NTNU – Trondheim
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Stability of Autonomous Power Systems on Ships and Offshore Installations

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Problem Description

The dynamic positioning (DP) vessels by far are the most reliable mean for the exploration of oil and gas in the sea. Drilling in deep water is possible due to the DP vessel. To keep the vessels, in continuous operation availability of power is important. In case of severe fault, situation arises sometimes which may lead to complete blackout of the electric supply in the vessel. This situation may cause life injury of undersea diver. This problem is more prominent when the power system is connected with autonomous grid.

The voltage fluctuation in case of fault may also lead to the blackout of the whole electric system. Non-linear devices in the ship power system produces harmonics in the system which ends up distorting the voltage. By understanding the behaviour of the power system components in different types of faults, possible reasons for the blackout can be estimated.

In this master thesis work has been done on the followings:

- Implementation of the power system model on the ship in SIMULINK™ SimPowerSystems™ and analyse its behaviour in different situations.
- Brief study of power quality issues in the ship power system by using literature studies and simulation results.
- Finding out the different techniques to mitigate these power quality problem in the system by using existing variable frequency drives.
- The development of different methods to minimize the effects of power quality issues.

This is done by simulating the power system model on ship and studied with different cases which may cause power quality issues. Understanding the working principle of variable frequency drives for thruster motor is done in this thesis. The design of control for both the rectifier and inverter is also performed for better results. The harmonics produced by the non-linear loads are successfully mitigated from the source current using the variable frequency drive (VFD) in the system. The voltage support is also being provided by the same VFD during the faulted condition, which keeps the voltage with in limits set by the IEEE and IEC.

Abstract

Advancement in technology has increased the reliability and ease of work in the ship power system, but these advancements are also adding complexities in the system. The ever increasing non linear loads, i.e. power electronic devices effect the stability of the system. In these power systems, voltage fluctuations can be observed with small change in load. Such systems are characterized by weak grids (The weak grid in the ship power system does not possess the same definition as in the long transmission lines, usually it is taken out as grids where voltage is not constant. It can also be described as, the grid where voltage fluctuations need to be considered because of the chances that it might change with minor change in the load). The frequent load variations and complex load dynamics are due to the frequency converters and motor drives.

The power quality problem such as voltage dips, swells and flickers cause the fluctuations in the grid voltage which in worse case may lead to blackout of the whole electric system. The non-linear loads in the ship power system produce harmonics in the source current, which produces fluctuations in the voltage. These problem can be handled if the converters on the ship power system works as active filters. A thorough review of these problems and their mitigation techniques are done in the theoretical part of this thesis.

The rectifier used in the variable frequency drive is bi-directional converter which can convert AC into DC and DC into AC. This rectifier not only supply the voltage to the propulsion motor but also regulates the voltage of the system by removing the harmonics from the source current and by injecting the reactive power into the system. In this thesis the vector control scheme is used for the control of both the rectifier and inverter, parallel operation of synchronous generators is also demonstrated. The harmonics and reactive power compensation is performed by the VSC converter, which increases the stability of the system by improving the voltage regulation.

The simulations were carried out to improve the total harmonic distortion in the source current waveform. The harmonics and reactive power compensation was first performed in the system with ideal power supply to check the operation of VSC converter. The total harmonic distortion is kept down to 0.70 % which is with in the standards set by IEEE and IEC.

The parallel operation of synchronous generators were performed to build the same model as on ship. The variable frequency drive was used, which had VSC converter for harmonics compensation. The simulations were carried out first with one and then with two variable frequency drives. The THD was reduced to 4.05 % with one VFD and 3.87% when two VFDs were installed.

By keeping the THD with in the limits, the fluctuations in the voltage can be removed

which helps in improving the stability of the system. The voltage support of the grid was also performed during the symmetrical three phase to ground fault with the help of VFD. The voltage was improved from 350V to 510V, which is with in the allowable limits for the ship power system.

The stability of the system can be improved by making the converter as active filter. It will not only compensate the harmonics but also provide the voltage support during fault.

Preface

This thesis is a case study of DNV GL AS type vessel D31945. The thesis work was started as a summer job at DNV GL AS office in Oslo, and was continued in the department of Electric Power Engineering at Norwegian University of Science and Technology (NTNU) during Autumn 2013. This thesis proved to be really helpful for me, regarding the knowledge of the ship power system.

My supervisor Kjetil Uhlen was really supportive and kind to me during the project work. I was able to explore the field of power system because of him. I would like to thank him for his important guidance and time he spent on me. He was always there to help me, whenever i needed.

I would like to thank DNV GL AS and, the whole Electrical Systems department in DNV GL AS for giving me opportunity to work on this project. Special thanks to my co-supervisor and contact person in DNV GL AS Sverre Eriksen. His guidance and time which he gave me in the meetings and follow up e-mails to make me understand the thesis work were really helpful.

My friend Dr. Nadeem Jelani was very generous and supportive to me, he kept my moral high and helped me a lot in understanding the problem. My friend Muhammad Usman helped me a lot in understanding the Simulink and Kristian Baricuatro helped me in learning Latex, i would like to thank them also.

Last but not least, i would also like to thank my father Muhammad Ashraf and my other family members. It would have been really difficult for me without their support. They never let me feel that i am thousands miles away from them.

In the end, i would finish by saying that the ship power system is a really big research field. I hope that the readers will get something useful in this thesis and this thesis may prove helpful in further research.

Umair Ashraf
Trondheim, June 2014

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Nomenclature

AVR	Automatic Voltage Regulator
DP	Dynamic Positioning
FC	Fixed Capacitor
FFT	Fast Fourier Transform
IGBTs	Insulated-gate Bipolar Transistor
IM	Induction Motor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PCC	Point of Common Coupling
PE	Power Electronic
PLL	Phase Locked Loop
PMG	Permanent Magnet Generator
PWM	Pulse Width Modulation
SG	Synchronous Generators
SVC	Static Var Compensator
TCR	Thyristor Controlled Reactor
THD	Total Harmonic Distortion
TSC	Thyristor Switched Capacitor
VFD	Variable Frequency Drive

1

Introduction

1.1 Background

After the discovery of oil and gas in sub sea, the most growing vessel in marine and offshore operations from early 1980 is the dynamic positioning vessel. Because it maintains the position of the vessel constant and it is cost effective also. Most of the DP vessels have diesel electric propulsion installed [42]. Due to their thruster size, the power range of such vessels varies between 10-40 MW [3]. In such vessels, continuous supply of power is required to attain the safety and reliability. The concept of electric propulsion is more than 100 years old, but the control system for the thruster and other drives was introduced after 1980 [36]. These vessels usually have the automation system for most of the functionalities installed into the ship. The electric propulsion in vessels usually consists of multiple generating units, which will contribute according to the load demand.

The load on vessels mainly varies from each other due to their different functionalities. Maximum power on the vessels is usually consumed by the thrusters for propulsion and it may vary from 80 to 90 % of the total power generation [37]. Recently, use of Power Electronic (PE) devices in variable frequency drives have increased abruptly, because of their low cost, light weight, high reliability and efficiency. In the modern ship propulsion system, thrusters uses power electronic converters. The PE converters provide better control and efficiency in electrical system. These can be used for the voltage and frequency conversion by controlling power flow, protections can also be installed in them. [9].

The electrical system on the ship like any other AC distribution system faces power quality problems. These problems are mainly due to the variations in voltage, harmonics in current and usage of reactive power. The load on the ship is mostly connected through PE devices which behaves like a non-linear load, this produces instability in the system because of increase in the reactive power and harmonic current. The induction machine uses reactive power in the system and in faulted condition increased demand of reactive power produces voltage fluctuations. There are so many ways to solve this kind of problems, such as injection of measured current by power electronic component. It will not only control the voltage of the grid but also the current waveform [19].

The dynamic changes in the voltage of the power system are due to the instability of the system with the autonomous grid. This is directly related with the values of reactive power and harmonic current in the system. The power system will be more heavily loaded in future due to ever increasing demand, which will take the system more closer to the instability. Due to this, it is very important to know the reasons behind voltage collapse, so that the system could be saved with these problems in future. When the system reaches its reactive power limits it become more sensitive to voltage breakdown [15].

The ship power system is considered the same as the smart grid concept, in which the system does not need external support for healing, reconfiguration and also for diagnosis. Typical electric ship has more than two generators. Although all the loads are important, propulsion load is considered as critical in the ship power system. Other loads may be in form of cooling system, lightning and control devices [22].

1.2 Objective

One of the DNV type DP vessel D31945 experienced a fault with major consequences, that resulted in instability of the complete power system on vessel. Due to voltage fluctuation, frequency converters started oscillating, which lead the converters to trip. The main purpose of the thesis work is to find out the possible reasons for the voltage fluctuation in the power system and the possible solutions for such problems.

1.3 Scope of Work

The main purpose of this thesis is to understand the ship propulsion system, examine the behaviour of different components in various situations. The power quality issues in the ship power system and mitigation techniques to attain the stability. The thesis work consists of following steps:

- Understanding the ship propulsion system.
- The diagnosis of power quality problems associated with the ship power system and its mitigation techniques.
- Literature review of harmonics and reactive power compensation in the ship power system.
- By using harmonics and reactive power compensation, improvement in the voltage fluctuation to attain the stability.
- Choosing component models and network topology for the power system modelling.

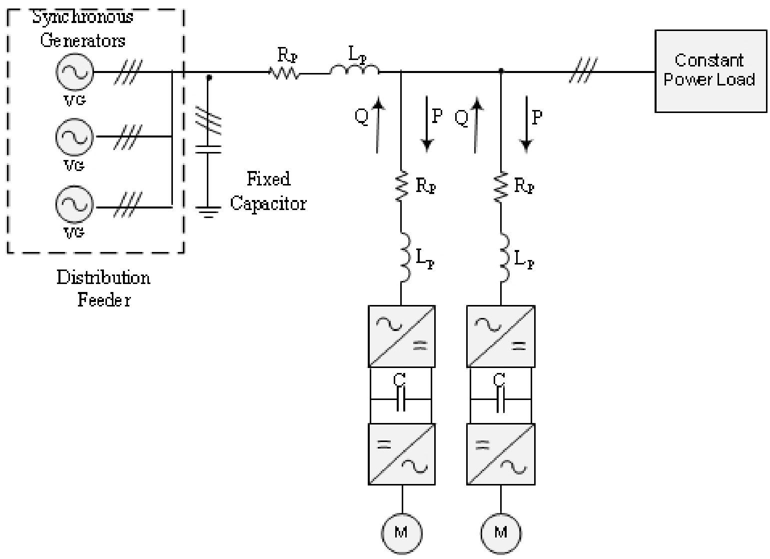

Figure 1.1: The typical electric power system topology on the vessel

- Implementation of the model with chosen components in Simulink.
- Analysis and discussion with respect to the choice of models and controls for representing the frequency converters for the motors .
- Design and analyse the dynamic simulation model of each case in SIMULINK™ SimPowerSystems™.
- Study the parallel operation of the synchronous generators.
- Analysis of first simulation results and possible validation of the model
- Preliminary conclusions and plan for further work.

1.4 Report Structure

Chapter 1: Introduction: This chapter presents the motivation behind the thesis, objective of the thesis and ends up with the report outlines

Chapter 2: Summary of Previous Work: This chapter summarized the overview of previous work done on this thesis in the last semester.

Chapter 3: Ship Power System: An Overview and Modelling: Starts the second part of the thesis in which different components used in ship power system are explained.

Chapter 4: Power Quality in the Ship Distribution System: Literature review: Explains the power quality issues in the ship power system and some of the mitigation techniques to improve the stability.

Chapter 5: Modelling of Ship Power System: Case Study: The test model with all required parameters to be simulated is presented along with the control scheme of voltage source converter.

Chapter 6: Simulation Results for Power Quality Improvement and Voltage Support: Presents and explains the results obtained from simulation of the test model.

Chapter 7: Discussion and Comparison: Discuss and compare the simulation results

Chapter 8: Conclusion: Concludes the thesis work.

Chapter 9: Recommendations for Future Work: Finishes the thesis work by giving some recommendation for future work.

Appendix A: Demonstrates the SIMULINK™ block diagrams used for the report.

Appendix B: Show some of the useful control blocks

Appendix C: Shows some of the useful figures from simulations.

Appendix D: Explains some of the reactive power compensation techniques.

2
Summary of Previous Work

Since this thesis work is a continuation of specialization project, a summary of the previously mentioned project is presented in this chapter.

2.1 System Overview

In the ship power system, most of the loads are designed to operate on AC voltage. In this work the synchronous generators (SG) are used to get AC voltage, because of high reliability parallel operation of these generator sets are preferred. These generators are designed to share the load when needed. Major consumers of the ship power system are the thruster motors used in propulsion.

