DURBAN UNIVERSITY OF TECHNOLOGY
INYUVESI YASETHEKWINI YEZOBUCHWEPHESHE

# The Study of the Upgrade and Improvement of Power Electronics Protection System for Locomotives.

**By**

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# DECLARATION

I hereby declare that this dissertation is my work, and each text has been correctly referenced or cited. Moreover, this work has not been previously published in portion or whole for another degree at any other University.

This research was duly supervised by Dr Evans E. Ojo at the Durban University of Technology.

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# Abstract

Power electronic processor unit used in electric locomotive for the operation of the traction AC motor has become an area of interest in South Africa. The previous locomotive uses the gate turn off (GTO) thyristors for its traction converter and this was later replaced by the insulated gate bipolar transistors (IGBTs). The replacement was due to the fact that GTO thyristor has disadvantages, as it has a complex gate drive and a moderately high power circuit was required to control the GTO thyristor. The application of the IGBT become necessary due some advantages it has over the GTO thyristor. The application of IGBT modules has the advantages in the aspect of switching, protection, power conversion and transformation. Consequently, based on the fact that GTO was replaced by the IGBT, it became necessary to carry out a study to compare both power electronics switches in order to justify this transition in the electric locomotive system. The study employed both analytical model and numerical model in the form of computer simulation to model, design, simulate and analyse the power processor unit for both switches. in this study, an extensive literature review was carried out to understand the concept of energy conversion/transformation using the power electronics switches. In comparison between the GTO thyristor and the IGBT a numerical model was developed and implemented on MATLAB/Simulink environment using the same propulsion system and the pulse pattern were used. This model was developed for the two converters topologies using the specifications for the transformer, converters and the induction motor. The computer simulation was done with the aim to justify the employment of newer types of locomotives with AC-DC-AC converter systems for the traction drive systems. Based on the analysis of the results, the power losses of an unsnubbered IGBT converter was reduced by 50% over a wide power range as compared to the GTO converter. Power losses are even reduced by up to 85% during partial load operation of the locomotive. From the simulation results, it is noted that conduction of current was fluctuating due to the switches ON or OFF states, in order to protect the locomotive propulsion and control the output voltage to the AC traction motors the variable voltage and variable frequency converter (VVVF) systems was used. Although, using the VVVF can also fluctuate the voltage, but voltage stability can be achieved by the ripple cancellation before any rectification process for the IGBT. The single control of each motor enables the use of the motors being independently controlled by each inverter at same frequency. With transistor is connected in parallel, allows the flow current in rapid way thus keeping the voltage at balance state allowing the use of components even when they are failure along the loop.

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# List of Abbreviations

| | |
|---|---|
| 2LC | Two-level Converter |
| 3LC | Three-level Converter |
| 4Q | Four Quadrant |
| AC | Alternating Current |
| ADC | Analogue-to-Digital Converter |
| CCV | Cycloconverter |
| CPU | Central Processing Unit |
| CSI | Current Source Inverter |
| CSR | Current Source Rectifier |
| DC | Direct Current |
| DQ0 | Direct-Quadrature-Zero |
| DSC | Digital Signal Controller |
| DSP | Digital Signal Processor |
| DPWM | Discontinuous Pulse Width modulation |
| DUT | Device Under Test |
| EMI | Electromagnetic Interference |
| EMU | Electric Multiple Units |
| ePWM | Enhanced Pulse Width Modulation |
| FET | Front-End Transformer |
| FW | Freewheeling State |
| GCT | Gate Commutated Thyristor |
| GTO | Gate Turn-off Thyristor |
| I2LC | Interleaved Two-level Converter |

| | |
|---|---|
| IEC | International Electrotechnical Commission |
| IEEE | Institute of Electrical and Electronics Engineering |
| IGBT | Insulated Gate Bipolar Transistor |
| IGCT | Integrated Gate Commutated Thyristor |
| LFT | Low Frequency Transformer |
| LPF | Low Pass Filter |
| MFT | Medium Frequency Transformer |
| MOSFET | Metal Oxide Field Effect Transistor |
| NPC | Neutral Point Clamped |
| PCC | Point of Common Coupling |
| PD | Phase Detection |
| PET | Power Electronics Transformer |
| Pf | Power Factor |
| PFC | Power Factor Correction |
| PI | Proportional Integral |
| SPWM | Sinusoidal Pulse Width Modulation |
| SVM | Space Vector Modulation |
| THD | Total Harmonic Distortion |
| PMIM | Permanent Magnet Induction Motor |
| PWM | Pulse With Modulation |
| VCB | Vacuum Circuit Breaker |
| VSD | Variable Speed Drive |
| VSI | Voltage Source Inverter |
| VVVF | Variable Voltage Variable Frequency |

# Chapter One

# Introduction

## 1.1 General Background

The device that is used for the transformation of the electrical power to the mechanical power which then provides the rotation needed at axle for the locomotive motion is regarded as the traction drives. These traction drives are mostly in the form of induction motors that are normally housed in the locomotive and operated by the variable speed drives i.e. power electronics converters. For the last 50 years, power electronics converters application for traction drives offers a more efficient and reliable means of operating locomotives. The electric locomotives use the application of power electronics switches in aspect of power transfer, voltage level and energy regeneration. The increased use of power electronic converters for traction application such as in the locomotives is due the advancement made in the development of semiconductor devices and the associated circuit drive properties for the purpose of the control of the switch. The application of the traction drives for the electric locomotive in South Africa, formally employed for its power converters, the Silicon Control Rectifier (SRC) switch, and during the 1980's the SCRs were largely replaced by the Gate Turn Off (GTO) thyristor [1]. In the beginning of the 1990s, with the application of the IGBT for locomotive traction drives, this then offered further improvements in high switching performance, more design consideration of these modules were wide bandgap, with safe operation and gate drive requirements to operate the switch is simple as compared to the GTO thyristors [2, 3]. Thus, there was a transition from Gate Turn Off (GTO) thyristor to the Integrated Gate Bipolar Transistor (IGBT) and this transition provided the avenue to produce converters systems that are compact and has a high power rating. Poor power cycling capability with regards to the GTO thyristor is an uncategorized failure mode which occurs after short circuits, which cannot be turned off and this can lead to possible explosion of the GTO modules during this failure mode. This was an important drawback for these power electronics devices with regards to use of the SCR and the GTO thyristor in the electric locomotives. In addition to this drawback, the GTO thyristors have the following disadvantages when used with regards to the locomotive protection [4]:

- It has a poor power cycling capability during switching

- The occurrence of the failure mode that occurs after short circuits and this causes the switch not to be able to be turned off
- As a result of the above, this can result to the possible explosion of the GTO thyristor modules
- To operate the GTO thyristor, it requires a high charge per pulse
- Operating the locomotive at low temperature will affect the switching operations of the GTO thyristors

The development IGBTs switches, which began to dominate its application for the traction drives, the power electronic converter manufacturers soon began to source for the switch in the power semiconductor market for the locomotive application due to its fast switching capability and the protection it offers for the traction drive [5]. Thus, the IGBTs switches enables the trains to run optimally and provides greater protection for the systems. The benefits of using this switch include the gradual acceleration and the ability to carry out the regenerative braking and this process allows power to be fed back to the grid.

Thus, relatively newer traction systems, the power processor system ensure that the trains consume less energy. This latest technology enables the power processor system to carry out switching at very low power levels and can also carry out regenerative braking of energy, which allow this energy to be fed back to the catenary system or stored in any storage devices like the batteries within the locomotive if present. This process has helped reduce the electricity tariff passed to the end users of locomotives by 20%.

## 1.2 Problem Statement

As already mentioned in the previous section, were the drawbacks of GTO thyristors, in which the chopper, SCR, diodes panel and GTO circuit could not be operated for a long time when used in the electric locomotives i.e. due to these disadvantages. Therefore, for these reasons, because the thyristors used could not carry out the fast switching operations, with insufficient blocking voltage available on it, this then resulted to them been burns up in the power electrical cubicle of the locomotive [6]. Investigation done as documented in [7, 8] which confirmed the content in [5], that the SCR's and or DC choppers can be damaged or destroyed. This is caused by the high voltage levels across the Anode/Cathode and high current levels through the Anode/Cathode injection of voltage, this situation now results with no protection been offered by the locomotive traction drives. This practice is harmful for the locomotive chopper resulting in a large input inductor current as the slow rate of rise current may allow the line switches to attempt to clear the high prospective currents before the trip level of the circuit breakers is reached [9, 10]. Therefore, for such system, the parameter of these chopper, SCR, diodes panel and GTO thyristor protection system for the locomotive were inappropriate or grossly not adequate [11]. Further investigations were undertaken to find the solution for the application of chopper, which is coupled with the switch in the locomotives, the GTO thyristor converter were studied and it was revealed that it lacks some properties such as regeneration of power, because of this disadvantage, this then lead to the replacement of the GTO thyristor with the IGBT in the freight locomotive used in the Republic of South Africa (RSA). The replacement was necessitated, as much improvement was needed to overcome the problem of the failure of the power processor unit and also take advantage of the regenerative braking. During the refurbishment of the locomotive, the existing four firing fast thyristors which is made up of the assemblies of two choppers and two commutations, had to be replaced by three identical press-pack IGBT which can be used to operate independently the induction motors and can also be used for the regenerative breaking of the locomotive.

## 1.3 Motivation

Recently, the South Africa railway system, in the area of the electric locomotives, upgraded their power electronics converters by replacing the GTO thyristors with the IGBTs switches. The insulated gate bipolar transistor (IGBT) is a promising power device for medium voltage high power application in the field of railway traction. This is based on the fact that the switch has a high voltage blocking capability and the new IGBT switch can serve as a good replacement for the GTO thyristors for both medium and high power electronics applications. In the previous locomotives used in South Africa, the GTO thyristor was used, in which the voltage blocking capacity was not sufficient enough, as a result, the effect of the transient were apparent on the traction converter configurations [12]. These days, the power processor systems that comprise the IGBTs with high blocking capabilities are now used in the electric locomotive. This is because, the parameters of IGBTs with relatively higher blocking voltage for the switch, thus, they have small leakage current coupled with a relatively lower blocking losses in comparison to the blocking losses of the GTO thyristors and this assist in the efficient working of the IGBTs [13]. This enhancement of the IGBT switches has led to the generation of carriers and increases blocking losses substrate, thus, if the losses are reduced, the power is stable and this results to voltage stability on the traction converter. When the IGBT is in blocking state, the voltage across the device is constant, hence, providing protection to traction converter, which is then used to operate and control the traction drive for purpose of producing the locomotive propulsion.

In a fault conditions, the IGBTs will safely guard the short circuit in event of over voltage, even in the occurrence of worst-case failure conditions.  Thus, which in this case, the IGBT has the capability to interrupt the operation of the inverter or traction converter immediately, this is advantageous in traction converters, which are devices that are connected in series for locomotive protection [7, 14, 15]. In addition, the reverse conducting IGBTs (RC-IGBTs) was developed to protect the thermal cycling of the traction converter [16]. Hence, this semiconductor device provides high power density and also has the advantages of thermal cycling. For its structure, the IGBT is integrated with the anti-parallel diode as a single chip to operate the IGBT in forward conduction mode and or the diode in the reverse conduction mode during locomotive propulsion. This new building block further enhance the compactness, reliability, and modularity of the high power electronic systems.

Based on this analysis, this research was conducted to investigate the transition from the use of the GTO thyristor to the IGBT for power converters use in the locomotives which are used to operate the freight trains in South Africa (SA). The focus of this research was to carry out both the analytical and numerical investigations of the power electronics converters in locomotives by comparing the operation of both power switches to ascertain why the upgrade or was the replacement necessary.  The upgrade and improvement is based on the fact that there has been a tremendous growth in power electronic technologies and this has brought about the need for the replacement of old locomotive with relatively newer versions in the aspect of changes with respect to the design, manufacturing concept and the operation of power electronic converter systems. On this bases, the need for the upgrade from GTO thyristor to IGBT.

Many of these developments in the aspect of power electronics converters are highly technical and complex; which warrant the need for the detail investigation and analysis of the power electronics technology and the protection it offers for the electric locomotives. Thus, this formed the bases for embarking on this study.

## 1.4 Aims and Objectives

The rail industry globally is experiencing steady growth, emerging economies such as South Africa is not an exception to the demand for more railway network for both cargo and public transportation. Hence, for the railway network to be able to operate with large volume of rail vehicles and the high efficiency in electric railways in South Africa has resulted in the expansion of the railway network with newer versions of trains being put into service. The expansion has necessitated the employment of newer types of locomotives with improved converter systems for the traction drive systems. The demand for railway freight locomotive has been showing a steady growth and in line with the context and with respect to the motivation and problem statement as discussed already, the following are the aims of this study:

- Study the concept of locomotives electrification systems
- Analyse the power flow from the catenary to the traction drives systems
- Analyse the power electronic converters systems in locomotive systems
- Model and simulate the power electronic converters systems as well as analyse the protection concept it offers to the locomotive

The objectives of this study are:

- Developed and analyse the models for the various aspect of the power converters in the locomotive
- Develop a numerical model for power electronic converters for the locomotive
- Carry out a computer simulation of the developed numerical model
- Analyses the concept fault mode of the system and the corresponding protection as provided by the power switches

These aims and objectives will be achieved with the analysis of the various topologies with respect to the developed numerical model in order to justify the replacement of the GTO thyristor with IGBT in terms of innovations in the of power electronics applications for the electric locomotives.

## 1.5 Significance of the Study

In this study, different medium-voltage power electronics converter topologies for electric locomotives are investigated and compared in the aspect of the power transmission, protection, power losses and component requirements. As it will be explained later, various topologies of the power converter were developed ranging from the GTO thyristors and the IGBTs for the locomotive, which analyses were used as the bases for this study. The improvement is based on the upgrade from the previous operated devices which was the SCR, GTO thyristors, to the IGBTs converters. Hence, for the justification of the upgrade from GTO thyristor to IGBTs, the improvement in the degree of locomotive electrical protection from the point of traction converter to where the intercepting devices is operated as achieved only by the electronic protection in the IGBTs switch via the pulse width modulation (PWM). Thus, the significance of this study is to investigate and justify the replacement with the aim to determine and compare the parameters between these switches in the locomotive. The application of these upgraded modules of IGBTs have proven to show a decline in the instability of voltage and the losses during switching and this reduction is due to the reduced number of components that are compounded [8]. It is important that at the end of this investigation, it will be established that whether improvement or upgrade was justified based on the comparison of the GTO thyristor to the IGBTs converters system using the same topology, pulse pattern and propulsion system. Also investigated is the possible application of the cycloconverters for electric traction drives for locomotives.

## 1.6 Scope of Study

The railway system is a very complex network and it comprises of many subsystems in order to function. For the operation of the railway system, the railway network comprises of various areas of science and engineering ranging from electrical, mechanical, civil, information technology (signal processing) etc.

The trains employ the rolling stock or locomotive which houses the traction drives i.e. the unit of the locomotives that provides the needed motion for trains and this is the area of interest for this study. Hence, it may be imperative to define the scope of the study, and for this study, the focus is on the power electronics converter systems located inside the locomotive as illustrated using Figure 1.1. Thus, this study will seek to explore the various concepts, configurations of the old converter systems as compared to the new converter systems and the protections offered by this replacement and draw the inferences accordingly based on the findings of this study.

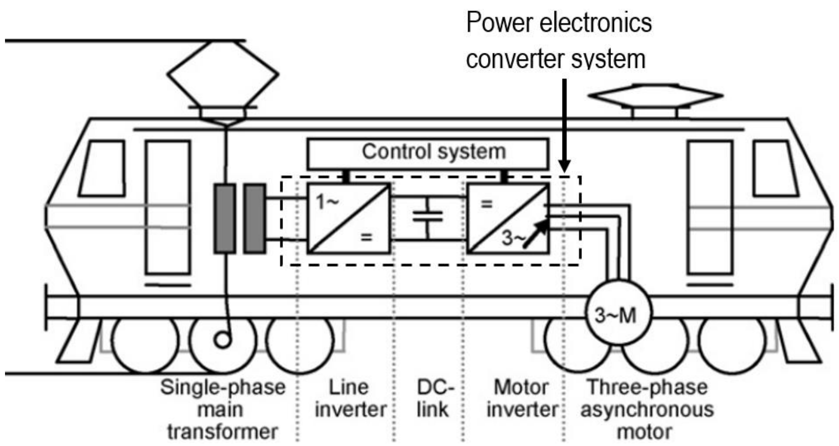



Figure 1.1: The various components of the electric locomotives [17]

## 1.7 Thesis Outline

This dissertation consists of five chapters and the brief explanation of these chapters are presented as follows:

Chapter 1-This Chapter was used to present the introduction of the study with regards to the general background, motivation, problem statement and the research aims and objectives. Also explained in this chapter is the significance of conducting this study as well as the scope of the study.

Chapter 2-This Chapter focused on the conceptual framework from literature, which are relevant to this study in line with the mentioned aims and objectives. The literature survey carried out in this Chapter covered areas such as the railway network, the mode operation of the electric locomotive, the power electronic converters application in AC electric locomotive, control strategy. This chapter helped to gain an insight on various concepts, mathematical, numerical and experimental work that have been conducted by different scholars and researchers regarding locomotive that helped to determine the research methodology.

Chapter 3-This Chapter was used to present the models that was used to implement the research methodology based on the literate review. The models presented where for components for the power flow, from the catenary wire to the traction drives. These models included the analysis of the line transformer, the alternating-direct (i.e. AC-DC) converter, the DC link, the direct-alternating (i.e. DC-AC) converters and the tractions motors that provides the propulsion. This chapter was used to develop the various models that were then implemented and analysed in Chapter 4.

Chapter 4-This Chapter presented the various simulation models for the power electronics converters. This includes the specifications of the main components of the locomotive used for both the analytical analysis and the numerical simulations. The developed simulation models were for the cyclcoconverters, GTO thyristors and the IGBTs converters for the locomotives. These simulation models were implemented on the MATLAB environment and the explanation of the various MATLAB simulation model were presented. Also, in this Chapter, presented were the simulation models and the obtained simulation results. The discussion of these results is documented in this Chapter.

Chapter 5-This Chapter presented the summary of the entire dissertation. Conclusions of the investigations of this study as a function of the achieved goals are highlighted. Also, explained is recommendation for further study or the possible improvement that can be done in this study, with a new study.

# Chapter Two

# Literature Review

## 2.1 Introduction

There are numerous ranges of electric railway systems that are used in South Africa to transport goods and people, connecting cites and industrial complexes. As shown in Figure 2.1, is the typical diagram of an electric locomotive. Many of these electric locomotives that have been used in South Africa were built decades ago and some of these electric tractions vehicle systems were built in parallel to the early era of the development and application of power electronics technologies for traction drives. In recent times, there has been some rapid advancements in railway locomotives with regards to the power electronics applications in the areas of switching, converters topologies, power electronics transformers and protection system which has necessitated the need to upgrade to an improved form of the electric locomotives. This improvement in the electric locomotives is largely based on the rapid advancement of power electronics converters systems and the microprocessors for the control of the converters systems and the traction drives.

This Chapter was used to presents the literature survey carried out to analyse some research work that are related to this study which will serve as the platform to accomplish the aims and objectives of this research. To achieve the task in this Chapter, the contents that are presented will includes concepts such as railway network electrifications, types of locomotives, concepts of power electronic, the analysis of power processor systems and locomotive traction drives. The Chapter is concluded with a discussion on the protection of the electric locomotive offered by the power electronics converter system.

Figure 2.1: The diagram of a locomotive

## 2.2 Description of the Railway Network

The railway lines comprise of many structures, before going specifically into the discussion of the rail vehicle or the rolling stock; firstly, it is imperatives to explain the railway network, in which the railway lines is situated, on which the rolling stock glide through. The diagram of the cross section of the railway lines indicating the main components is shown in Figure 2.2. As shown in the Figure 2.2, the railway network consists of the mast, dropper, message wire, contact wire, and the railway track. The railway track mainly composed of the rails, on which the rolling stock glides, railroad ties (sleepers), fasteners, railway switch, ballast (Coarse aggregate), usually fitted with the metal wheels as it moves. Also, there are other possible variations such as the “slab track", in which the rails are fastened to a concrete foundation resting on a prepared subsurface. The components of railway track play different roles in providing support for trains. It imperative to note that the electric railways network system have higher initial capital costs and higher maintenance costs as compared to the vehicle road network.

The rail vehicles that is used to transports the passengers and goods are normally propelled by the wheel running on rails, i.e. rail vehicles, which are incorporated in the tracks and guide its movement. The railway track is designed for rolling stock to glide along safely and smoothly. Thus, it should note that the rolling stock is a directionally guided vehicle and this guide is done by the tracks.

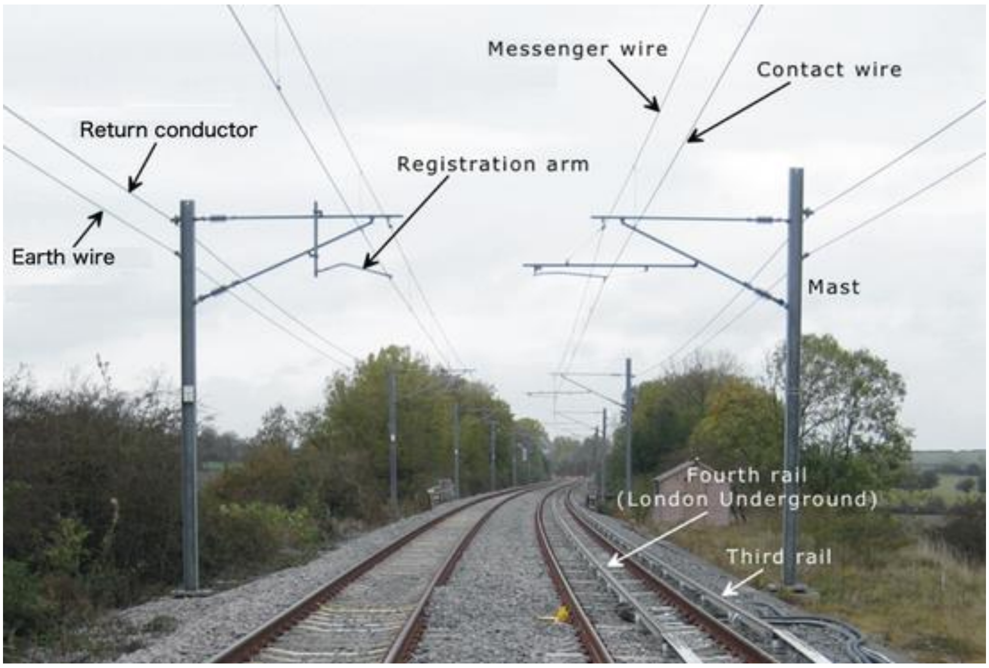



Figure 2.2: Components of a railway lines [18]

Rolling stock as shown in Figure 2.3 is a rail transport system, it glides on the rail and usually encounters lower frictional resistance at the wheels on the rails as compared to the road vehicles. To operate as a train, the passenger and freight carriages and wagons are coupled with the rolling stock to form a long train, stretching several meters or even kilometres. The operation of the railway network is normally under taken by the railway companies in order to provide the transportation between the train stations or the freight customer facilities. In South Africa, Transnet and passenger rail agency of South Africa (PRASA) provide the operation of the railway services either for port authorities or for passengers.

The rolling stock or locomotive is the railway transport vehicle that provide the mechanical power for the motion of trains, which can be either for passenger trains or freight. Railway systems requires a source of power supply or prime mover that the locomotive can continuously access in order to provide the needed mechanical power. The power that is provided to the locomotives can either be gotten form electric power, drawn from the railway electrification system (catenary) or generate the power within the locomotive, usually from diesel for the diesel engines or coal in the case of steam engines. Railway transport has the capability to transport high levels of passenger and cargo transportation by the utilisation of energy efficiently but is often less flexible and more capital intensive to construct the network as compared to the road transport system.


Figure 2.3: Locomotive on the railway track

Generally, the railways rolling stocks or locomotives can be categorized into three:

- Electrically powered system
- Fuel powered system
- Fuel-electric (hybrid) system

These classifications dictate the major characteristics of the rolling stock and their application; thus, the rolling stock can be used as a high-speed train, trams, intercity, freight locomotive etc.

For the electrified rolling stock, this form of locomotive uses the external power source system i.e. electric power, where the train is fed by the current that can either be direct current (DC) or alternating current (AC). This power supply source can be in the form of a third rail or an overhead line. For the overhead lines (contact lines) as shown in Figure 2.2, the power from the catenary lines is supplied to the locomotive via a sliding pantograph as explained later and this pantograph which is always in contact with the wire as it slides, through the means, the power is supply to the locomotive. The current supplied to the locomotive passes through the transformer and then to the converter system that provide the power need by the electric motors. Figure 2.4 is the figure that shows the block diagram of the electrically powered locomotive.

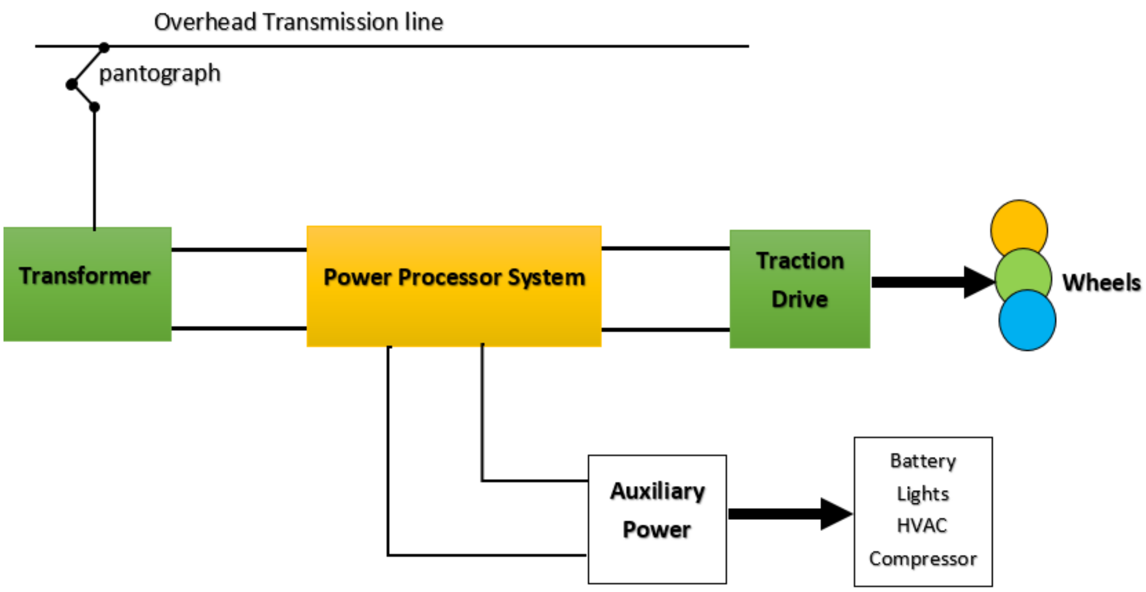


Figure 2.4: The block diagram of the electrically powered rolling stock

In the case of the fuel powered rolling stock as shown in Figure 2.5, there an on board system that is used by the train to carry its own fuel such as diesel oil. This form of locomotive converts the stored energy in the fuel to mechanical energy, which provide the motion to the trains by a means of combustion. For the locomotive operation, the fuel is burnt; firstly, heat energy is converted to mechanical power that drives the alternator. The alternator converts the mechanical power into electrical power, the converter systems transform this electrical power and the electric motor convert the electrical power finally to mechanical power which is used to drive the locomotive.

For the steam engine, the combustion of coal can be converted directly to the mechanical power which drive the wheels and the operation of this form of locomotive is similar to the internal combustion engine of road vehicles.

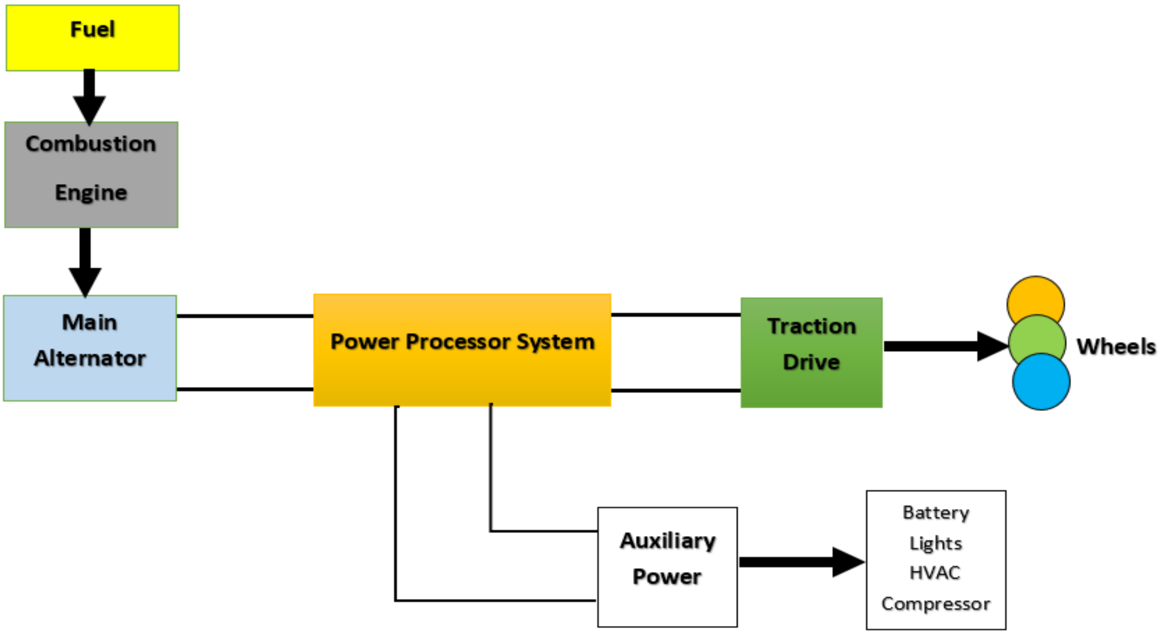



Figure 2.5: The block diagram of the fuel power rolling stock

For the fuel-electric or the hybrid (dual-mode or bi-mode) locomotive, this form of locomotive uses an on board fuel storage system which is placed between the electrical power source and the power processor system that is connected to the traction and finally to the wheels as shown in Figure 2.6. The hybrid locomotive which is mainly in the form of diesel-electric system, this type of locomotive can be powered either from an electrical power supply or by using the on board diesel engine to provide the power. This locomotive combines the features of both the electric locomotive and the diesel locomotive.

Generally, the diesel-electric locomotives are used to provide continuous motion along a rail network that are only partly electrified without the need for change of locomotive. This help to avoid excessive use in running of diesel engine under the centenary, therefore, using the diesel part of locomotive where electrified lines are not available and use the electrical aspect where the diesel engines are prohibited. These forms of locomotive are designed to operate mainly on electric power source where the railway line is routed with catenary lines and operate with diesel in the absence of the catenary line.

The newer version of these hybrid trains now uses energy storage systems where in the case of excess energy from the power source like renewable energy source or energy that can be obtained from the regenerative braking, which invariable can be stored in a storage system. During the deceleration of the rolling stock, kinetic energy is directed to the transmission system, this can be used to boost the power, which is available from the main power source. Most of the dual mode locomotives are mostly designed for regenerative braking as they use the regenerative braking process to recover energy some of the energy, Thus, during this braking condition, the motor will be operated as a generator. Thus, as the traction AC motors operating as generators, its operation can be used to convert much of the locomotive's kinetic energy back into electrical energy. However, if no energy storage system is put in place in the locomotive to store this regenerated electrical power, this energy is then converted to heat using the large rooftop resistor banks and this heat is then dissipated or liberated and blown by cooling fans to the surroundings.

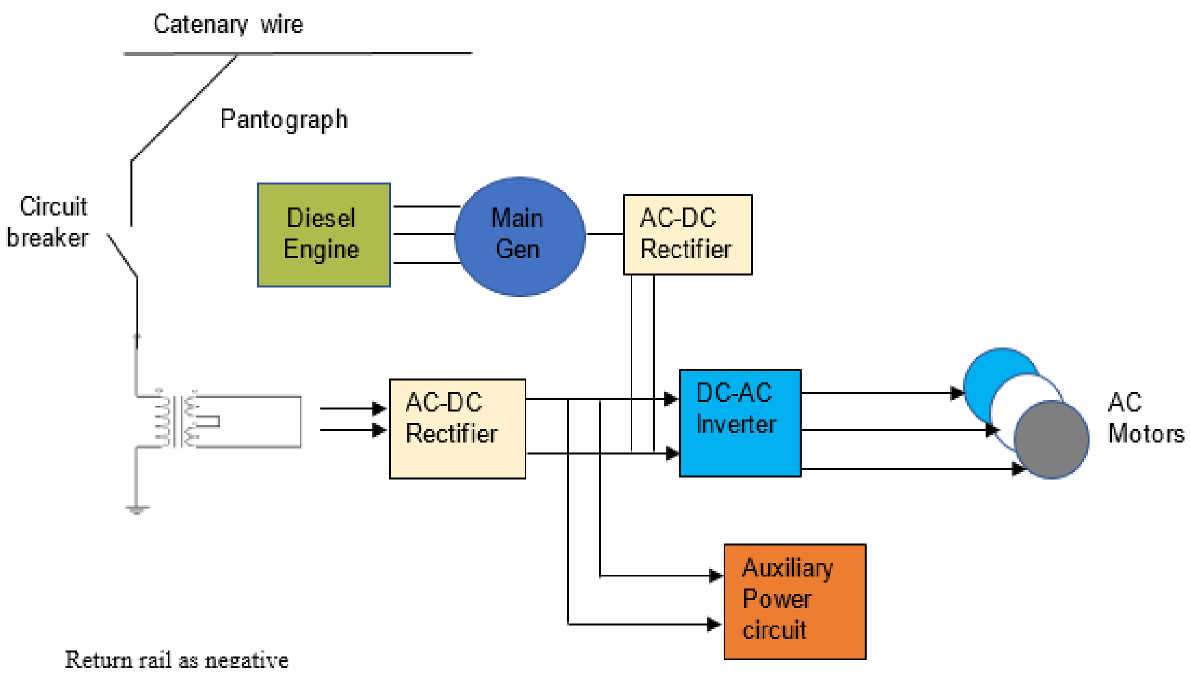



Figure 2.6: The block diagram of the electro-diesel locomotive

## 2.3 Railway Electrification System

The source of power for locomotive, which powers the trains, can be in the form of steam, diesel or electricity or a combination of these as a hybrid or dual mode system as explained in the previous section. For the electric trains, the power source can either be from the direct current (DC) or alternating current (AC), the former being used for many years, simpler for railway traction purposes, the latter being better over long distances and cheaper to install [18]. A railway electrification system is used to provide electrical power to the electric trains via the locomotive and the electric locomotives is used to operate the trains to transport passengers or freight. For the electric locomotive, electrical power is mostly purchase from an electric utility. In South Africa, the electric railways lines are normally supplied power by the national power utility, Eskom, which own and operate the generating stations and the transmission lines. The power from the grid is supplied at 132kV, 50Hz, before being fed to the railway electrification network. This power is then step down in the traction substation by the traction transformer as shown in Figure 2.7. The traction substations are usually placed at 10 km to 20 km apart along the line in order to balance the phases and for total harmonic distortion (THD) reduction.

