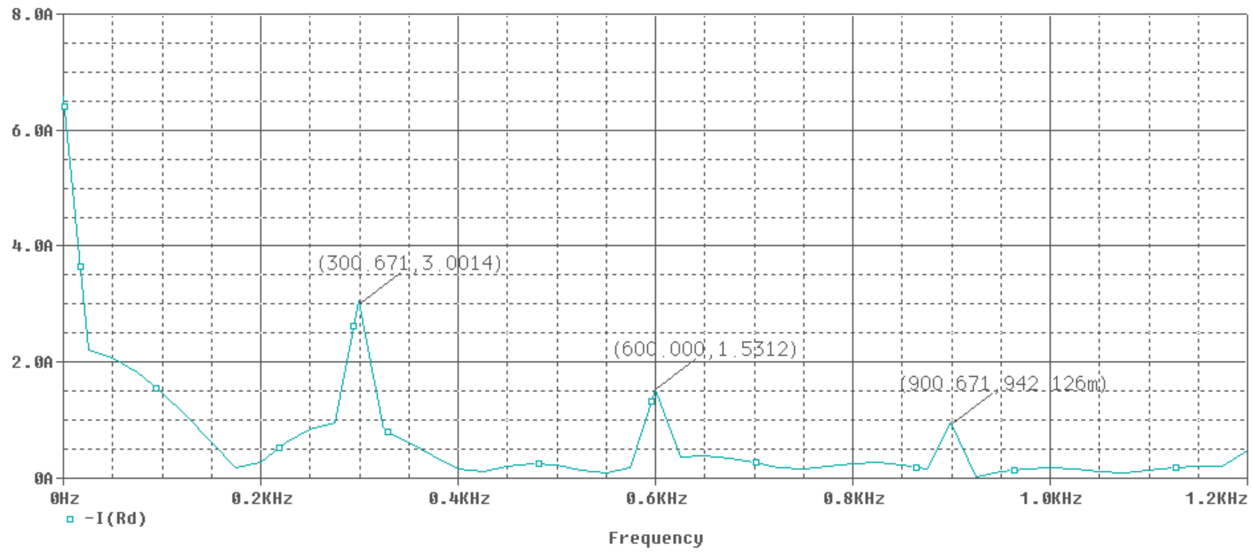


Figure 4.42 The harmonics output current for the firing angle 75° with LC filter (Id=5A).