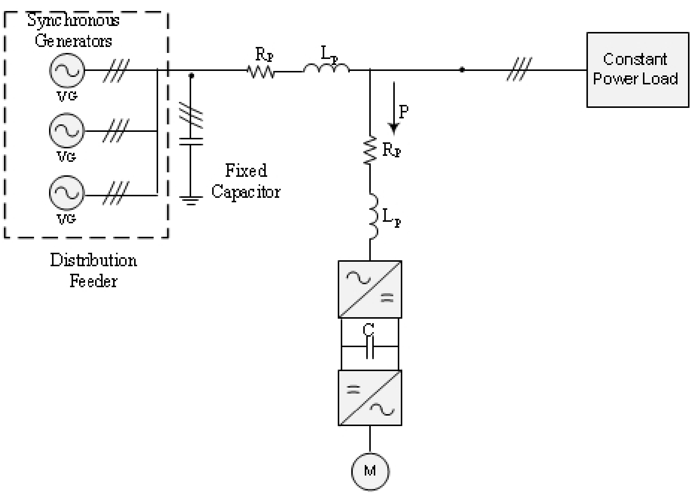

Figure 2.1: General figure of the power system on ship

The power system on ship uses motor drives for controlled and smooth operation. For supplying power to the system, parallel operating generator sets are used, where the consumers are thruster motor and parallel RLC load (the constant power load is modelled as parallel RLC load). Normally thruster is driven by an induction motor, and the power is supplied through drives to the IMs. The variable frequency drive is used for operation of the IM. The variable frequency drive operates by rectifying AC into DC voltage and then inverting this DC into AC voltage. The general figure of power system on ship is shown in the Figure 2.1.

2.2 Operation of Variable Frequency Drive

This section explains the behaviour of power system, when connected with the VFD. The induction motor was connected with the VFD as load, and could be operated on different frequency by changing the reference speed. Figure 2.2 represents the variable frequency drive used in the project work. The VFD operates by first rectifying AC into DC and then in the last stage inverting the DC into AC.

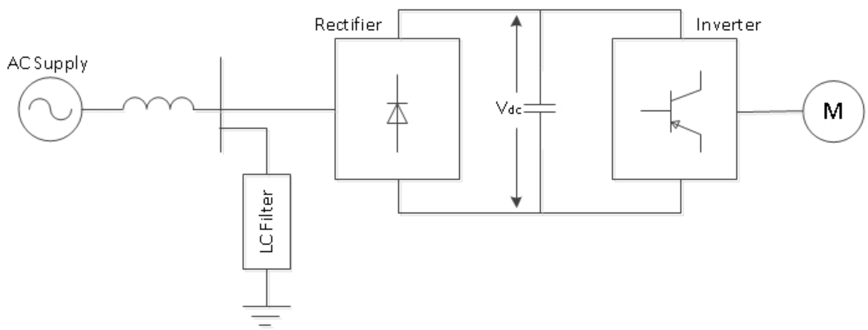

Figure 2.2: The general figure of variable frequency drive

For the rectifier section, diode bridge rectifier was used. The principle of its operation is well explained in chapter 3. The inverter section explained in chapter 5, is the same as used in the previous work. The operation of VFD in normal condition is explained in this section with the simulation results.

2.2.1 Induction Motor Starting

In the project work the induction motor was used as load on the VFD, and its performance during start can be seen from the Figure 2.3. During start up, the motor is operating on no load. After time *t*=1.5 sec a mechanical load of 200N.m was added on the motor. It can be seen from the figure that during start up, the motor takes high value of current due to the staring torque. Because of the starting torque speed is low in beginning and it increases gradually. The speed reaches its steady state value after time t=1 sec. The current and torque values are also normalized after motor start up.

After steady state has been achieved at time t=1 sec, the mechanical load of 200N.m is added at time t=1.5 sec onto the motor. When the load torque increases, the speed of the motor starts decreasing. The increase in load toque of the motor draws more current with reduced speed. Figure 2.3 (a) illustrates the current of the motor, Figure 2.3 (b) represents the speed of the motor and Figure 2.3 (c) shows the torque on the motor.

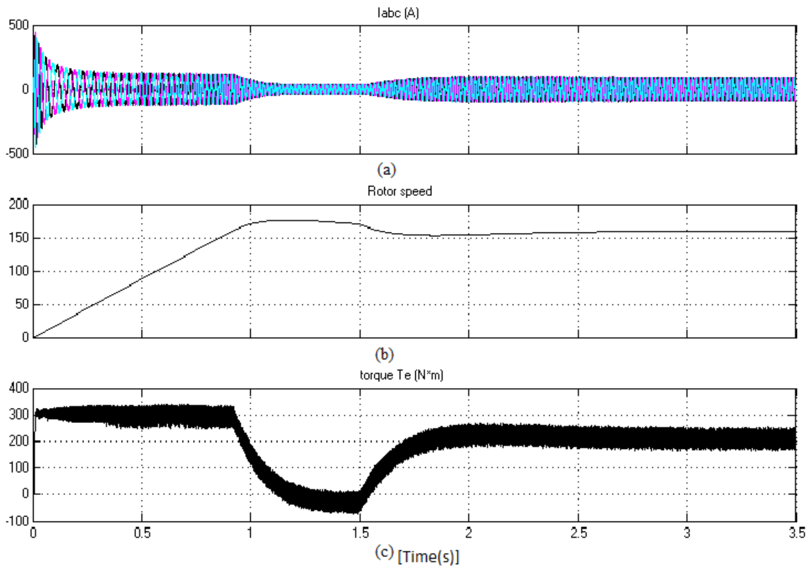

Figure 2.3: Induction motor variables when connected with VFD

2.2.2 Impact of Induction Motor on Grid

Figure 2.4 illustrates the impact of the IM on grid. Figure 2.4 (a) represents the real power consumed by the IM where as Figure 2.4 (b) shows the reactive power consumption of the IM.

The negative sign shows that the motor is consuming the power, both the active and reactive power consumed by the motor can be seen from Figure 2.4. In the beginning due to the starting torque the motor takes active and reactive power. It goes stable at time after t=1 sec. When the load was added at time t=1.5 sec, an increase in the power consumption was observed. During steady state the motor takes 40kw of active and 2kvar reactive power, which is quite high value for the reactive power. The change in active power of the motor is visible at time t=1.5 sec when load is added on the motor and it is taking full power in that duration.

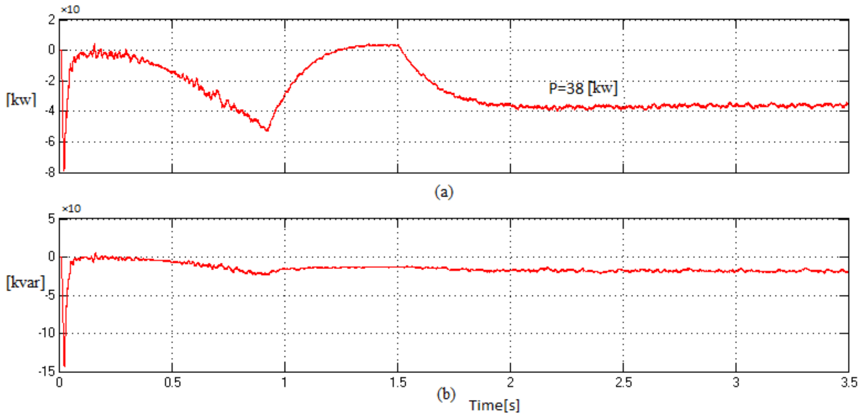

Figure 2.4: Impact of induction motor on grid in shape of active and reactive power

2.3 Fault Analysis with and without VFD

This section describes some of the fault analysis performed in the previous work. The simulation results for the single phase to ground fault is shown in case of VFD installed in the system and without VFD installed.

2.3.1 Impact of Single Phase to Ground Fault on Grid without VFD

A simulation analysis is performed for single phase to ground fault without the VFD installed in the system, the simulations were carried out for time t=3 sec. The single phase to ground fault was implemented on phase **a** at time t=0.5 sec to t=0.65 sec, with the fault resistance of 0.02 Ω. The behaviour of bus bar voltage in this case can be seen in Figure 2.5.

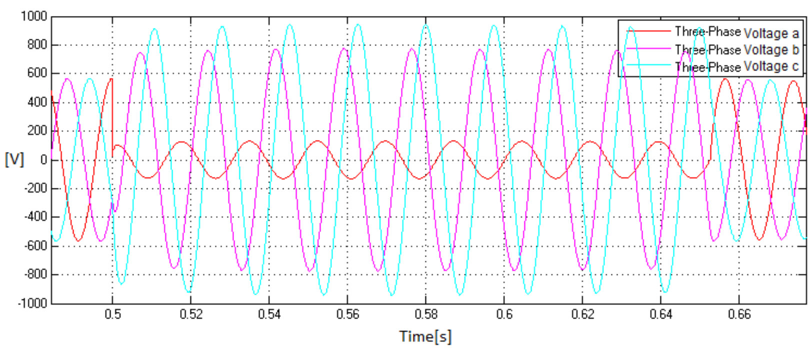

Figure 2.5: Voltage swell due to single phase to ground fault without VFD in the system

The voltage of faulted phase goes down due to short circuit, and two un faulted phases try to continue supplying power which cause swell in them. The reason for voltage swell in the case of single phase to ground fault is well explained in next section. It is also quite clear that voltage of both un faulted phases are not the same in single phase to ground fault. The voltage get stable right after the removal of fault at time t=0.65.

2.3.2 Impact of Single Phase to Ground Fault on Grid with VFD

Simulation were carried out with the VFD installed in the system. The simulations were carried out for the time t=3 sec. In the case of single phase to ground fault the voltages for all the phases **a**, **b** and **c** are shown in Figure 2.6. The fault was implemented on phase **a**, during the time interval t=2 sec to t=2.3 sec. It can be seen that voltage of the faulted phase goes down due to the short circuit, but the voltages of other two phases behave different than normal. The voltages of un faulted phases are not the same during the fault. The system does not recover immediately after the fault has been removed at time t=2.3 sec, it takes time to recover the voltage.

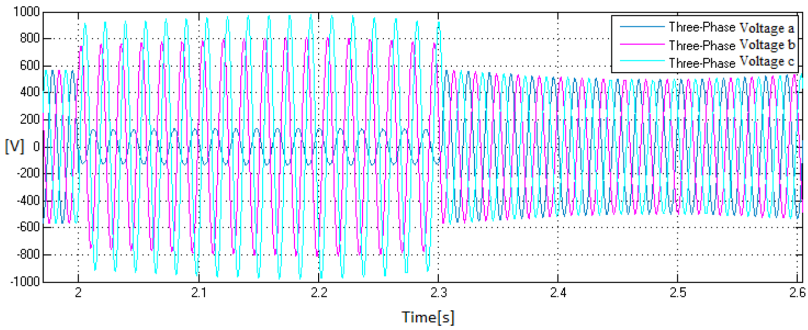

Figure 2.6: Voltage swell due to single phase to ground fault with VFD installed in the system

3 Ship Power System: An Overview and Modelling

3.1 Electrical Components

The power systems on ships usually consist of more than one generator operating in parallel. Some of these are used to provide the maximum power demand and at least one is reserved for the emergency supply only [20]. The electrical system on ship is the same as the electrical system on land, with the exception of it being isolated. The electrical system on ship needs both active and reactive power. Thruster motors get supply through the drives which controls its speed. Some of the main components of the ship propulsion system are as follow:

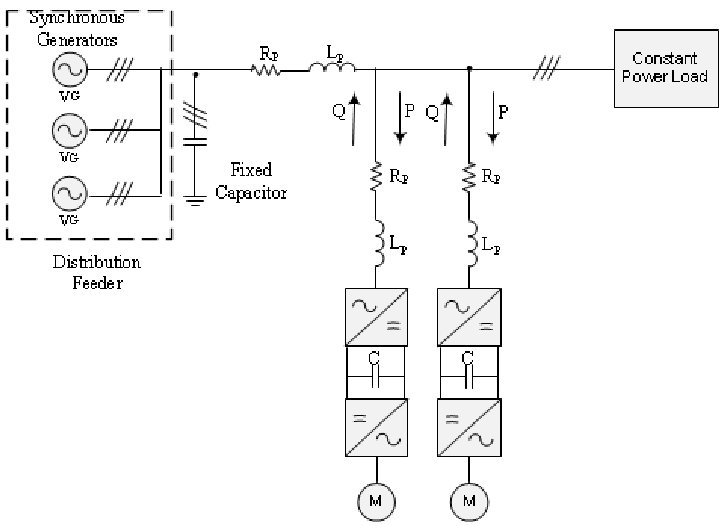

Figure 3.1: The general figure of the ship power system comprises of two VFDs

- Generators
- Motor drives
- Thruster Motors

3.2 Generators

Because the ship electric system is isolated, it needs power on board to supply the load. Selection of the generator depends on some factors, i.e. number of units, types of units voltage and frequency of the system [50]. In this thesis, three synchronous generator are used and they are operating in parallel.

The frequency of the SG can be found with the formula in equation 3.1, where P represents poles of the SG and N gives speed. The poles of the generator can be chosen according to the system design, the SGs with higher number of poles give less noise and are lighter in weight. The generators with high numbers of poles have less vibration, and also smaller components due to the higher frequency [10].

$$f = \frac{N.P}{120} \tag{3.1}$$

In electric ship propulsion, more than one generators are used to make the system redundant. These generator sets normally operate in parallel and load can be shared among them, according to the user by varying droop parameters. The terminal voltage of the generator can be calculated as [5]:

$$V_g = E - R_a I_g - jX_g I_g \tag{3.2}$$

In this equation V_g is the terminal voltage, R_a is the resistance of the winding and X_g is the reactance.

3.2.1 Parallel Operation of Generators

In the isolated system, more than one generators provide electricity to common bus bar. Due to the load demand, the generators on ship operate in parallel. When in parallel they act like frequency and voltage regulators, which control both the active and reactive power. The system with parallel operating generators give power to the larger consumers with higher reliability.