The railway transformer as shown in Figure 2.7, are used for stepping down the power grid voltage of 132kV or 88kV to either 1.5 kV DC or 3 kV DC or 50 kV or 25 kV AC, 50/60 Hz depending on the type of railway network. This step down power is transmitted through the catenary wire and then fed to the locomotive via the pantograph. Traction substations are an integral part of the railway infrastructure which ensure that power is supplied to the trains and other line equipment.

Figure 2.7: Railway substation transformer at Transnet SA

After stepping down the power to the required voltage, this power is then transmitted along the railway network lines i.e. the catenary as shown in Figure 2.8. For detail explanation of the operation of this railway line can be found in [18].  The South Africa railway companies are responsible for providing their own distribution lines, switches, and transformers for its operations.

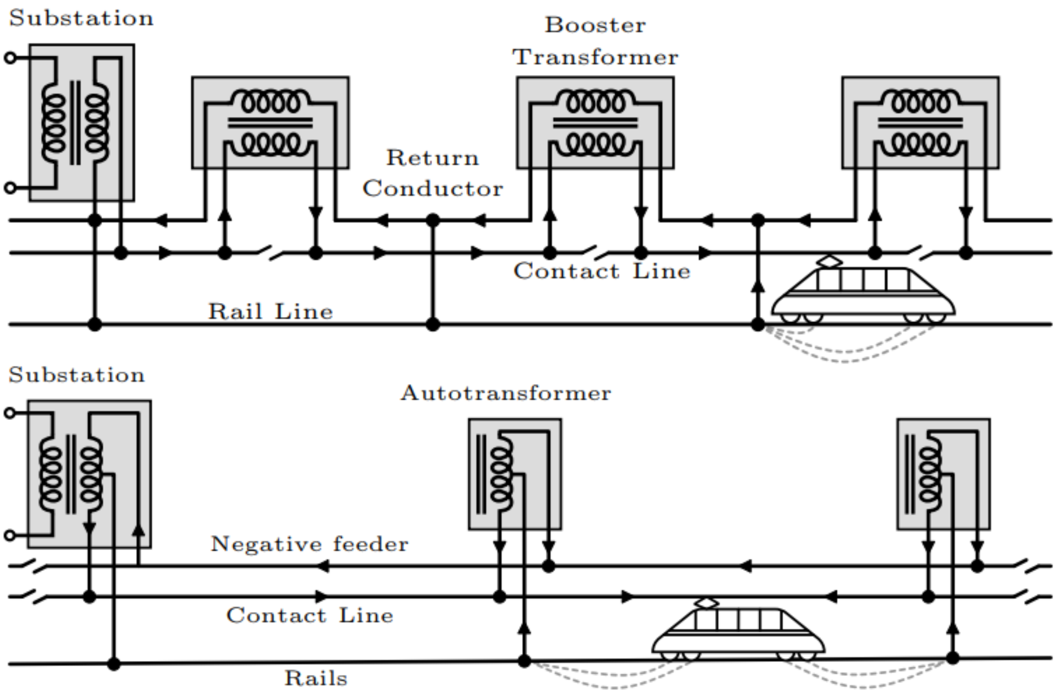



Figure 2.8. Single level (top) and bi-level (bottom) voltage distribution in AC traction network [19]

For the electric locomotives, the transmission of power is always along the track by means of an overhead line or along the ground track, using an extra or third rail laid close to the running rails. AC systems always use overhead wires; DC can use either an overhead wire or a third rail; both are common [18]. The overhead systems do require at least one collector line to be attached to the locomotive so that it can always be in contact with the power supply. The overhead lines, the current collectors or the pantograph fed power to the locomotive and to ensure the continuous supply of power, the current collector is always in contact with catenary, thus, there is always contact between the moving locomotive and the transmission lines. For the circuit to be complete, the return circuit is normally through the running rails which feed back to the traction substation. This is achieved because the running rails are at the earth potential as it connected to the traction substation.

Generally, the various categorises of the voltage level used in railway lines as supplied from the traction substation as follow:

**For DC lines**

DC 3kV or 1.5kV

DC: 750V, 1500V, 3000V

**For AC lines**

AC 15kV, 17.7Hz; 15kV, 16.7Hz

AC 25kV, 50/60Hz

AC 380V, 50/60 Hz

AC 400V, 50/60 Hz

The following subsections are used to provide brief explanation of the various railway electrification systems that are used to provide electrical power for different type of locomotives which are available in South Africa.

### *2.3.1 DC Railway System*

The DC railway lines were the earliest form of rail network in South Africa. The DC can be the preferred option for line where the DC catenaries power is carried by a third rail but the catenary uses the thick wire which are very expensive [12, 16, 20]. For DC electrifications, 3kV and 1.5kV are the predominant voltages for long distance locomotives. However, the shorter distance railway trains, such as trams, subway or city trains, uses the 750V as the main power supply [12]. DC catenary lines suffer from energy loss and increase line distortion leading to lower frequency at longer distance between the traction substations. In order to overcome this constrain, it is advise to deploy traction substations at close intervals for every two or three kilometres apart on a 750 V DC system [12]. For catenaries of 3 kV DC, the IGBTs of 6.5kV of blocking voltage are typically used, as they are able to operate directly from 3kV catenaries and can transmit up to 5 kV. For catenaries of 1.5 kV, IGBTs of 3.3kV or 4.5kV of blocking voltage can be used with the two-level converter configurations for railway protection [12]. The DC feeding system current increase smoothly whereas the fault current increase drastically, an all type fault selective relay is located on the substation to detect such fault within the line system.

### *2.3.2 AC Railway system*

The AC railway electrification of the locomotives is done at the medium voltage level, which is used for the mainline and high speed railways. In South Africa, the AC systems of 25 kV, 50Hz is commonly employed for the railway application. This 25 kV AC voltages are stepped down to desired voltage inside locomotive using the on-board transformer, which lower the voltage level of 25kV AC  to 400V AC for both the converter system and for the auxiliary operation [12]. This form of electrification is adopted in order to reduce the transmission losses. Generally, the higher the voltage used for AC transmission, the lower the current required with the same power and leads to reduce line loss. Consequently, allowing the higher power to be delivered to the locomotive. AC power is easier to transmit over long distances because it's the voltage can step up or down, so it's a suitable medium for operating the electric railways. This increase in voltage level with a reduction of current needed, result in the railway line providing the same electrical power levels necessary to achieve the rated speed needed for the propulsion of the locomotive. Because the power of the single-phase supply, the traction power systems (TPSs) can cause imbalance on the public grid. In other to avoid this problem, the train is made to run on the three phases but on one phase at a regular interval. [21]. The exchange between these phases taking place at the neutral sections that are located at regular intervals along the catenary line.

The AC system uses many types of infrastructure for protection, in the event where fault occurs, the combination relay located at a distance can detect this fault and trip the power circuit breaker in the nearby traction substation [22]. These combination relays monitor the impedance in the line, if any impedance fall below predetermine regular value, relay will send a signals for the circuit breaker to trip and isolate the fault [22].

### *2.3.3 Multi (AC/DC) Railway system*

The multi-system railway system, this is where the locomotive can operate under different types of voltages and current at different section of the railway line. Theses electrification systems are design to operates under the DC (for one of 1.5kV DC 3kV DC) and under AC (for one of 15kV, 16.7 Hz AC, 25kV, 50 Hz) systems as the locomotives cross the frontier of the freight traffic. This system is usually design for the locomotive to be able to interchange between AC and DC lines and vice-versa as it travels through different routes. This occur when there are variety of railway electrification systems, thus, this necessitate trains to be designed to adapt to different voltage source as it passes from one electrification system to another. The means by which this can be achieved is by changing locomotives or rolling stock at the switching stations. These multi-electrification systems, the rout of different voltage systems are present in South Africa which are used by the dual locomotives which can operate with the 3 kV DC and 25 kV AC. Some system is design to change between voltages and this takes place at railway stations using different rolling stocks. Hence, for this system, these stations have different overhead lines that can be switched from one voltage form to another, thus, the train arrives at the station with one locomotive and then departs with another.

In emphasis, although there are various railway systems that are being used in South Africa, but it is imperative to state that, the locomotive that was used in this study is that which run on the railway system that uses the 25 kV AC, 50 Hz.  Henceforth, the information that was used in this study in the aspect of numerical simulation and analysis is that of the AC locomotive that uses this catenary voltage and frequency.

## 2.4 Catenary line and the Pantograph

Power is supplied to the moving electric locomotives through a continuous conductor running along the track that usually takes one of two forms. The first form is the overhead line or the catenary line or wire, suspended from poles or towers along the track or from structure or tunnel ceilings. The second form is the third rail, which is mounted at the track level and is in contact with the moving train by a sliding "pickup shoe" [18]. Both overhead wire and third-rail systems usually use the running rails as the return conductor, but some systems use a separate fourth rail for this purpose [18]. As explained earlier, electrical power supplied to the locomotive can be either DC or AC. Most railways electrification uses the AC because of the use of transformers (both for the traction and on-board), which is used for stepping down the voltage.

Generally, the electrification system used for a railway network is based on economics of energy supply, maintenance, and capital cost as compared to the revenue obtained from the freight and passenger services. The electrification system used for urban and intercity areas are different and flexibility in operation, some electric locomotives can switch to different supply voltages.

In this section, because the emphasis is on the AC locomotive, the description of the AC network systems will be discussed. In AC electric locomotives, the electricity that powers the locomotive is supplied through a device place on the roof of the locomotive that is known as the pantograph. The diagram of the pantograph is shown in Figure 2.9 and the pantograph is always in contact with catenary wire that is suspended along the arm of the track. The pantograph is a high tension current collector, which collect current from the catenary line and fed it to the locomotive i.e. it is required to supply power to the locomotive for propulsion purpose. Each locomotive is provided with two similar pantographs on the roof. Therefore, the pantograph is the power collector for the locomotive and this pantograph must always make a good contact with catenary wire at a set distance, pressure, and time. For the single phase 25 kV, 50Hz AC catenary lines, the pantograph is the used to collect the power and then the power is supplied to the locomotive. The pantograph is usually the single point power contact for the locomotive, and it must maintain good contact under all running conditions. Thus, the locomotive is always in contact with catenary wire via the pantograph i.e., the current is collected from overhead lines by pantographs.

When the locomotive is moving at a higher the speed, it is difficult to maintenance good contact. Pantograph contact is maintained either by the spring or by the air pressure. Compressed air pressure is preferred for the high speed operation. The pantograph is connected to a piston in a cylinder and the air pressure in the cylinder is used to maintain the pantograph position with catenary line.

The contact strips of the pantograph are supported by a lightweight transverse frame which has "horns" at each end. These are used to transverse the position of pantograph in order to reduce the risk of the pantograph being hooked over the top of the contact wire as the train moves along the tracks. A train moving at speed with its pantograph hooked over the wire can bring down several kilometres of line before it can be detected. The most sophisticated pantographs have horns which are designed to break off when struck hard, for example, by a dropper or catenary support arm. These special horns have a small air pressure tube attached to it, which, if the pressure is lost, will cause the pantograph to lower automatically, thereby reducing the possible damage to the catenary line.

The safe allowable distance between pantograph and catenary wire is 5 meters apart and 5 to 8 second rising time of the pantograph in order to achieve a constant power supply from the catenary wire. These design parameters are to ensure a good quality of electric power is supplied to the locomotive and for protection purpose. The following characteristics are important for the optimum operation of the pantograph [22]:

- Meeting the train/locomotive power requirements
- Uniform height above the rail to optimize pantograph power collecting capabilities
- Must have minimum vibration to avoid pantograph hook up and also reduce arching from occurring
- Tension must be maintained to ensure a constant power flow from the overhead line to the pantograph

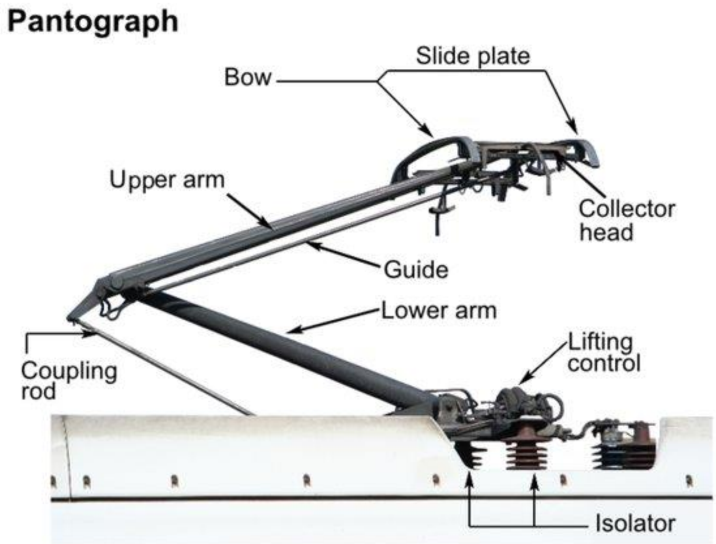



Figure 2.9: Diagram of current collector .i.e. Pantograph [23]

## 2.5 Analysis of Catenary/Pantograph Contact System

The contact wire on the catenary line is always not smooth, thus, the occurrence of problem between the contacts on the pantograph with catenary cannot be completely avoided. The problem can be caused by incorrect installation of catenary line which results in long wavelength (slags) and this can result to irregularity along the line, or it can be caused by the manufacturer, in which the manufactured causes a defect of an unevenness in the contact wire [24]. Also, the problem can be due to short wavelength that create a lot of vibration on the pantograph, resulting in pantograph hook up. Unfortunately, there is no developed standard that can be implemented to take care of such irregularity or problems resulting from the catenary with the contact system. It is obvious that the quality of contact become worse if the pantograph/catenary or single cosine irregularity is used to determine the contacting system between the catenary and the pantograph because this is influenced by its dynamic behaviour. The pantograph/catenary contact system is a function of the speed and wavelength, and how these parameters is used to determine the locomotive contact areas are documented in Table 2.1. It can be deduced from the table, that the influence of irregularity on contact-feeding and it becomes larger with the decrease in wavelength of the harmonic. For a speed of 120km/h, when the wavelength is less than 2 m, the minimum contact force become zero and contact feeding is impossible [24]. Therefore, the critical wavelength is 2.5 m, but by increasing the running speed of the locomotive, such critical wavelength will increase and there may be a possibility of hook up. Longer critical wavelength is not good for high speed trains, thus, in order to overcome this problem, a good contact surface between pantograph and catenary can be obtained by ensuring that the contact-feeding and the space between two droppers must be larger than critical wavelength according to the running speed of trains[24].

Table 2.1: Electric Wire contact force with wavelength [17][24]

| Wavelength/Contact force | | 0.5 | 1.0 | 2.0 | 2.5 | 3.0 | 4.0 | 5.0 |
|---|---|---|---|---|---|---|---|---|
| Speed 120km/h | Maximum | 711.4 | 618.7 | 624.8 | 137.2 | 127.8 | 122.5 | 115.9 |
| | Minimum | 0 | 0 | 0 | 40.5 | 37.0 | 51.3 | 55.1 |
| | Root-mean square | 115.6 | 135.8 | 115.2 | 20.9 | 17.5 | 15.5 | 14.8 |
| Speed 150km/h | Maximum | 558.6 | 602.1 | 629.9 | 667.3 | 197.1 | 177.1 | 171.2 |
| | Minimum | 0 | 0 | 0 | 0 | 0 | 0 | 9.1 |
| | Root-mean square | 117.7 | 134.4 | 137.0 | 122.7 | 40.9 | 35.5 | 34.2 |

For the analysis of the dynamic behaviour of the pantograph and catenary system, the occurrence of vibration of locomotive itself should be taken into consideration. In fact, the vibrations of the locomotive will affect the quality of contact surface between the catenary wire and pantograph due to the large amount of the dynamic force. With the influence of vibration of the locomotive, the contact force between the catenary and pantograph will be reduced as compared to the situation with less vibration of locomotive. It is common knowledge that increasing the running speed of the locomotive, the influence of the vibration of the locomotive on contact force will increase as well, but eliminating the slag on the catenary line will not have any direct influence on the power output and hence the occurrence of the pantograph hook up can be reduced [24].

## 2.6 Description of the AC Electric Locomotive

A typical locomotive system, indicating it main components is shown in Figure 2.10. The rolling stock or the locomotive is a railway vehicle that move along the railway track with the purpose to provide propulsion to the train that is attached to it. The AC locomotive is powered by electricity which is obtained from an external source, usually from the catenary wire or the overhead cables via the pantograph. As can be seen from the Figure 2.11 are the various main components or equipment that is found in the locomotive. These main components or systems ranges from the pantograph, the circuit breaker, the on-board transformer, the rectifier, the DC link, the inverter, the traction motors and as well as the auxiliary components.

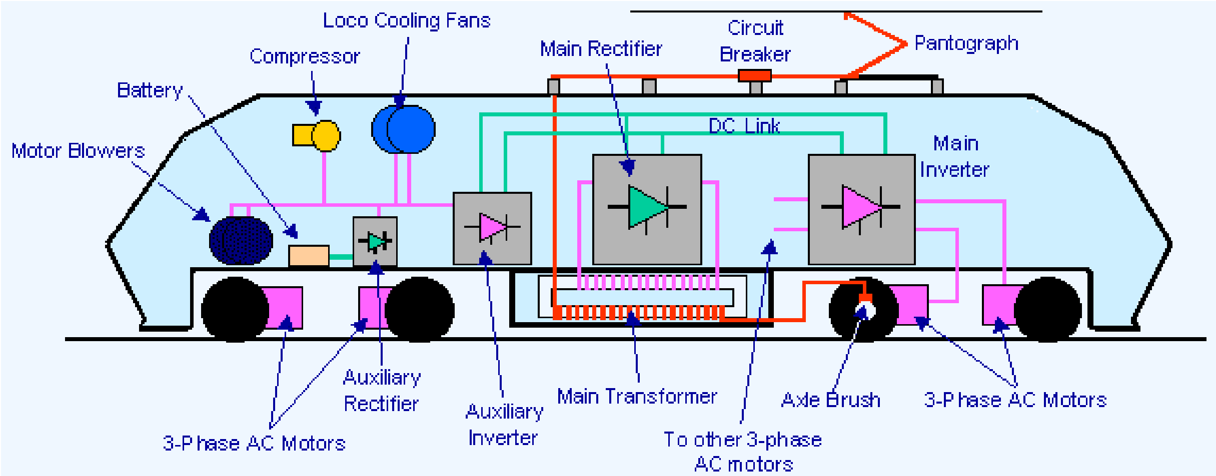



Figure 2.10: The various components of locomotive [18]

Figure 2.11 is used to highlight the various process that takes place in various systems as a function of the power flows from the catenary via the pantograph to the traction motors. As illustrated using Figure 2.12, the power flow from catenary to the locomotive through the pantograph, which is the supplied to the transformer that steps down the voltage for the converter system. The converter system carries out the power conversion/transformation before feeding it to the traction drives, and this is used to operate the traction motors and the auxiliary loads. The following diagram is used to describe how the power flow along the components of the locomotive.

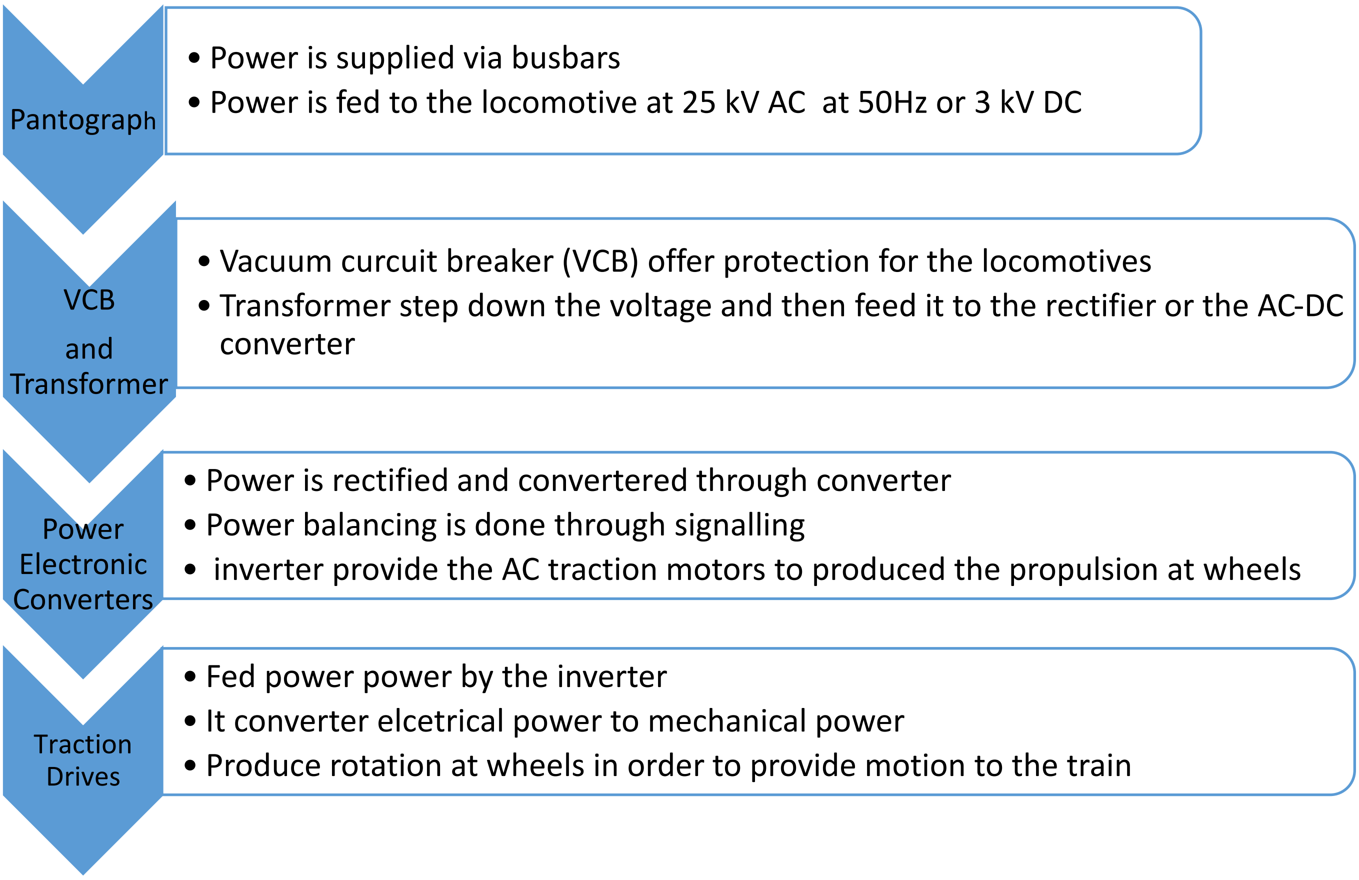



Figure 2.11: Highlights of processes that takes in various components of locomotive

## 2.7 The Power Flow in AC Electric Locomotive

Figure 2.12 shows the schematic diagram which is used to illustrate the concept of power flow of the 25 kV AC locomotive. As shown in this diagram, the pantograph is the prime mover for this electric locomotive system and the electrical power flow direction with respect to each component for this electrical locomotive. Figure 2.12 gives the overview of the power flow from the catenary to the induction motor which is used to produce motion at rail of the wheels. For the power flow, the voltage from the pantograph collector is sent via the vacuum circuit breaker (VCB) to the on-board transformer which step down the voltage from the input of 25 kV AC supply to 400 V. From the transformer, after the power is step-down, the power is fed to the power processor unit or the power converter system. The power processor unit is made up of two converters systems and the DC-bus or the DC link. The power from the secondary side of the transformer is fed into the first converter system and this first converter system is used for rectification. This converter is known as the front-end (line) twin 4-quadrant line converter type where the AC is converted to the DC and the output from the rectification process is fed to DC link for smoothing. This supply from the rectification is linked with the input side of the DC link, which is a reservoir of energy. The resultant DC voltage from the DC link is supplied to the inverter.

Generally, in an AC locomotive, the AC current from the catenary or the alternator is rectified to DC; then the DC is converted to AC by an inverter, which is controlled by the locomotive's computer. This permits the varying of frequency and the duty cycle of the AC current that is fed to the traction motors. The inverter or the drive converter, which is the form of the variable voltage variable frequency (VVVF) converter, then converts the DC supply into the 3-phase voltage, which is then used to drive the 3-phase traction motors. The output of drive converter (inverter) in the form of the VVVF supply, helps in controlling the starting and running torques of three-phase induction motor by using the Pulse Width Modulation (PWM) technique.

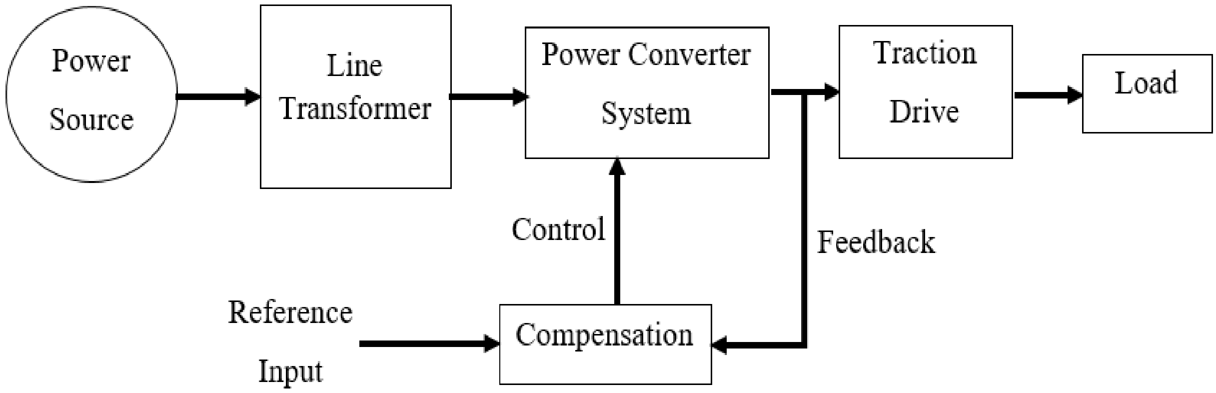



Figure 2.12: The power flow in an electric locomotive

The locomotive traction drive system as shown in Figure 2.13 is designed to have at least one traction converter per traction stations and each traction is used to operate a three induction motors. As explained in the next two subsections are the two power electronics switches that were employed in locomotives used in SA. These switches were used with regards to the previous locomotives and the relatively newer version or the upgraded locomotives. Hence, the SCR and GTO thyristors were used in the previous locomotives and IGBT is now been used in the upgraded locomotives. Both switches are used as the high current AC-to-DC-to-AC converters.

### *2.7.1: The Previous Locomotives with GTO Thyristors*

Since the inception of railway transport system in South Africa, the rolling stocks have gone through numerous transformation from steam engine locomotive which was then replaced by both the diesel locomotive and the electric locomotives [4]. For the last 50 years, power electronics devices have experience growth in the application for power conversion to the extent that as at today, about 15% of electric power produced undergoes some form of electronic conversion. The Traction drives of the locomotive originally employed mainly Silicon Control Rectifier (SCR), during the 1980's the SCRs were then replaced by the GTOs [25]. For investigation purposes, during the 1990s, the GTO thyristor was commissioned to operate the shunt locomotive in South Africa as a prototype system. This investigation, the locomotive was used to prove the capability of switching frequencies of the GTO, which was limited to a frequency up to the maximum value of 300 Hz and could go up to the voltage of about 690 Vrms. This revealed that this system using the GTO was limited due to the complex circuit and the snubber losses which was found out to be high in cost [15]. In this prototype design, it was established that GTO efficiency was relatively low, making it to be uncertain with regards to protection and also snubbers were needed for high efficiency of the system but this increase the cost of the converter to the railway locomotives cost [4]. Regarding this additional stresses or limitations due to the snubber circuit, the costs of the GTO thyristor technology has found it unfavourable for this applications at the expense of the life span of the locomotive [15].

For these locomotives that uses the GTO thyristor, the latching current and forward leakage currents are considerably higher and the gate drive cannot be removed if the anode current is above the holding current level. This causes the anode current to dips below the holding current level transiently, which forces a high anode current at a high rate back into the GTO. This can be potentially destructive to the GTO thyristor. To avoid the rate of voltage (dv/dt) triggering and then protect the device during turn OFF, it was either recommended that a resistance must be connected between the gate and cathode or a small reverse bias voltage (typically -2V) must be maintained on the gate terminal. This prevents the gate cathode junction to become forward biased during the turn OFF state.

It is important that the traction converter has to provide protection against voltage, current, real power and apparent power from the machine under failure condition, which could not be achieved by the GTO thyristor, the overvoltages has to be monitored by transducers in order to protect this traction converter [26, 27]. Poor power cycling capability is an uncategorized failure mode, and this fault occurs after short circuits and the causes the switch, nit be able to be turned off and this can lead to a possible explosion of the GTO modules during this failure mode, this is an important drawback for this power electronics device. In the past, the 10E locomotive series, which was in operation then, uses the four GTO thyristor that was connected in series in a sequence. During operation, if one or two of the GTO in a single sequence are defective, the circuit is still considered to be operational but with less protection of the locomotive, which means that the voltage into traction motors must be reduced to achieve the limp mode in the entire locomotive [4]. However, if three or more GTO are defective, the circuit is considered to be defective and must be replaced, so the locomotive will register the fault on the driver's desk. This implies that, if not replaced, when the GTO thyristor is switched on during the start-up of the locomotive, this can result to the power converter system been damaged. Thus, if the initial current levels are too high, this result to the device being burn up that can affect many other components within the power processing unit and can also extend to the entire electrical cubicles of the locomotive.

### *2.7.2 The Upgraded Locomotives from GTOs Thyristors to IGBTs*

The demand for railway freight locomotive has been showing steady growth in South Africa. The recent upgrade of the AC locomotive in South Africa was brought about because of the application of different power electronic switch. In the 2000s, the GTOs were broadly replaced by the better, in terms of switching, IGBTs in the traction drive applications. As explained, the power fed into the locomotive via the pantograph is rectified from AC to DC, in the past locomotive used the GTO, but with the upgrade, this was now done by the IGBT switch. This replacement was done due the fact that the original GTO system had numerous disadvantages as explained in the previous section. The operation of IGBT resulted in a low level of harmonics influenced, which affected the operation of the traction motors and transformer both in the normal operation and during regeneration. Achieving the low level of harmonics with a two-point topology would demand a high switching frequency. This implies greater switching losses as well as increased stress on the insulation materials. Besides the electrical connection and the energy handling capacity advantages, the adoption of the 3.3 kV three-level typology also avoids the need to connect IGBTs in parallel. Specifically, the grid side converter (there is one converter for each of the two bogies) which is made up of a total of four phase-module units. IGBT allow instantaneous switching powers of up to 16 MW into the high power traction converter, and this may require series or parallel connection to obtain for an optimum operation and better propulsion of the locomotives. These IGBT are generally for medium high voltages of about 10 kV and above, which can be achieve by the series connection of the switch.

In fact, the inverters of up to 100 MW have already been realized for locomotive application using first generation IGBT in direct series connection at line frequency of DC link [24].

Based on the analysis of both GTO thyristor and the IGBT, the following are the benefits of the IGBT when compared to the GTO thyristor:

- Better energy efficiency and less heat generation during operation of locomotive
- Higher availability of power to the motor in case of motor failure due to per axle control
- Easy maintenance and reduction of operation
- The switch device cost lower
- It operation is robust with few axillary components
- It has high reliability
- It has a high voltages blocking capacity
- Fast switching (short on/off delays, short rise/fall times, short turn-on/off times)
- The switch has a Low loss and can be operated a relative high frequency

### *2.7.3 IGBT Switch Applications*

Numerous investigations can be found in literature in the aspect of IGBTs converter applications. Generally, the IGBT converter system topology comprising of switches of series, can be used for power conversion, the voltage and power level which may be easily scaled up and down. [16, 28]. The IGBT has ability to synthesize higher number of output voltage levels with an excellent harmonic spectrum, at low cost and low power. However, some drawbacks of this topology are the large number of power devices which are connected in a complex way to be able to achieve a high voltage requirement in order to supply each section of device and this requires expensive isolated transformer [29].