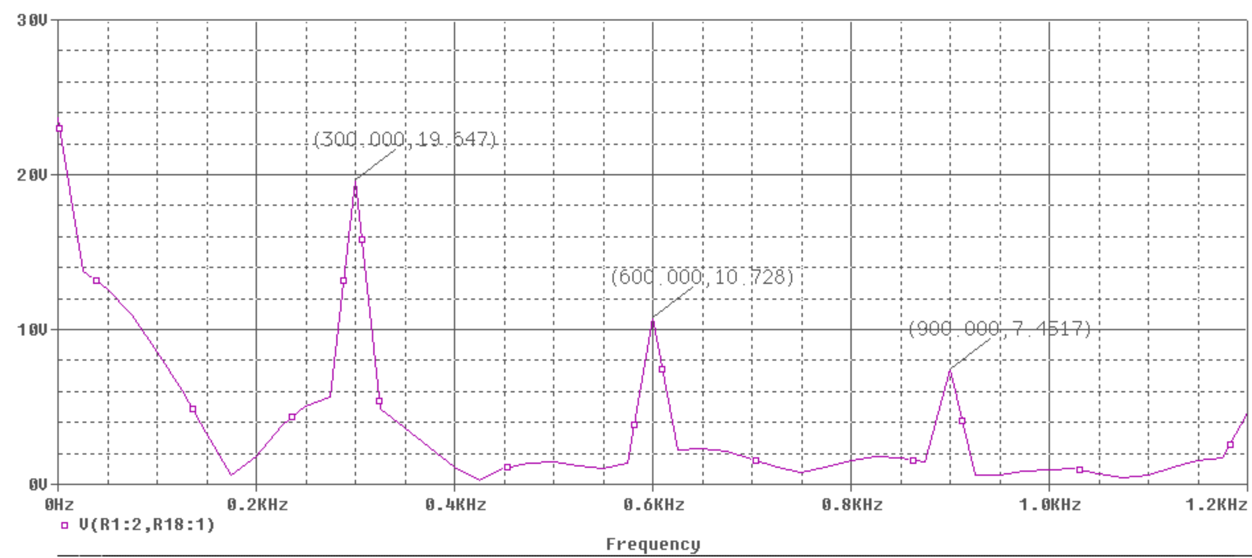


Figure 4.43 The harmonics output voltage for the firing angle 75° with LC filter (Id=5A).

Notice that the value of harmonics output current and voltage output for the firing angle 75° before and after LC filter is added to the system at Id=5A is taken at second harmonics since the first harmonics in incomplete and the right value for that harmonics cannot be obtain for the comparison purpose.

Table 4.3 Summary table for the harmonics voltages and currents output before and after filter.

| Degree(°) | Circuit | Harmonics Voltage (V) | | | Harmonics Currents (A) | | |
|---|---|---|---|---|---|---|---|
| | | $1^{st}$ | $2^{nd}$ | $3^{rd}$ | $1^{st}$ | $2^{nd}$ | $3^{rd}$ |
| 0 | Before Filter | 74.631 | 6.0253 | 1.0409 | 4.8377 | 372.644m | 85.018m |
| | After Filter | 68.129 | 5.7725 | 0.9971 | 4.4162 | 355.883m | 79.144m |
| 15 | Before Filter | 70.310 | 8.8303 | 5.4166 | 5.0142 | 592.816m | 371.502m |
| | After Filter | 64.074 | 8.1763 | 5.1138 | 4.5682 | 546.999m | 350.808m |
| 75 | Before Filter | 21.651 | 11.489 | 8.4507 | 3.3015 | 1.6378 | 1.0575 |
| | After Filter | 19.542 | 10.728 | 7.4517 | 3.0014 | 1.5312 | 0.9421 |

Table 4.3 above show the summary table for the harmonics voltages and currents output before and after LC filter is added to the system for easy comparison. From this table, it is obvious that after the LC filter is added to the system the harmonics voltages and currents is reduces. The suitable value of the cut-off frequency for the filter also plays the important role to make sure the right purpose can be obtained.

## 4.5 Conclusion

All the simulation is successfully conducted and archives all the objectives. The simulations are compared with mathematical calculations using the graph to prove the results. The GTO thyristor model is constructed for the further design of 6 pulse GTO thyristor converter and the 6 pulse GTO thyristor converter with LC filter is constructed to reduces the harmonics and improve the 6 pulse GTO thyristor converter.

# CHAPTER 5

# CONCLUSION & RECOMMENDATION

## 5.1 Summary of the Project

All the simulation is successfully conducted and archives all the objectives. The GTO thyristor model is constructed for the further design of 6 pulse GTO thyristor converter and the 6 pulse GTO thyristor converter with LC filter is constructed to improve the 6 pulse GTO thyristor converter. The simulations are compared with mathematical calculations using the graph to prove the results.

From the simulation results, it is known that this GTO thyristor model can be successfully turn-on and turn-off in the range of anode current of 15A to 60A. This range of current will be used and implemented in the design of 6 pulse GTO thyristor converter circuit and further development.

The effect of current distortion on power distribution systems can be serious, primarily because of the increased current flowing in the system. In other words, because the harmonic current does not deliver any power, its presence simply uses up system capacity and reduces the number of loads that can be powered. Harmonic current occur in a facility’s electrical system can cause equipment malfunction, data distortion, transformer and motor insulation failure, overheating of neutral buses, tripping of circuit breakers, and solid-state component breakdown. The cost of these problems can be enormous.