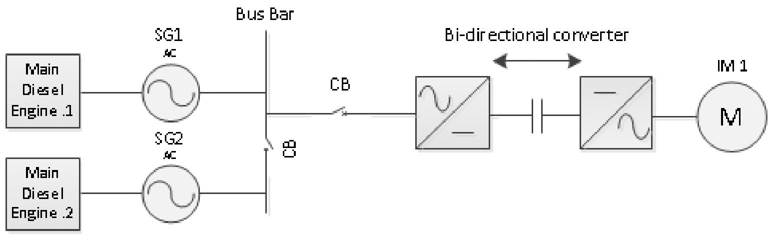

Figure 3.2: Parallel operation of generators in ship electric system

3.2.2 Diesel Engine and Governor

The diesel engine controls power in generator with the help of governor. By controlling the fuel to engine, governor keeps the speed with in the limits. Main function of the governor is to keep the speed constant, during varying load demand [2]. During the parallel operation, reference speed of the droop governor determines the load on engine. In parallel operation, changing the speed of the engine causes change in the load of engine but not the speed [51]. The governor controls energy to the prime mover and fuel after sensing the speed. It works first by sensing the actual speed and then comparing it with the desired setting. The governors can operate either in isochronous or droop mode. [52].

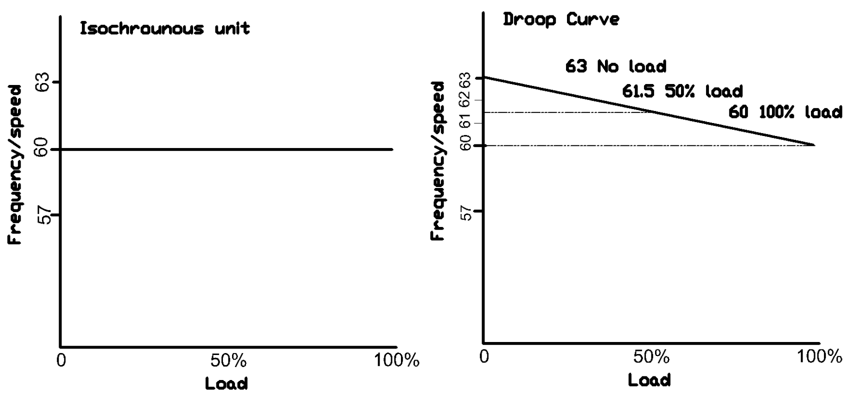

Figure 3.3: Typical figures of Isochronous unit and 5% Droop curve [52]

In isochronous mode at full load engine maintains the actual speed. Where as in the droop operation at full load speed decreases within the limits [52].

3.2.3 Speed Droop

The speed droop helps the engine to reduce speed when the system is loaded and also to increase the speed during no load. The droop can be calculated as follows:

$$\%Droop = \frac{\omega_{nl} - \omega_{fl}}{\omega_{fl}} \tag{3.3}$$

Where:
ω_{nl}=speed at no load
ω_{fl}=speep at full load

Incorrect action which causes the negative droop will produce instability in the governor. When the two engines are connected in parallel, only one can operate in isochronous mode. If both engines operate in this mode, then one out of two will get all the load.

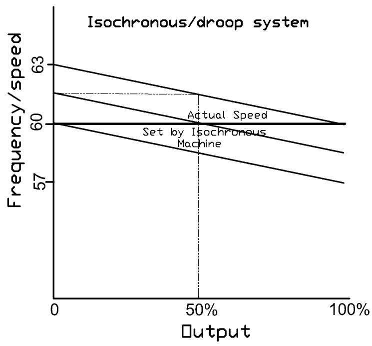

Figure 3.4: System with combination of both Isochronous and Droop curves [52]

In such a system, an alternator with the isochronous unit is called the swing unit which will control the power output in order to balance the load. All other units works at constant load according to their droop setting [52].

3.2.4 Automatic Voltage Regulator

The automatic voltage regulator (AVR) controls the field current of synchronous generator, to keep the output voltage within limits. In SG operation, the AVR has functions like voltage/frequency control and soft starting. The voltage and frequency control is used to protect the system from over excitation on low speed. The soft starting provide initial stability, by setting time for the generator output voltage to reach reference value [30].

During starting of the generator or when the system is heavily loaded, the speed of engine goes down which also reduces the frequency. During this period, voltage and frequency functions stop the system from over excitation, by reducing the voltage with respect to the speed or frequency. Any type of the voltage dip in distribution causes reduction in the load voltage. In such scenario compensating function for the load voltage is important to provide constant output voltage [31].

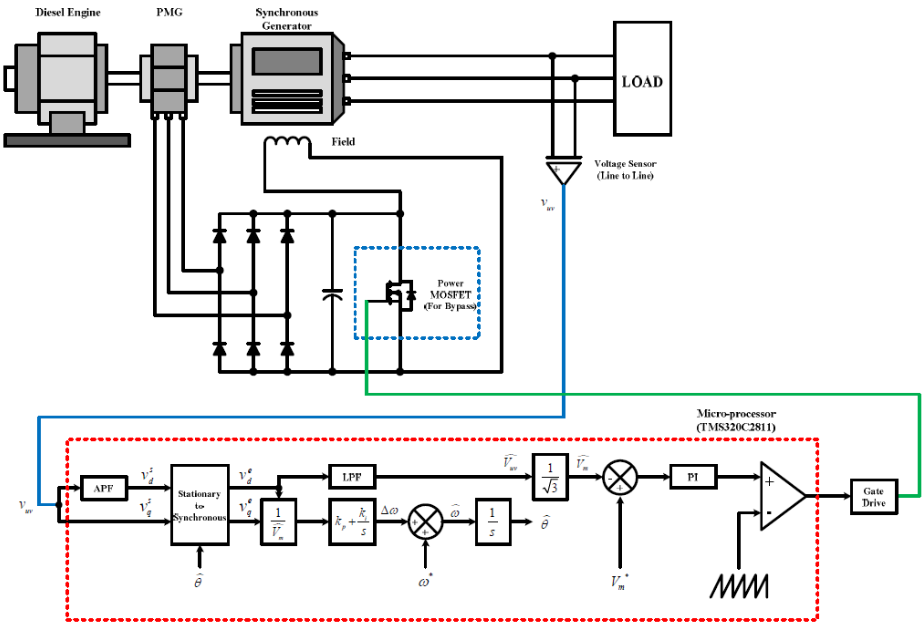

Figure 3.5: Complete block diagram excitation control of ship SG [31]

Figure 3.5 shows the SG excitation control which consists of AVR and permanent magnet generator (PMG) having rectifier and power metal oxide semiconductor field effect transistor (MOSFET) for bypass. The PMG supplies energy to the exciter with the help of both the rectifier and power MOSFET. The error signal which is difference of measured and actual value of the voltage, controls the exciter field current by varying the switching of MOSFET.

3.3 Motor Drives

Induction motors (IM) are mostly used in the ship propulsion system with variable frequency drives, which control both the speed and starting torque of the IM. Normally the IM takes 5-7 times more current in starting than in the steady state condition, which is also main reason for the voltage dip in the network. Via VFD, the motor can start with a lower frequency as 7Hz, which reduces both current in beginning and the voltage dip. By using the VFD, IM takes just 1.5 times of rated current which is much less than before. Via scalar control, the VFD maintains a constant ratio of voltage and frequency during start-up as follow:

$$\frac{Voltage}{frequency} = K \tag{3.4}$$

Due to this even after changing the speed, ratio of both the voltage and frequency is always constant. When using the drive, the voltage of the motor can be calculated as follows: [25]

$$V = \frac{Voltge}{frequency} \times VFDfrequency = \frac{V}{f} \times f_1 \qquad (3.5)$$

here:
f_1= frequency of VFD in start
f = 50/60 Hz
V = terminal Voltage of Motor

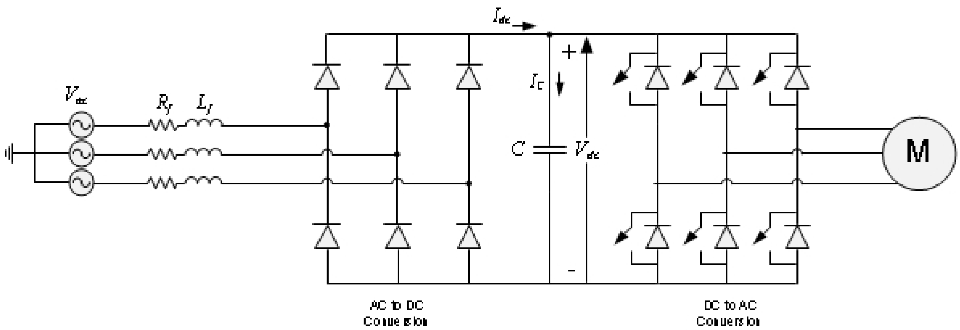

Figure 3.6: The variable frequency drive block diagram in general

The variable frequency drives work by first rectifying alternating current (AC) voltage of the network to direct current (DC), and in last stage by inverting this DC voltage in varying AC voltage and frequency. To invert DC into AC, switching devices are used which may be Insulated-gate bipolar transistor (IGBTs) or thyristors [39]. For the rectification of one phase, two rectifiers are needed. The rectifier is called 6 pulse, because in three phase system, six rectifiers are needed. If the VFD uses transistors in the rectifier then it can be said that is has an active front end.

In this section generally used VFD circuit is shown, which is using diode rectifier. The active front end rectifier with IGBTs is explained in chapter 5, the control scheme is also explained in that part for the rectifier. After the rectification capacitors are used to store power and in next stage deliver it to the inverter. The inverter has transistors which can switch several times to transfer power from the capacitors to motor. For switching of the transistors the most common technique used is pulse width modulation (PWM) [11].

3.3.1 Diode Rectifier

For AC-DC conversion diode rectification is normally used, because they can handle higher power. In Figure 3.7 three phase diode rectifier circuit is shown. The diode with highest value of potential at anode will be forward biased while other two will be reversed biased. Likewise underside diodes with minimum value of potential will conduct but others will not. The equations below are taken from [49].

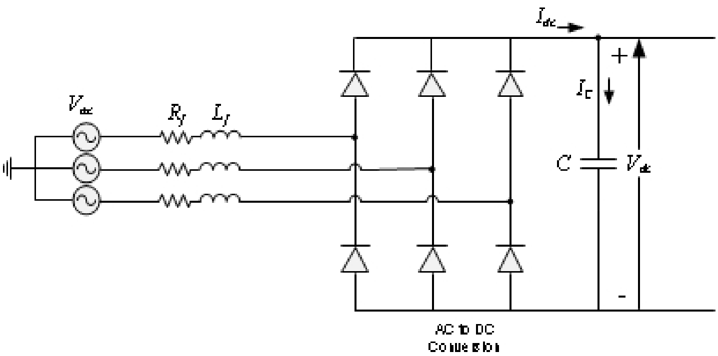

Figure 3.7: Three phase diode rectifier

$$V_d = V_{pn} - V_{Nn} \tag{3.6}$$

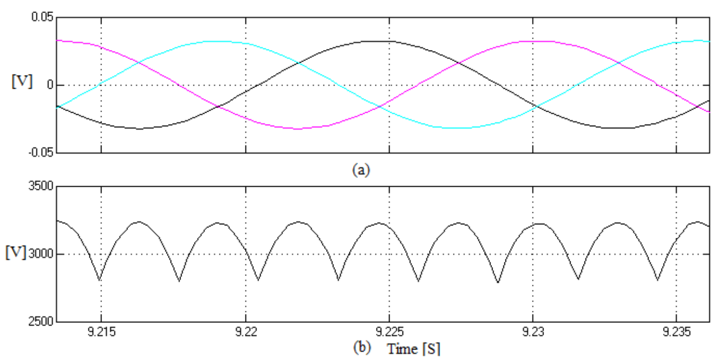

Figure 3.8: Voltage waveform before and after rectification

In Figure 3.8 three phase voltage and corresponding rectified voltage is shown. This kind of rectifier called as six pulse because V_d has six segments in one cycle. For average value, just consider one segment and get its value for the interval $\pi/3$.

$$V_d = \sqrt{2}V_{LL}Cos\omega t \quad -\frac{1}{6}\pi < \omega t < \frac{1}{6}\pi \tag{3.7}$$

The equation for the diode rectifier are given in [5]:

$$3V_g I_g = V_{dc} I_{dc} \tag{3.8}$$

In this equation V_{dc} and I_{dc} are the DC side voltage and current respectively. The value of the DC side voltage can be calculated as:

$$V_{dc} = \frac{3}{\pi} \int_{-\frac{\pi}{6}}^{\frac{\pi}{6}} V_{LL,peak} \cos\theta d\theta = \frac{3}{\pi} V_{LL,peak} \tag{3.9}$$

The value of V_{LL} can be obtained from the equation 3.9 which is:

$$V_{dc} = \frac{3\sqrt{2}}{\pi} V_{LL} \tag{3.10}$$

3.3.2 Inverter

In ship power system VFD supplies energy to three phase load, so for that purpose three phase inverter is used. The inverter takes DC voltage from the capacitors and convert it into three phase AC using IGBTs with anti parallel diodes. It can be seen in Figure 3.9 that the phase voltage just depends on V_{dc} and switching of transistors.