IGBTs are available with ratings of 3.3 kV and 1.5 kA, and new devices with higher voltage ratings which is now up to 6.5 kV at 0.6 kA are now commercially produced which is now utilised in the newer forms of electric locomotive [30]. Investigation done by [31] specify the properties of 6.5 kV IGBTs in two-level configurations where high switching losses relatively limit the efficiency of a power converter at 90- 92% in operation of locomotive during motoring or braking. In addition, the 6.5 kV IGBT based converters provide good reliability due to the minimal component requirements. There are two separate DC-links in the DC mode of the IGBT converter [27], each DC-link has its own crowbar and its own brake chopper during the braking mode of the locomotive [11]. In the AC mode both DC links are integrated into one bogie and connected to other in parallel in order to achieve voltage stability and also to reduce mechanical losses. Therefore, only one series resonant choke is needed for filtering the double line frequency [27, 28]. The crossed input choppers are well suited for an even number of motor side inverters, but they cannot be used if there is only one motor side inverter or if three motor side inverters are needed, each motor has its own inverter/IGBT [27]. This allows a 75% redundancy in the AC mode, but in the DC mode, the two inverters of one bogie are connected via the input choppers. So the redundancy is reduced to only 50% on DC mode due to introduction of choppers [27]. The development of the 6.5kV IGBT has led to the rapid introduction of the IGBT to locomotive application, this IGBT allowed the design of a 2-level inverter operated directly on the 3 kV DC-line [36][32]. The high starting torque of a locomotive requires a high output current at a low fundamental frequency which can be achieved by the IGBT, such that the traction converters use a modular design concept, in which the whole converters or phase legs is connected to a common DC-link [7]. Using a modular concept, it is expected that a failure is limited to the failed component, thus not damaging any other parts of the IGBT and that both converter system are interconnected with DC link [33]. The development of the 6.5 kV IGBTs have brought about the possibilities for such transistors to offer the possibility to avoid series connection of IGBTs for proper blocking of voltage during motoring or braking [34]. Thus, providing higher efficiency, high power density and reliability, the application of the newer components of the IGBT circuit can also provide protection for the locomotive [4, 16].

From the analysis of the IGBT switches for traction drive converter with the application to high mode of operation in the AC electric locomotive, the following can be achieved [35].

- The volume of traction converter system is reduced
- There is a significant reduction in terms of the weight of traction converter, which improves the power density and increase the efficiency
- Reduction in the volume of current transformer when compared to the GTO thyristor.

To conclude this section, Table 2.2 is used to present the comparison between the GTO thyristor and the IGBT switches.

Table 2.2: The Comparison between the GTO thyristor and the IGBT

| Description | GTO | IGBT |
|---|---|---|
| Costing of GTO | Very expensive | Very cheap |
| Number of line-side converters | The more line side converter the high the current distortion | The less line side converter the lower the current distortion |
| Redundancy concept | 30% or less | 50 to 75% is reached |
| Converter size | It big and heavy in weight | It medium and light in weight |
| Performance | Provide inconstant DC for all operation that interrupt operation | Provide constant DC for all operation |
| Traction motor design | Allow a small range since it up to 4.5kV | Allow a big range since it up to 6.5kV |
| Complexity | Chokes are necessary | No chokes and few switches |
| 1.5kV DC operation | The line limits operation of step up voltage full power available. | Star-delta switch of motor restrictions on power |
| Efficient DC | Additional losses of chopper | Only VSI losses |
| Efficient | It can operate or control small motors | Can operate or protect up to 700V traction motor |
| Temperature | Operating temperature can reach 120 degree with increase, which can result in failure. | Operating temperature can reach 150 degree with increase of 25k |

## 2.8 On-Board Transformer and Power Electronics Converters

With highlights of the various component of AC electric locomotive as illustrated using Figure 2.10, it is now important to do a detailed study of the main equipment of various power conversion process concerning the power flow concept in the locomotive. Firstly, the main component encountered is the on-board transformer. Power transformer in locomotive play crucial role in the power conversion from AC-AC by stepping down the power to the desired voltage of 400 V before it is fed to the power electronics converter systems.

After the on-board transformer, the next equipment is the power electronics converters. Generally, power electronics converters are the application of the solid-state technology or semiconductor devices to perform the actions of convert, process, and regulate the electric power flow in terms of voltage and current from one level to another. Generally, the main concepts of power electronics involve power semiconductor switching devices. The concept of power electronics is known to revolve around semiconductor devices and circuits and its applications can be found in the generation, transmission, distribution, and utilization of various forms of electric power in static as well as in the operation of the rotating electric machinery. In the development of electric railways, one must mention the development of power electronic technologies. The replacement of rotary converter and mercury rectifier with diode rectifier to generate DC power was epoch-making for the operation and maintenance of DC traction substations [36].

The processing or converting of electric power is achieved through a power electronics converter, also known as power converters or switching converters. The power converters change one form of electric power into some other form with the use of a power semiconductor device. The devices are used in various converter configurations such as the phase-controlled converters, front-end rectifiers, DC-to-DC converter, voltage or current source inverters and AC-to-AC Converters, AC-to-DC as well as the DC-to-AC converter. The majority of power electronics application deals with conversion and controlling of various levels of electric power from medium to high voltage application. This means the converter and controller are the two major components for the power process unit. For the locomotive, the converter system is regarded as the medium voltage level, the fundamental operation of the power electronics converter is for processing, and controlling the electric energy by making such the required voltage and current level suitable for various traction drive applications are supplied. The power controllers are the ones that are responsible for producing control signals relative to turning on or off the switching devices present within the circuit of the switch. Figure 2.13; indicate the various block diagram, which is used to describe the configuration for a typical AC locomotive system. As explained earlier, the upgrade of the locomotives was prompted by the advancement of power electronics devices, which in this case was the IGBT. For traction motor operation for the electric locomotives, the control is brought about by the implementation of power semiconductor switching devices such as thyristors, transistors, gate turn-off thyristors (GTOs), and insulated gate bipolar transistors (IGBTs). Also, the evolution of power converters in chopper and PWM inverter technologies have contributed to the high performance, reduced maintenance, energy saving, and downsizing [36].

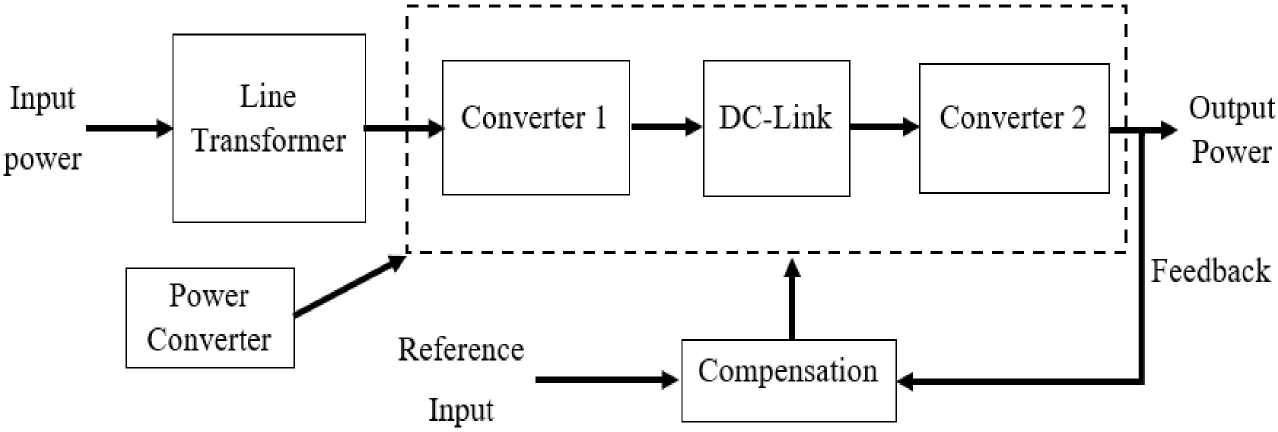
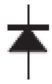
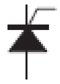
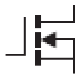



Figure 2.13: The block diagram of a typical power electronic system

The power semi-conductor devices and their symbols are shown in Table 2.3

Table 2.3: Semiconductor switches and symbols [12]

| | |
|---|---|
| Diode |  |
| Thyristor |  |
| MOSFET |  |
| GTO |  |
| IGCT |  |
| IGBT |  |

## 2.9 The Power Processor Unit

Generally, power supplies represent one of the major applications of power electronics switches, which also finds its usefulness in electric locomotives. The power conversion stages using the power electronics switches is normally referred to as the power processor unit or simply the converter system. As shown in Figure 2.14 is a generic power converter topology that was used to illustrate the power conversion processes in the AC electric locomotive system. Thus, as presented and discussed in this section is the generic converter topologies that are used in the AC electric locomotive power processor systems. The actual semiconductor devices that are used which will be presented later are the GTO thyristor and the IGBT converter topologies.

. This converter system is usually made up of the semiconductor devices which are in the form of transistors, thyristors, IGBTs, diodes, MOSFETs, IGCTs, that are used to carry out the process such as switching mode and uninterruptible power supplies.

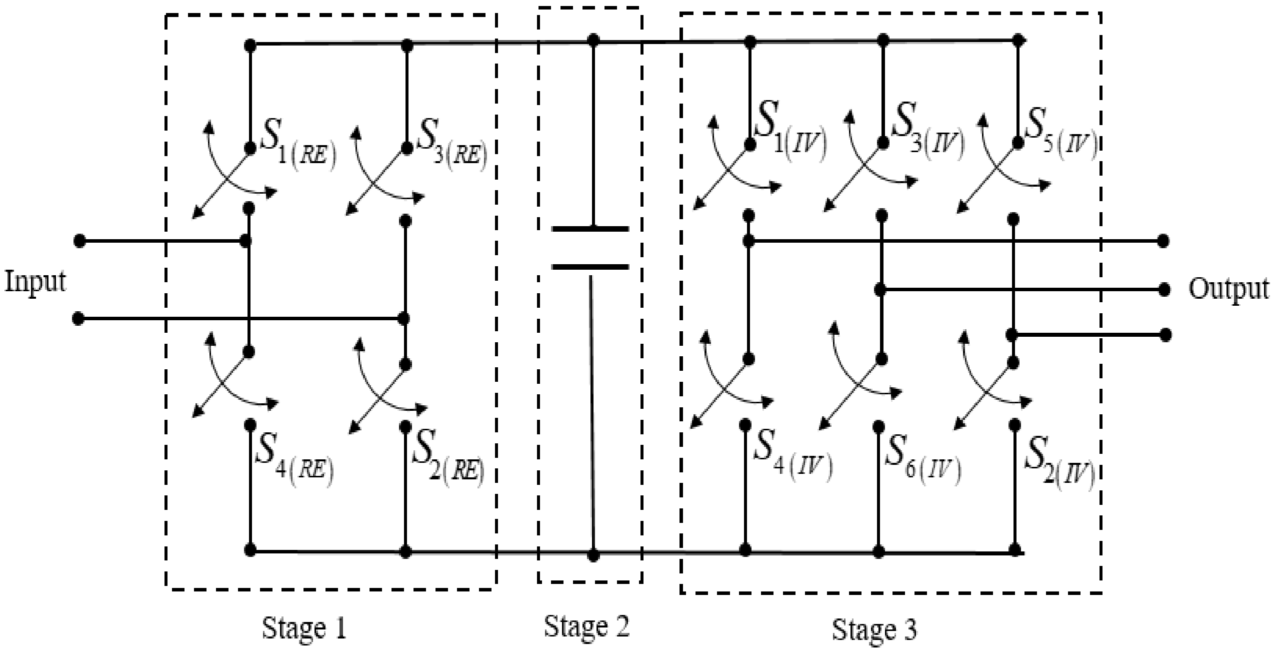



Figure 2.14: The various stages of the power processor

In Figure 2.14, shows the power processor unit and the power processor unit which comprises of three stages. These stages are:

- Stage I (Rectification) where a rectifier is used to converts the input AC supply to the outputs the DC voltage
- Stage II (Intermediate circuit) where a DC link is used for smoothing the DC output from the rectifier
- Stage III (Inversion) where the inverter is used to converts the DC voltage to an AC output via a high frequency switching and then delivers the inverted power to the AC motor

Power electronics converters is one of the main technologies that is used to achieve energy conversion with high efficiency in the locomotives, it has been ascertain that depending on the devices, above 80 % of electric energy supplied can be converted by power electronics devices before it reaches the traction motors [37, 38]. Recently, the power electronics has become a fundamental technology critical for the development of energy conservation, switching and protection especially in the case of locomotive regenerative braking. The multi-level H-bridge converters is based on a series connection of three-phase traction converters, this converter topology has several advantages that made it useful for both medium and high power drive for railway locomotive applications [29].

The AC locomotive traction electrical system mostly consists of the front-end on-transformer (FET) which is made up of multiple secondary windings, the front-end rectifier converters, DC link, the traction inverter and traction motors. The detailed explanation of each of the subsystem for the AC locomotive traction systems are presented in the following subsections.

### *2.9.1 The Rectifier System*

The rectifier system which is also known as the AC-DC converter system is used to convert the step-down AC voltage form the transformer to the DC output. Generally, for the AC locomotive systems, the rectifier application as voltage source rectifier topologies can be one of the following:

- The two-level 4Q rectifier
- The three-level 4Q rectifier
- The series connected multilevel rectifier
- The interleaved two-level rectifier

Using the IGBT three-level neutral point clamped (NPC) configuration, the output voltage has approximately the voltage that doubles the DC link voltage for a given power switch voltage rating on the locomotive. This feature has made it possible to apply 3.3-kV IGBTs in NPC inverters as compared with the 3-kV DC link voltage permitting a direct replacement of two-level GTO [30]. Based on the investigation as documented in [39], using the same principle of pulse width modulation (PWM) controlled for the IGBTs which have the potential to replace GTO thyristor since the IGBT switches allow substantial cost savings, less operated circuit and less prone to the reverse current. The investigation as documented in [27], the research simplifies the topology for the multi-system of the IGBTs configuration in a form of a chopperless multi-system converter, which is already a state of the art for both the 7500 V and 1500 V of AC-to-DC converter. The European locomotive class 189 is the first locomotive with a chopperless multi-system converter including DC 3000V which is also used by some locomotives in South Africa [31, 40]. The following are advantages of the IGBT for locomotives, on the based that it possesses snubberless:

- For reduced line harmonics
- For better power factor correction (at nearly at unity)
- For substantially smaller filters being used

- To achieve a higher system efficiency
- It has thicker silicon which reduces the tendency to snap

The information in [7] was used to compare the IGBT with the GTO thyristor and also explain why there was the replacement of the GTO thyristor, it is very important to understand some fundamental differences in their respective ratings, parameters and their basic application for the design purpose in the locomotive. Investigation of [41], demonstrate the comparison on the bases of voltage ratings which is relatively straight forward as both breakdown point or rated voltage with DC link voltage at steady state of IGBT devices. It also very essential to consider fault operation of the new design using the IGBT as compared to the replaced GTO thyristor, however, more maintenance is required which must be taken into consideration when comparing current, voltage and frequency ratings for the GTO [32]. The GTO thyristors are usually rated for maximum controllable anode current, i.e. the maximum current that may by commutated by gate controller [2]. Whereas, IGBTs will be or is rated for a nominal DC collector current which is based upon the maximum permissible heat dissipation at a given temperature [16, 31]. The IGBT can control twice its rated collector current and often more in locomotive applications with both turn-on and turn-off snubberless, considering the thermal properties of the device [2, 42]. The Table 2.4, tabulate the values for the calculation for the two-way converters and also provided in the same table are the values of the power at temperature ranges of 16 – 25 °C. The current is being calculated using ohms' laws. The following formula was used to calculate the power for the traction converter:

$$P = \frac{V^2}{R/T} \tag{2.1}$$

Where $V$ is the voltage (V), $R$ is the resistance per unit (Ω), T is the temperature (K)

Table 2.4: Configuration calculations

| **Temperature at °$C$** | **Resistance (Ω)** | **Current (A)** | **Rated Power at (W)** |
|---|---|---|---|
| 16 | 4.9448 | 768,5 | 1536 |
| 17 | 4.94535 | 768.4 | 1536 |
| 18 | 4.9459 | 768.3 | 1536 |
| 19 | 4.94645 | 768.2 | 1536 |
| 20 | 4.947 | 768.1 | 1536 |
| 21 | 4.9477 | 768 | 1536 |
| 22 | 4.9481 | 767 | 1535 |
| 23 | 4.94865 | 767.9 | 1535 |
| 24 | 4.9492 | 767.8 | 1535 |
| 25 | 4.94975 | 767.7 | 1535 |

### *2.9.2 The DC Link*

As shown in Figure 2.14, is stage 2, which is the intermediate circuit (DC bus or DC-Link) as found in the power processor. The DC bus or DC link is normally used as the bridging (intermediate) circuit between converters system of different kinds, it is used to couples the different converter system to one DC voltage level. Thus, the DC link circuit is mainly used in power processor system as the intermediary circuit to couple between the input source to the output load that operate at different instantaneous power, voltages, and frequencies. They also help as filters which can protect the subsystems from voltage spikes, surges, and electromagnetic interference (EMI). The DC bus is usually comprised of capacitors, inductors, or a combination of both, due to the fact that it possesses high capacitance and its ability to supply power very quickly. The intermediate circuit provide constant DC voltage value that can be realized even if a high current peak are generated by the system.

The configuration of the drive with a DC link varies depending upon the power rating of the drive. For medium voltages, the DC link mainly have inductor and capacitor and this is applicable to the AC electric locomotive.  The DC link for the locomotive converter system, the DC-link is used to feed energy from the rectifier where the AC voltage is converted into a DC voltage i.e., intermediate circuit voltage. This energy from the DC link is converted into an AC voltage with variable frequency by means of a pulse inverter which is used to operate or drive the AC motor. Since the pulse inverter also acts as H-bridge, the energy flow can also be in bidirectional power flow which means the power can flow both ways through an inverter, such that the regenerative power can flows back along the DC link.

For regenerative braking, which occurs during braking or slowing down of the motors can add the energy recovered to the DC bus, and other motors/drives can use this recovered energy, if they share a common bus. For the motor applications, a variable frequency drive controls the motor by supplying it with energy, which then powers the load. However, sometimes, the energy flow will be in reverse, that is, from the load, through the motor, back to the drive. This will occur if the load is giving up energy, during slowing of the load. The phenomenon of regeneration will take place as the high inertia load is decelerated where the energy stored in the rotating mass flows back into the grid as the motor is operating as a generator.

In the aspect of controls, an optimized DC-link control strategy was proposed in [1] which was acclaimed to be able to minimize the losses in the DC-to-DC converter and in the traction inverter without limiting the motor control dynamic performance. This can be implemented if the DC-link voltage is properly in line during driving, in order to minimize the losses in the two coupled converters. Although this proposed adaptive DC-link control was designed for electric vehicle equipped with a 6-phase motor drive with the advantage that the developed DC-to-DC control does not depend on the type, ratings, or number of phases of the electrical machine and this configuration will have good prospect in the application for the locomotive power converter systems.

The DC-link inverter side oscillations caused by output currents from DC-link was investigated in [2], in which the impact of balanced and unbalanced sags on adjustable speed drives (ASD) operations in term of DC-link voltage drop and AC current peaks was analysed. From this investigation it is evident that applying the discontinuous pulse width modulation two (DPWM) strategy can give rise to a higher amplitude DC-link current oscillations at low frequencies as compared with those of the space vector modulation (SVM) technique. This issue may affect the adjustable speed drive's (ASD's) input current interharmonic amplitudes, when implementing the SVM and DPWM techniques on the inverter. Thus, the problems associated with the interharmonic distortions are the light flicker, the sideband torques on the electrical machines shaft, interference with protection signals, dormant resonance excitations.

### *2.9.3 The Inverter System*

In this subsection, the three-phase inverter system for the electric locomotive is analysed. As shown in Figure 3.15, is the third stage of the power processor, which is known as the inverter. The inverter can be voltage source inverter (VSI) or current source inverter (CSI). For the locomotive, the VSI is applicable. Generally, the inverter is to convert the output DC voltage and current from the DC link to the AC voltages and currents required to operate the AC machines. For the traction AC machines, the AC waveforms supplied by the inverter to the machine require variable voltages, and frequency in order to optimally drive the machines. The DC output from the DC bus serves as the input for the DC-AC converter system, with proper switching, the inverter can produce the desired frequency needed to operate the AC motor, from the DC supply. For the AC locomotive, the traction inverter is the DC-AC converter system that is used to generate a stable AC voltage, which is used to drive the 3-phase AC motor.

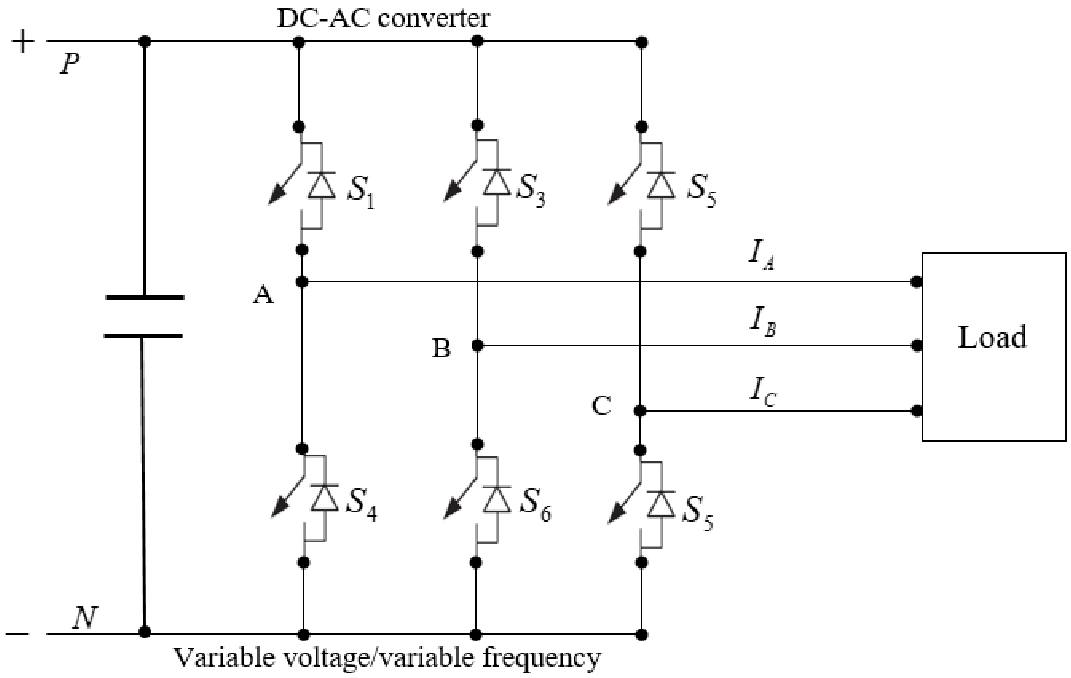



Figure 2.15: The locomotive voltage source inverter

From the diagram which is shown in Figure 2.15 is the inverter that consists of the power electronics switches, which is connected to the supply power from the DC source such as the batteries or DC bus, and it then serves as the voltage source inverter (VSI) which that operates the induction motor. The inverter needs to supply power to the AC motor with a specific frequency in order for it to rotate at the desired speed. In order to operate the AC motor, it needs a power source that has variable frequency which can adjusted into any frequency the motor desires. The VSI for operating the three-phase traction drives normally consists of three legs, each per phase. Sown in Figure 2.15 is the VSI in which each phase of the three-level neutral point of the inverter is formed by six switching devices ($S_1$ to $S_6$) which in the case for this study, can be either the GTO thyristor or the IGBT.

For the operation of the VSI, in order to increase the power handily capacity, with the stability is to reduce the harmonics at the input line side. Also, to achieve a unit power factor, a number of converters can be connected in parallel, possibly in a cascade configuration. Generally, for the application of the converters, these converter systems are usually controlled by the PWM technique. There are various PMW techniques that can be used to control the VSI. The PWM control, is a high speed pulse generating devices which is used to control the operation of the gate of switches such as the GTO thyristor or IGBT. Thus, this can be used to obtain a unit power factor by controlling the converter output voltage.

For the supply of power to the AC motor by the inverter, the inverter is used to convert the fixed-voltage, fixed-frequency supply from the DC link to variable-voltage, variable-frequency (VVVF). This process can be achieved by controlling the supply either to the stator or to the rotor. To achieve this, the inverter usually operates at the desire voltage and with high switching frequency in order to generate PMW for the Motors. Also, the inverter provides protections for under voltage, over voltage, overloads, short circuit, reverse polarity, over temperature for the locomotives.

## 2.10 The Traction Drive System

The traction drive system as shown in Figure 2.16 is used to produce the mechanical power which rotate the axle and then produce the propulsion of the locomotive. For the AC locomotive, the traction motor is normally either the induction motor or the permanent magnet induction motors (PSIM). There are different kinds of traction motors available for industrial applications these todays, for the locomotive traction system, the induction motor is preferred. This is because the induction motor construction is simple, ruggedness, light in weight, relatively small volume, low operation and maintenance cost [43].

For the locomotive application, the induction motor has the following advantages:

- A relatively longer life span
- It has simple and flexible electric drive control system
- It has a high fault tolerance capacity in the protection circuit
- It has a very low level of acoustic noise
- The motor has a better starting torque
- It has a high efficiency
- The connection normally requires less cables and low current is usually drawn
- It has a relatively high power density
- Its operation requires constant torque and constant power over a wide range of speed
- It has a quick torque response and high reliability at different operating conditions and offers a continuous power supply

The following factors should be considered for the application of traction motor and motor control technique for the locomotive:

- The maximum capabilities of speed-torque characteristics of the motor, also, the range of system voltage, current, frequency, power and load levels

- The number and arrangement of traction motor drives used either to control the single or the multiple speed transmission and its configuration
- The capacity and type of electrical energy storage devices for the traction motor
- The maximum energy and power capabilities and power protection system the power processor system offer to the traction motor.

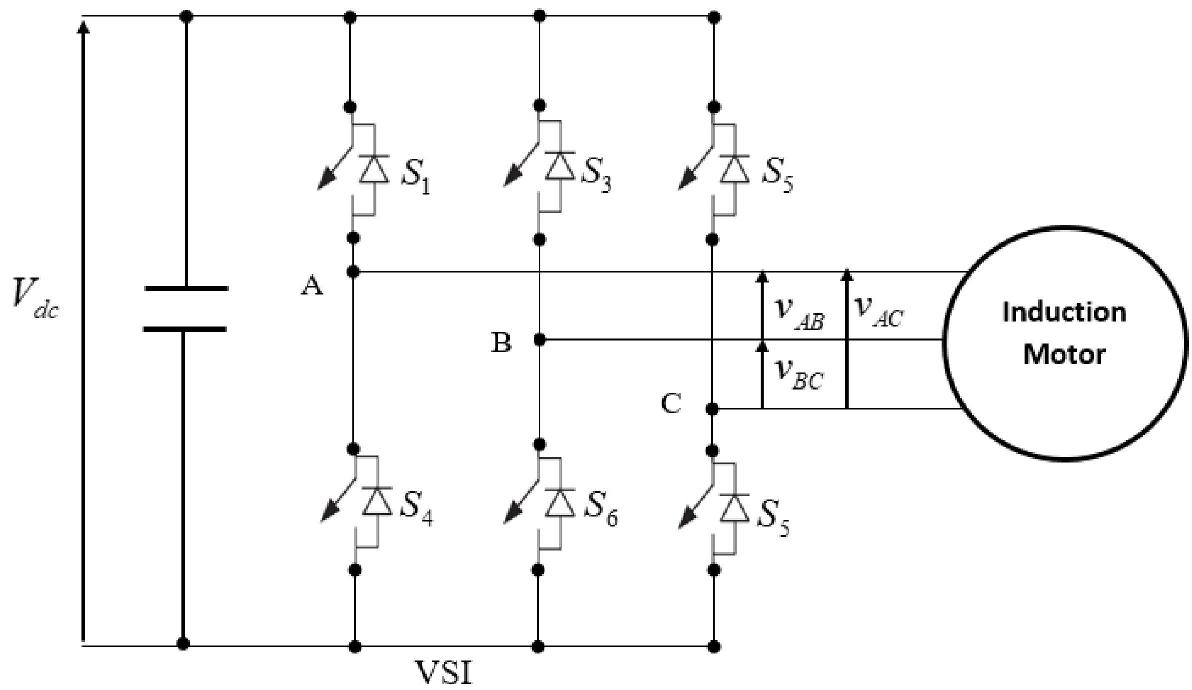



Figure 2.16: The diagram illustrating the traction drive

## 2.11 Protection of Electric Locomotive

The locomotive power converter protection is achieved by the means of the voltage sensors and the brake resistors. The voltage sensors measure voltage on converter DC link, if the voltage exceed 3800V DC than the power will be shunted to the brake resistors. Then this power will be dissipated as heat, this heat is liberated into the atmosphere using the brake resistor blowers. In a situation where the heat is more than the maximum, temperature of 30°C, to protect the converter system, the traction converter through the IGBT will send a signal through PWM system to open and separate the contactor so that vacuum circuit breaker (VCB) will open and disconnect the power in the locomotive. The maximum voltage through the voltage sensors that is allowable is 4000V. For the locomotive protection, explained in, reference [44] was able to provide the methods and tools to prove the concept as developed in [45], in which the input capacitor is charged with the DC test voltage and the measurement of this current is by the Device Under Test (DUT) that is switched on using a defined pattern until the test current in the load is reached. The desired switching conditions (turn-on and turn-off) are reached. DUT is used to simulate, by emulating the real scenario of the working environment of the traction application which in real locomotive, it depends on the inductor value.

The required test voltage and current on the pulse test duration can last from several tens to several hundred micro sec to prove it can eliminate any transient occurring on the IGBT [44]. The current can be calculated using:

$$I_c = \frac{\left(T_{j\max} - T_c\right)}{V_{ce} * R_{th}\left(T_{j\max} - T_c\right)} \tag{2.2}$$

Where Rth is the junction thermal resistance of the IGBT, Vce sat is collector emitter saturation voltage at Ic for the operating condition, Tjmax is the maximum temperature.

If the values of $R_{th}$ = 8 Ω, $V_{ce}$ = 3 V, Tjmax = 150° and Tc = 5°, Therefore, the value of the current is

Ic = 0.0417 A

The maximum isolation voltage can be determined for all the 8 modules terminals and the insulated base plate of the IGBT for better protection of traction converter of the locomotive [20, 46]. The isolation voltage can be evaluated using:

$$V_{isol} = \frac{2V_{ces}}{\sqrt{2}} + 1000 \tag{2.3}$$

If Vces is 3300 V tested at Vge = 0

$$V_{isol} = \frac{2 \times 3300}{\sqrt{2}} + 1000 = 5666.905\,V$$

It is noted that each module of the IGBT carry the characteristic of high isolating voltage rated at 4.3 kV when the line system is operated at 3 kV DC [31], such that there is no peak to peak current which can result to the damage of the entire IGBT modules [47]. It is very crucial to also determine the internal resistance, this internal resistance of the IGBT switch is measured between collector-emitter terminals [11]. The collector-emitter voltage is measured at the busbar level that is connected to the IGBT collector. Therefore, the voltage values that are needed to operate the IGBT switch is defined and calculated using equation (2.4) [8]:

$$V_{ce}(busbar) = V_{ce}(sat) + R\text{int} * I_c \quad (2.4)$$

$$V_{ce}\left(basbar\right) = 3300 + 9 \times 0.04167$$

= 3.3 MV

Hence, it can be established that high internal resistance can be used to withstand all transient conditions during the operation of the locomotive both for the switching and the control phase [48]. The following formula can be used to determine the maximum power that is dissipated on the IGBT during the control and protection of the locomotive under 3300V DC only [46].

$$P_{\max} = \frac{\left(T_{j\max} - T_c\right)}{R_{th}(j - T_c)} \quad (2.5)$$

If T*jmax* is 150°, Tc is 25°, and Rth is 8 Ω, thus Pmax is 0.125 W;

It should be noted that this is the maximum power the IGBT can withstand during switching and controlling of the converter, therefore, this value had proven to be a reduction of total losses in the IGBT without sacrificing the above mentioned performance advantages [37, 49]. This was recently achieved for the 3300V DC employing the new Enhanced-planar IGBT technology for the cell design [46]. This new technology provides more than 25% reduction in on-state voltage drop for the same turn off losses on the IGBT. These losses can be evaluated by the integration of the collector-emitter voltage and the collector current. The turn-on energy loss per pulse is defined as Eon, which can be calculated by

$$E_{on} = \int_{to}^{t1} \left(I_c\left(t\right) X V_{ce}\left(t\right)\right) dt \quad (2.6)$$

The turn-off energy loss per pulse of the IGBT is defined as $E_{off}$, this loss is the integration of the collector-emitter voltage and the collector current. This turn-off energy loss per pulse of the IGBT is evaluated by:

$$E_{off} = \int_{to}^{t1} \left(I_c\left(t\right) X V_{ce}\left(t\right)\right) dt \quad (2.7)$$

Higher rating voltage of the IGBT must have a lower tum-off current density capability for protection purpose during the locomotive operation, because the hole injection from p collector layer is needed at higher voltage of IGBT operation in order to reduce voltage drop in thick n-drift layer [8, 31].

The gate resistors can be variably controlled so that an improvement of IGBT for the turn on can be achieved, accomplishing this, the switching losses can be reduced and this enhances the locomotive protection and control. Adoption of high switching at low losses is achieved as per investigation done for the purposed as intended for the high power application of IGBT for locomotive [8, 42, 50]. By considering the IGBT turn off when the throttle of the locomotive is switching from motoring to regeneration, the fault condition that can happen and or generated can be five times or more than the rated capacitor values [26]. Trying to shutting off the high current transient in the IGBT can produce extremely high dangerous rate of change of current (di/dt) which can be potentially detrimental to the IGBT [32]. The decoupling capacitor in the IGBT circuit seem to provide the solution in order for the protection of IGBT itself and the locomotive control circuit [16]. As the IGBT is turned off, the energy is trapped in the stray DC loop and this energy is forced to be transferred to the capacitor in parralel so that the diode can block off any oscillations from occurring in order for charges on the capacitor to discharge through the snubber resistor which are in series with high resistance [51].