Rectification is a process of converting an alternating current or voltage into a direct current or voltage. The rectifier circuit can be classified broadly into three classes: uncontrolled, fully-controlled and half-controlled. The 6 pulse GTO thyristor converter is fall under the fully-controlled rectifier which used GTO thyristor as the rectifying elements and the DC output voltage is a function of the amplitude of the AC supply voltage and the point-on-wave at which the thyristor are triggered is called firing angle, $\alpha$.

The six-pulse converter is developed to improve the three-phase converter. The three-phase converter requires special types of converter transformer to prevent DC magnetisation. By developing the six-pulse converter, large output and least ripple content can be provided. Six-pulse connections are most widely used for industrial applications, whereas for transmission lines, 12-pulse connections are preferred.

At the end of this project, the knowledge about converters is well known since it has been discussed in this thesis. The theory of the GTO thyristor and multipulse converter has been presented to explain the important operating characteristic of the GTO thyristor and 6 pulse converter to be used in this project. The filter has an advantage to improve the circuit by reducing the harmful harmonics or distortion of the circuit.

## 5.2 Recommendation

This 6 pulse GTO thyristor converter with LC filter can be used in various applications. From the literature review we know that this 6 pulse GTO thyristor converter with LC can be used in large scale system such as HVDC. It can be used as the power converter in HVDC transmission systems and as a DC speed controller for the DC motor application. This contribution can be very useful particularly for the operation and maintenance personnel who can perform better with greater insight into the functioning of the complex system obtained through the model as developed.

For the future plan for this project, it is recommended to other candidate or engineers to do more studies on the related information and do some modifications to improve this project. Some modifications can be made make sure this project is useful for our world nowadays.

The recommendation suggested for future work is upgrading the 6 pulse GTO thyristor converter to 12 pulse GTO thyristor converter or more higher multipulse converter. The advantage of using the multipules is the power quality at the input and output is improved. Besides that, higher pulse number means fewer input harmonics that can cause a better power factor, and smoother output or smaller smoothing components.

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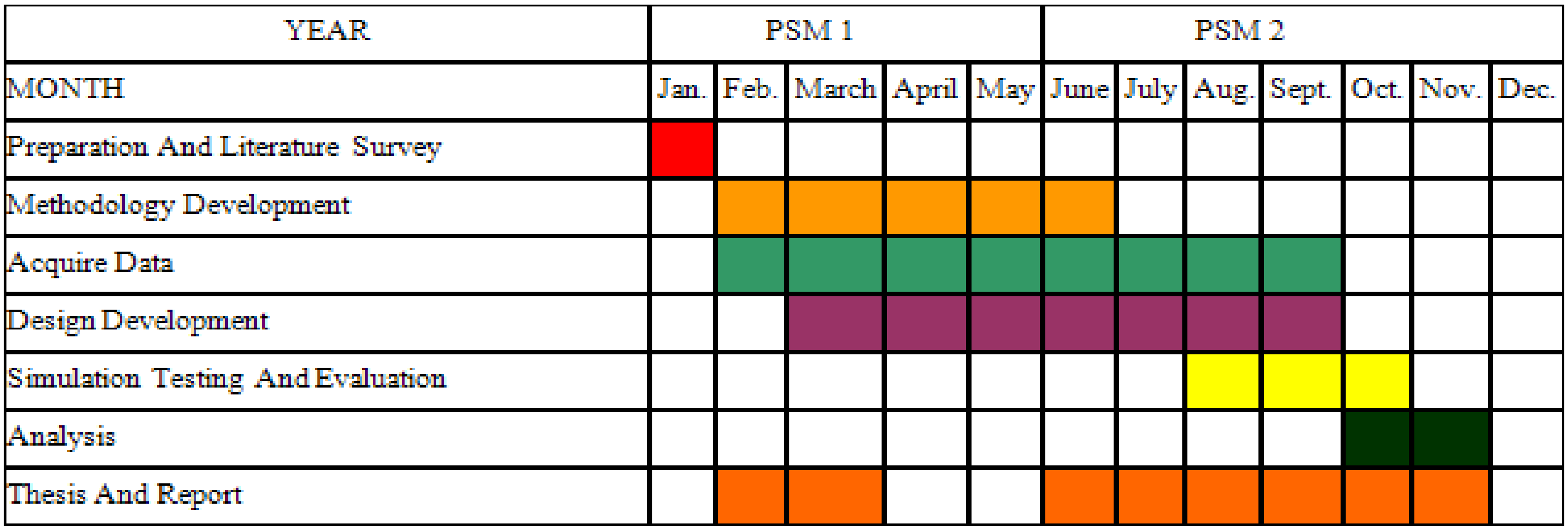
# APPENDIX A