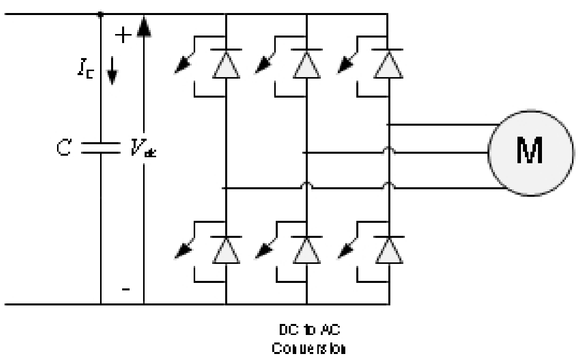

Figure 3.9: Circuit diagram of three phase inverter

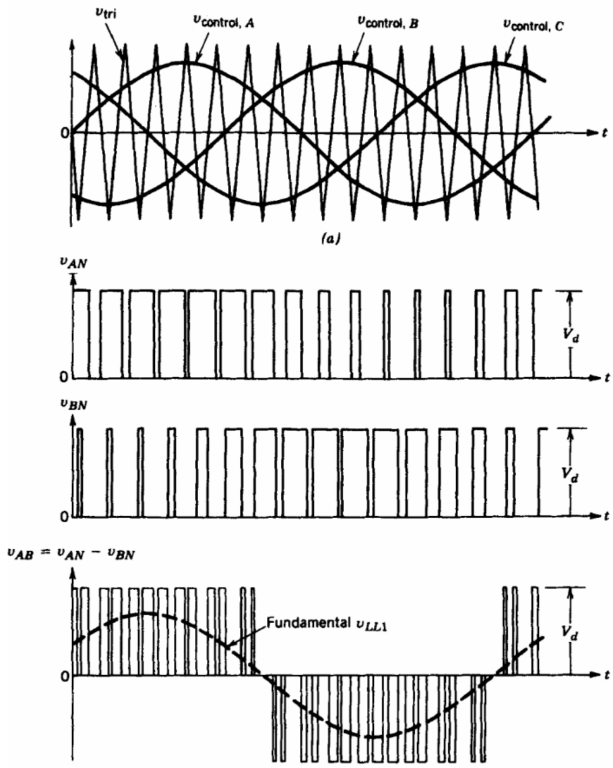

Figure 3.10: Three phase inverter waveform with PWM [49]

Pulse width modulation is used for the switching of transistors, which consists of triangular and control wave. By comparing V_{tri} and V_{con} a switching signal is generated, which switches the transistors of the inverter. Figure 3.10 demonstrates three phase inversion from constant voltage V_{dc} with the pulse width modulation. The main purpose of PWM in the inverter is to control frequency and magnitude of voltage [49].

3.4 Thruster Motors

Induction motors are normally used in the ship propulsion system for thrusters, these are connected with the grid on board, directly or with VFDs. The equivalent circuit in Figure 3.11 for IM is used to find out parameters of the IM in starting and normal operation. Some of the factors which influence the start-up of induction motor are as follows: [24]

- Voltage on terminals
- Load and inertia

- IM parameters
- Impedance of distribution system

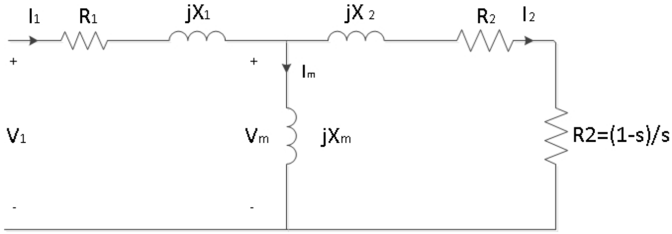

Figure 3.11: Induction motor equivalent circuit

In an induction motor, the rotor current is induced from the magnetic field rather then from the electrical connections. From Figure 3.11, parameters of the IM for normal conditions can be derived as: [24]

$$Z_m = (R_1 + jX_1) + \frac{(\frac{R_2}{S_1} + jX_2)(jX_m)}{\frac{R_2}{S_1} + j(X_2 + X_m)} \tag{3.11}$$

$$I_1 = \frac{V_m}{Z_m} = \frac{V_m}{(R_1 + jX_1) + \frac{(\frac{R_2}{S_1} + jX_2)(jX_m)}{\frac{R_2}{S_1} + j(X_2 + X_m)}} \tag{3.12}$$

$$V_m = V_S - V_{dop} \tag{3.13}$$

$$I_2 = \frac{jX_m}{\frac{R_2}{S_1} + j(X_2 + X_m)} I_1 \tag{3.14}$$

3.5 Autonomous Grid Characteristics

The weak grid in the ship power system does not possess the same definition as in the long transmission lines, usually it is taken out as grids where voltage is not constant. It can also be described as the grid where voltage fluctuations need to be considered because of the chances that it might change with minor change in the load.

The typical problems which can be associated with the autonomous grid are the variation in frequency, flickering of voltage, varying load and some times load shedding. Mostly, this type of grids are found in remote areas and in the isolated systems like on ship. In these system when load is added then voltage goes down from minimum level [6].

4 Power Quality in the Ship Distribution System: Literature review

4.1 Power Quality and Faults

The electric power system on ship faces power quality problems like all other electric systems. The ship electrical system consists of many components which operates both on AC and DC voltages. Voltage and the frequency variation is done for several devices which make the system complex. This complexity raises many problem in the power quality and produces different kind of faults. These faults results into problems in voltage quality, such as dips and swells [35].

Normally generators in the ship power systems are of smaller ratings. Some of the consumers on ship have higher ratings as compare to the sources. The short circuit impedances of the alternators on ships are also high. These altogether make the system more complex, which causes electromagnetic disturbances in the system. The voltage deviation which is allowed on ships by IEC standard 6002-101 is +6 %, -10% [48]. Non periodic faults results into the significant changes in voltage and current of the network like dips and swells.

4.2 Voltage Dips

An abrupt change in the current of the system causes voltage dip. The magnitude of dip depends on many things like distance from the fault, type of the fault and also impedance of the fault [34]. The voltage dip can have 10% to 90% reduced magnitude and can last from 500 ms to several seconds [23].

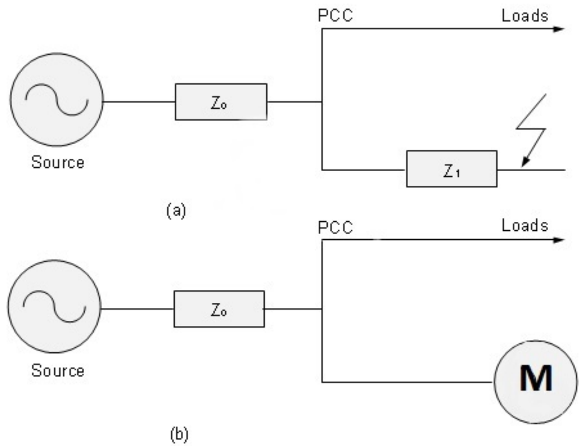

Figure 4.1: Representation of fault in power system (a) line fault (b) starting of motor [35]

How much the dip in voltage will harm the equipment it depends mainly on the sensitivity of the equipment, where as the magnitude depends upon the resistance of the fault. The magnitude of the dip can be calculated as follows [35]:

$$V_{dip} = \frac{Z_f}{Z_f + Z_s} \times E \tag{4.1}$$

Where V_{dip} is voltage at point of common coupling (PCC), Z_f is impedance between fault place and pcc, Z_s is source impedance and E is voltage before fault. In case of non symmetrical faults, this equation is required with the negative and zero sequence impedances.

Some possible causes of the voltage dip in power system are:

- Starting of induction motor
- Three phase to ground fault
- Two Phase to ground fault

A three phase to ground fault in the system it always causes voltage dip. All the three phase voltages will be zero in such case, and because of the symmetrical fault, both zero and negative sequence quantities will not be considered.

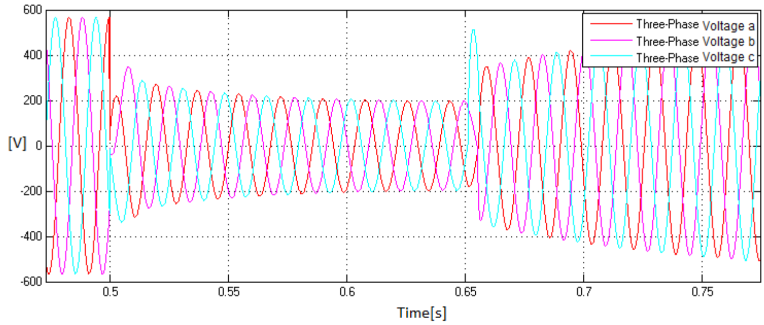

Figure 4.2: The voltage dip in case of three phase to ground fault

Figure 4.2 shows a three phase to ground fault, it can be seen that when the fault appears at time t=0.5 sec the voltage goes down. All the three phases of the system behave the same in case of a three phase to ground fault which shows that the fault is symmetrical in nature. When fault is removed at time t=0.65 sec the voltage recovers from the fault.

4.2.1 Causes of Voltage Dips

The main cause of the voltage dips in the power system is short circuit. For the stability of the power system, analysis of short circuit events are very important to understand the nature of voltage dips and its mitigation techniques. Some of the different reasons of voltage dips are explained below:

Symmetrical and Asymmetrical Faults

The voltage dips are mostly due to the symmetrical and asymmetrical nature of the faults in the power systems. Whenever a fault is symmetrical in nature, then it just needs positive sequence impedance. However in an asymmetrical faults all positive, negative and zero sequence impedance should be considered. The continues operation of induction motor during the asymmetrical faults causes pulses of torque and current. These kind of faults, if sustained for longer period of time can cause heating in the motor windings which may end up in damaging the motor insulation [16].

During balanced fault, i.e. three phase to ground fault, all the three phases will have the same kind of voltage dip in this case calculations can be done only on the single phase with the help of the positive sequence impedance. In case of asymmetrical faults the voltage dip will be different in all the three phases, the voltage divider model should be used to calculate the dip in the voltages using positive, negative and zero sequence parameters.

Figure 4.3 shows the voltage dip in case of single phase to ground and three phase to ground fault. Figure 4.3(a), shows the single phase to ground fault which is an asymmetrical fault, it can be seen in the figure that none of the phases are equal, the voltage of each

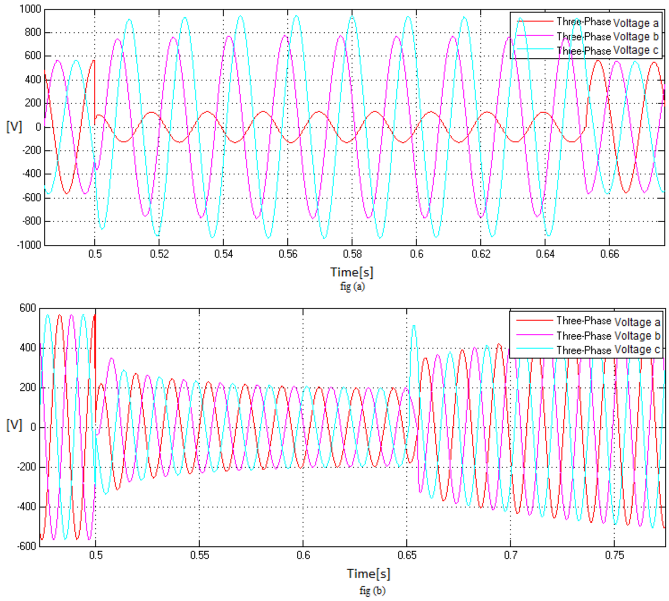

Figure 4.3: The voltage dips due to different types of fault (a) The asymmetrical fault due to single phase to ground fault (b) The symmetrical fault due to three phase to ground fault

phase is different from each other. Whereas Figure 4.3(b) represents the three phase to ground fault. It can be seen from the figure that all the three phase have the same value of voltage after the fault has occurred, which shows that the fault is symmetrical in nature.

Phase Angle Jump

Phase angle jump can be defined as shift of the zero crossing in the instantaneous voltage. This is mainly due to the difference in the X/R ratio of grid and generator in three phase faults. Most of the equipment in power system are unaffected by phase angle jump. However those power electronics devices which use phase angle as a reference in switching are effected by this phenomenon [33].

Starting of Induction Motor

The induction motors used for propulsion are the biggest consumers in the ship power system, which is around 70% of total generation [45]. The induction motor during start up requires five to six times higher current than in steady state operation. Due to the high current voltage dip occurs during start up of the induction motor, which mainly depends on the system it is connected and motor parameters [35]. The starting current of an IM can be calculated as [46]:

$$I_{st} = \frac{P_m \times a^2}{\sqrt{3} \times V_m \times p_{fm}} \times K \qquad (4.2)$$

where P_m is the actual power of the IM , V_m is rated voltage, P_{fm} is power factor, K is starting to rated current ratio and **a** is percentage of actual voltage to the voltage when some starting method is used.

The large amount of current in the starting of motor causes dip in the voltage, however there are some methods to reduce the starting current of motor, i.e soft starter but these are not very common because of high price.