The blocking diodes can increase the overall snubber inductance, thus, the low inductance snubber is not needed in the application of the locomotive as this can produce an increase in Vce to overshoot, but normally the Vce must always be kept at zero. In the worse case if Vce = 80 V which can not trigger any IGBT gate to switch on or off [50]. Switching at a high magnitude of currents in a short duration of time, giving rise to potentially destructive voltage transients in the control circuit of locomotive at low voltage cubicle, the higher current converter normally consist of several IGBT chips in parallel [31, 52]. Each individual chip switches its share of three traction motor (TM) and the rate of current di/dt is determined by the gate drive circuit connected to low voltage side of the locomotive. The total current and di/dt seen by the external power circuit is the sum of currents and di/dt through each IGBT chip. The di/dts produced could easily be a few thousand A/us [53].

It is pertinent that proper attention is needed with the aim to protect the locomotive devices from destructive content, it is determined that the snubbers offer optimized protection against voltage transients during the normal turn-on and turn-off switching of the IGBT which controls the locomotive propulsion [49, 50]. Employing such protection circuits allow faster and safer operation with the goal of containing the operating of the switch within the boundaries of the rated safe operating area.  The IGBT circuits reduce external harmonics by its operation  in the converter system, they consequently improve the power factor to unity as a means of improving the real power [7, 14]. For proper operation of the rectifier in the locomotive, the PWM pattern must generate a fundamental frequency in the locomotive control unit which should be approximately equal to the frequency of the power source, this concept was later explored during the computer simulation of the locomotive.

## 2.12 Methods use in Locomotive Protection

The use of power electronic converter can offer protection to the locomotives. The method in which this protection is offered to the locomotive is by means of the PWM and IGBT and by decoupling method.

### *2.12.1 Protection by means of PWM and IGBT*

As discussed previously is the protection concept of the power electronic converter offers for the operation of the AC locomotive. The method by which the protection can be offered is by means of the PWM and IGBT. The IGBT switch can be used to achieve a better tractive effort independent of the variations of loads and for better availability of power to the locomotive in cases of the inverter or the motor failures.

The used of IGBT devices in the traction inverters can achieve the following [45, 27]:

- A higher traction converter efficiency
- Simple locomotive gate drive cards control for the IGBTs
- Help to protect the locomotive against various short circuit conditions.

Physically, in the locomotive, various current, voltage and temperature sensors are used for monitoring and protection of both inverter and AC motor during the locomotive propulsion. For the protection, the use of PWM fundamental component are maximize and reduce, this lower the order of harmonics in the system so that filter size will be reduced in the IGBT [54]. PWM is an inherent control technique within the inverter, which is used to control and implement the VVVF and the PWM based control inverter is very suitable for the control of the voltage of the AC induction motor. By using PWM Methods, the control of inverter is achieved with the help of DSP processor, the PWM also reduces the harmonic content thereby reducing power loss and hence efficiency of system is being increased on traction motor [49, 55]. For the gate signals for the 3-phase, 4-leg, IGBT inverter converter type is usually operated using the digital logic, which reduces the implementation time.

The new converter systems are now equipped within the module, the protection and the control of the IGBT, instead of DC fuses, these helps the semiconductor switches to disconnect immediately the rectifier from the DC link in case of an inverter failure to protect the locomotive traction drive [41, 56]. The reaction of this switch to fault is so fast in milliseconds, that the line current does not rise more than some percent above the normal level of operation. During failure, the energy from the DC-link capacitor is fed into the failed inverter, no additional energy from the line goes to the failed device, and thus, any mechanical destruction is then avoided in the AC induction motors.

The pre-set protection voltage of the inverter is 4 kV, the voltage across the inverter is rated at 3040 V DC and the peak voltage is 3600V which implies that at the maximum point of peak voltage the IGBT and the control circuit of the locomotive is protected [20, 27]. Investigation of [14] in traction inverter drives/brakes, in this configuration, each motor can be controlled independently so that locomotive can continues with the propulsion even in the absent of one motor. Digital Signal Processor is used for instigating vector motor control using Space vector PWM to carry out the VVVF control of each traction motor in both the motoring and the dynamic/regenerative braking [27].

### *2.12.2 Decoupling Method*

The second method of protecting the locomotive is by the use of the decoupling method. To protect the locomotive using the decoupling method, at the line side of the rectifier, no fuses are needed as long as the transformer impedance is high enough to the tap of the converter topology. In the case of the diode failure, which has a low probability, the locomotive MV breaker with its overcurrent protection acts fast enough to protect the rectifier from transient destruction, also the fast switching transistor act to separate the protection circuit of the locomotive [14, 26, 56]. Investigations carried as documented in [13, 42] on the fault detection on the locomotive in the medium voltage was more carried to observe the concept of redundancy, which is a measure of the available power after a fault is detected on the locomotive during propulsion. Also, what is needed to be considered are, how the systems handle the faults at the time they occur, the highest level of fault tolerance, and the operation of locomotive can continue its operations without interruptions regardless of the fault that occurs within the electrical system. For partially redundant systems, the 500 faulty per minute system is implemented which is self-diagnoses processes to ascertain whether the locomotive has the capacity to run at normal capacity or else the propulsion of locomotive will automatically then be operated at lower capacity, or at the limp mode for the protection purpose. A slightly lower level of fault tolerance can be identified in cases where interruption is allowed for a short period after the occurrence of fault in the traction converter [57]. For a longer fault condition, the automatic protection system will shut down the application of locomotive and possibly disconnect the faulty system within the entire locomotive, before the remaining systems can be made to start again, it doubles the check safety of the system through the IGBT.

# Chapter 3

# Analytical Modelling and Design

## 3.1 General Overview

As explained in Chapter one, in which the scopes of this study were defined concerning the operations of the power electronics converters, housed inside the AC electric locomotives. As shown in Figure 3.1, it can be deduced that, using the direction of the power flow, it can be ascertained how the power that is supplied from the catenary is transferred/transformed by various components in the locomotive before been utilized by the traction induction motors to produced propulsion at the wheels. In addition, as shown in this diagram, the power electronics converters do not operate in isolation but part of the entire electrical system of the locomotive. Therefore, it is imperative that in order to model and analyses the power electronics converters system, the complete system has to be modelled with regards to the power flow but the analysis will be focused on the power electronics converters systems, which will be in line with the scope of this study. This Chapter was use to explain the various models that were used for the modeling and implementation of the numerical simulation of the power processor components of the electric locomotive. The modelling and analysis of the various models of the electric locomotives was done in a chronological order starting from the AC source/filters (the catenary side connected filter) model, the single-phase multi-winding transformer model, the power electronics converters models and finally the traction motors model.

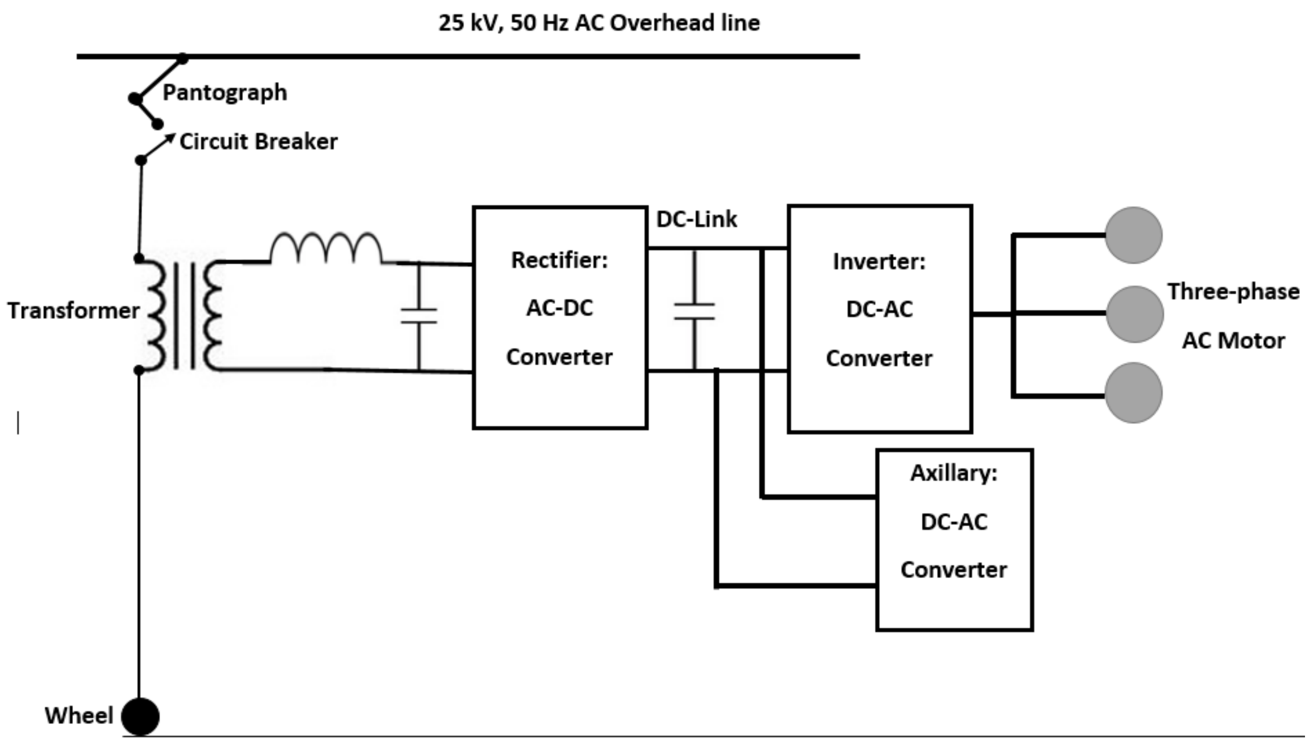



Figure 3.1: The Block diagram of various aspect of the AC electric locomotive

## 3.2 The AC Source and the Locomotive Transformer Model

The AC electrified railway systems are designed in such a way that the electricity network directly supplies the electric locomotives power through the pantographs or conducting shoes as already discussed in Chapter 2. For the electric AC locomotive used in South Africa, the power supply to the trains is by the single-phase 25 kV AC at 50 Hz. The main advantage of the 50 Hz is the simplicity of the traction feeder substations to get power from the public three-phase grid, and the ability of the transformer to step the voltage down from 132 kV to 25 kV at 50 Hz. This voltage is then supplied to the catenary lines.

In the modeling of the locomotive system, the catenary line is regarded as the AC voltage source for the system. As shown in Figure 3.1, the power is supplied, is fed to the transformer in the electrical locomotives, place between is the vacuum circuit breaker (VCB). Thus, with the power supplied to the locomotive from the catenary, the next component that is involved in the power transformation is the transformer. The function of the transformer is to transfer electric power from the catenary to the power electronic converter systems by lowering the network's medium voltage to a lower voltage level for use by the converters. This on-board transformer should possess the characteristics of been compact in size, lighter in weight, and

reliable in operation, as they are often a non-redundant traction component. The transformer is used to step down the voltage from the 25 kV AC to 400 V.
The model used for this the single-phase on-board transformer is as shown in Figure 3.2, which is the multi-winding transformer, which has both core and winding losses in the primary side. The multi-winding power transformers comes with a phase-shifting secondary windings which makes this form of transformers to have a complex design. The fact is that in this type of transformer, the secondary winding is split into multiple outputs and consists of isolated coils, the number of the winding depends on the number of converters connected, which in this case for the multi-winding on-board transformer used for this study is three.

The multi-winding transformer is an important component for connecting the multi-level voltage rectifier in a cascade connected converter circuit, shown later in Figure 3.6. This transformer for the front-end rectifier performs the following functions:

- Converts single-phase mains high voltage of 25 kV from the catenary into single-phase low voltage of 400V to each rectifier
- Provides isolation between the power grid and the converter
- Due to the phase shift of the secondary windings, provides a high quality of power consumption from the catenary line

The single phase, multi-winding transformer (single primary side and multiple secondary side) component models, the three coupled windings of the secondary side are on the same core. The magnetization inductance, *Lm* of the coil winding can be regarded as linear or with saturation and the is modelled on the primary side of the multi-winding transformer.

As shown in the diagram, as located on the primary side of the multi-winding transformer is the resistance *Rm* and the reactance, *Xm* which represent the core (Ohmic) losses and magnetizing reactance respectively.

As shown in Figure 3.2, consider the four winding transformer on a common magnetic core with $N_1$ as the primary turns and $N_2$, $N_3$ and $N_4$ as the secondary turns. For this transformer, the voltage scale as function of its turn's ratios is:

$$\frac{V_1}{N_1} = \frac{V_2}{N_2} = \frac{V_3}{N_3} = \frac{V_4}{N_4} \tag{3.1}$$

If the magnetic core is assumed to be infinity, hence, the following equation holds:

$$N_1 i_1 = N_2 i_2 = N_3 i_3 = N_4 i_4 = 0 \tag{3.2}$$

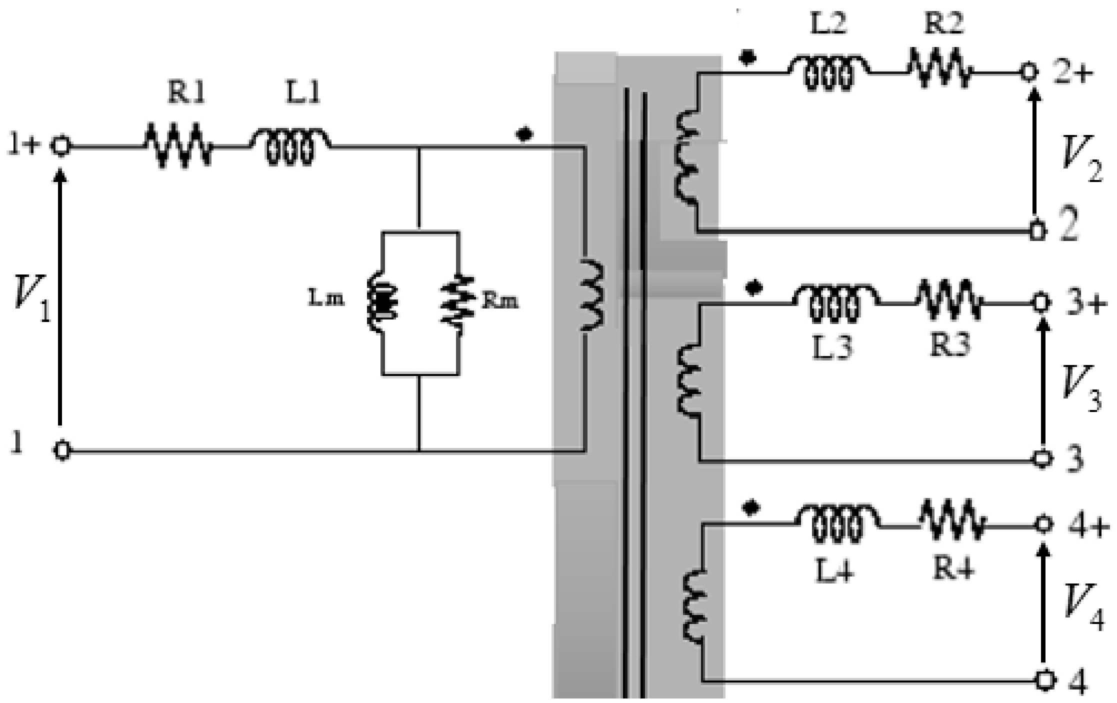



Figure 3.2: The diagram of multi-winding Transformer

## 3.3 Catenary-Side Connected Filter Model

In last section where the modelling of the on-board locomotive transformer was done with respect to the AC source and circuit breaker. From the railway catenary, there is the grid side filter that is placed before (optional) the end-front rectifier as shown in Figure 3.3. It is important to highlight that the function of this filter is to minimize the injection of the current and voltage harmonics generated by the switching of the traction converter into the catenary line. On the bases that, the different characteristics of the traction converters application, parameters such as voltage level, the current ratings, switching frequency, thus, and several filter topologies can be found in literature. For this study, the type of filter that was used to model the filter place on the grid side is the LC filter.

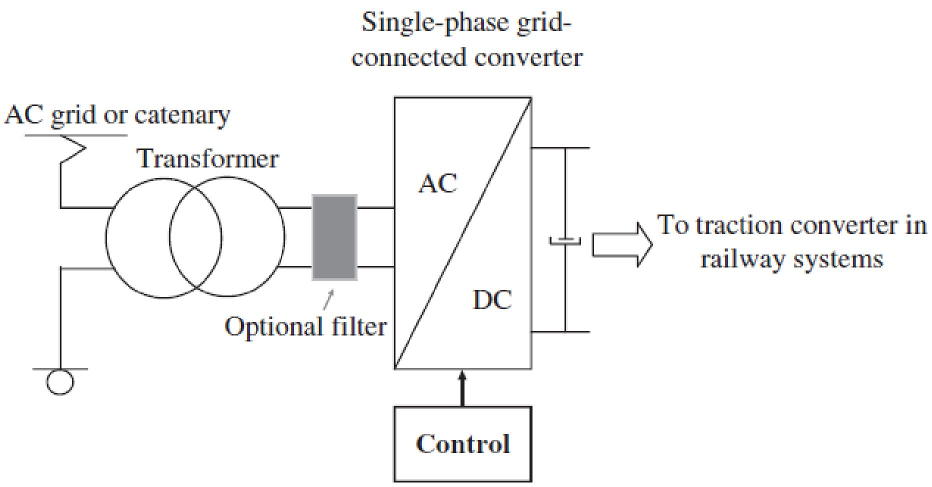


Figure 3.3: The grid connected LC filter [12]

The LC input filter's play crucial role in railway network and trains in terms of preventing harmonics from being injected into the grid. Thus, they are used to prevent the high frequency harmonics that are generated by the VSI switching and also this filter can also be used to provide certain inductive behaviour between the rectifier converter and the catenary.

For the locomotive power electronic applications, there are harmonics current that are being injected into the catenary lines as a results of the switching behaviour of the traction drive inverters and this phenomenon need to be avoided from occurring in order to avoid any line interference with signals operating in the railway infrastructure [12]. For the LC filter type, the capacitor component is used to absorb high frequency harmonic currents, which means only the low harmonic current can be injected into the medium voltage or the catenary line.

The first step in selecting the LC filter is to determine the parameters with regards to the main traction rectifier. This is because this rectifier normally injects the low frequency voltage ripple onto the catenary network. The AC electric locomotive power processor system are composed of either the 6-pulse or 12-pulse rectifier. The 6-pulse rectifier has a simple configuration but the primary line current generate numerous harmonics that includes 5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th, etc [12]. Normally the dominant harmonic is the 5th and it is usually the largest harmonic component, the next is the 7th harmonic. For this type of rectifier, the total harmonic distortion (THD) for the input current is usually vary between 35 and 100%. For the 12-pulse rectifiers, the THD normally varies between 10 and 20%. A 12-pulse rectifier system can be obtained by combining two 6-pulse rectifiers and connecting them in series for the purpose of achieving a less current distortion. For the 12-pulse rectifier configuration, each 6-pulse rectifier is used to generates one-half of the DC-link voltage and the voltage can be evaluated using equation (3.3).

$$V_{dc} = \frac{3\sqrt{3}\sqrt{2}V_{rms}}{\pi} \tag{3.3}$$

With regards to this filter, the next step is to determine the cut-off frequency of the LC filter. This cut-off frequency is normally selected close to the supply frequency or harmonic, i.e. 50Hz. This cut-off frequency can be calculated for by using:

$$f_{cut-off} = \frac{1}{2\pi,\sqrt{L.C}} \tag{3.4}$$

In order to determine the desired ripple current on the inductor and the required ripple voltage for the filter capacitor, thus, the following two equations are used to evaluate the current and the voltage ripple for the 6-pulse rectifier at fundamental frequency.

$$\Delta i_L = \frac{V_{\max}}{L.\omega} 18.07e - 3 \tag{3.5}$$

$$\Delta V_c = \frac{\Delta i_L}{C.100\pi.6} \tag{3.6}$$

Normally, the current ripple is selected to be around 10% of the nominal current, and the voltage ripple around 1% of the DC-link nominal voltage. To determine these values, an iterative process is normally employed to evaluate the values of L and C that comply with the impedance and ripple limitations of the locomotive. The grid sinusoidal voltages are usually generated at constant amplitude and frequency on the railway line side, thus, to model the filter model for the single-phase line, the currents between the grid and converter are calculated using the following equations.

The traction grid voltage:

$$V_f = R_F.i_g + L_F.\frac{di_g}{dt} + v_g \tag{3.7}$$

The traction grid current:

$$\frac{di_g}{dt} = \frac{1}{L_f}.(v_g - R_f.i_g - v_g) \tag{3.8}$$

## 3.4 Power Processor System

The power supplied from the grid via the transformer to the locomotive traction drives, for this systems, there are various conversions processes that takes place between AC and DC power and these power conversions is done by the power processor system or the power electronics converter system. After the modelling of the transformer and the filter systems, the next system is the power processor system that comprises of three stages of two power electronics converters and one DC-bus. The circuits of the power electronic converters or simply the converters are responsible for the power conversion that takes place in the power processor unit. The converter type for the locomotive is the AC-DC-AC converters. Figure 3.4 shows the block diagram of the power processor system as applicable to the locomotive i.e. the AC-DC-AC converter. As shown in the diagram, the AC-DC-AC conversion in the locomotive is achieved by the two stages (firstly AC-DC and then DC-AC) using the semiconductor switches.

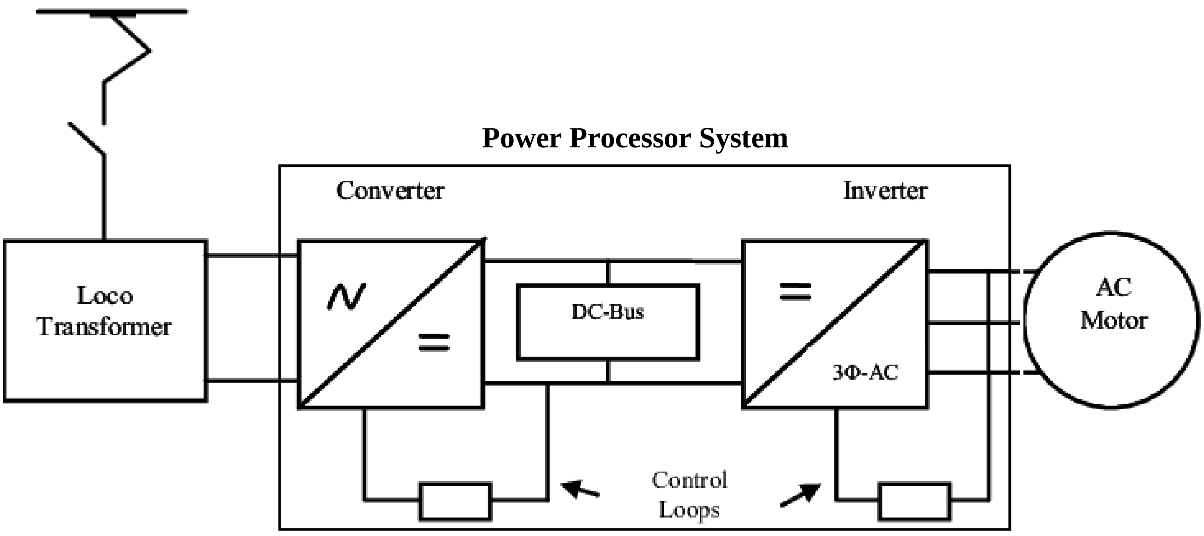



Figure 3.4: The block diagram for power electronic converter for AC supplied locomotives

For the power processor unit of the electric locomotive, the first part of the power processor systems is the converter, which is known as the rectifier, which converts the power from the single-phase AC from the transformer to variable voltage DC. Next is the choppers or the DC link, which convert the power from variable DC to fixed DC. Finally, is the inverter, which convert the power from the DC to the variable magnitude and variable frequency in the form of the three-phase AC voltage.

Already as shown in Figure 2.5, in Chapter 2 is the configuration of the power electronic converter systems using the generic arrangement of the power electronic switches that is applicable to the AC locomotive. This generic switches configuration was used because in the study two power electronics switches were implemented in the aspect of the numerical simulation. The two switches configuration are for the GTO thyristor as shown in Figure 3.5a and for the IGBT configuration as shown in Figure 3.5b.

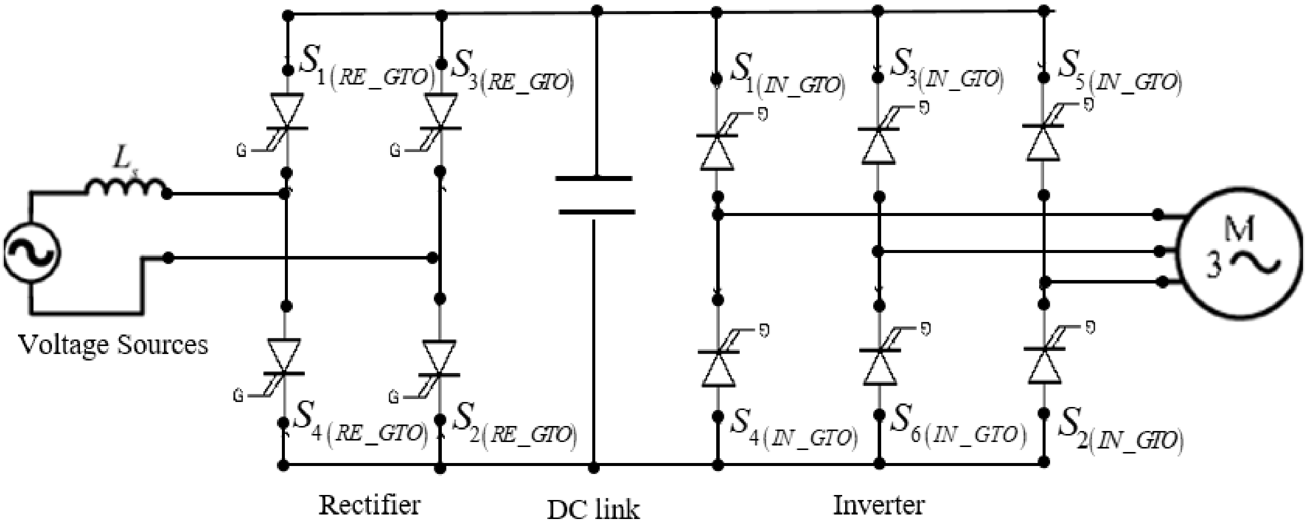



Figure 3.5a: The converter system using the GTO thyristor switches

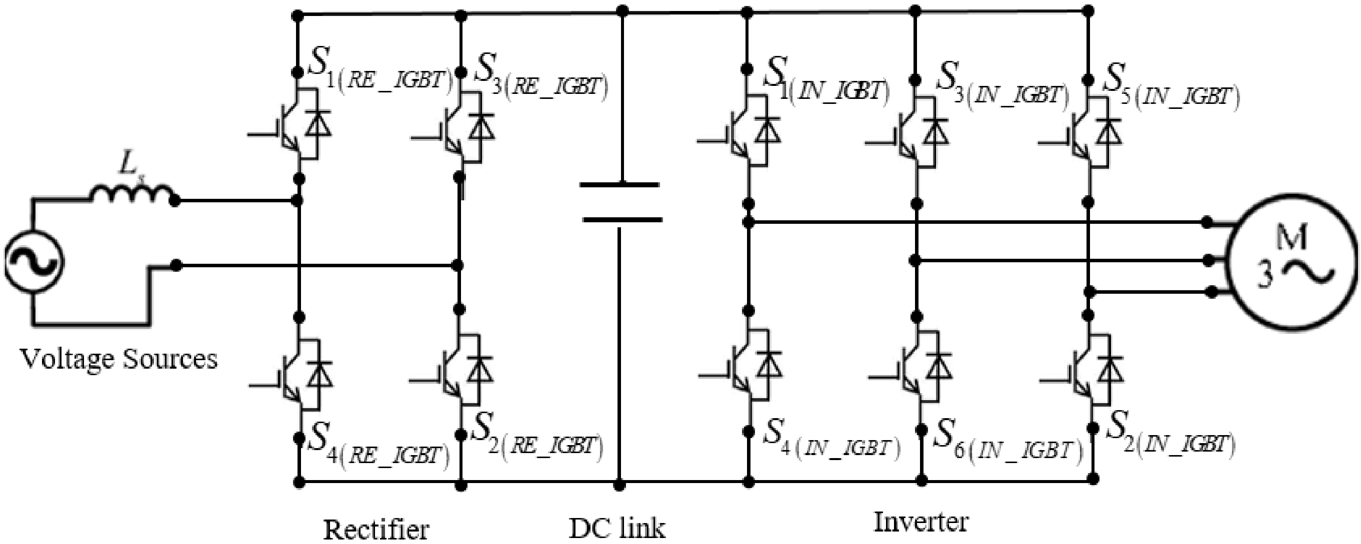



Figure 3.5b: The converter system using the IGBT switches

In order to model the entire converter system which is shown in Figure 3.5, was achieved by modelling each subsystem in the power processor (rectifier, DC link and the inverter) and then incorporate or assembled these models together to form the entire power processor system. Hence, these individual models were assembled to obtain the entire power electronics converter system as a unit, which was then used for the numerical simulation. The explanation of each of these converter models are given in the subsequent sections.

## 3.5 The AC-DC Converter Model

As explained in section 3.4, an illustration using the Figures 3.5, is the first part of the power processor system, which is AC-DC converter that carry out the rectification process. The infeed AC voltage supplied from the grid, after being step down by the transformer, it has to be rectified from AC to DC using the rectifier. Thus, power semiconductors or switches presented on the rectifier of the AC locomotive performs the task of regulating the DC link voltage and also, carryout the modulation of the converter input current waveform.

In carrying out the rectification operation, locomotives use the power electronic switching converters to convert the supplied AC to DC voltage using the 4-quadrant chopper (4-QC). The purpose of the 4-QC in electric traction drive of the locomotive is to transform the single-phase input mains voltage from the main transformer into the DC voltage. The term 4-QC signifies that the phase angle between voltage and current is freely adjustable dominantly to suit the required operation of the electric locomotive, by the control of this phase angle between voltages and current, hence, all the four operational quadrants can be obtained [42]. These switching converters introduce harmonics into the supplying network while the locomotive is moving along the line [58, 59].

There are various rectifier topologies that are applicable to the design of rectifier generally as mentioned in Chapter 2, for this study, the interleaved two-level 4Q converter topology was adopted. This converter model used for the rectification is shown in Figure 3.6. In order to speed up computations within the converter, each traction converter station consists of parallel connected converters of same types switches operating together to power to the DC link [60]. This interleaved 4Q converter topology is composed of three rectifiers which are connected in parallel using the same DC link but connected to the AC supply from the multi-winding transformer with separate isolated secondary windings. For this topology, the multiple converters supplying the same DC link has the advantage of providing redundant operation. The operation of each of the rectifier is the same as that of a single, two level rectifier. This form of rectifier, due interleaved configuration has the capability of reducing the harmonic distortion at the supply from the primary side of the on-board transformer. The advantage of interleaving the rectifier is to distribute the rated power among several individual converters, and hence the current rating of the power semiconductors can be reduced.

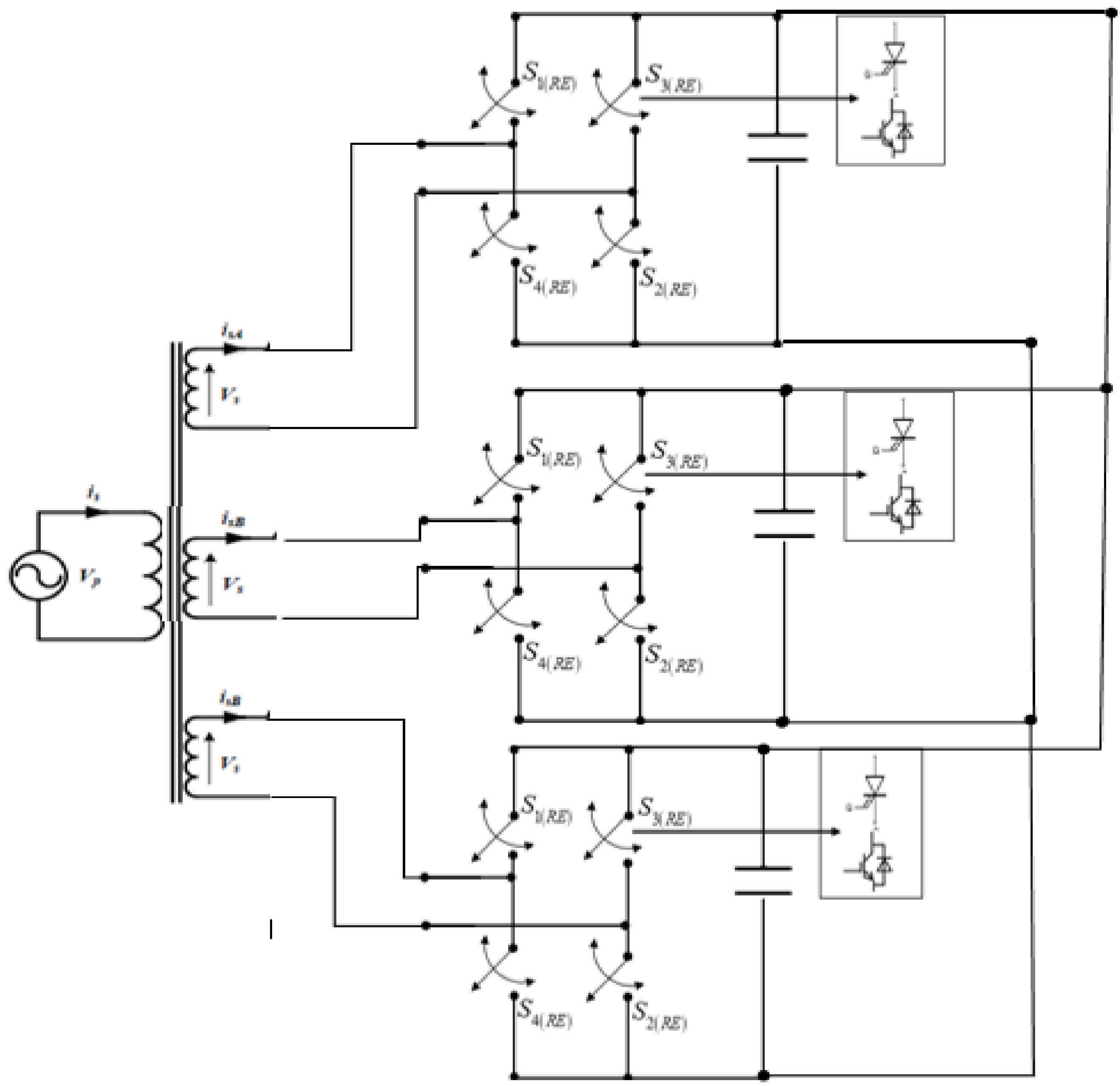



Figure 3.6: The rectifier converter model

For the operation of this interleaved 4Q rectifier topology, the supplied AC voltage leads to a periodic excitation of the system, the control system for the rectifier should be able to provide the required DC component of the output voltage, and also the desired the phase relation between current and voltage should properly march in the AC side in order to obtain a unitary power factor. This concept can be achieved through a well-designed feedback control system which monitors the output voltage and maintain this voltage level by sending the error signal, which is processed by the control unit in order to obtain any desired input voltage reference signal used as the modulating signal for the PWM technique that operates the power process unit rectifier of the locomotive [61].