# Gantt Chart

Below in figure shows the work planning gantt chart for this project;



# APPENDIX B

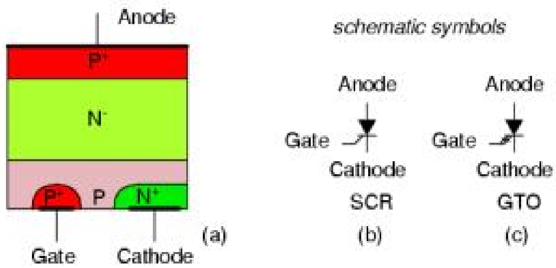
# Gate Turn Off Thyristor (GTO)

# Gate Turn Off Thyristor(GTO)

Posted by **admin**

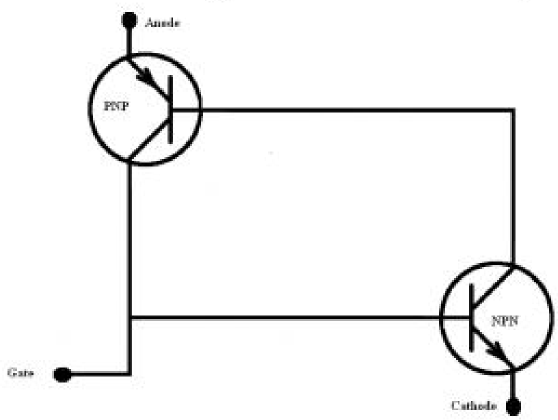
October 18, 2008

GTO is a special thyristor which can be turned on by a positive gate signal and can be turned off by a neagative signal.Evidently the use of GTO in power electronic circuit eliminates the need of forced commutation circuit because turnoff is achieved by applying a negative circuit.




## The two transistor analogy of a GTO

Two transistor analogy of transistor is shown in figure below




When a positive signal is applied,a GTO switches into conduction state like the ordinary thyristor.However in ordinary thyristor the current gains of NPN and PNP transistors are very high so that gate sensitivity for

turn on is very high and on state voltage drop is low.However in GTO,the current gai of PNP transistor is low so that turn of fis possible if significant current is drawn from the gate.When a negative gate signal is applied the excess carriers are drawn from the base region of NPN transistor and collector current of PNP is diverted to the gate.Thus the base drive of NPN transistor is removed and this inturn removes the base drive of PNP transistor and turnoff is achieved.