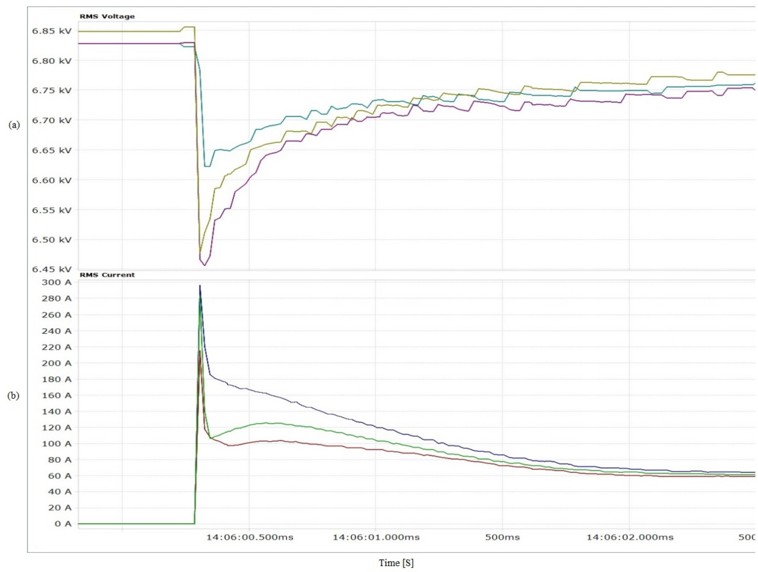

Figure 4.4: Starting of induction motor (a) voltage dip (b) starting current [29]

From Figure 4.1(b) voltage dip in case of induction motor starting can be calculated as:

$$V_{dip} = \frac{Z_M}{Z_0 + Z_M} \times E \qquad (4.3)$$

Where E is the input voltage, Z_o input impedance and Z_M is the impedance of the motor. Figure 4.4 shows the voltage dip when induction motor is starting, which can be seen in the figure at time t=500μs. The rise in the current at the same time interval can be observed, and it get stable afterwards.

4.3 Voltage Swell

The voltage spikes can cause many problems to the system, such as improper tripping of equipment. Improper shutting down of components some times may lead to the blackout in the whole power system [34]. Quite often, faults are of single phase to ground in nature which causes problem in the protection. In such cases, voltage on the faulted phase goes to zero but the system continues supply from the other two phases. The phenomenon of voltage swell is well explained in [21] [53].

The ship power system is of underground nature, which helps in continuing supply when there is single phase to ground fault. But this supply is with higher voltages which cause voltage swell [35]. This can results in loss of data, blinking of lights and some times tripping of heavy load if the voltage is very high [13].

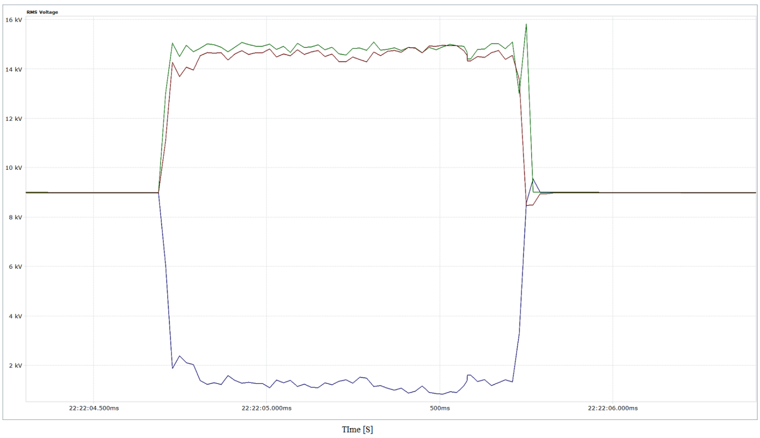

Figure 4.5: Voltage swell in case of single phase to ground fault [29]

The voltage swells can also be due to the switching of huge capacitors, single phase to ground fault and large inductive load. Figure 4.5 shows a voltage swell in case of single phase to ground fault. It can be seen from the figure that voltage of the faulted phase goes down where as voltage swell can observed in other two phase.

4.4 Current Harmonics

Distortion in the current waveform of the power system is due to the harmonics. The non-linear load, saturation and magnetization of transformer and distorted line current are the main causes of harmonic distortion in the power system. Interaction of source current and current from these loads causes harmonics. These harmonics creates lot of problems in the system such as the voltage fluctuation, losses of power and malfunctioning of devices [28]. Ever increasing power electronic devices are the main cause of harmonics generation in the power system, because of the switching devices such as rectifier which produces the harmonics in the system [47].

The word harmonic number represents multiple of fundamental frequency, i.e. 2nd order harmonics means the frequency of that signal is 100Hz if system frequency is 50Hz. The same kind of waveforms are shown in Figure 4.6, where 4.6(a) is the fundamental frequency component and the other three are the multiple of fundamental.

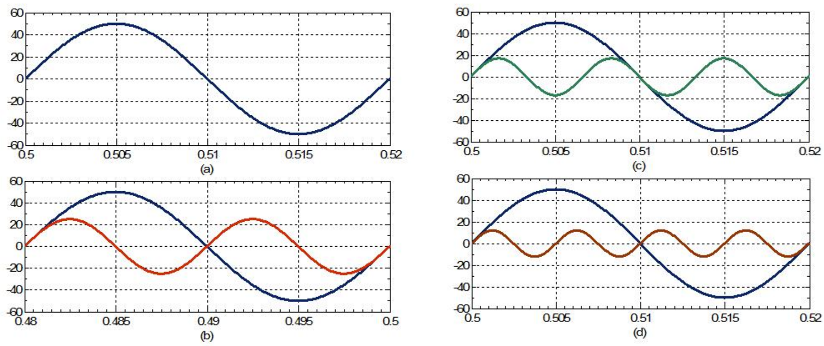

Figure 4.6: Comparison of Harmonic and fundamental components of the voltage (a)fundamental component (b) second harmonic with fundamental component (c) third harmonic and fundamental component (d) fourth harmonic and fundamental component

Non-linear loads are the reason behind production of the harmonics in the system. Main reason of this is the variable resistance of the equipment, which vary almost in every sinusoidal signal. It lead the fact that in such non-linear loads voltage and current are inversely proportional to each other. Following are some examples of these kinds of loads which cause harmonics in the power system:

- Adjustable frequency drive
- Static VAR compensator
- DC/DC converter
- Rectifiers and inverters
- Power supply of Television
- Switch mode power supply

4.4.1 Current Harmonics due to Power Electronics Devices

Now a days power electronics devices are increasing very rapidly. Huge amount of commercial and private loads are becoming non-linear. In industry, most of the load consists of induction motor, and use of variable frequency drive is very much common. The variable frequency drive consists of rectifier and inverter, which are non-linear load and causes the harmonics in the system. These rectifier and inverter are mostly diode and thyristor which are very good switching device, but they produce harmonics in the system and draw reactive power [4].

4.4.2 Current Harmonics due to Rectifier

The devices with the converter inside, i.e. variable frequency drive, contains rectifier in it. These rectifiers produce harmonics and its order can be calculated by $(6n^{+}_{-}1)$, this means that order of the harmonic will be one less and one more than the each multiple of six. The magnitude of the harmonic can be calculated by just taking the reciprocal of the order, i.e. 33% of the 3^{rd} order harmonic and 14% of the 7^{th} order harmonic would be present. Figure 4.7 and Figure 4.8 represent the distorted current signal from the three phase rectifier and its FFT analysis respectively.

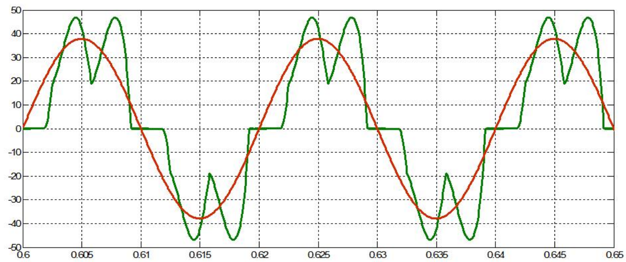

Figure 4.7: Current waveform of three phase signal with harmonics

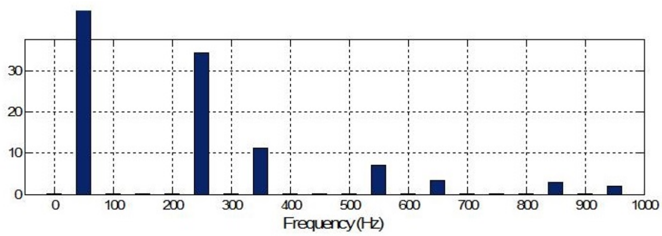

Figure 4.8: FFT analysis of current waveform with harmonics

4.5 Current Harmonics Consequences

The increase in the current due to harmonics can cause serious damage to the power system. The distorted current does not provide any power to the load but it consumes the power, which limits the amount of loads which can be supplied from the same source. The impedance of the transformer varies with frequency, and because of the harmonics, losses in the transformer increases rapidly.

4.5.1 Current Harmonics Consequences on Motor

The current harmonics in the machine increases the losses, for either a synchronous or an induction machine. This ends up in reducing the efficiency of that motor. For a motor, oscillating torque is a problem and harmonics is one of the reason it can occur. Some time the motor starts making the noise which is because of the non-sinusoidal signal and it is caused by harmonics.

4.5.2 Current Harmonics Consequences on Transformer

The transformer is the most efficient machine, it is designed to supply power with least amount of losses. Both the current and voltage harmonics produce heating in the transformer, which reduces its efficiency. Some of the reasons of heat production in the transformer due to current harmonics are as follow:

- The current harmonics increases the power ratings of the transformer, which also increases the losses.
- Because of the harmonics current, eddy current losses increase.
- The core losses of the transformer also increase because of the current harmonics.

4.5.3 Current Harmonics Consequences on Converter

The converters are also known as switching devices, because they are used to switch the supply voltage or current with the help of switching devices. These switching devices such as thyristors produce harmonics which can effect the synchronization of the other converters. In such cases unwanted firing of switching devices may happen.

4.5.4 Current Harmonics Consequences on Protection Relay

The protective relays are very sensitive devices and they are designed to trip on a certain value of current or voltage. The current harmonics change the rated value of voltage and current, which may cause malfunctioning of these relays. Protective relays are also designed to operate really fast in the time of fault. Current harmonic may delay the operating time of the relay when voltage is very high. This shows that current harmonics can cause improper tripping in case of high voltage or current, which is not acceptable in any case.

4.5.5 Decomposition of Signal

The signal composing of harmonics is not pure sinusoidal waveform, distorted signal over fundamental component give the harmonic order. By using the Fourier analysis these distorted signal can be decomposed into many different forms. The main purpose of the Fourier analysis is to make a relationship of function in time and frequency domain [29]. The relationship is given as:

$$f(t) - F_0 + \sum_{h=1}^{\infty} f_h(t) = \frac{1}{2}a_0 + \sum_{h=1}^{\infty}\{a_h \cos(h\omega t) + b_h \sin(h\omega t)\} \tag{4.4}$$

whereas:

$f(t)$= non-sinusoidal periodic function

$F_0 - \frac{1}{2}a_0$= average value of the function $f(t)$

$a_0 - \frac{1}{2\pi}\int_0^{2\pi} f(t)d(\omega t)$

$\omega = \frac{2\pi}{T}$ 'T' is the periodic function of $f(t)$ and $T = \frac{1}{f}$

f= frequency

a_h and b_h can be calculated as:

$$a_h - \frac{1}{\pi}\int_0^{2\pi} f(t)\cos(h\omega t)d(\omega t) \qquad h = 1, 2, 3, 4..... \tag{4.5}$$

$$b_h - \frac{1}{\pi}\int_0^{2\pi} f(t)\sin(h\omega t)d(\omega t) \qquad h = 1, 2, 3, 4..... \tag{4.6}$$

Now

$$f(t) - F_0 + F_{m1}\sin(\omega t + \phi_1) + F_{m2}\sin(\omega t + \phi_2) + ... + F_{mk}\sin(\omega t + \phi_k) \tag{4.7}$$

In this equation

$F_0 =$ DC component

F_{m1} =DC maximum value of fundamental component

F_{m2} =DC maximum value of 2^{nd} order component

F_{m3} =DC maximum value of 3^{rd} order component

F_{mh} =DC maximum value of 'h' order component

ω = angular frequency

ϕ_1 = phase shift of fundamental component

ϕ_2 = phase shift of 2^{nd} harmonic component

ϕ_h = phase shift of 'h' harmonic component

4.5.6 Total Harmonic Distortion

The total harmonic distortion (THD) is a broadly used tool to find out the amount of harmonics present in the signal. There are two ways to define the THD. One is defined as the harmonic content compared with its fundamental. Whereas the other is defined as, the harmonic content of signal is compared with the signal's rms value. To differentiate both these definitions they are denoted as THD_F and THD_R, described by the following equations [40]:

$$THD_F = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \tag{4.8}$$

$$THD_R = \sqrt{\frac{\sum_{n=2}^{\infty} I_n^2}{\sum_{n=1}^{\infty} I_n^2}} \tag{4.9}$$

In these equations I_n is the rms value or amplitude of the harmonics. When the value of THD is low then there is negligible difference between them. But when measuring the harmonic content in the signal with high THD, these two different definitions can create problems.

4.5.7 Fast Fourier Transform (FFT)

There are so many techniques used for the measurement of continuous signals, i.e. frequency and amplitude from the sample images of continuous signal. To perform all these methods, discrete or fast Fourier transform is used, which is a nice method to perform fast spectrum analysis [17]. The fast Fourier transform is most efficient way to compute the discrete Fourier transform of a continues signal.