After the transformation, the DC voltage output is fed into the DC link, the DC voltage current are fed directly through input filters built-up by a separated choke. Two independent converters are built in one traction converter assembly, each line converter is working as a 4-quadrant chopper for AC and by-passed in DC operation, and since the DC chopper application has proven to have high failure. The DC connection of the phase module is made to protect the traction converter propulsion, to protect the converter, in a situation, if the peak current is not reduced but released, the energy is limited, and the faulty element is isolated from the DC-link. This occur in the case of the IGBT traction modules. For the snubbed operation of an IGBT press pack, a choke will also limit the peak SC current to values to around 140kA. The mechanical impact will usually be contained within the phase module, so it's clearly these operation conditions, places the lowest requirements on the semiconductor [48][49].

## 3.6 The DC Link Model

The power conversion processes of the two power converter systems in AC electric locomotives are interlinked by an intermediate stage where the power is transferred at the DC voltage and current. After the rectification process which is normally carried out by the rectifier to produce the DC voltage, the DC voltage produced is fed to the DC-link which is shown in Figure 3.7. The DC link is used to store some certain amount of energy in the parallel capacitor as shown in the diagram i.e. serves as energy storage. The DC-link capacitor as connected, normally provide the path way for the low impedance for high frequency switching currents as a results of the power converters operations. The input stage can be as simple as a rectifier of a DC line input voltage or it may be for power factor correction (PFC) circuit that generates a constant medium or high voltage DC [6].

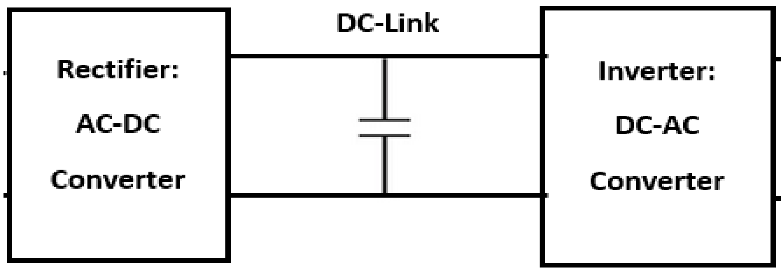



Figure 3.7: The DC link

The DC-link capacitor acts as the PFC stage output filter, absorbing the switching currents in order to achieve the minimum ripple voltage [6]. The output stage could be in the switched mode converter or inverter taking high frequency current from the DC-link capacitor. The capacitor has to be sized in order to meet specifications for minimum ripple voltage at the DC-link and energy storage between mains cycles or when input power is lost. This means that the DC link should have a low equivalent series resistance and a minimum capacitance and ripple current rating. These specifications have to be met at the required operating voltage, temperature, power output, line and switching frequencies, for longer life span of the choke [6].

The main requirements for the capacitor used for the DC link used in the locomotive power converters are as follow [12]:

- It should have long life span in locomotive (should be for about 30 years)
- It should be able to provide reliability for the traction converters
- Possess a low internal stray inductance
- The DC-link should be able to achieve a compact design

To achieve these requirements, the capacitors for locomotive DC-link are designed to have the self-healing properties and the used of the dry polypropylene film separator capacitor suite in the locomotive configuration and design. The self-healing ability of the capacitor makes it possible that the capacitor remains operational even if an internal failure does happen, with a backup of the self-charged electron to operate the DC-link when the failure does occur. When there is excessive DC voltage, which can be above the maximum rating of 4 kV DC or transient voltage spikes higher than the dielectric withstanding voltage, this will trigger as internal failures in capacitors film, for the protection the DC-link.

Figure 3.9 shows the DC link model which is applicable to the AC electric locomotives. For this DC link model, to determine the DC bus voltage, it should be noted that the voltage is dependent on the current through the capacitor. Thus, the voltage can be evaluated using [78].

$$V_{bus} = \frac{1}{C_{bus}} \int i_c . dt \qquad (3.9)$$

The current that flows through the capacitor can be calculated by using this equation:

$$i_{C_2} = i_{DC\_RE} - i_{DC\_IN} - i_{DC} \qquad (3.10)$$

Where $I_{DC}$ is the current through the resistance, $I_{DC\_IN}$ is the DC current flowing from the DC-link to the inverter, $I_{DC\_RE}$ is the DC current that flows from the rectifier part into the DC link.

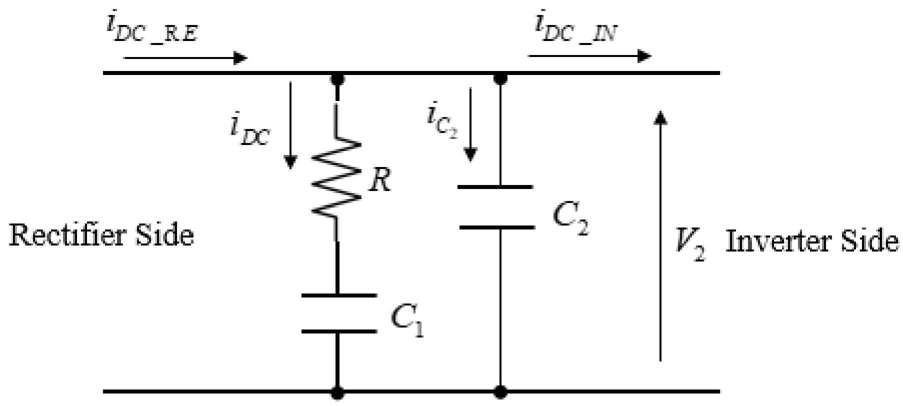



Figure 3.9: The DC link model for the AC electric locomotive

## 3.7 The DC-AC Converter Model

After the DC link, next on the trail is DC-AC converter. From the DC link, the stored energy has to be converted from the DC to AC using DC-AC converter which drives the AC motors. The modelling of DC-to-AC converters is explained based on the characteristics of the AC traction motors as used in the electric locomotive, illustrated by Figure 3.10. This type of converter system used in electric locomotive is bidirectional in order to achieve regeneration.

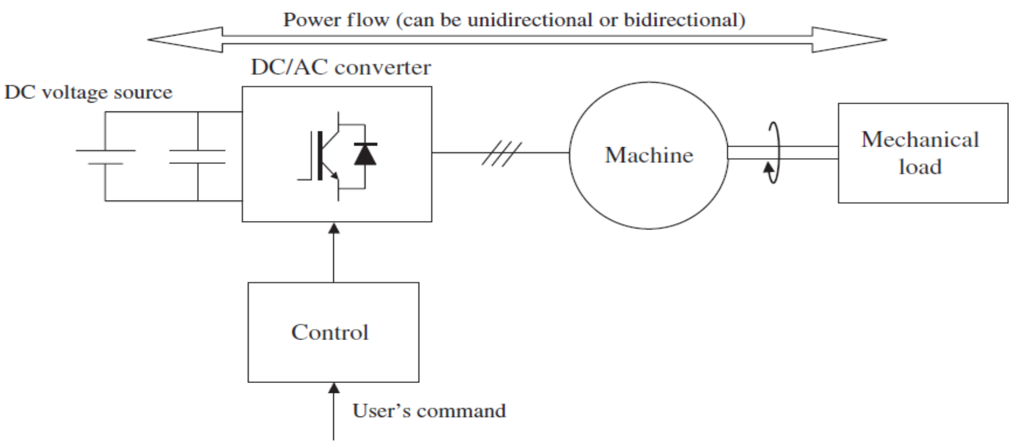



Figure 3.10: Locomotive traction drive with DC/AC converter [12]

A DC-AC converter is also known as the inverter. The inverter as used in power electronic system, which converts the DC power into the AC power at the required output voltage and frequency. The AC output voltage could be fixed or variable voltage and frequency. This conversion can be achieved by controlled turn on and turn off devices. The DC-AC conversion mechanism uses the power electronics switches such GTO thyristor, IGBT, MOSFET, Diode and these switches configuration changes the ON/OFF intervals to create the pulse waves with different widths. Therefore, the magnitude of fundamental frequency of the output voltage from the inverter can be controlled for it to be variable and this can be achieved by the controlled unit within the inverter, such that no external control unit is required. The most efficient method of achieving this process is by the pulse width modulation (PWM) and the control circuit used is within the inverter. There are various PMW techniques that can be used to drive the AC load, for this study the sinusoidal Pulse Width Modulation (SPWM) was implemented and the wave forms are shown in Figure 3.11.

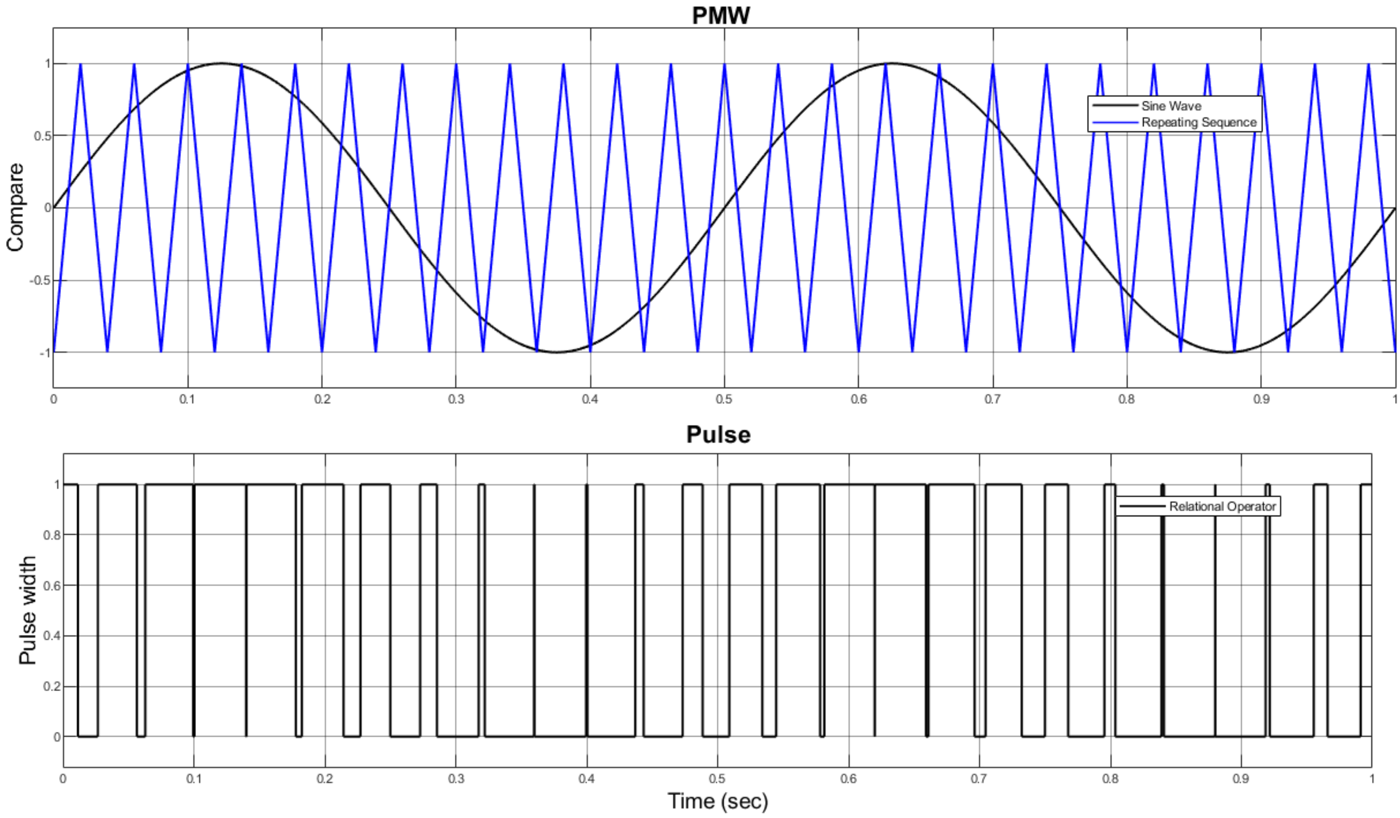



Figure 3.11 Pulse width modulation (PWM)

Thus, main for the locomotive application, the inverter device's role is to control the voltage and frequency of the power supply from the DC source, from the DC link and transforms it into the AC output, which is fed to generate the rotation of the induction motors. Thus, shown in Figure 3.12 is a three-phase full-bridge inverter, with a high power and medium voltage levels, which uses six power electronic devices to create the required voltage for operating the AC electrical motors.

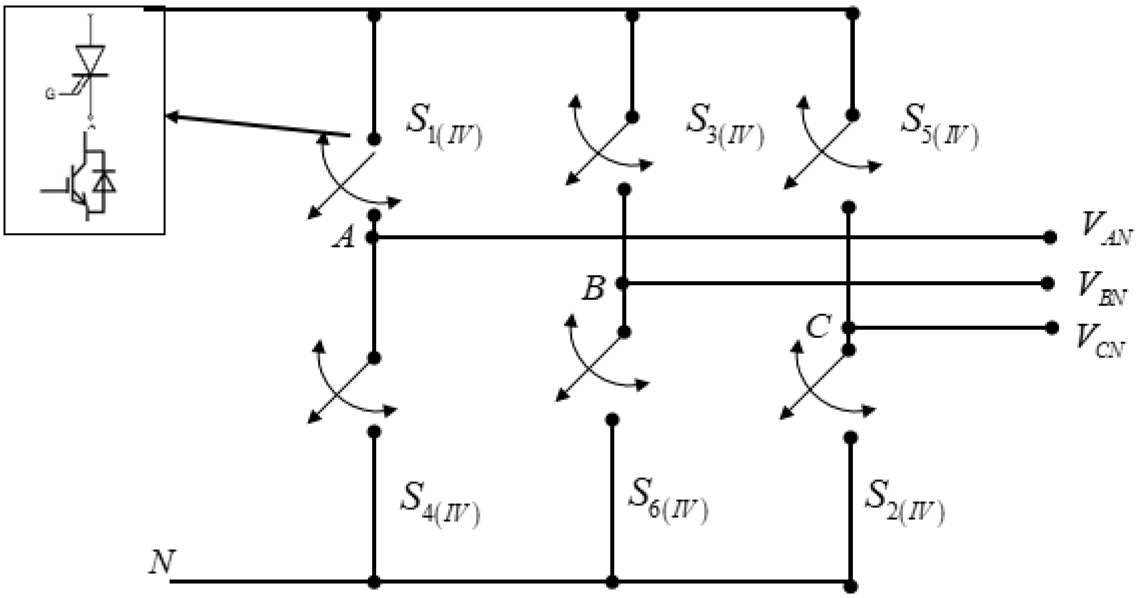



Figure 3.12: The 3-phase inverter model

The AC locomotive uses model of the two-level, three-phase, voltage source inverter (VSI) and these forms of converters are also called the traction inverters. Various semiconductor power switches used in these inverter topologies but these days the insulated gate bipolar transistors (IGBTs) switches are now commonly used. These switches operated at voltage level for these power switches is 600–1200 V [56]. Each bridge leg consists of a higher and lower side IGBT switch. Usually, the switching frequency is in the range of 5 kHz to 20 kHz [56]. The high-power IGBT switches require isolated gate drivers to control their operations. The isolation is the galvanic between the higher voltage output of the gate driver and the lower voltage control inputs generated by the PWM controller. Moreover, these gate drivers should have an integrated protection features such as desaturation and short-circuit detection [56]. As documented in reference [61], revealed that for locomotives, the adjustable speed drives of this locomotive use the PWM-controlled converters for both to rectify the voltage of the AC supply system and to feed AC motors. Hence, equipped with the PWM modulated multistage inverter as applicable to this study due to the rectifier topology, can guarantee the operation at nearly unitary power factor. The switching functions of single-phase 4Qs rectifiers and of the three-phase inverter are simply obtained from the SPWM modulation technique parameters adopted for each of converter systems.

Generally, the traction inverter outputs are in the form of approximately an alternating current with varying voltage and frequency. Thus, the inverter which is used to transform both voltage and frequency; this is called the variable voltage variable frequency (VVVF) converter system.

In the aspect of the SPWM, the amplitude of the sinusoidal voltage and the triangular voltage relationship for pulse generator determines the maximum value of the fundamental line to line voltage of the inverter. Also, the ratio of the reference wave amplitude to the triangular wave amplitude is called the amplitude modulation ratio (m) or modulation index.

For the analysis of the inverter, the remainder of this section is mostly obtain from reference [62]. To drive the induction motor, this form of voltage source inverters, the approximate sinusoidal voltage waveform output as presented in Figure 3.13 is used.

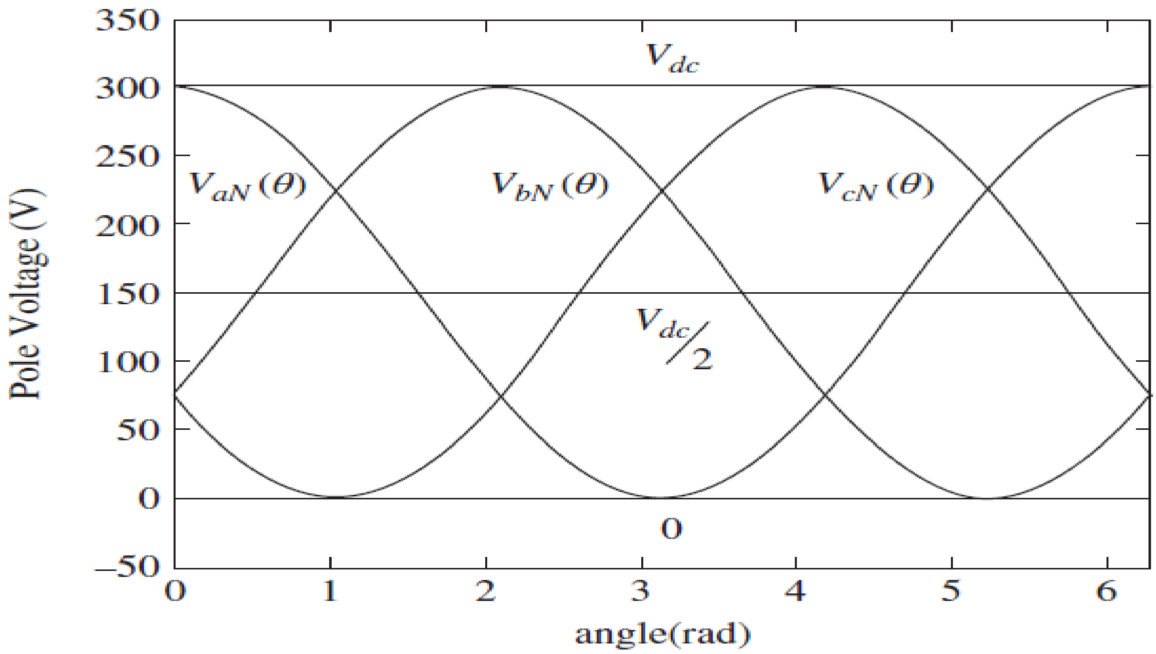



Figure 3.13: The inverter pole voltages [62]

The line output voltage or the pole voltage is sinusoidal waveform and the DC voltage level equal to half the DC link voltage, as presented in Figure 3.13. At the minimum and maximum voltage values, the pole voltage which is a sinusoidal form will be alternating between the DC values for negative at 0 V and then the DC positive at +Vdc. Thus, the line (pole) voltages for each leg a, b, and c with respect to the negative of the DC link N, as indicated in Figure 3.12, can be evaluated using the following equations [62]:

$$v_{aN(\theta)} = \frac{V_{dc}}{2} + \sqrt{2}V_{ph}\cos(\theta) \quad (3.11a)$$

$$v_{bN(\theta)} = \frac{V_{dc}}{2} + \sqrt{2}V_{ph}\cos\left(\theta - \frac{2}{3}\pi\right) \quad (3.11b)$$

$$v_{cN(\theta)} = \frac{V_{dc}}{2} + \sqrt{2}V_{ph}\cos\left(\theta - \frac{4}{3}\pi\right) \tag{3.11c}$$

Where $V_{dc}$ is the DC voltage, $V_{ph}$ is the root mean square value of the phase voltage and the angle $\theta = \omega$t.

To determine the line-line voltages is by using the phasor diagram as shown in Figure 3.14. From this phasor diagram, using the phase to neutral voltages as the reference, the three line-line voltages, which are represented by $v_{ab}$, $v_{bc}$ and $v_{ca}$ can be determined by multiplying the phase voltage by the square root of 3 with the phase-shifting to obtain the resultant values as [62]:

$$v_{ab}(\theta) = \sqrt{6}V_{ph}\cos\left(\theta + \frac{\pi}{6}\right) \tag{3.12a}$$

$$v_{bc}(\theta) = \sqrt{6}V_{ph}\cos\left(\theta - \frac{\pi}{2}\right) \tag{3.12b}$$

$$v_{ca}(\theta) = \sqrt{6}V_{ph}\cos\left(\theta - \frac{5\pi}{6}\right) \tag{3.12c}$$

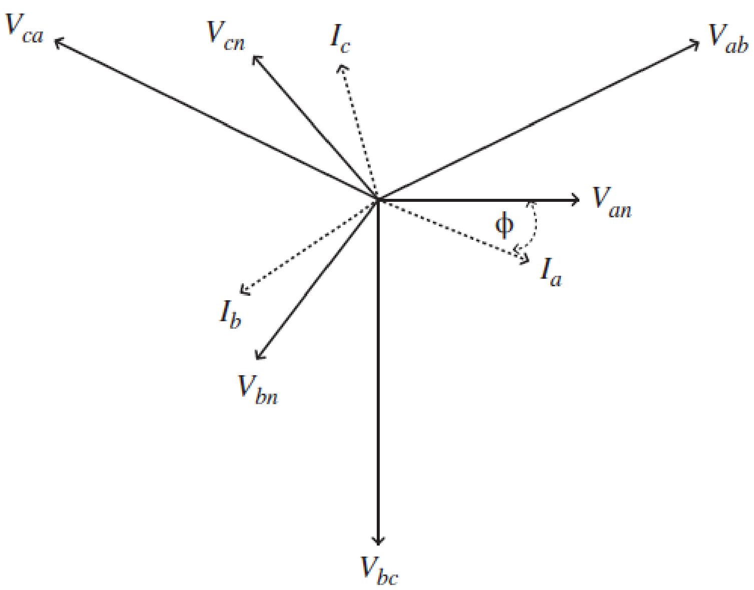



Figure 3.14: The phasor diagram [62]

As the VSI is operated using the PWM technique, whose modulating signals to drive the gate are obtained by means of the indirect-field oriented control, the voltages with respect to point N as shown in Figure 3.12 can be evaluated as [62]:

$$v_{aN(\theta)} = \frac{V_{dc}}{2} + \sqrt{2}V_{ph}\cos(\theta) \tag{3.13a}$$

$$v_{bN(\theta)} = \frac{V_{dc}}{2} + \sqrt{2}V_{ph}\cos\left(\theta - \frac{2}{3}\pi\right) \tag{3.13b}$$

$$v_{cN(\theta)} = \frac{V_{dc}}{2} + \sqrt{2}V_{ph}\cos\left(\theta - \frac{4}{3}\pi\right) \tag{3.13c}$$

For the inverter, evaluating per-phase voltage as the function of the angle θ, the following equations for the phase voltage and current is obtained as:

$$v_{ph}(\theta) = \sqrt{2}V_{ph}\cos(\theta) \tag{3.14}$$

$$i_{ph}(\theta) = \sqrt{2}I_{ph}\cos(\theta - \phi) \tag{3.15}$$

In the situation that, the line current is fed to the load which in the form of the phase winding of the star-connected inductor motor.

Thus, for the switch used for the inverter, the various DC currents are:

$$I_{Q(\mathrm{dc})} = I_{ph}\left(\frac{1}{\sqrt{2\pi}} + \frac{V_{ph}}{2V_{dc}}\cos\theta\right) \tag{3.16}$$

$$I_{D(dc)} = I_{ph}\left(\frac{1}{\sqrt{2\pi}} - \frac{V_{ph}}{2V_{dc}}\cos\theta\right) \tag{3.17}$$

$$I_{HV(dc)} = 3\frac{V_{ph}}{V_{dc}}I_{ph}\cos\theta \tag{3.18}$$

The various rms current for the switch are:

$$I_{Q(rms)} = I_{ph}\sqrt{\frac{1}{4} + \frac{4\sqrt{2}}{3\pi}\frac{V_{ph}}{V_{dc}}\cos\theta} \tag{3.19}$$

$$I_{\mathrm{D}(rms)} = I_{ph}\sqrt{\frac{1}{4} - \frac{4\sqrt{2}}{3\pi}\frac{V_{ph}}{V_{dc}}\cos\theta} \tag{3.20}$$

$$I_{\mathrm{HVdc}(rms)} = I_{ph}\sqrt{\frac{\sqrt{6}}{\pi}\frac{V_{ph}}{V_{dc}}(1+4\cos^2\theta)} \tag{3.21}$$

$$I_{\mathrm{CHV}(rms)} = I_{ph}\sqrt{\frac{\sqrt{6}}{\pi}\frac{V_{ph}}{V_{dc}}+\left(\frac{4\sqrt{6}}{\pi}\frac{V_{ph}}{V_{dc}}-9\left(\frac{V_{ph}}{V_{dc}}\right)^2\cos^2\theta\right)} \tag{3.22}$$

For the switch used for the inverter, the conduction loss can be evaluated using:

$$P_{\mathrm{D}(cond)} = V_{VCEO} I_{Q(dc)} + r_{CE} I^2_{Q(rms)} \tag{3.23}$$

For the diode used in the inverter, the conduction loss can be evaluated using:

$$P_{Q(cond)} = V_{fo} I_{D(dc)} + r_f I^2_{D(rms)} \tag{3.24}$$

For VSI, the average switching current can be evaluated using:

$$I_{Q(\mathrm{sw,avg})} = \frac{2\sqrt{2}}{\pi} I_{ph} \tag{3.25}$$

Thus, the switch power losses can be evaluated using:

$$P_{\mathrm{Q}(sw)} = \frac{f_s}{2}(E_{on}+E_{off})\frac{V_{dc}}{V_{test}} \tag{3.26}$$

The diode switching loss can be evaluated using:

$$P_{\mathrm{D}(sw)} = \frac{f_s}{2} E_{rec} \frac{V_{dc}}{V_{test}} \tag{3.27}$$

The total losses for the switch can be evaluated using:

$$P_Q = P_{Q(cond)} + P_{Q(sw)} \tag{3.28}$$

The total losses for the diode can be evaluated using:

$$P_D = P_{\mathrm{D}(cond)} + P_{\mathrm{D}(sw)} \tag{3.29}$$

The hotspot temperatures for the switch can be evaluated using:

$$T_{jQ} = T_{HS} + R_{JQ-HS}.P_Q \tag{3.30}$$

The hotspot temperatures for the diode can be evaluated using:

$$T_{jD} = T_{HS} + R_{JD-HS} X P_D \tag{3.31}$$

The total power loss for the inverter can be evaluated using:

$$P_{loss} = 6\times(P_Q + P_D) \tag{3.32}$$

The efficiency of the inverter is

$$\eta = \frac{P_0}{P_0 + P_{loss}} \times 100\% \tag{3.33}$$

## 3.8 Modelling of the Three-Phase Induction Motors

In this section, the mathematical model of the three-phase induction motors is presented, starting with how the induction motor operates. The derivation of the dynamic equations, describing the motor is explained. The induction machine is used in a wide variety of applications as a means of converting electric power to mechanical power and this also applicable to the AC locomotive propulsion drives. As stated in Chapter 2, the induction motors are most commonly used for industrial applications because of the fact that they offer better performance than other forms of AC motors.  For the rolling stock, for the traction motor, is normally the three-phase, squirrel-cage type, forced ventilated, double bearing asynchronous motor, specially designed for the inverter supply and this form of traction motor has the reduced pulsating torque, losses and noise level and this is achieved by the efficient performance of the inverter supply.

The diagram illustrating the variable speed drive for AC motor is shown in Figure 3.15, which consists of a continuous DC voltage source and a three-phase inverter which supplies power to the AC motor i.e. the induction motor. The main function of the three-phase inverter is to provide an approximately sinusoidal wave form, for the operation of an induction machine. The two-level, three-phase, and voltage source inverter (VSI) application is employed for locomotive traction drive hence, its applied to supply power to the induction machine. For the application of the VSI fed, three-phase induction motors can be considered as the optimum solution for energy saving for the locomotive for the reasons that these motors are simple and rugged in their construction, a low operational and maintenance cost.

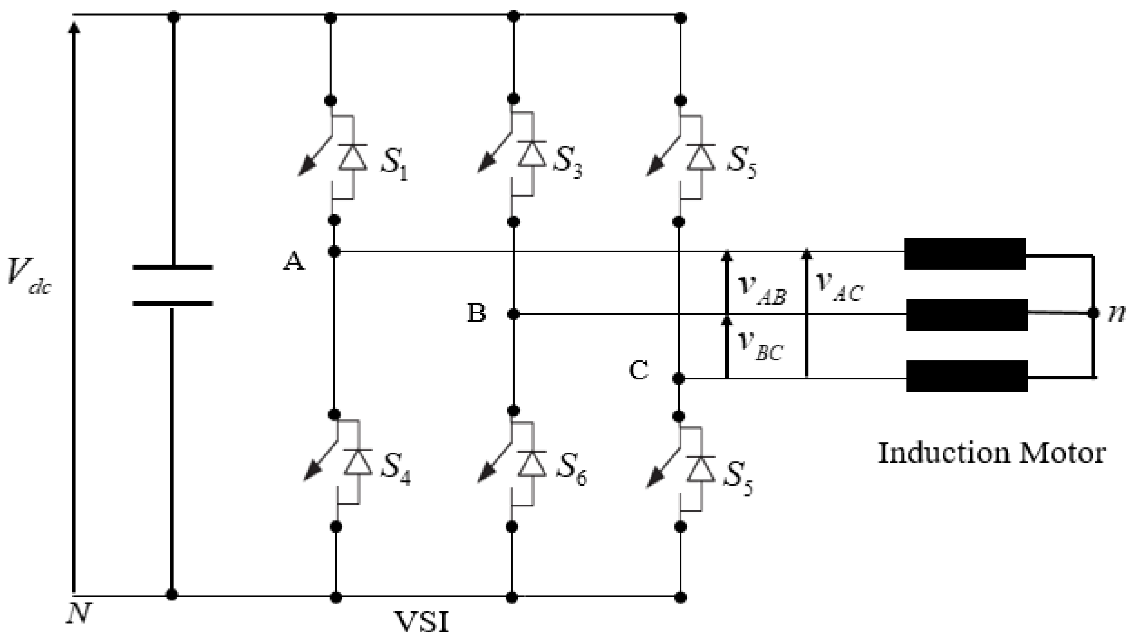



Figure 3.15: Traction motor fed by voltage source converter

Figure 3.15 shows, consist the DC constant voltage source Vdc connecting, the two-level, three-phase, voltage source inverter (VSI) with six idealized switches, $S_1$ to $S_6$, connected to the three-phase induction motor. As indicated in the diagram, this motor is represented by the three balanced loads of impedance Z.