# APPENDIX C

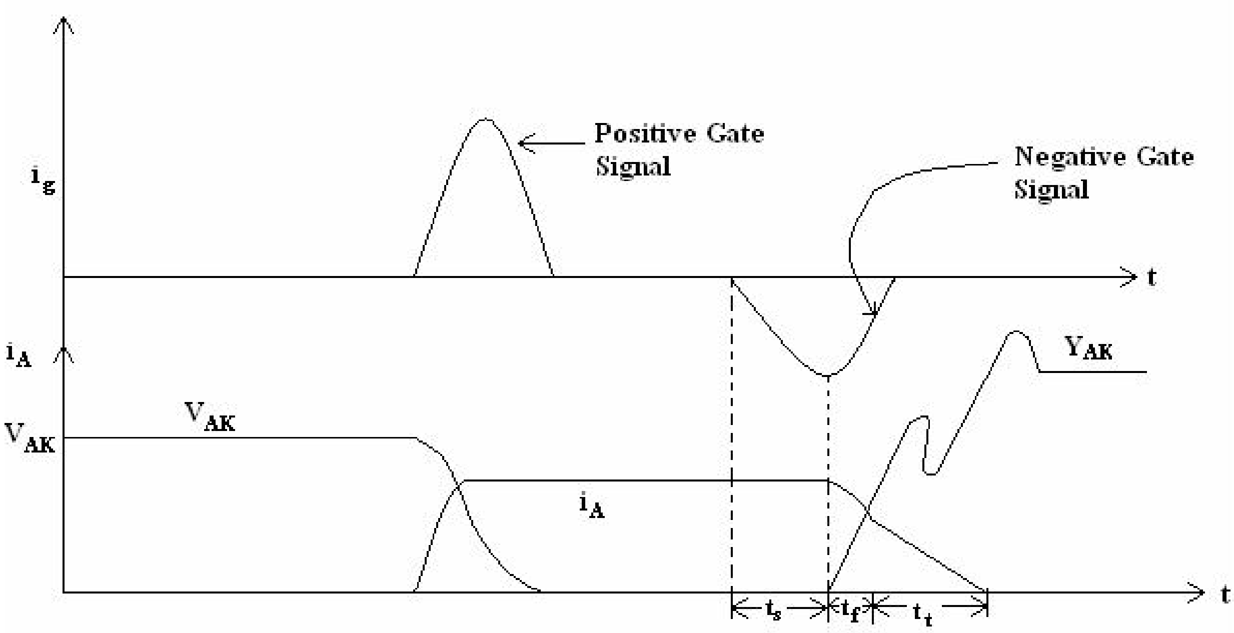
# Turn On and Turn Off Characteristic of GTO

# Turn on and Turnoff Characteristics of GTO

Posted by admin

October 18, 2008

The voltage and current wave forms of a GTO is show in figure below.The positive and negative pulses are shown.




Turn on and Turnoff Characteristics of GTO

When a positive signal is applied,GTO starts conducting.Before initiation of conduction anode current ($i_A$)is zero and anode- cathode voltage $V_{AK}$ is the peak reverse voltage.When conduction starts rises $i_A$ to full value and the $V_{AK}$ becomes very small(equal to on state voltage drop which is about 1V or so).when a negative gate signal is applied,the anode current becomes zero and the $V_{AK}$ rises to peak reverse voltage.

The total turnoff time is composed of three distinct times,storage time($t_s$ ),fall time($t_f$) and tail time($t_t$).

Initiation of turn off process starts immediately on the application of negative gate signal. The time elapsing between application of negative gate current till this current reaches its negative peak value known as storage time ($t_s$ ). During this period, the excess charge are removed by the -ve gate currentt and GTO gets ready to turn off. During fall time $t_f$,the anode current decreases rapidly and anode cathode voltage rises.This time $t_f$ in most GTO is about 1μs.After tf is over,the current falls slowly to zero value durung tail time $t_t$..The voltage gets a spike because of the present of elements R and C of the snubber circuit(for protection of GTO).At the end of the tail time,the anode current $i_A$ becomes zero and $V_{AK}$ becomes equal to peak reverse voltage.

# APPENDIX D

## Time Delay Table

**Time Delay Table**

Alpha = 0

| GTO | Turn On | Turn Off |
|---|---|---|
| 1 | 1.6666666 | 8.333333 |
| 2 | 4.9999998 | 11.6666662 |
| 3 | 8.333333 | 14.9999994 |
| 4 | 11.6666662 | 18.3333326 |
| 5 | 14.9999994 | 1.6666666 |
| 6 | 18.3333326 | 4.9999998 |

Alpha =15

| GTO | Turn On | Turn Off |
|---|---|---|
| 1 | 2.4999999 | 9.1666663 |
| 2 | 5.8333331 | 12.4999995 |
| 3 | 9.1666663 | 15.8333327 |
| 4 | 12.4999995 | 19.1666659 |
| 5 | 15.8333327 | 2.4999999 |
| 6 | 19.1666659 | 5.8333331 |