4.6 Reactive Power Generation

One of the reason behind the voltage fluctuation in power system is reactive power. The reactive power can effect the system stability and also cause malfunctioning of the protective relays, which is very dangerous situation. The reactive power generated by the harmonics makes the system more complicated and hard to solve the issue. The reactive power is very common in the industry where load is in the form of motors, mills and power electronic converters [54]. Some of the reactive power generator are explained in this section:

4.6.1 Electric Power Generator

The main purpose of the generator is to provide the active power to the system, but it also stabilize the voltage by reactive power. How much reactive power is produced by the generator is also depends upon the production of the active power from it.

4.6.2 Power Electronic Converter

The voltage output from the converter is always operating at lagging power factor, and the amount of reactive power it draws from the system can be drive as:

$$Q = -1.35 V_{LL} I_d \sin(\alpha) \tag{4.10}$$

here

$\alpha =$ firing angle of the thyristor

To transfer maximum active power, reactive power should be minimize by keeping the value of I_d low.

4.7 Harmonic Current and Reactive Power Compensation Methods

Both the current harmonic and reactive power compensation improves the quality of voltage in the power system. There are so many ways to compensate the current harmonic and the reactive power. The desired result from all of these techniques are as follow:

- Limits the reactive power, keeps the voltage fluctuations within the limits and remove the harmonics from the source current.
- By limiting the reactive power it actually improves the real power production ability of the system.
- It keeps the losses within the limits

The parallel connected capacitors and reactors for the reactive power compensation are controlled by the thyristors. The value of capacitor is constant or it may change with the switching of thyristor. On the bases of this reliability, operating time and flexibility Static Var Compensator (SVC) is developed [8]. Some of the reactive power compensation schemes are explained in the appendix.

Some SVCs are as follows:

- Thyristor Controlled Reactor (TCR)
- TCR plus fixed capacitor (FC)
- Thyristor switched capacitor (TSC)
- TSC plus TCR

The reactive power compensation is used to regulate the voltage and to stabilize the system. The reactive power compensation is done with a couple of methods: load compensation and improvement of voltage. The load is compensated by improving the voltage quality and removing the harmonics, which helps in balancing the active power from the system. The reactive power is compensated by series or parallel connected Var generators. In these techniques by controlling the reactive power, power quality of the system is improved.

In past few years, rotating synchronous condensers, manually switched capacitors and inductors were used for the reactive power compensation. But now modern techniques i.e thyristor switched capacitors and reactors are used to compensate reactive power [14]. There are many techniques to compensate the reactive power in the system. The most feasible method is to use the VSC converter in the VFD. By doing the minor modification in the control of VSC converter, the reactive power can be compensated. This method is well explained in the simulation and result section of this thesis.

The process of compensating harmonics and reactive power through the converter control is called as active filtering. This method is now widely used to compensate the harmonics and reactive power in the system. This method is also used to remove the fluctuations from the system voltage, which can help in overall stability of the system. In this scheme, the harmonics produced by the non-linear devices such as fluorescent lamp and power supply to computers are removed by harmonics and reactive power compensation [41].

5 Modelling of Ship Power System: Case Study

5.1 Power System on ship

The power system on ship consists of various kind of loads. It is very important to understand how they are installed in the ship and how each component will behave in faulted condition. Fluctuation in the voltage due to different faults may cause the removal of propulsion from the system or blackout in worse case. This makes it really important to observe the change in the characteristics of each load during fault.

The single line diagram of the ship power system used in this thesis is shown in Figure 5.1 below [22].

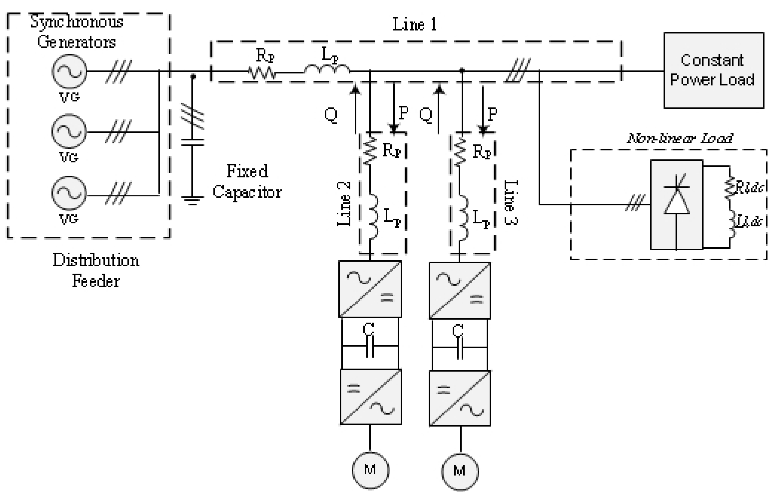

Figure 5.1: General figure of the power system of ship

To observe the behaviour of different component in case of fault, the system shown in Figure 5.1 is used. The synchronous generators are connected with the main bus bar and supplying to the propulsion system. A circuit breaker is used to disconnect and connect the load with the grid. The modelling of each part is described below.

A simulation model is built with the propulsion load, the passive load and non-linear load. The passive load is in form of parallel RLC load, which represents the loads like lightning, computer load and cooling system. The non-linear load represents the load which creates harmonics in the system, which could be of any type. The non-linear load in this simulation model is in form of thyristor connected, which is used to create harmonics in the system. This simulation model will be used for the analysis of different kinds of cases, which can occur during operation of the ship.

The ratings and modelling method used for different components in this simulation model are explained in this section:

5.1.1 Synchronous Generators

Three synchronous generators are used in the simulation model and the ratings of all of them are shown in the table below.

Table 5.1: Parameters of Generators connected to main grid Grid

Generators	Voltage (V_{LLrms})	frequency(Hz)	Power(MVA)
Gen.1	690	60	1.8
Gen.2	690	60	1.58
Gen.3	690	60	1.48

Figure 5.1 shows the block diagram of generators, they are operating in parallel. A simple control system for the turbine and governor is used which compare the actual speed with desire speed and generates the related torque single, which is feed to the alternator. The governor tries to maintain the speed and voltage of the alternator within the limits [22].

5.1.2 Line Parameters

In this work three lines are used. The main line connects all the loads. Line two and three are for the VFD-1 and VFD-2 respectively. The values of resistances and inductances of the lines are low, because lengths of the lines in ship is normally small. The capacitance between load and grid can be neglected because of the small length of lines. The impedance between distributed load and non-linear load can also be neglected due to their small values. The parameters of lines are given in the table below:

Table 5.2: Line parameters

Line no.	Resistance (mΩ)	Inductance(mH)
Line-1	1	10
Line-2	0.1	1
Line-3	0.1	1

5.1.3 Thruster Motor

The thruster motors for propulsion are the main consumers on ship power system, and mostly thrusters use induction motors. These motors are not directly connected to the bus bar. For their control, drives are used. The induction motor is simulated in this work, which is connected through the VFD. All the motors are modelled as three phase machines. The parameters of the IMs are given below:

Table 5.3: Parameters of the induction motor used as thruster motor

Nominal Power(MVA)	1.2
Frequency (Hz)	60
Nomial Voltage (V_{LLrms})	690

5.1.4 RLC Load

The main consumers on the ship power system are the thruster motors for propulsion, but there is demand for other loads also. The passive load is in form of a parallel RLC load, which represents the loads, i.e. lightning, computer load and cooling system. The parameters of the parallel RLC load are given below:

Table 5.4: Parameters of RLC load connected to the system

Nominal Power(MVA)	1
Frequency (Hz)	60
Nomial Voltage (V_{LLrms})	690

5.1.5 Non-Linear Load as Thyristor Bridge

The non-linear loads in the ship power system normally generates the harmonics in the system, which causes fluctuations in the voltage. To represent these non-linear load, a thyristor bridge connected load is used. It is shown in Figure 5.1, and its parameters are shown in the table below:

Table 5.5: Parameters of non-linear load connected through thyristor bridge

Voltage V_s	$690[V_{L-L,rms}]$
Frequency f	60 [HZ]
Resistive load R_l	50 $[\Omega]$
Inductive load L_l	50 $[mH]$
DC side capacitance C	1 $[mF]$
Firing angle α	25
Snubber resistance R_s	1 $[K\Omega]$
Snubber capacitance C_s	$0.1[\mu F]$
Internal resistance R_{in}	$1[m\Omega]$
Rated power P	$9.5[KW]$

5.1.6 Snubber Resistance and Snubber Capacitance

The main cause of harmonics in the power system is the non-linear load, which is thyristor connected load in this model. Figures 5.2 and 5.3 show the three phase bridge rectifier with diode and thyristor respectively. To save the system from oscillations, snubber resistor R_s and capacitor C_s are used with both these rectifier circuits. The value of both of them can be calculated using following formula [49].

$$R_s > 2\frac{T_s}{C_s} \tag{5.1}$$

$$C_s < \frac{P_n}{1000(2\pi f)V^2 n} \tag{5.2}$$

In this equation:

$P_n =$ rated power of rectifier $[KW]$

$V_n =$ rated voltage $[V_{rms}]$

$f =$ fundamental frequency $[HZ]$

$T_s =$ sample time $[S]$

The inductance L_{in} is taken as zero, whereas value of R_s and C_s can be calculated using following assumptions:

- The leakage current should be less than 0.1 % of rated current at fundamental frequency, when PE devices are not conducting.
- The time constant RC should be higher than two times the sample time.

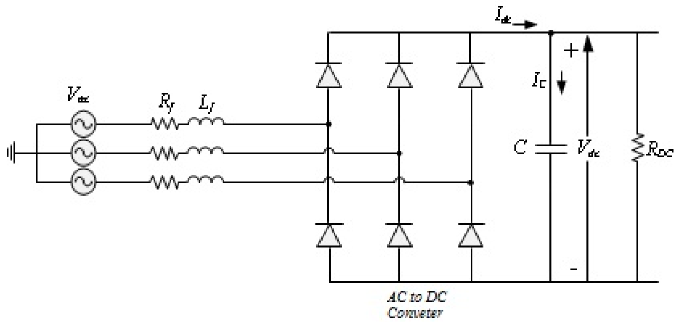

Figure 5.2: Three phase diode bridge rectifier

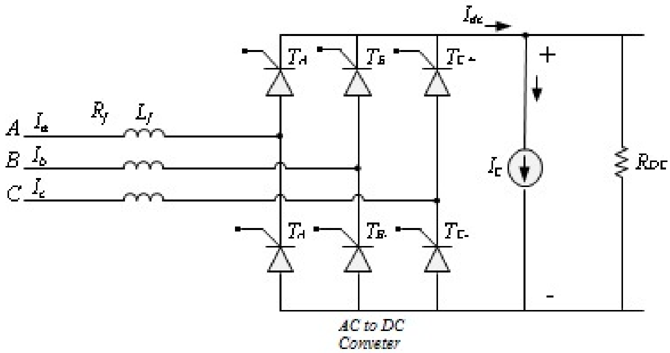

Figure 5.3: Three phase thyristor bridge rectifier

5.2 Variable Frequency Drive

In the VFDs voltage from the generator set is feed to the rectifier circuit, which converts AC into DC voltage. After the rectifier, a capacitor bank is used to reduce the ripples and to smooth output DC voltage. This DC voltage is then supplied to the inverter circuit, which converts this DC into AC voltage.

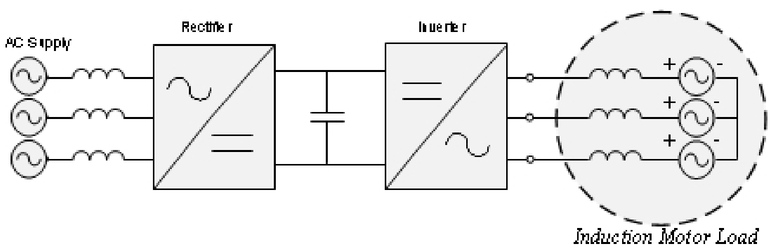

Figure 5.4: Variable frequecy drive with IGBT rectifier and inverter

Figure 5.4 represents the block diagram of VFD. Both for the rectification and inversion, IGBTs with anti parallel diodes are used. The control scheme for IGBTs switching is explained below for both rectifier and inverter. To remove harmonics from the system LC filter is designed, which is connected on AC side of the rectifier.

5.3 Voltage Source Converter Control Scheme

The voltage source converter scheme provides the controllable AC voltage. This method gives constant DC voltage, lesser harmonics, bidirectional flow of power and controlled power factor. Due to these many qualities, this technique is adopted in high power systems or in the system where efficiency is expected to be very high [7]. The VSC can perform as active rectifier, which can not only control the DC voltage but also the power factor. It can also be used to compensate the harmonics, by using PWM with closed loop current controller which reduces the source current harmonics by keeping the THD lower than 5 % [26].

There are many advantages which can be associated with the VSC based converter design. Some of these advantages are well explained in as follows [38]:

- It provides the continuous operation, reactive power compensation and voltage regulation which produce stability in the system.
- It controls the real and reactive power both in steady state and dynamic conditions.
- This technique is very useful for harmonics mitigation from the source current.
- It uses modern technologies, with low amount of losses, cheaper in price and highly reliable.

This method is simple and give dynamic response. The vector control uses Clark and Park transformations. In these transformations *d-q* rotatory coordinates are achieved from three phase stationary axis. For this transformation $\alpha - \beta$ stationary axis are used. With the help of *d-q* transform, handling of the current and voltage become easy. The Clark and Park transformations are explained below as in [44] [12]. The Clark transformation identifies the real and imaginary currents, and the Park transformation converts these currents into rotational frame from stationary frame.