The three-phase voltages that are applied across the three-phase induction motor, the net effect is obtained as the DC bias of the line voltages cancel out, hence, the line or phase voltages supplied to the machine are only AC without the DC bias. As shown in Figure 3.15, the three-phase voltages, $v_{An}$, $v_{Bn}$, and $v_{Cn}$ are with respect to the motor neutral (n) point can be determined by:

$$v_{An} = v_{AN} - v_{nN} \tag{3.34a}$$

$$v_{Bn} = v_{BN} - v_{nN} \tag{3.34b}$$

$$v_{Cn} = v_{CN} - v_{nN} \tag{3.34c}$$

Where $v_{An}$, $v_{Bn}$ and $v_{Cn}$ are the phase-to-neutral voltages.

$$v_{An} + v_{Bn} + v_{Cn} = v_{AN} + v_{BN} + v_{CN} - 3v_{nN} \tag{3.35}$$

Assuming that the system is balanced operation

$$v_{An} + v_{Bn} + v_{Cn} = 0 \tag{3.36}$$

Thus,

$$v_{nN} = \frac{v_{AN} + v_{BN} + v_{CN}}{3} \tag{3.37}$$

Therefore,

$$v_{An} = \frac{2v_{AN} - v_{BN} - v_{CN}}{3} \tag{3.38a}$$

$$v_{Bn} = \frac{2v_{BN} - v_{CN} - v_{AN}}{3} \tag{3.38b}$$

$$v_{Cn} = \frac{2v_{CN} - v_{AN} - v_{BN}}{3} \tag{3.38c}$$

Considering the system to be a balanced three-phase system, the neutral voltage of the motor is equal to half of the DC link voltage. Hence, the motor neutral voltage is

$$v_{nN} = \frac{V_{dc}}{2} \tag{3.39}$$

To evaluate the voltage equations for the induction motor, this can determine as:

$$v_s = R_s i_s + \frac{d\lambda_s}{dt} + j\omega\lambda_s \tag{3.40}$$

$$v_r = R_r i_r + \frac{d\lambda_r}{dt} + j\left(\omega - \omega_r\right)\lambda_r \tag{3.41}$$

Where $v_s$ is stator voltage, $v_r$ is the rotor voltage, $R_s$ is the stator winding resistance, $R_r$ is rotor winding resistance, $i_s$ is the stator current, $i_r$ is the rotor current, $\lambda_s$ is stator flux linkage, $\lambda_r$ is the rotor flux linkage. The stator and rotor flux linkages can be determined using:

$$\lambda_s = L_s i_s + L_m i_r \tag{3.42}$$

$$\lambda_r = L_r i_r + L_m i_s \tag{3.43}$$

From the above equations,

the stator self-inductance is $L_s = L_{ls} + L_m$; (3.44)

the rotor self-inductance $L_r = L_{lr} + L_m$; (3.45)

Where $L_{ls}$ is the stator leakage inductances, $L_{lr}$ is the rotor leakage inductances, and $L_m$ is the magnetizing inductance.

For the induction motor with regards to the above equations, the electromagnetic torque for the motor can be determine using:

$$T_e = \frac{3P}{2} \frac{L_m}{\sigma L_s L_r} \lambda_s \lambda_r \sin\theta_T \tag{3.46}$$

Where $P$ is the number of pole pairs for the induction motor.

The equation of motion for the induction motor is defined by:

$$\frac{d\omega_r}{dt} = \frac{P}{J}\left(T_e - T_L\right) \tag{3.47}$$

Where $J$ is the total moment of inertia of the rotor and $T_L$ is the load torque

## 3.9 Cycloconverter Model

There are many applications in terms of power conversion which requires an AC variable voltage at a frequency different from the standard and the usual power system frequency. Traditionally, as already explained, one method to achieve this frequency conversion is to use the power process unit which is the rectifier-DC link-inverter combination. The rectifier converts AC to DC and the inverter convert DC to AC of the desired frequency based on the requirements of the load. To avoid this two-stage process, cycloconverter (CCV) can be used. A cycloconverter is a device that converts AC at one frequency to an AC of another frequency. Thus, it is an AC-AC converter without any intermediate DC link.

Cycloconverters can be classified as single phase to single phase, three phases to single phase, 3 phases to 3 phase devices. They can also be classified as step-down and step up. A step- down cycloconverter gives an output whose frequency is lower than that of input. Step-down cycloconverter uses line or natural commutation. However, a step-up cycloconverter require forced commutation.

For this study the aim was to hint at the possible application of the cycloconverters for traction applications such as the operation of the locomotive traction motor. Thus, presented is the conceptualised concept of cycloconverter, which in the case is better to start from the bases which the single-phase to single-phase cycloconverters (1ϕ-1ϕ) cycloconverter. It is pertinent to indicate that this concept requires in-depth investigation, employing various CCV configuration and also taking into cognisance the advent of newer forms of switches, the possibilities of the application of CCV for traction drives for the locomotives. The computer modelling, the simulation and analysis of results for single-phase to single-phase were presented in Chapter 4 current.

For the operation principles of cycloconverters, the single-phase-to-single-phase cycloconverter is shown in Figure 3.16. This form of converter consists of back-to-back connection of two full-wave rectifier circuits and shown in Figure 3.17 is the operating waveforms for this converter using a resistive load.

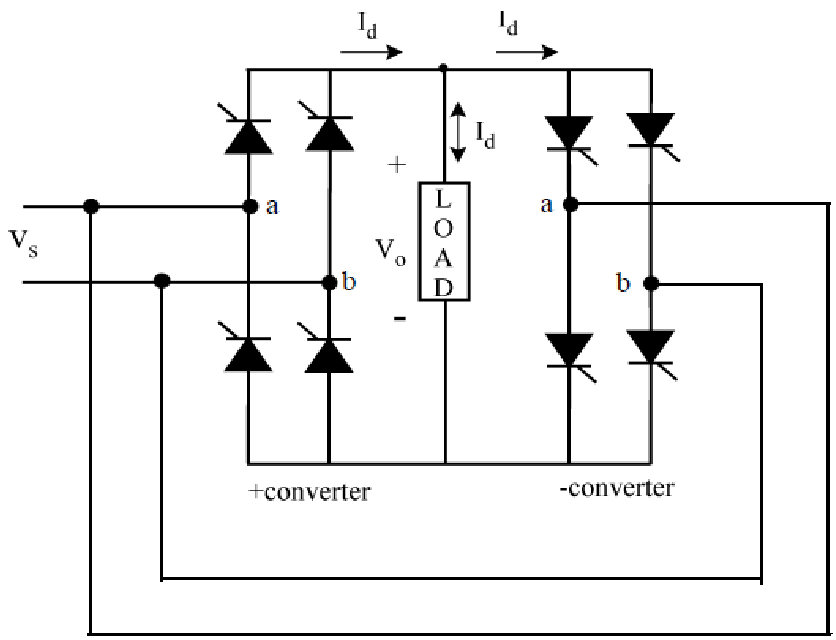



Figure 3.16: The diagram of the single-phase to single-phase cycloconverter

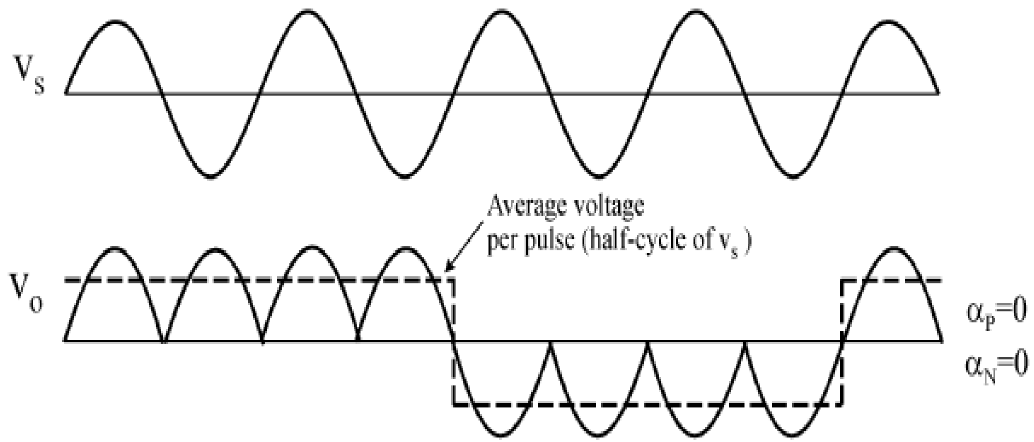



Figure 3.17: The waveform of the single-phase to single-phase CCV

From Figure 3.16, the input voltage, vs is an AC voltage at a frequency, fi. For the analysis of the operation of this converter, the whole of the thyristors are fired at α = 0° firing angle which makes the thyristors to act like diodes.

Thus, the condition for the firing angles should be met with the following:

$$\alpha_P + \alpha_N = \pi \tag{3.48}$$

Where $\alpha_P$ is the firing angle for the positive converter, $\alpha_N$ is the negative firing angle for the negative converter. This CCV can only supply a certain voltage at a certain firing angle $\alpha$ . The output DC voltage for each rectifier can be evaluated as:

$$V_d = \frac{2\sqrt{2}}{\pi} V \cos\alpha \tag{3.49}$$

Where V is the input rms voltage.

Then the peak of the fundamental output voltage can be evaluated by

$$V_O = \frac{4}{\pi} \frac{2\sqrt{2}}{\pi} V \cos\alpha \tag{3.50}$$

## 3.10 Traction Converter Protection

This Chapter is concluded with the analysis of the protection offered by the traction converters systems. Firstly, the protection of the entire locomotive system from the external input AC voltage from the catenary wire is done mainly by the vacuum circuit breaker (VCB). This circuit will trip and isolate the locomotive in case of fault along the catenary lines. Therefore, the external protection of the locomotive is done by VCB in order to protect the entire locomotive from any transient occurrence.

For internal faults, for the upgraded locomotives, the internal protection is by the IGBT switches, located in the power processor unit. To achieve this internal protection of the locomotive, the 4-QC has two separate control inputs and their function is for decoupling the network, also, for these control units, the interaction between the two inputs cancel each other out for protection purpose of the control circuit in the locomotive [53]. This results in two independent control inputs of the IGBT, one for the IGBT for the active current and the other for the reactive current. In this way [16, 39] the power factor at unity can be established when the locomotive. When the transfer functions between the IGBT input and output are identical for the balance of current; both current controllers can operate with the same parameters settings to avoid any transient current toward the power converter [14, 26, 28]. Through these controllers, a DC-link voltage is stabilized by the voltage controller, which is supplied by the 4-QC for better switching, and less harmonics. The voltage of the DC-link is regulated by the Proportional Integral (PI) controller, the PI Controller is a feedback control loop that calculates the error signal by taking the difference between the input and the output signal of the system as depicted by Figure 3.17, which in this case as the power is being drawn from the DC link (which acts as the battery) at the set point.

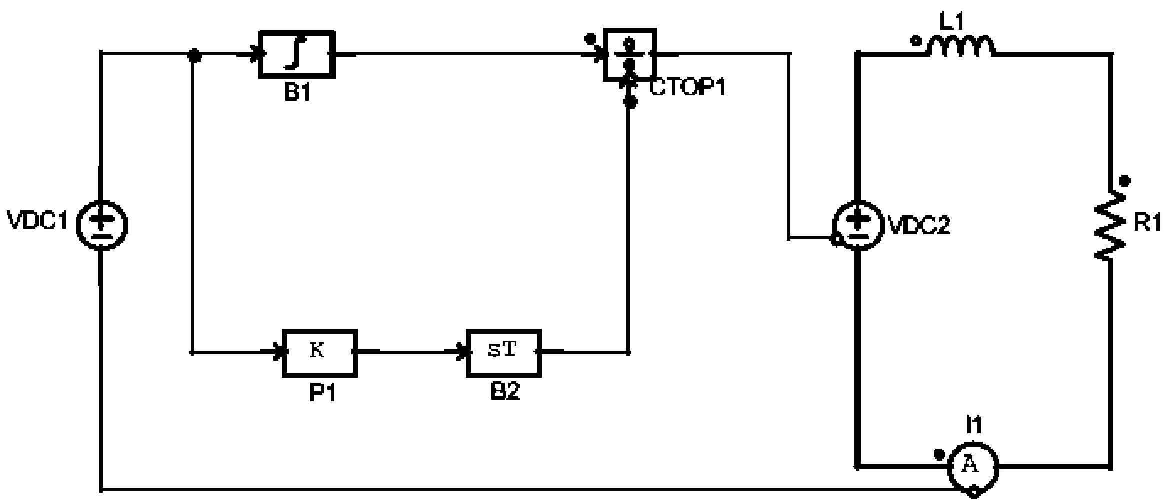



Figure 3.18: The PI circuit diagram

Also, the short circuit protection from the external components of the locomotive can profits directly from the fast switching of the IGBT during motoring and braking conditions [4, 26, 41]. If a filter or the cable inductance limits the di/dt of the external short circuit current, the IGBTs can turn off before the maximum turn-off current of the semiconductors is reached. In the case of internal short circuit, the di/dt clamp of the inverter will limits the maximum peak current for the protection of traction converter [4, 8, 20, 26]. This is achieved because the IGBT press pack device is designed to overcome short-circuit, the failure of IGBT is detected by an electronic circuit within the converter and signal is sent via the fibre optic cables to drivers desk for alert purpose and then the limp mode is activated automatically for the protection of the entire locomotive [15]. This Failed device can be replaced later during routine maintenance. In addition, the concept of the redundancy in the IGBT help to reduce the stress of voltage on each individual component operated by traction converter that include any snubber circuit. This concept is known as the lifetime of the individual IGBT device and it is depended on the voltage stress that it can withstand per second during:

- The starting of the locomotive
- The braking of the locomotive
- The continuous operation of the converter at maximum speed

Locomotive vector control technique is typically employed to the single inverter with the 3-level IGBT which is connected to the parallel configuration of the boogie six (6) induction motors [41, 42]. However by using the phase angle of primary flux, which is considered to be a common state variable, the protection of IGBT can be employed in order to overcome the current and voltage positive and negative direction fluctuation during this transient states [26].

# Chapter Four

# Simulations, Results and Analysis of Results

## 4.1 Simulation

The numerical technique of computer simulation is an important tool for the design, modelling, simulation and analysis of engineering concepts and systems. This technique was employed in this study to analyse the power electronics converters for the AC electric locomotive using power electronics switching devices. The computer simulation, implementation and analysis of the power processor unit in the locomotive is vital because it helps in the analysis of the converter system without actually building it.

As discussed in Chapter 3 were the various models for components pertaining to the power flow in an AC electric locomotive from the power source to the traction motor. This Chapter presents the simulation models, results and analyses of the results of the implementation of these models in the MATLAB/Simulink environment. Hence, this Chapter was used to presents the simulation models of the developed power processor system i.e. the AC-DC-AC converter with the switch mode power electronics switches. As indicated earlier in this report, the two switches were selected for both converters in the power processor system of the locomotive. The first is the GTO thyristor which was used in previous locomotive and the second switches is the IGBT which is now been used in the upgraded locomotives.

Presented in Figure 4.1 is the schematic diagram of the 25 kV, 50Hz AC locomotive which was used to model, design and the implement the various models as discussed in Chapter 3. Presented in Figure 4.2 is the developed general form of the Matlab/Simulink model for the AC electric locomotive. This model consists of subsystem models of the various components of the locomotive. The design and implementation of the entire system model was done in a pragmatic manner in which the various components as shown in Figure 4.1 were modelled individually before been assembled to produce the model for the entire system. The details analysis of the power electronic switch for the converter topology as implemented in the various MATLAB/Simulink simulations are presented in later sections of this Chapter.
Based on the fact that each induction motor is operated by the single converter systems, three separated subsystems were used, each model for each of the 3 three-phase induction motor. Based on the topology of the model as analysed in Chapter 3, both the rectifier and the voltage

source inverter, the sinusoidal PWM method was chosen for the simulation system. Thus, for the implementation of the converter's models, this follows the concepts as described in the previous Chapter which includes the power switching frequency, the filter design, the control approach and protection schemes. At the end of this Chapter, the performance between the two switches is analysed and compared and an inference was deduced.

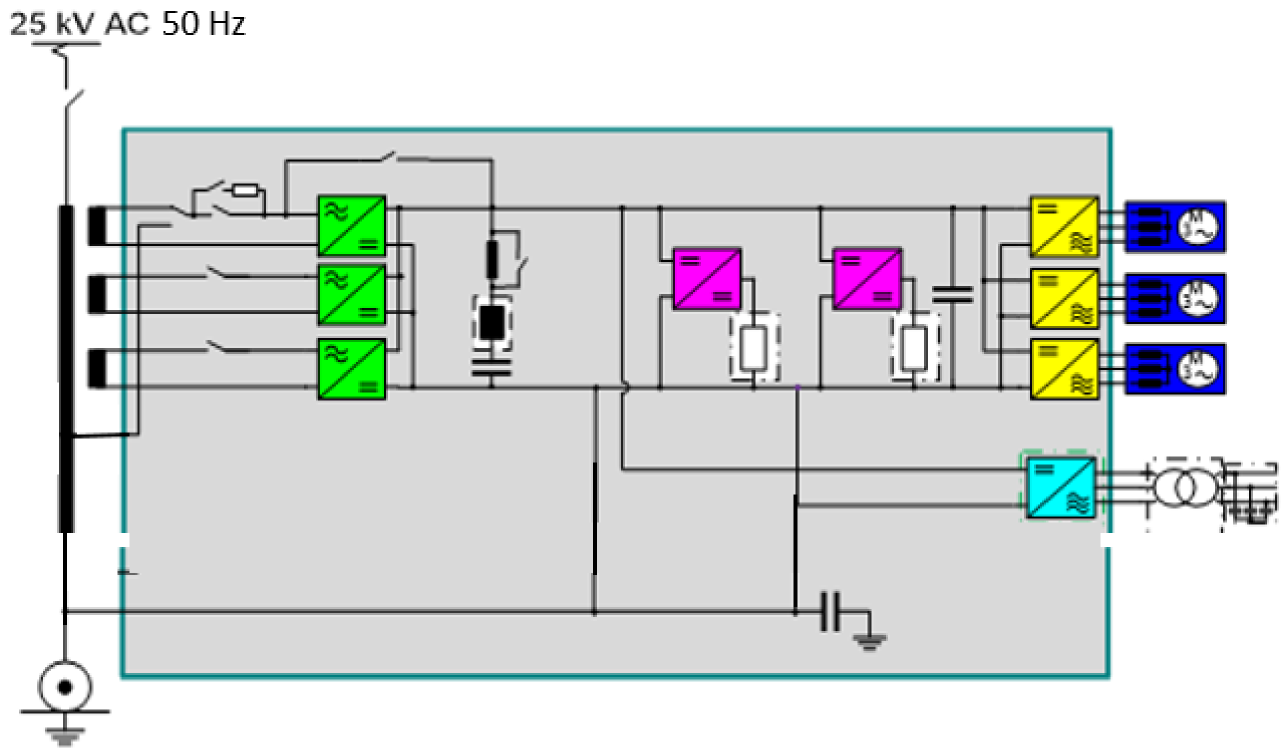



Figure 4.1: The components of the 25 kV, 50Hz AC electric locomotive

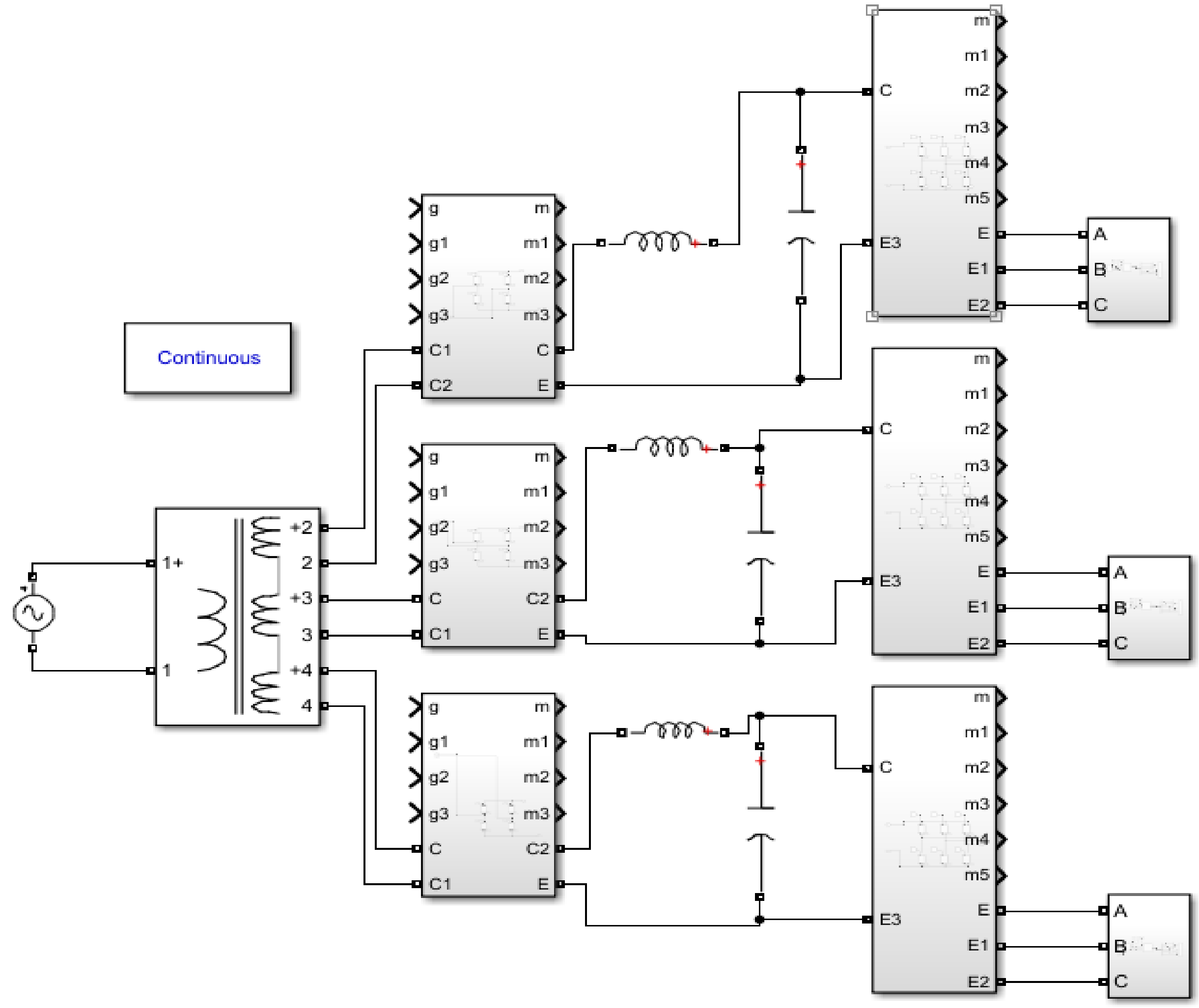



Figure 4.2: Matlab/Simulink model of the 25 kV, 50Hz AC electric locomotive

## 4.2 Components Specifications

Before the implementation of computer simulation models for the electric AC locomotive can be carried out, it imperative to indicate the specifications of the various components that were used to carry out the numerical simulations. Consequently, with the completion of modelling and analysis of the various models for the components of the AC locomotive as presented in Chapter 3, it is now important at this junction to stipulate the specifications of the components that were used to implement the models in the aspect of computer simulations. As shown in Figure 4.1 is the schematic diagram of the 25 kV, 50 Hz locomotive in which the various components of the electric locomotive are indicated, tabulated below is specifications of these components.

Starting with the specification for transformer, the parameters for the transformer is tabulated in Table 4.1. Next, is the specification for the power converters switches, which is documented in Table 4.2. The parameters for the traction drive (induction motor) are documented in Table 4.3. These specifications values were used to implement the computer simulation models and the results from these simulated models are presented in subsequent sections of this Chapter.

Table 4.1: On-board Transformer specification

| Specification | Value | Unit |
|---|---|---|
| Power rating | 20 | MVA |
| Primary voltage | 25 | kV |
| Secondary voltage | 400 | V |
| | | |

Table 4.2: Parameters for the Traction Converter

| **Description of converter/IGBT** | **IGBT** | **GTO** |
|---|---|---|
| Nominal voltage of locomotive | 30 KV AC | 25 kV AC |
| DC link filters voltage range | 25 kV to 27 kV | |
| DC link capacitance | 6.9mF per DC link | 4.5mF |
| Resonance filter capacitance | 4.8mF | 4mF |
| Resonance filter inductance | 0.55mH not inside converter | 0.32mH |
| Input current nominal RMS | 425 A per leg | 325 A |
| Input current maximum RMS | 483 A | 432 A |
| Input voltage nominal RMS | 1786 V/60Hz | 1616 V/50H z |
| Switching frequency | 450 Hz | 100 Hz |
| Motor inverter voltage RMS | 0-2572 V | 0-1250 V |
| Motor inverter frequency | 130 Hz | 50 Hz |
| Output current max RMS | Approx. 300 A | 210 A |

Table 4.3: Specifications for the three-phase, squirrel cage Induction motor

| **Description of locomotive** | **Value** | **Unit** |
|---|---|---|
| Rated Power | 160 | kW |
| Rated speed | 1487 | rpm |
| Number of poles | 6 | |
| Inertia | 0.05 | Kg,m$^2$ |

Before commencing the concept of computer simulations, it important to emphasise that, in the aspect of the induction motors which is coupled to the load or the axle of the locomotive is not the main focus of this study but the output parameters from the induction motors is very critical in analysing the operation of the power electronics switches used. This is due to the fact that the induction motor performance characteristics is a function of the operations of the power processor unit.

## 4.3 Simulation Configuration

In this section, the general simulation model as implemented on the MATLAB/Simulink environment for both converter configurations as previously discussed is presented. The MATLAB/Simulink model as shown in Figure 4.3 is composed of the catenary line, the transformer, front-end PWM rectifier, control block of the PWM rectifier, the DC link, the voltage source inverter (motor drive system) and the traction motor. In the next two sections, the components as contained in each of the subsystem will be explained, but due to the fact that the subsystems are identical, for the purpose of illustration, the components along a single path of the power flow was used for demonstration.

For the subsystems inside the load, which is for the induction motor, for both converter topology, the 160 kW, three-phase, 400V, 6-pole, squirrel cage induction machine was used and the parameters used for the implementation are documented in Table 2.1. Thus, for adequate comparison, the same induction motor parameters were used for both converter topologies.

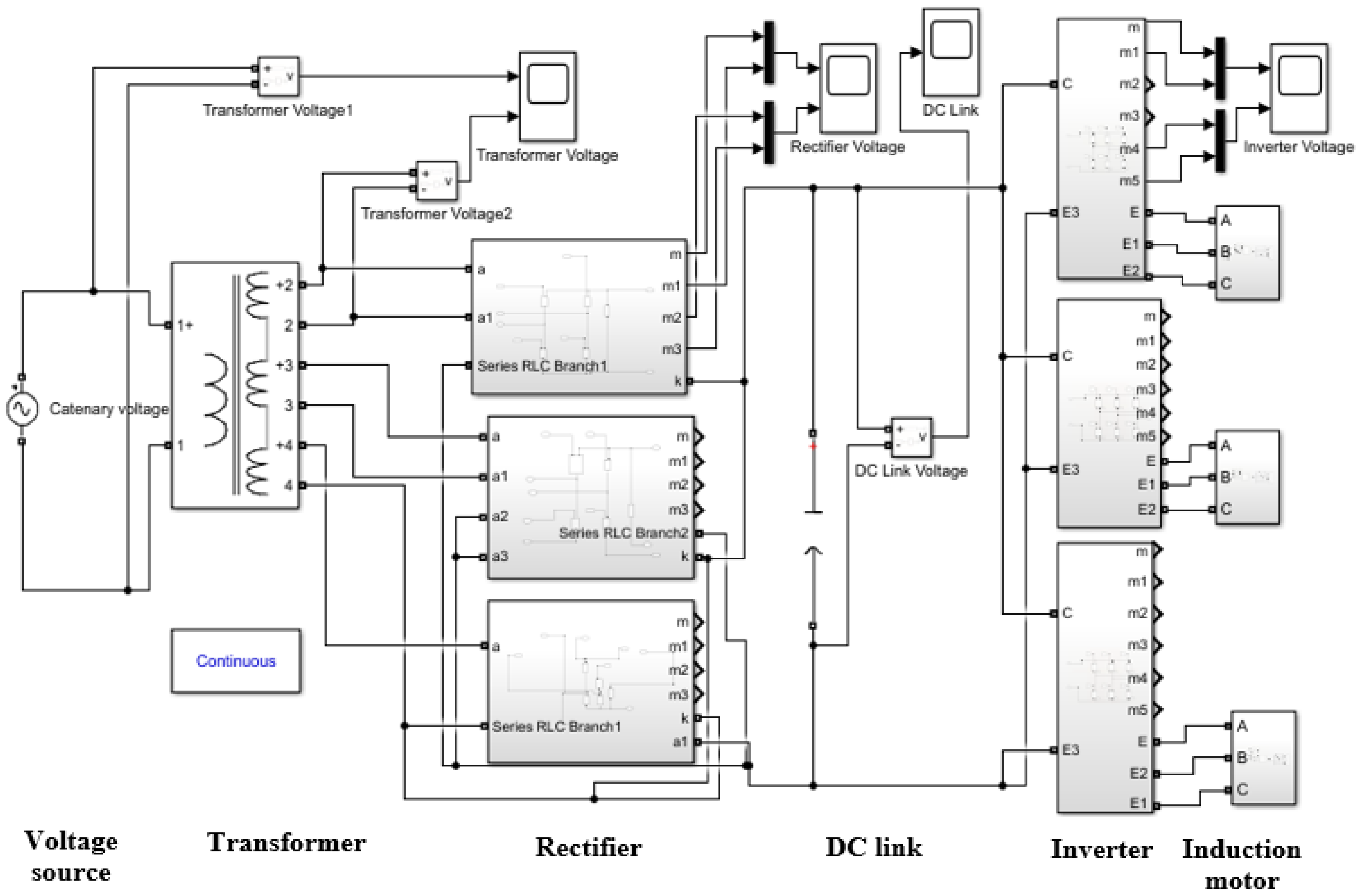



Figure 4.3: The general Matlab/Simulink model

## 4.4 Power Converter Simulation using the GTO Thyristor

To verify the concepts as already discussed regarding the GTO thyristor, reasons for which the replacement of the GTO thyristor with the IGBT, thus, the simulation model for this system was developed. Figure 4.4 shows the simulation model for each subsystems with regards to Figure 4.3, which in this case, the construction was done using the GTO thyristor. Therefore, with respect to Figure 4.3, and due the fact that the subsystems are identical, what is displayed in Figure 4.4 is the content of one of the subsystem of the rectifier and inverter with it associated PWM control circuit. For this model, it consists of a single-phase full rectifier of GTO thyristor, DC-link and the inverter of 3-legs with two GTO thyristor per leg which is then connected to the three phase induction motor. The parameters for the GTO thyristor as tabulated in Table 4.2 was used for the simulation. The SPWM for the rectifier was developed to have the firing angle of $30^{o}$, line frequency of 50Hz and the pulse with of 50%. The switching frequency for the inverter was chosen to be 100 Hz.

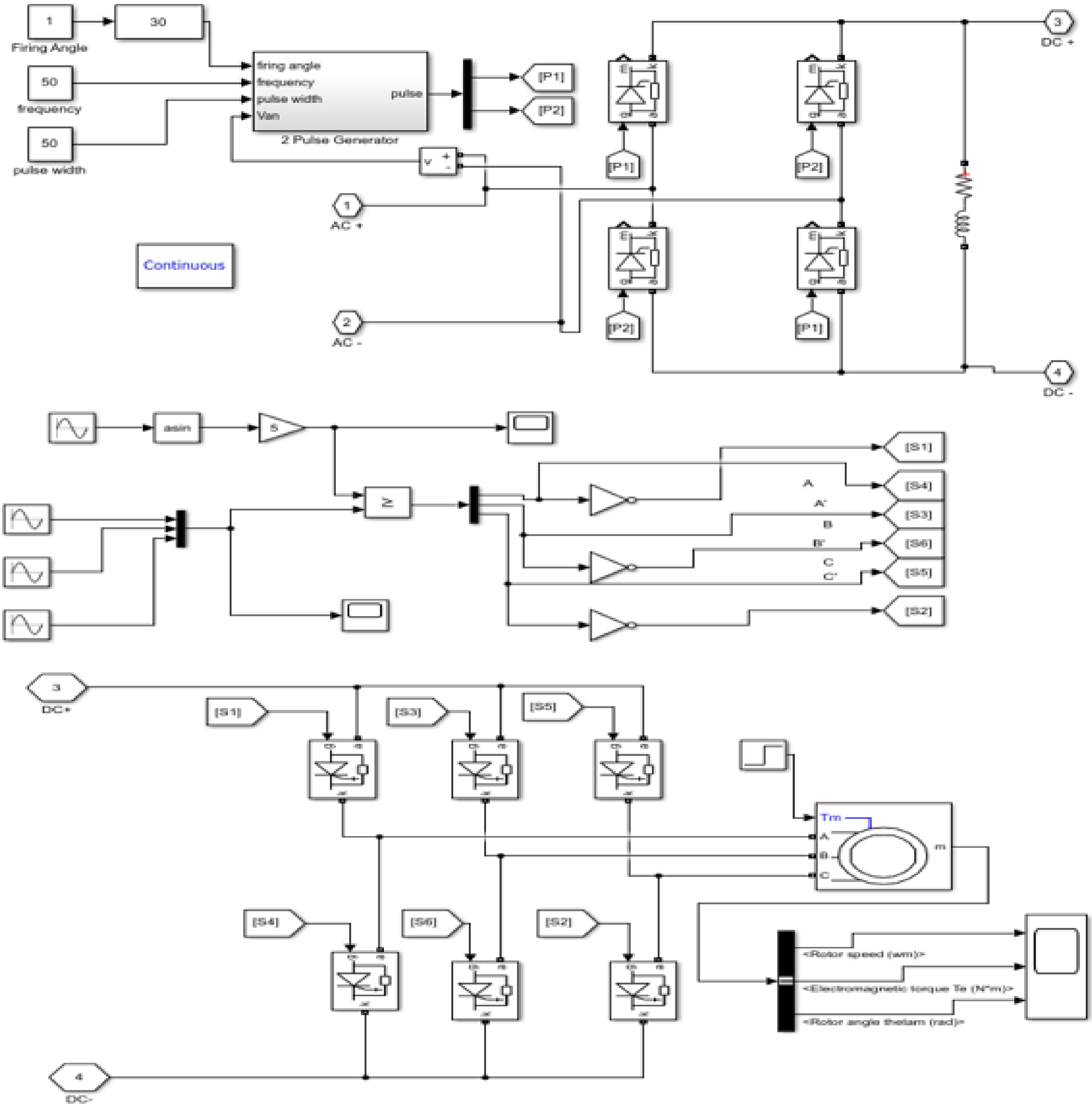



Figure 4.4: Matlab/Simulink simulation model using the GTO thyristor

## 4.5 Power Converter Simulation using the IGBT

Similar to the simulation model done for the GTO thyristor, the same concept was reproduced for the multi-level HV IGBT circuit, which consist of a single-phase full rectifier of IGBT, DC-link and inverter of 3-legs with two IGBTs per leg and finally three phase the induction motor as shown in Figure 4.5. The switching frequency was chosen to be 450 Hz. Also, the parameters used for the development of this numerical model are documented in Table 4.2. Three-level continuous sinusoidal PWM was used for both the rectifier and for the VSI. Although for the VSI, the SPWM was designed to carry out variable voltage, variable frequency operation.