Alpha =30

| GTO | Turn On | Turn Off |
|---|---|---|
| 1 | 3.3333332 | 9.9999996 |
| 2 | 6.6666664 | 13.3333328 |
| 3 | 9.9999996 | 16.666666 |
| 4 | 13.3333328 | 0 |
| 5 | 16.666666 | 3.3333332 |
| 6 | 0 | 6.6666664 |

Alpha =45

| GTO | Turn On | Turn Off |
|---|---|---|
| 1 | 4.1666665 | 10.8333329 |
| 2 | 7.4999997 | 14.1666661 |
| 3 | 10.8333329 | 17.4999993 |
| 4 | 14.1666661 | 0.8333333 |
| 5 | 17.4999993 | 4.1666665 |
| 6 | 0.8333333 | 7.4999997 |

Alpha =60

| GTO | Turn On | Turn Off |
|---|---|---|
| 1 | 4.9999998 | 11.6666662 |
| 2 | 8.333333 | 14.9999994 |
| 3 | 11.6666662 | 18.3333326 |
| 4 | 14.9999994 | 1.6666666 |
| 5 | 18.3333326 | 4.9999998 |
| 6 | 1.6666666 | 8.333333 |

Alpha =75

| GTO | Turn On | Turn Off |
|---|---|---|
| 1 | 5.8333331 | 12.4999995 |
| 2 | 9.1666663 | 15.8333327 |
| 3 | 12.4999995 | 19.1666659 |
| 4 | 15.8333327 | 2.4999999 |
| 5 | 19.1666659 | 5.8333331 |
| 6 | 2.4999999 | 9.1666663 |

Alpha =90

| GTO | Turn On | Turn Off |
|---|---|---|
| 1 | 6.6666664 | 13.3333328 |
| 2 | 9.9999996 | 16.666666 |
| 3 | 13.3333328 | 0 |
| 4 | 16.666666 | 3.3333332 |
| 5 | 0 | 6.6666664 |
| 6 | 3.3333332 | 9.9999996 |

Alpha =105

| GTO | Turn On | Turn Off |
|---|---|---|
| 1 | 7.4999997 | 14.1666661 |
| 2 | 10.8333329 | 17.4999993 |
| 3 | 14.1666661 | 0.8333333 |
| 4 | 17.4999993 | 4.1666665 |
| 5 | 0.8333333 | 7.4999997 |
| 6 | 4.1666665 | 10.8333329 |

Alpha =120

| GTO | Turn On | Turn Off |
|---|---|---|
| 1 | 8.333333 | 14.9999994 |
| 2 | 11.6666662 | 18.3333326 |
| 3 | 14.9999994 | 1.6666666 |
| 4 | 18.3333326 | 4.9999998 |
| 5 | 1.6666666 | 8.333333 |
| 6 | 4.9999998 | 11.6666662 |

Alpha =135

| GTO | Turn On | Turn Off |
|---|---|---|
| 1 | 9.1666663 | 15.8333327 |
| 2 | 12.4999995 | 19.1666659 |
| 3 | 15.8333327 | 2.4999999 |
| 4 | 19.1666659 | 5.8333331 |
| 5 | 2.4999999 | 9.1666663 |
| 6 | 5.8333331 | 12.4999995 |

Alpha =150

| GTO | Turn On | Turn Off |
|---|---|---|
| 1 | 9.9999996 | 16.666666 |
| 2 | 13.3333328 | 0 |
| 3 | 16.666666 | 3.3333332 |
| 4 | 0 | 6.6666664 |
| 5 | 3.3333332 | 9.9999996 |
| 6 | 6.6666664 | 13.3333328 |

Alpha =165

| GTO | Turn On | Turn Off |
|---|---|---|
| 1 | 10.8333329 | 17.4999993 |
| 2 | 14.1666661 | 0.8333333 |
| 3 | 17.4999993 | 4.1666665 |
| 4 | 0.8333333 | 7.4999997 |
| 5 | 4.1666665 | 10.8333329 |
| 6 | 7.4999997 | 14.1666661 |