5.4 Rectification

In chapter 3 rectification using diode is explained, but the VFDs in this report uses IGBTs based rectifiers. The benefits of having IGBTs over diodes are their controlled operation. By using diode rectifier, power can be transferred just in one direction. When using the IGBTs, power can be supplier either ways. Figure 5.5 illustrates the rectifier circuit used for this thesis.

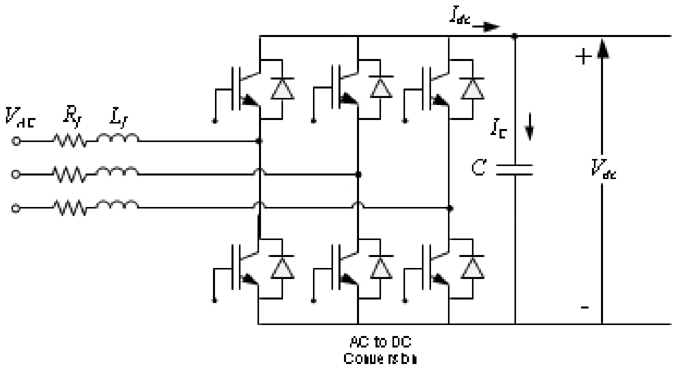

Figure 5.5: Circuit diagram of IGBT based rectifier used in the VFD

The rectifier circuit in this work uses IGBTs, having anti parallel diode connected with them. Because of the high power of the VFDs, the IGBTs are preferred over MOSFETS. On the AC side of the rectifier, LC filter is connected to reduce the ripples in circuit. For switching of the IGBTs, PWM technique is used and explained in section 5.6.1.

The voltage source converter can perform both as rectifier and inverter if switching is performed with the combination of IGBTs and anti parallel diodes. In this model rectifier can supply reactive power, active power and remove the harmonics from the grid. When it supply power to the grid it behaves as inverter. The switching frequency of 1.6[kHz] is selected. During the normal operation, rectifier provide power to the motor and in case of fault it provides reactive power to the system, which helps in regulating the voltage.

5.5 Modelling of Rectifier

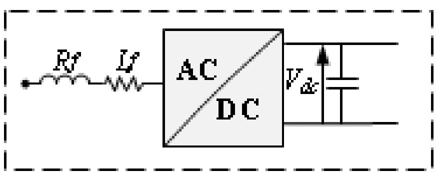

Figure 5.6: The block diagram of rectifier used for the modelling

The main goal when designing the rectifier control was to make it bidirectional, in order to work both as rectifier and inverter at times. The change in control is first performed in one rectifier and then it is copied in the other one also. By installing this rectifier in the power system, it will help remove the harmonics from the grid. The VFDs would be helpful for the grid support of the ship power system, because it would remove the harmonics and provides the reactive power when needed.

Figure 5.7 shows the rectifier modelling method for the control. The control of this rectifier is done with vector control scheme.

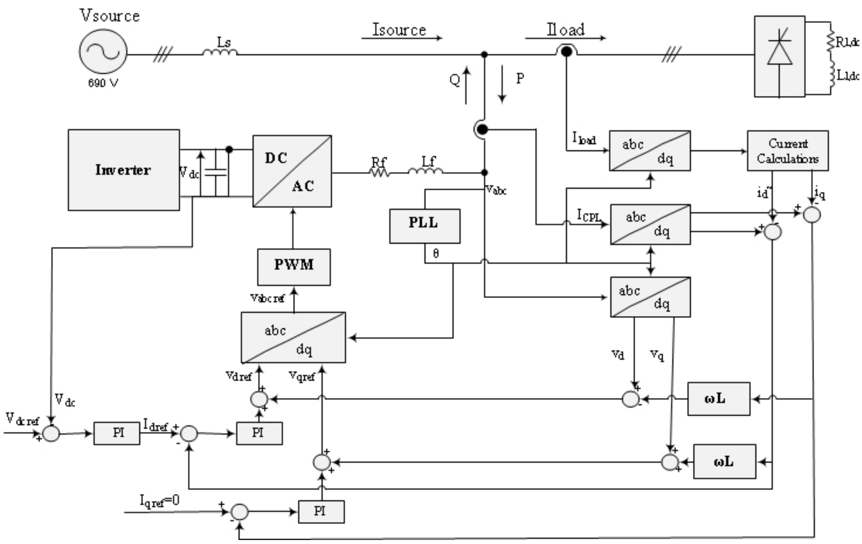

Figure 5.7: Control of VSC rectifier [27]

The controller takes values of the phase voltages and currents from the PCC, and convert these values from *abc* to *dq* by using the Clark and Park transformation, which is shown in Figure 5.8 below. The voltage waveforms after *dq* transform are as follows [32]:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} V_{dconv} \\ V_{qconv} \end{bmatrix} - R_f \begin{bmatrix} i_d \\ i_q \end{bmatrix} - L_f \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{5.3}$$

$$V_{s,d} - V_{c,d} = Ri_d + L\frac{di_d}{dt} - \omega L i_q \tag{5.4}$$

$$V_{s,q} - V_{c,q} = Ri_q + L\frac{di_q}{dt} - \omega L i_d \tag{5.5}$$

In these equations $V_{s,dq}$ and I_{dq} represents the voltage and current components of supply system. Where $V_{c,dq}$ show *d,q* voltages of the rectifier and ω is frequency of the grid. The PLL is used to synchronize *dq* frame in a way, which makes phase *A* in phase with d-axis, $V_{s_d} = V_S$ and $V_{s_q=0}$. The real and reactive power taken and given can be calculated as:

$$p = \frac{3}{2}.v_d.i_d \tag{5.6}$$

$$q = -\frac{3}{2}.v_d.i_q \tag{5.7}$$

These equation illustrates that the power can be controlled by just controlling the d and q axis by using the VSC. The real and reactive power harmonics and average components are give as equation below:

$$p - p_{avg} + p_{osc} \tag{5.8}$$

$$q - q_{avg} + q_{osc} \tag{5.9}$$

In these equations p_{avg} and q_{avg} represent the DC components of both the powers, whereas p_{osc} and q_{osc} represent the harmonics components in both the powers. Because in VSC both the power are controlled by dq currents, so its equations can be written as:

$$I_d - I_{d_{avg}} + I_{d_{osc}} \tag{5.10}$$

$$I_q - I_{q_{avg}} + I_{q_{osc}} \tag{5.11}$$

It can be seen from the equations that by controlling the $I_{d_{avg}}$ and $I_{q_{avg}}$ real part of both the powers can be controlled, controlling $I_{d_{osc}}$ and $I_{q_{osc}}$ parts, on the other hands means harmonics can be controlled. By controlling the value of I_q reactive power can be controlled, which helps in reactive power compensation. By injecting the reactive power in the case of three phase to ground fault, the voltage of the system can be regulated. Figure 5.8 shows the use of Clark and Park transformation in the control scheme.

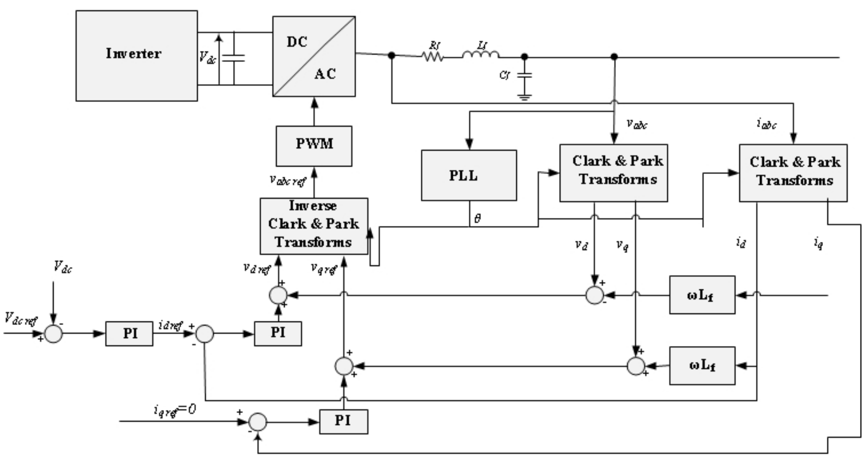

Figure 5.8: Use of Clark and Part transformation in the control of rectifier

5.5.1 Clark Transformation

With the help of Clark transformation phase values of current and voltage are transformed into stationary $\alpha - \beta$ reference. Figure below shows two coordinate system.

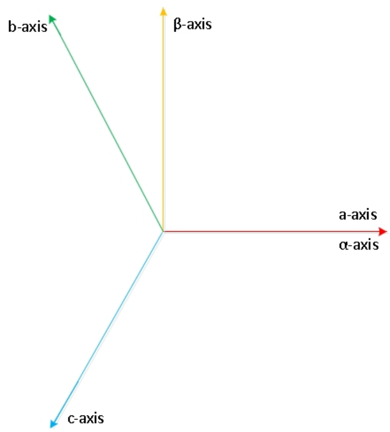

Figure 5.9: Three phase and $\alpha - \beta$ coordinates [44]

To keep the analysis simple α-axis are kept parallel with a-axis. The Clark transformation matrix is:

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{5.12}$$

The considered system is balanced which makes V_0 zero. V_0 will have non-zero value, when the system is unbalanced. By considering the system symmetrical, V_0 can be neglected which makes the matrix as follows:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{5.13}$$

Three phase voltages can be achieved by taking inverse of the Clark transformation which is given as:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{5.14}$$

5.5.2 Park Transformation

To transform this $\alpha-\beta$ coordinate into the rotating *d-q* frame, Park transformation is used. The *d-q* coordinates rotate at speed ω with respect to the $\alpha-\beta$ coordinates. With the help of equation 5.15 position of d-axis can be determined.

$$\theta = \omega.t \tag{5.15}$$

For the Park transformation matrix is given as

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{5.16}$$

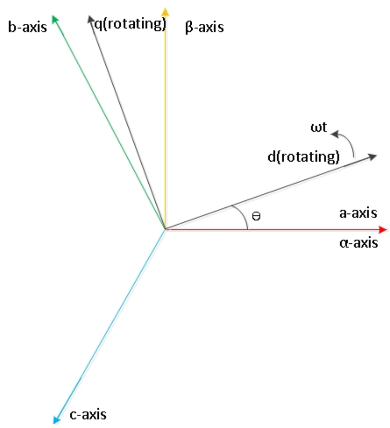

Figure 5.10: Three phase coordinate system, $\alpha-\beta$ coordinates and *d-q* coordinated systems. [44]

By taking the inverse of Park transformation $\alpha-\beta$ frame can be obtained which is

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} V_d \\ V_q \end{bmatrix} \tag{5.17}$$

Same type of calculations can be done for the current transformation.

5.5.3 Phase Locked Loop PLL

The phase locked loop (PLL) is a frequency control close loop function, which is used to control angle. The PLL is well explained in Figure 5.11 below:

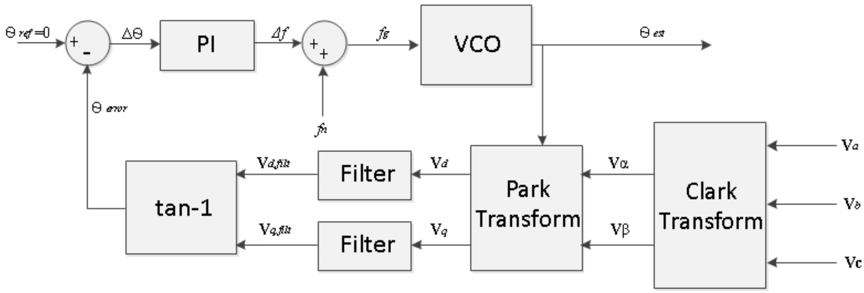

Figure 5.11: Block diagram of Phase Locked Loop [44]

The PLL takes value from *dq* rotating frame, and measures phase angle of grid voltage referred to the space vector. To remove noise from the *dq* voltages, a filter is used. Normally θ_{ref} is kept zero, and the error determined by comparing the measured value with θ_{ref} is fed to regulator. The regulator output is added with the base frequency and the actual grid frequency is achieved.

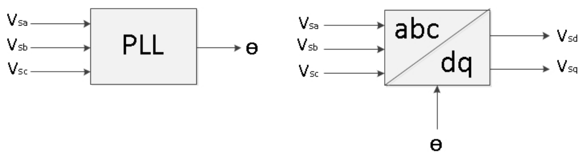

Figure 5.12: Phase Locked Loop block [44]

This angle is an input to *dq* rotating frame, also used while measuring the currents and inverse park transformation. As far as output angle is right the PLL is locked, if it is different from grid angle then regulator changes frequency to keep angle in limits.

5.5.4 Current Controller

Fast and dynamic response of active and reactive power is because of outer and inner current loops. The inner current control loop take the reference value of the AC current from the outer current control loop and controls it. For the PLL reference, the voltage and current are at the point of common coupling, which is before rectifier in the control diagram. The block diagram for the current control is shown below.

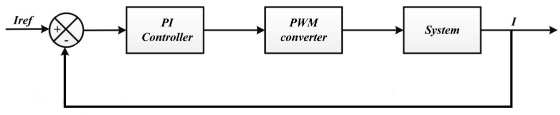

Figure 5.13: Current loop for rectifier [44]

Figure 5.13 shows that the current loop has PI regulator, PWM converter and feed forward term. There are two PI regulators for the d and q axis. These regulators compares the error signals and generate the respective voltage in response.