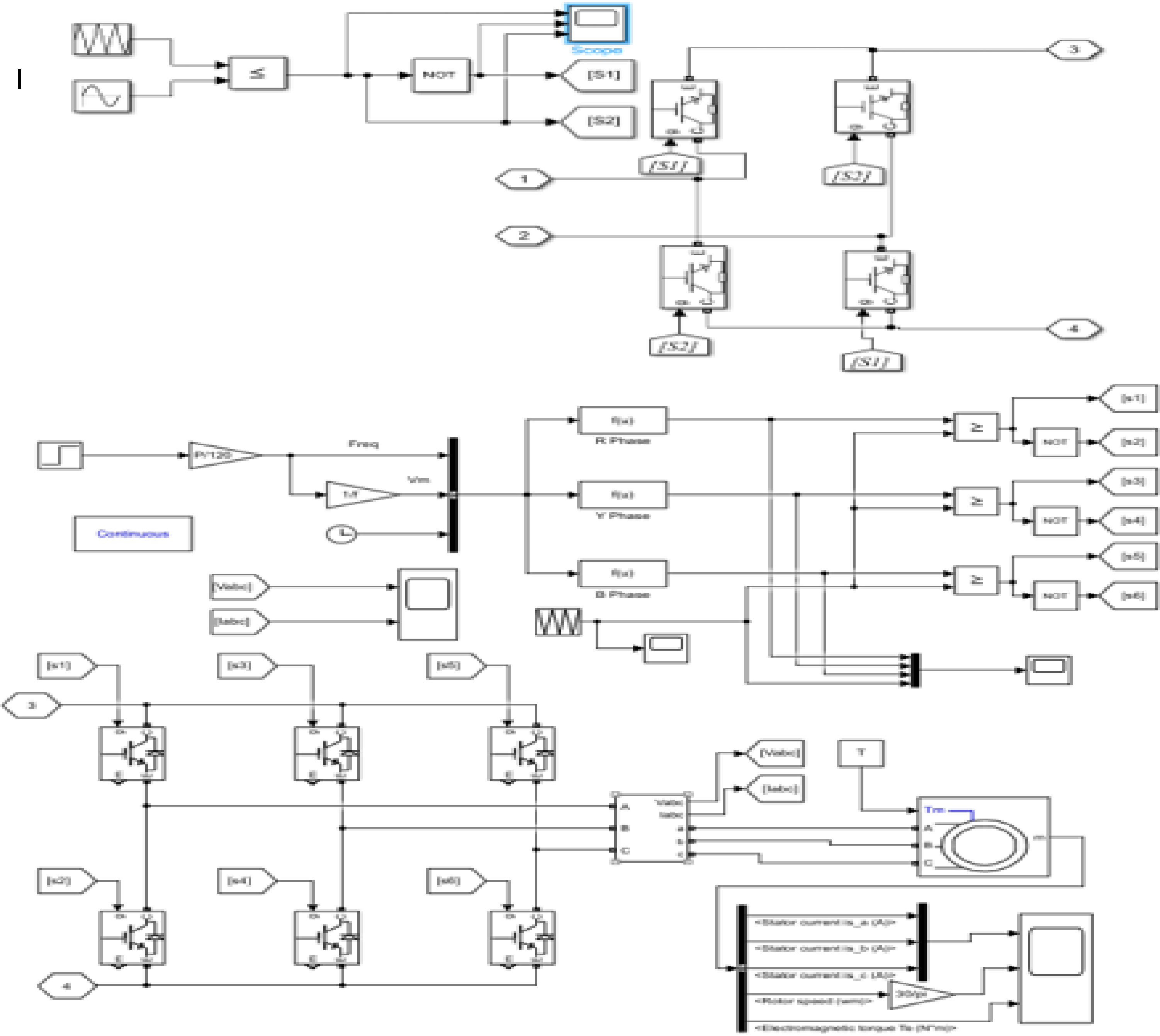



Figure 4.5: Matlab/Simulink simulation model using the IGBT

## 4.6 Cycloconverter Simulation

As presented in Chapter 3 was the analytical model for the cycloconverter. The simulation model was developed as a conceptualized power processor system with the possible application for the AC electric locomotives. The cycloconverte for traction system that was considered for this study was on the single-phase system i.e. the 1ϕ to 1ϕ bridge CCV was adopted for this study. The CCV consists of 8-SCRs that were fired at 0°, and this model was implemented on MATLAB/Simulink. Thus, the CCV fed induction motor model for traction application was implemented on MATLAB as depicted in Figure 4.6 for frequency control and motor speed control. The traction motor employed in the simulation model is the single-phase induction motor. The design process of the proposed model considered the three system performance criteria: efficiency, harmonics, and reliability. The efficiency of the system was determined based on the voltage, current, and frequency losses of the major components of the system. The harmonics generated were analysed based on the wave distortion of the three parameters. Lastly, the reliability of the system was analysed based on the speed response of the induction motor.

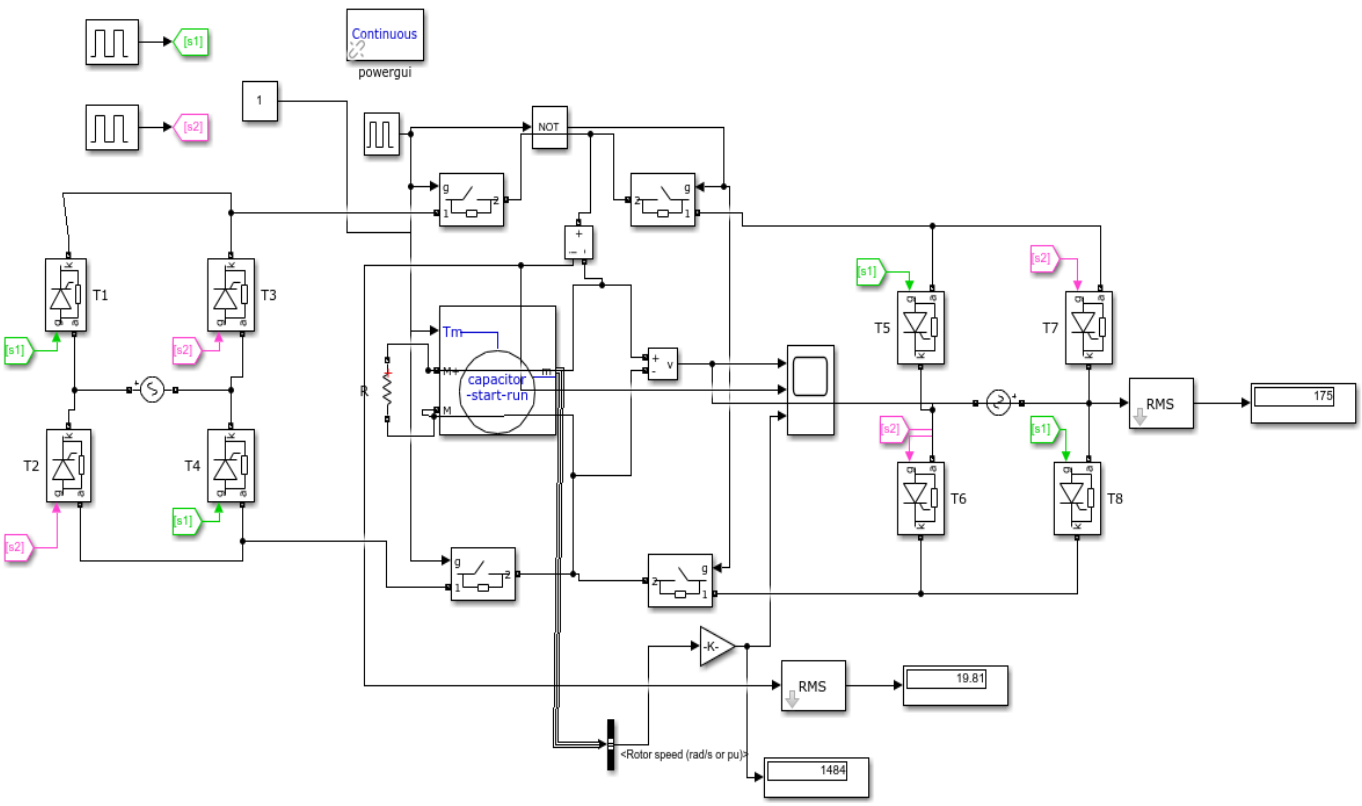



Figure 4.6. 1ϕ to 1ϕ bridge CCV Fed Induction Motor

## 4.7 Simulation Results

This section is used to present the results for the simulations that were carry out for the GTO thyristor, the IGBT and also for the cycloconverter. It is pertinent to note that, for the locomotive application, power processor systems were designed not only to meet the input and output requirements, but also to be compact or lighter in weight. These qualities of the converter systems can be ascertained based on either experimental or simulation work. To increase the power density of the switch can be achieved by increasing the switching frequency that leads to lower loss in the devices.

For both switches used for the numerical simulations, the transformer model with respect to the inputs and outputs values were the same. From the catenary, the on-transformer is supplied with a voltage of 25 kV and the step-down output voltage is 400V. Presented in Figure 4.7 are the input and output wave forms for the on-board transformer. The output graphs depict the sinusoidal output voltage of 400V which in this case is required by the rectifier in order to fine tune the ripples. Also, common, but not the same results are the output results for the induction motor as applied to both GTO thyristor and the IGBT. The next four subsections are used to present, first the calculated result for the IGBT and then the simulation results for the GTO thyristor, the IGBT and the cycloconverter.

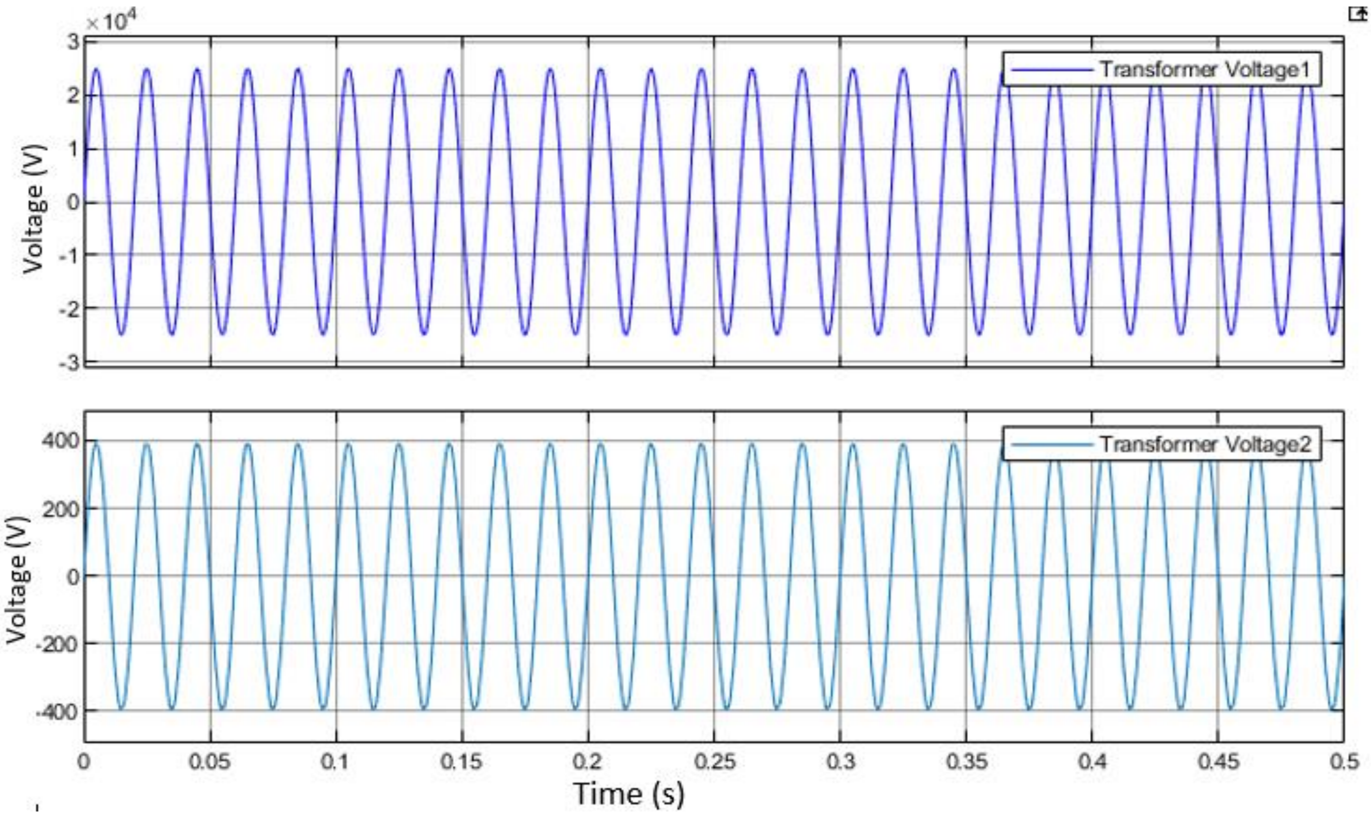



Figure 4.7: Measurement of the input and the output voltages of the on-board transformer

### *4.7.1 Calculated Results for IGBT*

A numerical calculation was carried out, using the equations as developed for the IGBT inverter system as presented in section 3.7. The developed MATLAB code to implement these equations for the system is presented in Appendix A and the data sheet for the IGBT is presented in Appendix B that was used for the evaluation of the efficiency of inverter for the IGBT. The numerical analysis was done using a squirrel-cage induction motor with the properties as documented in Table 4.3. Using the slip of 1.5% at the operated condition of the locomotive. Hence, the rated rotor torque is 107.5992 N-m and pf is 0.9087

The phase current and voltage for the induction motor were obtained as:

$$I_{ph} = 423.7073A$$

$$V_{ph} = 221.7337V$$

Using the following parameters that was

$V_{CEO} = 0.85\ V$,

$r_{CE} = 1.25m\Omega$,

$V_{f0} = 0.8\ \text{V}$

$r_f = 1.3m\Omega$

The switch and diode switching energies at $125^{\circ}C$ respectively.

The switching energies was taken at the test voltage of $3000\ V$ and this was then used to determine the conduction and switching losses of the IGBT.

Hence, the losses can be calculated numerically as follows:

The average switching current for the switch was evaluated as:

$$I_{Q(\text{sw,avg})} = 381.4706A$$

From the Appendix B, the approximate losses for the IGBT switch from the Figure B were evaluated as:

$E_{on}(I_{Q(\mathrm{sw,avg})}) = E_{on}(381471) \approx 2mJ$

$E_{off}(I_{Q(\mathrm{sw,avg})}) = E_{off}(381.471) \approx 4.34mJ$

$E_{rec}(I_{Q(\mathrm{sw,avg})}) = E_{rec}(381.471) \approx 3.32mJ$

Using these above values for losses interpolated from the Figure in Appendix B for IGBT and diode evaluate power losses for the inverter. Using the heat sink to be maintained at $80^{\circ}C$, and the thermal resistances of the IGBT and diode are $0.08^{\circ}C/W$ and $0.16^{\circ}C/W$, respectively [61].

The inverter loss was evaluated as

$P_{loss} = 1591.3W$

The inverter efficiency is

$\eta =$ 0.9818 or 98.18 %

### *4.7.2 Simulation Results for GTO Thyristor*

After the voltage was stepped down by the step-down transformer, the output voltage was fed into the power processor unit starting from the rectifier. Hence, the simulations results presented is for the converter configuration using the GTO thyristors for both rectifier and inverter converters in the power processor. The simulation results were for the constant torque which invariably represented the steady state. Figure 4.9 shows the DC output waveform from the DC link after rectification and smoothing.

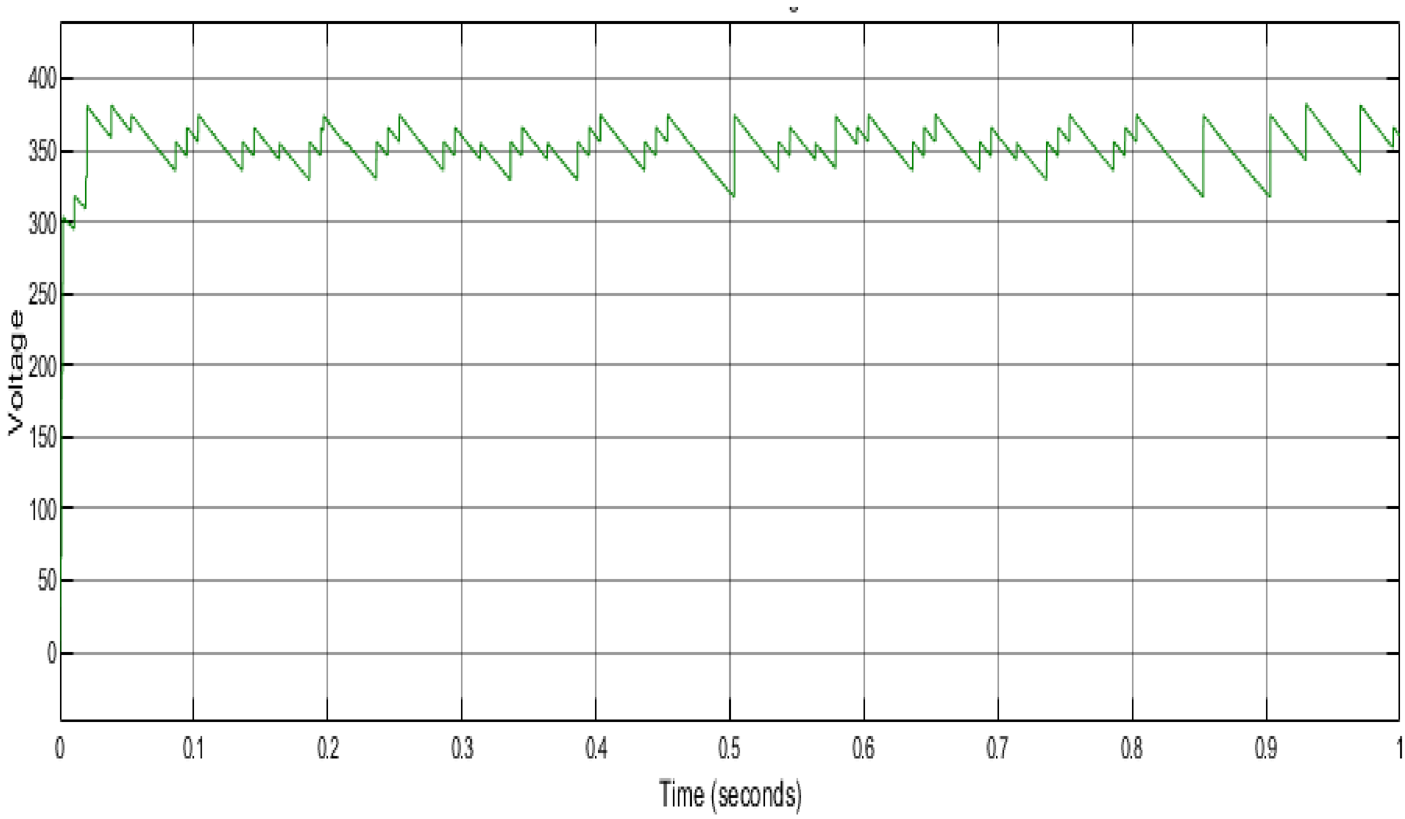


Figure 4.9: DC link output voltage for the GTO thyristor configuration

The full power steady state waveforms for the voltage source inverter using the GTO thyristors is shown in Figure 4. 10. This wave forms are the result for the simulated line to line voltages. From the result, it can be observed that GTO have a lot of ripples as the rectifier is not regulated in a DC mode during operation, hence all thyristor are not switched at same time. The GTO switching is not as fast, which result in more distortion that result to current inrush to the traction converter. Consequently, output power demand for the load is not met as the results depicts more distortion of the current.

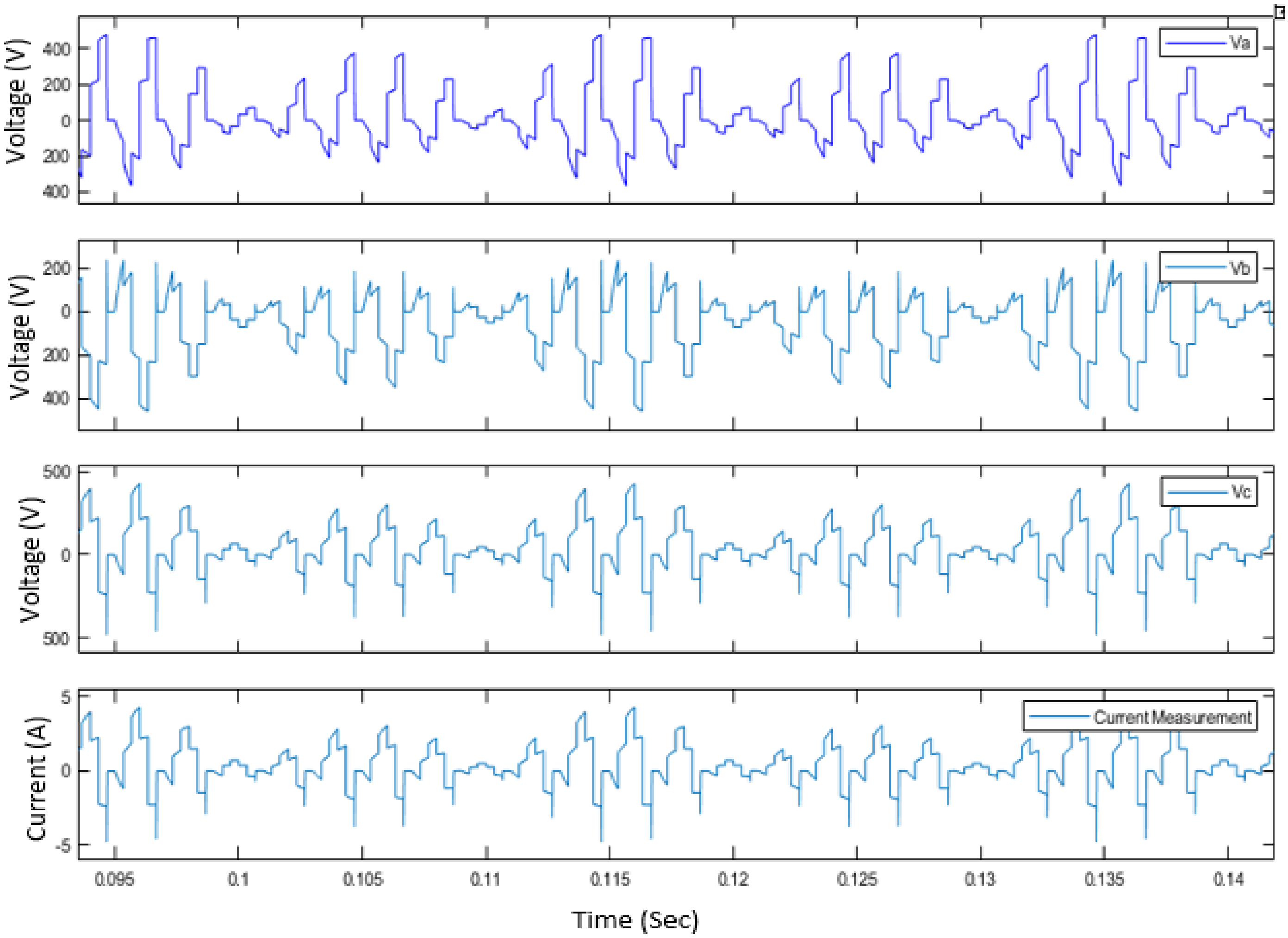



Figure 4.10: The inverter output waveforms using the GTO thyristor

The harmonic spectrum analysis of this inverter waveform was done as shown in Figure 4.11. This Figure presents the FFT and the spectrum analysis for the PWM voltage waveform as shown in Figure 4.10 for the 100Hz switching frequency. Since for the power processor unit is a the non-regenerative, three-level rectifier that is a voltage source rectifier, the input filter design and the DC-link capacitor selection was based on the parameters tabulated in Table 4.2. Waveforms for the FFT analysis of the inverter (AC-DC System) without any PFC circuit, the line current has THD = 58.11% and pf = 0.9396

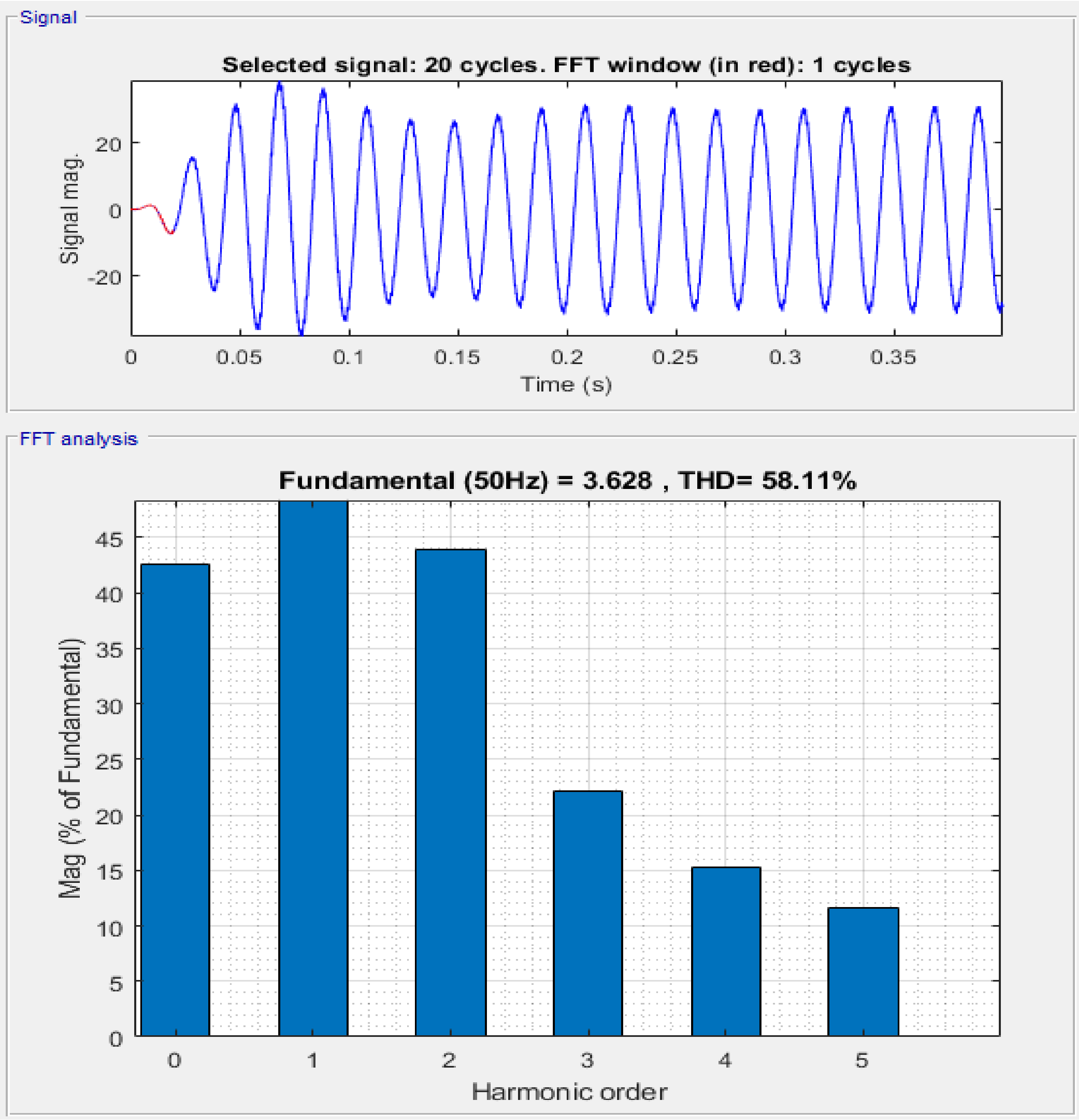



Figure 4.11: FFT analysis for the steady state simulation results for VSI using GTO thyristor

### *4.7.3 Simulation Results for IGBT*

A similar procedures used to carry out the computer simulation for the GTO thyristor, was also used to implement the computer simulation for the IGBT using the specifications as documented in Table 4.2. Due to reliability the considerations of the HV IGBT, the 6.5 kV IGBT switch was used, with the switching frequency of 450 Hz, for the purpose of this study. Firstly, Figure 4.12 is used to display the pulse generator that was employed to drive the switch with its respective the phase shifted SPWM operation for switch i.e. the gate drive signals of two corresponding IGBTs of each module.

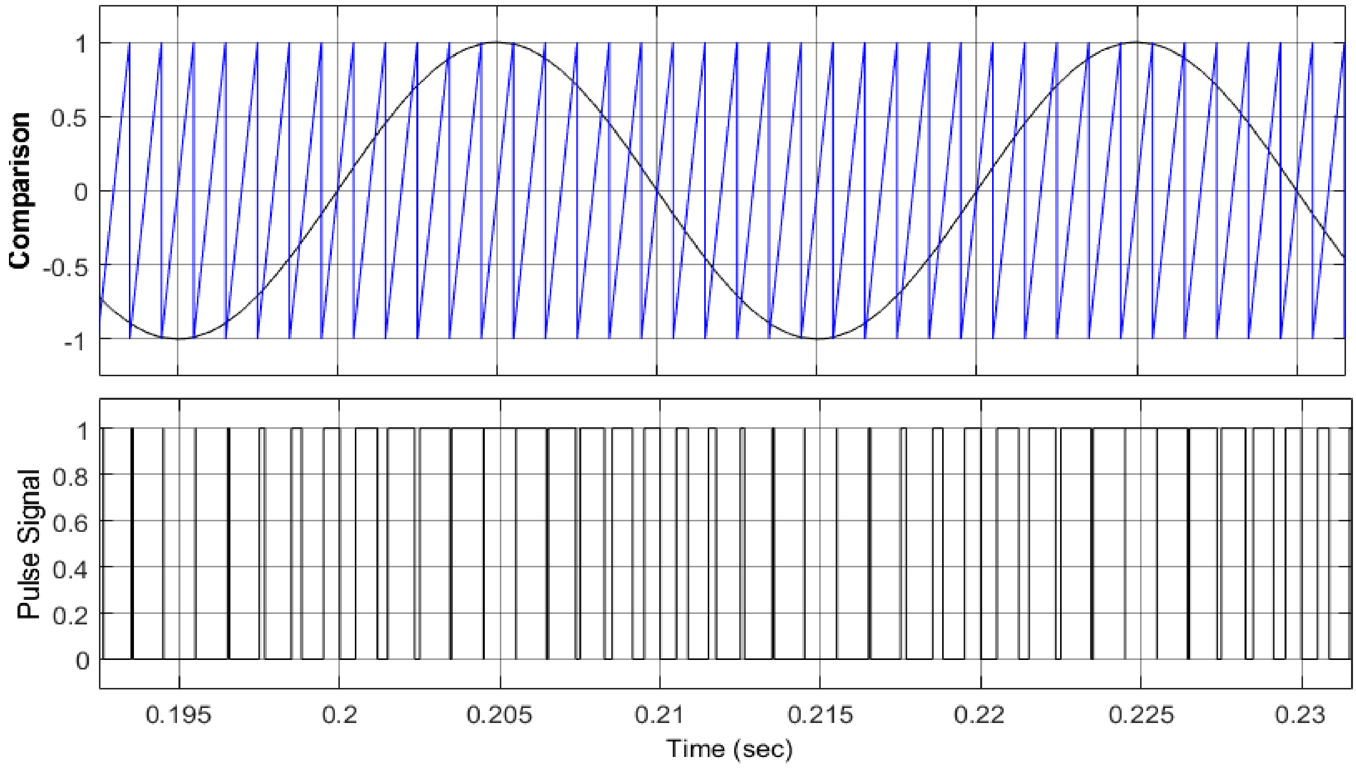



Figure 4.12: SPWM for operating the IGBT switch

Figure 4.13 shows the output waveform for IGBT rectifier connected to the regulated DC link. This wave form is the DC output waveform from the DC link after rectification and smoothing. From the result, it can be observed that DC link voltage is smooth with little or no ripples after the rectifications. This can be attributed to the fast switching of the IGBT which resulted in less distortion and invariably result in less current inrush being supplied to the traction converter, thus, output power demand for the traction motor is met as the results depict less distortion of the current.

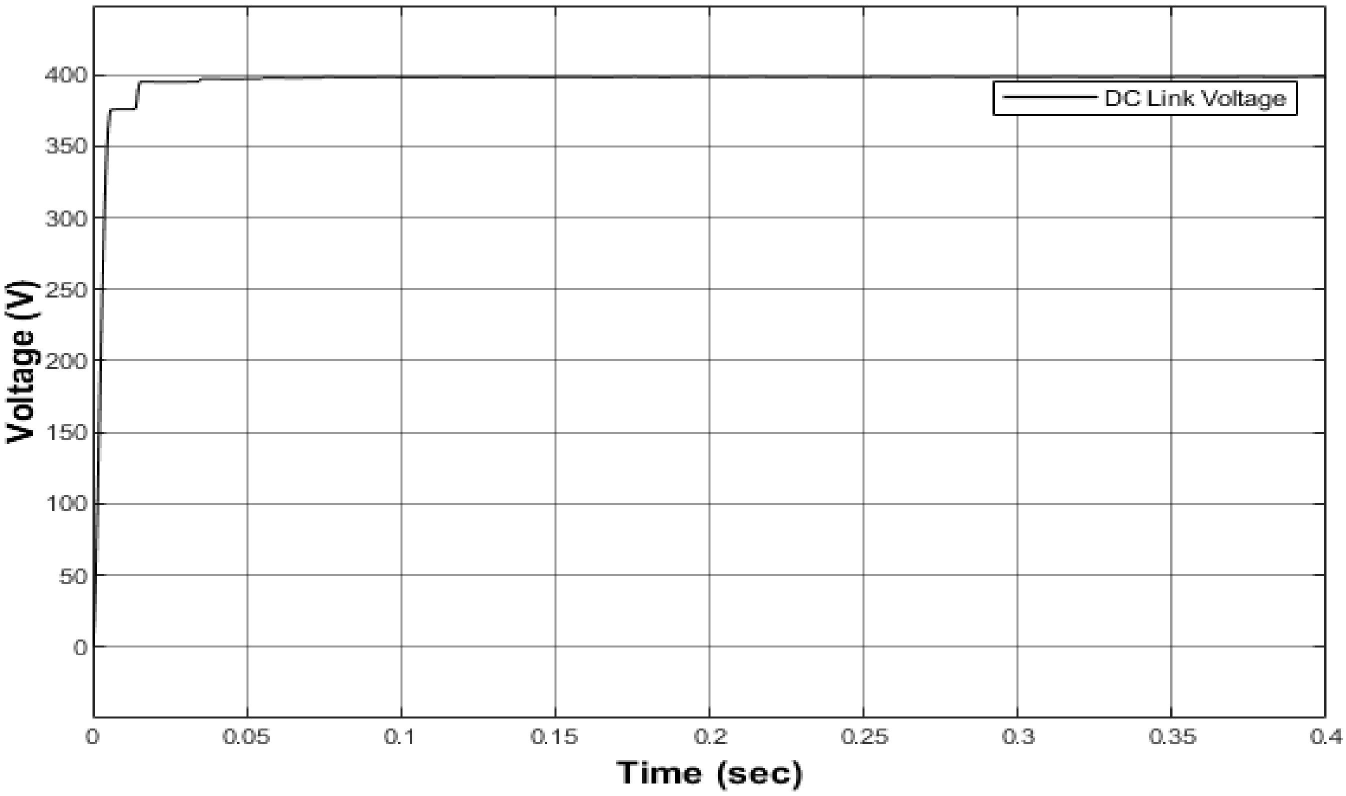



Figure 4.13: DC link output voltage for the rectifier IGBT configuration

Figure 4.14 is the simulation waveforms of approximately AC line voltages and current and for the VSI. The HV IGBT is operated by the SPWM as previously indicated in order to carry out the VVVF as required by the induction motor. This thus provide the regenerative capability for two-level, three-phase voltage source inverter. Under the conditions in which the measurements were taken at different load was to prove the capability of and the switching time of the IGBT in the traction converter.

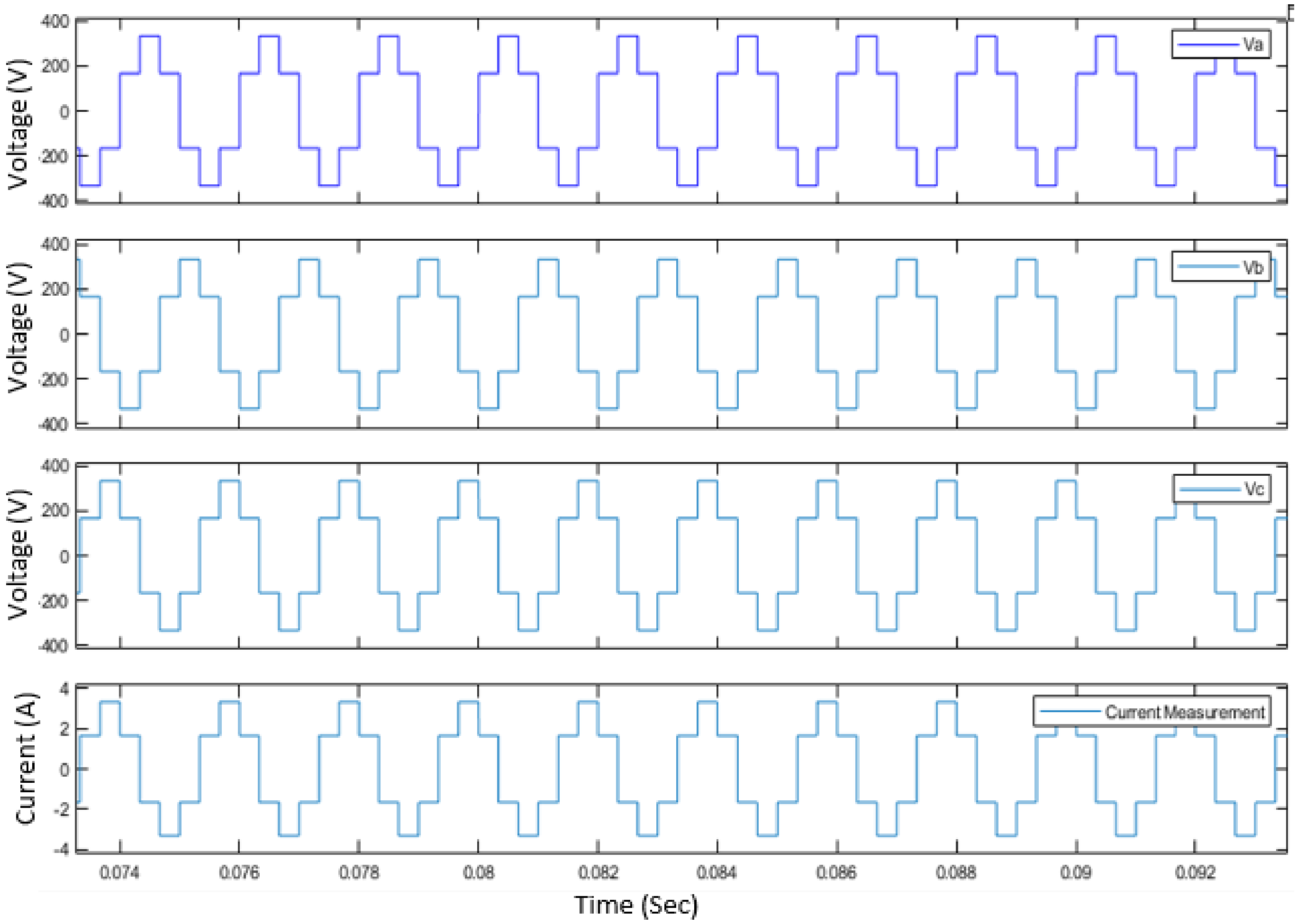



Figure 4.14: The inverter output waveforms using the HV IGBT

Figure 4.15 shows the FFT analysis and the spectrum analysis for the waveform of the PWM voltage presented in Figure 4.15. This Figure present the spectrum analysis for the PWM voltage waveform for the 450Hz switching frequency. FFT analysis of the wave for the line current has THD = 19.89% and pf = 0.9706

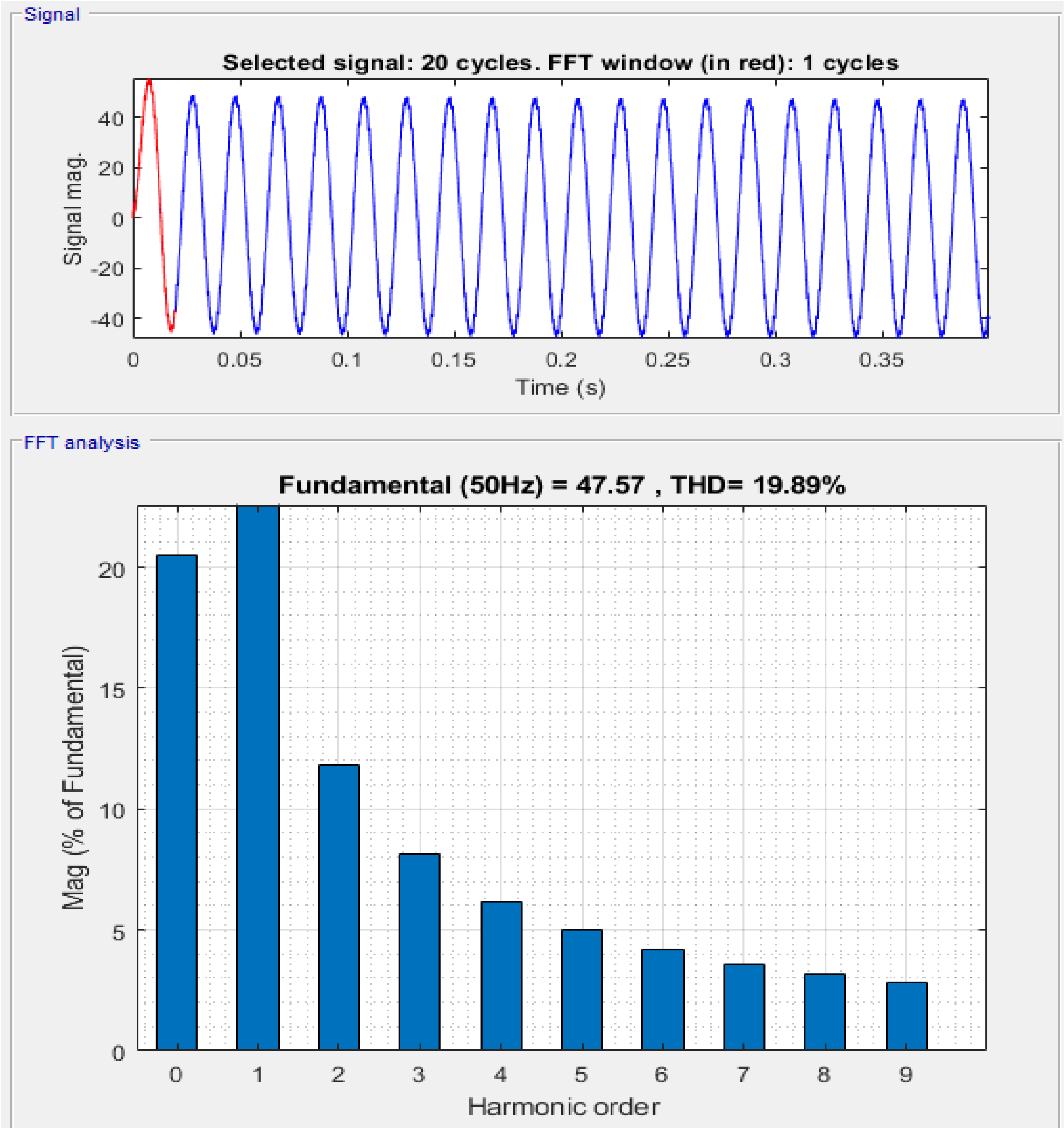



Figure 4.15: FFT analysis of the steady state simulation result for VSI using IGBT

### *4.7.4 Cycloconverter Simulation Results*

Figure 4.16a illustrates the input voltage of 230V, 50 Hz of the CCV. A purely resistive load was connected to the output of the CCV, from the Figure 4.16b and c it is clear that there is a 1/4 decrease in frequency. The SCRs were fired at 0° which is evident from the output waveforms of the CCV. As observed from the waveform, the input frequency is greater than the output frequency and therefore, this step-down CCV can be utilize for the traction applications for the 25Hz frequency.

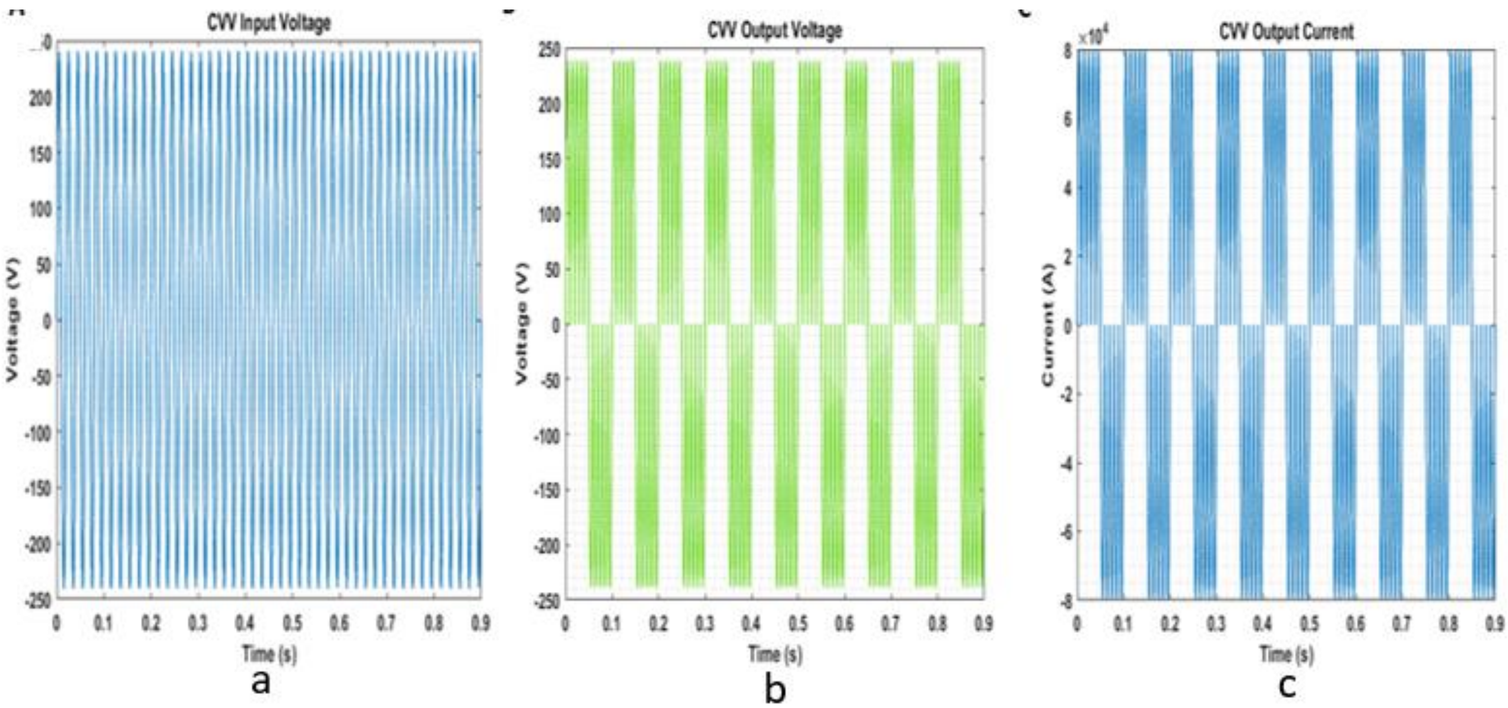



Figure 4.16. (a) CCV Input Voltage, (b) CCV Output Voltage (c) CCV Output Current

Figure 4.17(a) illustrates the output voltage of the single-phase induction motor, the waveform is not a pure sinusoidal wave, this is due to the implementation of the power electronics device as it is connected to single phase induction. Figure 4.17(b) shows the results of the speed response of the CCV fed induction motor. From the Figure it is evident that the CCV was able to control the speed of the induction motor. The speed of the induction motor reduces as the frequency reduces.

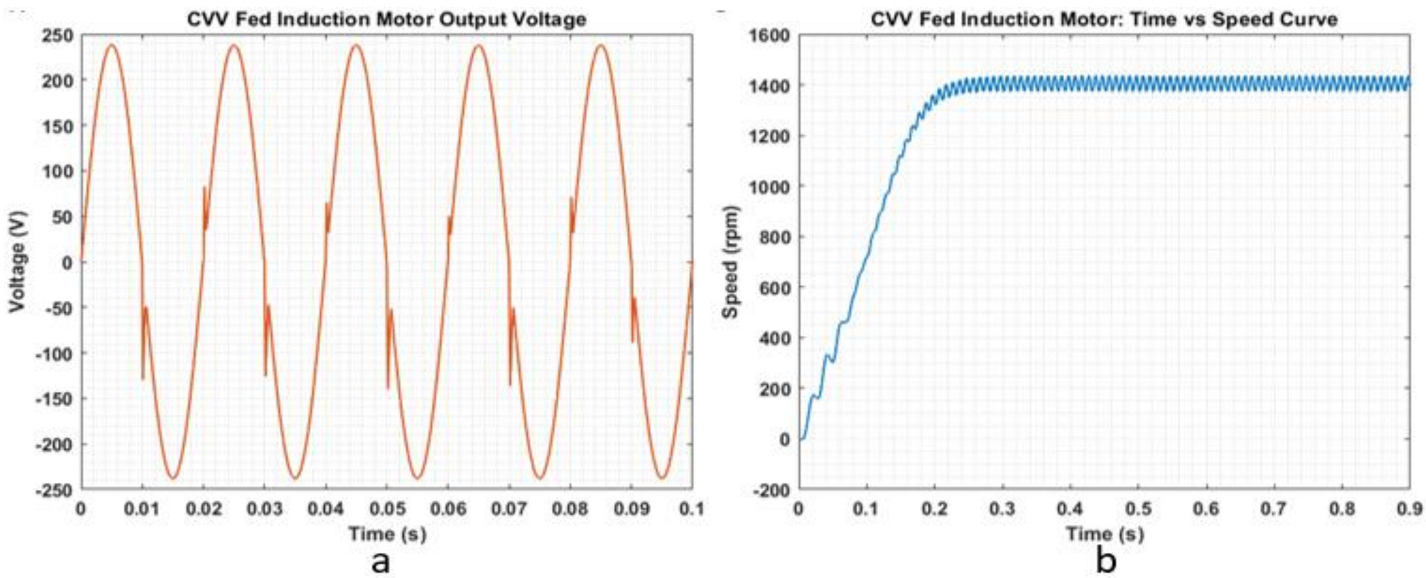



Figure 4.17(a) CCV Fed Induction Motor Output Voltage, (b) Speed Response

## 4.8 Analysis of Results

In this section, the simulation results obtained from the simulation models which was implemented on the MATLAB/Simulink environment was presented. The simulation models composed of the catenary line, on-board transformer, the front-end rectifier, control block of the PWM rectifier, VSI system and the AC traction motor. For the successful implementation of the models in the aspect of the AC electric locomotive using the MATLAB software, the results obtained were compared for both switches used. This study result was used as the bases of comparison between the use of the GTO thyristors and the replaced IGBT switches.

From the simulation results for the GTO thyristor, it was observed that the DC link wave form had a lot of disturbance. This is a proof that the inductor in the DC link will produce some harmonic which cause lots of disturbance on the line, using the GTO thyristor. Also, inference can be made, based on the output voltage, after the induction motor was connected to traction converter; a lot of distortion was produced as observed by the ripples in the voltage wave forms.

Based on the result as shown in Figure 4.13 for the IGBT, it shows the voltage for the DC without ripples which indicates that the power factor near to unity. It can be inferred that based on the output voltage after the induction motor or traction motors is connected to the traction converter, which indicate that less distortion was produced to the load. This is due to the rapid switching of the IGBT, which reduce disturbance before it reaches the end output voltage of the converter. According to the simulated result for the IGBT, it is observed to have less distortion due to the reduce inrush current. This signifies a better current and voltage for the operation of the load. The rapid switching of IGBT, which correct the disturbance before it reaches the end output voltage, therefore HV IGBT is well regulated by PWM techniques. The voltage stability is 90 % balanced due to no crowbar and other external components in the IGBT circuit, it is noted with GTO thyristor it will have a lot of ripples as the rectifier is not regulated in the AC mode during operation.

Hence, all thyristors are not switched same time and are not faster at optimum operation when compared to the IGBT. With the parameters of GTO, the $T_{off}$ (turn off) time is not as fast as compares to IGBT $T_{off}$, thus, in the application of GTO thyristor during transient has an impact, due to turn off time that can be delayed. This can result to possible explosion of the converter module, but with the IGBT, this phenomenon can be avoided due to enhances parameter of the turn off as proven in the simulation results. The use of the switch has provided more than 25% reduction in on-state voltage drop for the same turn off losses for the IGBT in comparison with which the GTO thyristor. With the compactness of IGBT, it was noted from calculation and simulations results that, capacity of maximum power was increased as compared to the GTO thyristor, thus, the handling power capabilities when transient of over voltage can be withstand by the IGBT. As a result, the locomotive traction effort was improved by 9% as compared to the GTO thyristor because the lower losses from switching of the IGBT make it more efficient when compared to the GTO thyristor.

It is shown and proven that the converter system using the IGBT can achieve regenerative braking, GTO thyristor cannot achieve regenerative braking instead, the Reostate braking is employed, in the case, the resistor was used to dissipate the power as heat and liberated to the surroundings.

The power losses of an unsnubbed IGBT converter are reduced by 50% over a wide power range as compared to the GTO thyristors converter with similar configuration. Power losses are even further reduced by up to 85% during partial load operation of locomotive. From the analysis of results, the following were observed with respect to the outcomes of this study:

- The harmonic filters impact at 50 Hz line is reduced to the acceptable levels with the application of IGBTs.
- Physically, the IGBT configuration on the inverter side consists of cascade arrangement of IGBTs in a fuseless phase modules in a turns (Ns = 8 + 4) which is design to protect the respective line of about 20 km before encountering another traction substation.
- The multi-level converter concept allows the filter less operation of the railway side IGBTS inverter to be implemented due fact that little harmonics is generated with line losses are reduced substantially i.e. no need for filters
- Four DC-voltage choppers with the IGBTs can fulfil the ripples filtering and the power factor of the VSI is kept at unity.
- The efficiency of converter as a result of the simulation work with respect to IGBT was consistent with the calculated theoretical efficiency.

In conclusion, based on the results presented for the operation of the power processor unit for both switches, IGBT has proven to be the faster switching device which resulted in a significant reduction in the switching losses. Thus, the upgrade of the locomotive using this form of converter systems is justified.

## 4.9 Analysis of the Study Locomotive Protection

As iterated in this study that the upgraded locomotive converter systems offer some level of protection to the locomotive. For IGBT application for the medium and high voltage power electronic in locomotive offers some level of protection to the locomotive. Based on the analysis of results of the computer simulation of the AC electric locomotive, these concepts were deduced with respect to locomotive protection. All switches are assumed to open after the failure is detected, and the input side of the circuit breaker opens when the phase current crosses zero. Also, the parameters of the passive components in converters systems will also dictates the failure mode performance of the system. As can be observed, based on the results for the high rating voltage IGBT, in the aspect of protection, the switch must have lower tum-off current density capability for protection purpose during the locomotive operation. This is because the high efficiency of hole injection from p collector layer and this is needed for the higher voltage of IGBT operation in order to reduce voltage drop in thick n-drift layer.

IGBT possess monoltythically structure that is used to integrate the antiparallel diode, so, the gate drive, are capable to discontinue the power supply in order to protect the locomotive, making snubberless IGTB to turn off at high di/dt. The main advantage of the IGBT in comparison with the GTO thyristor, is that IGBT has a low component count due to dynamic blocking of voltages up to 6 kV with an inherent high reliability and low losses. This features enables the IGBT converters to have far less probability for explosion during high rate of change of current and as addition, the switch also has the capability of limiting the fault currents using current limiter by means of reducing the rate of change of current. Thus, the IGBT possess the following advantage to the locomotive protection by means of the traction converter (4-QC)

- Thermal cycling capacity of IGBT
- Fault protection on the collector
- Cosmic ray withstand capability of the IGBT
- Less random failures within the press pack.

## 3.10 Inference Based on Results

As presented in this Chapter is the simulation results and its analysis. Based on the analysis of the results, the following inference were made. These inferences were based the on the evaluation procedure for comparing the topologies for the two switches as carried out in this study. Conversely, the inference was based on approximation of similar topology of the semiconductor devices either IGBT or GTO thyristor. The inferences based on the results, the IGBTs application in medium power converter technology application for the AC electric locomotive can be summarized as following:

- The IGBTs module can have high blocking capability of voltage ratings
- ·Lower switching losses which can results to a possible higher switching frequency.
- The IGBT switch has easy gate drive which makes it easy for it, as they can be voltage controlled using the SPWM.
- The switches snubberless (i.e., no snubber circuits), this directly result to converters system to have reduced weight, less volume and a high power density.
- For the rectifier to employ the interleaving converter systems makes it possible to carry out redundant operation. The concept of redundancy is when the locomotive operation continues but with lesser capacity in a situation, that a failure does occur in any of the converter systems.
- In line with the last inferences, the converter systems using the IGBT have a less harmonic distortion, with the possibility of redundancy operation when one or two converter fails and equitable power sharing among the various converters module and these leads to the reduction of the switch current ratings.

Therefore, the IGBT switches have demonstrated that they are the best-suited semiconductor devices for high power AC locomotive traction applications.

## 4.11 Retrospect to the Study Motivation

Railway traction system technology is continually improving due to the constant and consistent advancement made in the area of semiconductor/power electronics technologies. This is one of the very important factor responsible for the continuous improvement of the power processor unit in the locomotives.  As indicated at the onset of this study, the main objective of this study was to compare the two topologies for the power electronic processor systems for the AC electric locomotive. As such, this has resulted in the development of the numerical models in this study, which was used to simulate the power electronics converters systems, with its implementation in the Matlab/Simulink environment. This numerical model has provided a more realistic technique that is very useful in the interpretation of power electronics operations in an AC electric locomotive. Thus, this numerical model for the converters served as the basis for the interpretation and analyses of the results for the operation of the locomotive. This model has helped in the evaluation of the energy balances on the basis of the power flow that serves as the means of quantifying the different transformation and utilization of energy, starting from the catenary to the traction motor.

In embarking on this study, the initial concept was to validate the findings of this study with real world scenarios in the aspect of IGBT converters systems. This concept in reality, obtaining information and resources turns out to be a “black box”, in which the user is not given access to information. This was largely due to the confidential clause, in which information were not allowed to be used or shared by companies responsible for the manufacture of locomotives. Alternately, the focus was now turned to using resource from peer-reviewed papers, scholarly published articles and textbooks. The major problem with this alternative has to do with the contradicting concepts, inferences or claims not substantiated and most of the outputs from these sources are not validated.

In conclusion, as a retrospect to the motivation for this study, on bases of the resources available, the work presented has satisfactory proven that the aims and objective for the study was fulfilled.  Hence, in a nutshell, the outcomes of the analysis of the simulation results has validated and then justify the transition from the GTO thyristors to the IGBTs for the power electronics converters application for the AC electric locomotive.

# Chapter Five

# Conclusion and Recommendation

## 5.1 Conclusion

The development of the medium power switching power electronic processor for operating AC motor applications with respect to the locomotives traction has been of interest in area of power electronics engineering. This is due to the ever evolving, and rapid advancement in semiconductor technologies, which are being used to solve many challenges that are associated with the complicated power converter system. In this study, there arose the need to investigate the power electronics converters for traction drives, in comparison using two power electronics switches. In this study, the design and simulation of the power electronics converter systems for the locomotive traction systems was carried out. This entails the modelling of the rectifier topologies such as the interleaved, two-level rectifier converter, the series connected inverter with common DC link, coupled to the induction motors. The converter configurations for the two switches were investigated and then compared in terms of parameters such as the line current harmonic, converter efficiency, reliability, and the concept of redundancy of the converter systems. For the topologies presented in this study, the voltage source based topology which is composed of single phase, two-level front-end rectifier which is connected to a common DC link, fed by isolated secondary multi-windings of a front-end transformer and controlled with phase shifted SPWM method.

Hence, in this dissertation, a systematic methodology to design and analyse the medium power density power processor i.e. the AC-DC-AC converter system was developed for the AC electric locomotive. The main factors of the converter system were investigated with the goal to ascertain the justification of the transition from GTO thyristor to IGBT as the switches in the converter system.

Firstly, based on the developed model, the computer simulation for the topology for the GTO thyristor was carried out. The simulations were carried out with the functional integration concepts of converter in line with the physical characteristics. The topology evaluation was presented, which provided insight into the relationships between the system constraints, operating conditions and design variables. Secondly, a similar computer simulation was carried out for the IGBT topology. Both computer simulations were then compared based on the computer simulation approach, in addition, the converter failure mode operation and corresponding protection approaches was discussed. For both simulation, the three-phase AC induction motor converter was used. Based on the computer simulations, the IGBT switches were able to demonstrate that their operations are better suited for medium power AC locomotive traction applications.

In conclusion, the key concept and idea developed in this study was the implementation of the numerical simulation which was then used to verify that IGBT application in traction drive is of better operation as compared to that of the GTO thyristor. The design and verification of the power processor system for the AC locomotive, controlled by SPWM using the simulation technique have been justified the replacement of the GTO thyristor by the IGBT.

## 5.2 Recommendations

This study was able to establish the performance of GTO thyristor and IGBT as used for the power processor application in the AC electric locomotives. It is an established fact that the area of power electronics is very dynamic and there are always advancements in semiconductor technologies. Firstly, due to rapid development of faster switching device such as wide bandgap IGCT. It well known that the wide bandgap semiconductor switches are more reliable power electronic devices that allow the transfer/conversion of higher power and voltage with faster switching. Therefore, locomotive converters application in traction drives, this offers new opportunities for high efficiency and power density with the use of a newer form of switches such as the wide bandgap power semiconductor.

It should be noted that the cycloconverter converter technology possible application was done in this study. It was conceptualized as possible application in the power processor in the locomotive for the future. It was envisaged that to develop this form of power converter system for the AC electric locomotive power processor unit, further investigations are needed for this possibility to be ascertain.

Finally, this research may entail theoretical analysis, numerical modelling coupled with computer simulation, and an experimental work can be developed where a laboratory prototype is built to perform experimentation. The experimentation can be used in validating various converter system configurations, including the cycloconverter. Hence, prototype design may compose of the developed cycloconverter system, the AC inductor motor that can be considered as representation of load.

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# Appendix A

Matlab Codes for Evaluating the IGBT Efficiency

```
Pr=160000;                                          % Rated power

Wr = 1487;                                          %Rotor speed
Tr =Pr/Wr                                           % Rated torque
fr=Wr/(2*pi);                                       %Rotor frequency
s=0.015;
fsyn=fr/(1-s);                                      %Synchronous frequency
fslip=fsyn-fr;                                      %Slip frequency
p=6;
fe=(p*fsyn)/2;                                      %Electrical frequency
Tnl=2;
Pcfw=Tnl*Wr;                                        %No load losses
%Tr=140;
Tem=Tr+Tnl;                                         %Electromagnetic Torque
Pem=Pr+Pcfw;                                        %Electromagnetic Power
Rrr=0.0048;
Irr=sqrt(s*Pem/(3*Rrr*(1-s)));                      %Secondary current
Irrr= Irr+0i;
Llr=40e-6;
Lls=50e-6;
we=2*pi*fe;                                         %Angular speed
Zrr=Rrr/(s)+we*Llr*1i;                              %Reflected rotor
impedance
Em=Irr*Zrr;                                         %Back emf
Lm=2e-3;
Imm=Em/(we*Lm*1i);                                  %Magnetizing current
Iphase=Irrr+Imm;                                    %Phase current
Iph = abs(Iphase)
Rs = 0.012;
Zstator = Rs + we*Lls*1i;                           %Stator Impedance
Vzs=Iphase*Zstator;                                 %Stator voltage drop
Vphase=Em+Vzs;
Vph = abs(Vphase)
Pmloss = Pcfw + 3*Rs*(Iphase)^2 + 3*Rrr*(Irr)^2;    %Machine power losses
Pin = Pr + Pmloss;                                  %Input power
Efficiency = Pr*100/Pin;                            %Efficiency
PF=Pin/(3*Vphase*Iphase);                           %Power factor


%Inverter Currents
% Vph=104.21;
Vdc=580;
% Iph=301.5;
cosx=0.9087;

    %Various DC Currents
Iqdc = Iph*(1/(pi*(2^0.5)) + Vph*cosx/(2*Vdc));
Iddc = Iph*(1/(pi*(2^0.5)) - Vph*cosx/(2*Vdc));
Ihvdc = 3*Vph*Iph*cosx/Vdc;

    %Various rms Currents
Iqrms = Iph*(0.25+ 4*(2^0.5)*Vph*cosx/(3*pi*Vdc))^0.5;
Idrms = Iph*(0.25- 4*(2^0.5)*Vph*cosx/(3*pi*Vdc))^0.5;
Ihvdcrms = Iph*(Vph*(6^0.5)*(1 + 4*(cosx^2))/(pi*Vdc))^0.5;
```

```
Ichvrms = Iph*( Vph*(6^0.5)/(pi*Vdc)+ (4*Vph*(6^0.5)/(pi*Vdc)-
9*(Vph/Vdc)^2)*cosx^2)^0.5;

%Inverter Power Loss

Vce0=0.85;
Vf0=0.8;
Iqqdc=115.45;
Idddc=20.28;
Rce=0.00125;
Rf=0.0013;
Iqqrms=199.87;
Iddrms=74.19;
Iq = (2*Iph*sqrt(2))/pi

Vdc=580;
Eon=2e-3;
Eoff=4.38e-3;
Erec=3.32e-3;
Vtest=300;
fss=10e3;

Pqcond=Vce0*Iqqdc + Rce*Iqqrms^2            %Diode conduction losses
Pdcond=Vf0*Idddc + Rf*Iddrms^2              %Switch conduction losses

Pqsw = (0.5*fss*(Eon + Eoff)*(Vdc))/Vtest  %Power losses
Pdsw = (0.5*fss*(Erec)*(Vdc))/Vtest        %Diode switching losses


%IGBT Module
Po=85652;
Pq = Pqcond + Pqsw;
Pd = Pdcond + Pdsw;
Ploss = 6*(Pq+Pd)                           %Inverter loss
InvEfficiency=Po/(Po+Ploss)                 %Inverter efficiency
```

# Appendix B

Graphs for Extrapolating IGBT Switching losses