5.5.5 PI Regulator

The equation of the PI regulator is given as:

$$R(S) = K_p + \frac{K_i}{s} = K_p \frac{1 + T_{i.s}}{T_{i.s}} \tag{5.18}$$

In this equation K_p and $T_i = \frac{K_p}{K_i}$ are the design components. But for PI regulator equation can be written as:

$$[I_{ref(s)} - I_s][K_p + \frac{K_i}{s}] = V_{conv(s)} \tag{5.19}$$

5.5.6 Output Voltage Controller

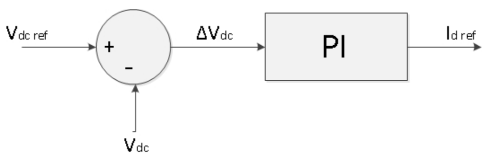

Figure 5.14: DC voltage control block

This block keeps the DC voltage constant at the required value. The DC voltage should be double than $V_{peak,ph}$, which is 563V in this case. This DC voltage stops over modulation and keeps control voltage of the pulse width modulation into the peak of triangular wave.

$$V_{LLrms} = 690V \tag{5.20}$$

$$V_{dc} = 2.\sqrt{\frac{2}{3}}.V_{LLrms} = 2.563 = 1126V \tag{5.21}$$

This V_{dc} is set as reference value and compared with the measured value. The error signal $\triangle V_{dc}$ is feed to the PI controller. The output from PI regulator is set as reference for I_d and used as I_{dref} in current controller.

5.5.7 LC Filter

Due to the switching of IGBTs higher order frequency components are added in the fundamental frequency, which is known as harmonics. To remove these harmonics from the system, an LC filter is connected on AC side of the rectifier. The resistance of this LC filter is negligible where its inductance is 0.4mH and capacitance is 0.45nF.

5.5.8 Modelling

Equation 5.4 demonstrates all the features of the system. It can be seen from the equation, that VSC consists of various inputs and outputs having non-linear load attached to them. With the help of two different current controllers for both d-axis and q-axis currents, it gives reference value for the voltage, which is supplied to the converter and it gives reference for the system.

With the help of equations 5.18 and 5.19 reference can be calculated as:

$$V_{d_{conv}} = (i_{d_{ref}} - i_d).[K_p + \frac{k_i}{s}].[\frac{1}{1+T_{as}}] \tag{5.22}$$

$$V_{q_{conv}} = (i_{q_{ref}} - i_q).[K_p + \frac{k_i}{s}].[\frac{1}{1+T_{as}}] \tag{5.23}$$

By introducing cross coupling and feed forward parameters

$$V'_{d_{conv}} = -(i_{d_{ref}} - i_d).[K_p + \frac{k_i}{s}] + \omega L i_q + v_d \tag{5.24}$$

$$V'_{q_{conv}} = -(i_{q_{ref}} - i_q).[K_p + \frac{k_i}{s}] - \omega L i_q + v_q \tag{5.25}$$

The end equation for the system after calculating all the terms is as follow:

$$V_{d_{conv}} = Ri_d + L\frac{di_d}{dt} \tag{5.26}$$

$$V_{q_{conv}} = Ri_q + L\frac{di_q}{dt} \tag{5.27}$$

With the help of Laplace transform one of the equation can be transformed as follow:

$$G(s) = \frac{1}{R}.\frac{1}{1+s.\tau} \tag{5.28}$$

Here $\tau = \frac{L}{R}$ is known as the time constant.

5.6 Modelling of Inverter

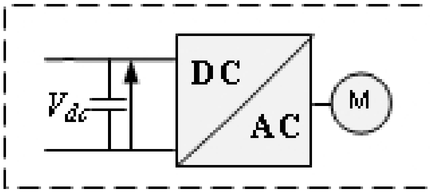

Figure 5.15: The block diagram of inverter used for the modelling

The purpose of the VFD in this report is to change the speed of induction motor according to the reference value. Due to this reason the VFD is also called as adjustable speed drive. Mostly VFD uses current regulator for safe operation of motors. For this VFD, control is done by using the field oriented vector control technique [43]. The figure 4.11 represents the control of this drive.

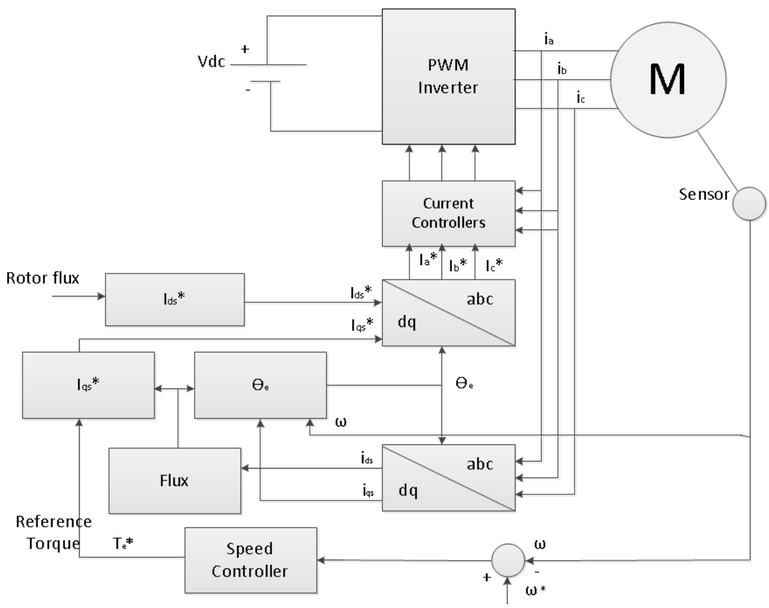

Figure 5.16: Control scheme for inverter of variable frequency drive

The speed controller is a proportional integral regulator, which takes the speed error as the input. Where ω is the speed of motor and ω* is reference speed. The value of currents can be calculated from *dq* transform, which controls the switching of the transistor through PWM. In this system, the PWM based inverter works as current source for the IM.

$$i_{qs}* = \frac{2}{3}.\frac{2}{p}.\frac{L_r}{L_m}.\frac{T_e*}{\psi_r} \tag{5.29}$$

$$i_{ds}* = \frac{\psi_r}{L_m} \tag{5.30}$$

In equations 5.29 and 5.30, i_{qs}* and i_{ds}* represents the stator dq currents, which are again converted from *dq* to *abc* axis for the current regulator. Where L_r and L_m are the rotor and mutual inductances. In case of vector control method values of instantaneous real and reactive power can be calculated as follows [27]:

$$p = \frac{3}{2}.v_d.i_d \tag{5.31}$$

$$q = -\frac{3}{2}.v_d.i_q \tag{5.32}$$

5.6.1 Pulse Width Modulation

The PWM is a technique used to convert three phase AC to DC voltage and also DC to AC voltage. In the pulse width modulation, a triangular voltage and three phase voltage from the Clark transformation is compared with each other for the IGBTs switching.

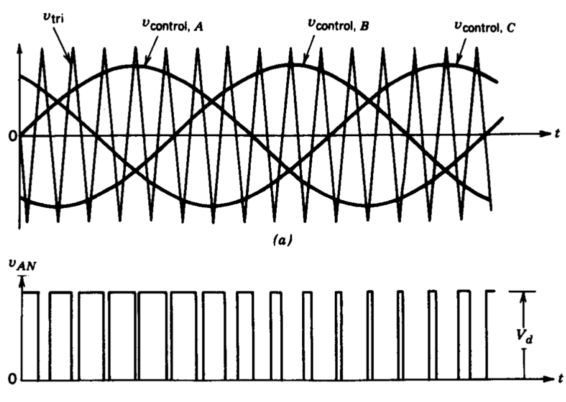

Figure 5.17: Pulse width modulation waveform [49]

In the figure above triangular voltage and control phase voltage can be seen. V_d is the DC voltage. When this equals V_{an}, IGBTs will conduct. Area above linear modulation in figure is called over-modulation. In the over modulation, control voltage's peak exceed from triangular voltage's peak. Which keeps the switches on or off even when reference voltage is higher or lower than triangular, this introduce instability in the system [49].

5.7 Frequency Droop Control

The concept of frequency droop is explained in chapter 2. The control scheme for frequency droop is shown in Figure 5.18. In Figure 5.18, f* and P* represent the reference frequency and power of the system respectively. Where as P and f are the measured parameters of the system.

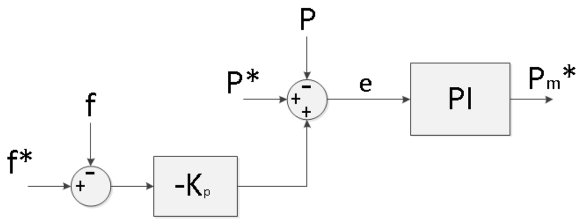

Figure 5.18: Frequency droop control with constant power control [18]

In steady state condition control error signal **e** is zero. The frequency reference is normally a constant value, which is 60HZ in this report. The frequency control of the system can be expressed with the help of equation given below:

$$f - f_0 = -k_p(P - P_0) \tag{5.33}$$

In equation 4.16 P_0 is the set point for active power, and f_0 is rated frequency of the system. The controller gets error signal from frequency and power, and then generates reference mechanical power for the generator.

6 Simulation Results for Power Quality Improvement and Voltage Support

In this study the parallel operation of three synchronous generator sets are supplying power to the grid, the VFD is also connected in the system. The non-linear load connected through thyristor bridge causes harmonics in the system, which produce fluctuations in the voltage and lead to instability.

In this chapter model of the power system explained in previous sections is simulated using MATLAB/SIMULINK™. The non-linear and motor load is connected with the grid using thyristor rectifier and the VFD respectively. In such systems the power electronic devices cause power quality problems, the VFD in this work consists of power electronic based rectifier and inverter. The simulations are carried out with different cases to find out the power quality problems and their mitigation techniques in the system.

The harmonics produced by the non-linear loads are compensated with the help of VSC converter used in the VFDs. The harmonics compensation technique is first implemented in the system with ideal power supply. After successfully compensating the harmonics in ideal power supply case it is further extended to the power system on ship. The harmonics are removed first by using one VFD in the system and then extended to two drive system. To find out the harmonic content in the source current FFT analysis were performed, its results are listed in the table form.

The VSC based converter used in the VFDs can be used for reactive power compensation, the control is explained in the previous chapter. The reactive power compensation is first performed in the system with ideal power supply and then further implemented in the ship power system. The VSC based converter supply reactive power in case of fault, which keeps the voltage with in the allowable limits.

6.1 Parallel Operation of Generators

In the ship power system, more than one generators are used to supply power. These generators operates in parallel, which is well explained in the literature review. Figure 6.1 illustrates the parallel operation of three synchronous generators connected with the constant power load.

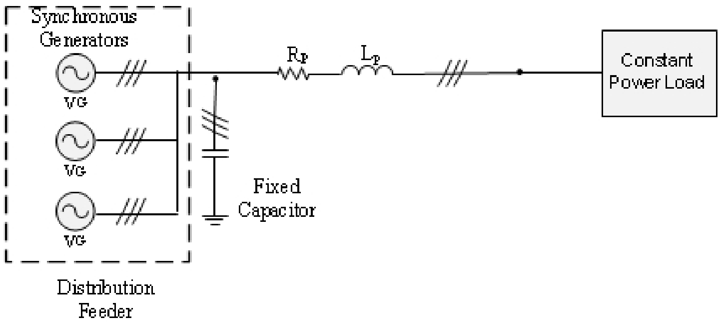

Figure 6.1: Parallel operation of three synchronous generators

The simulations were performed with the nominal voltage of the grid, which is $690V_{LL,rms}$. In this work three generator sets are operating in parallel and sharing the load, the simulation results for the load on every generator set is shown in Figure 6.2.

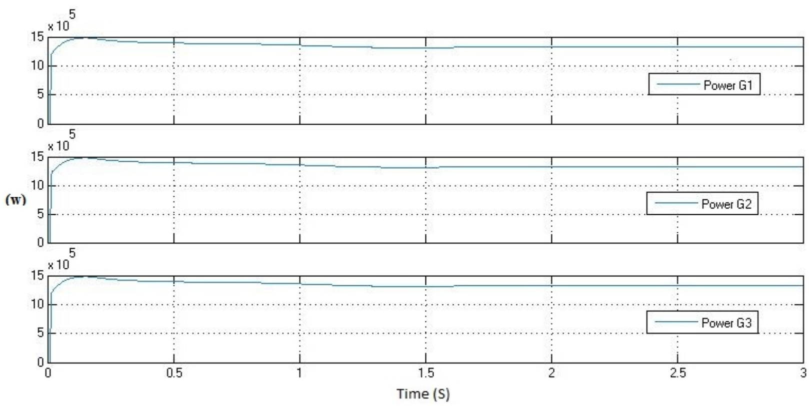

Figure 6.2: Power supplied by each generator when operating in parallel

Figure 6.2 shows the loads on generator G1, G2 and G3, the generators normally share the load in parallel operation. The load of 4Mw was connected with the common bus bar of these gen-sets, each of them is supplying equal power to the load. Each generator is giving 1.33Mw, which shows that these generator are operating in parallel and sharing the load.

6.1.1 Bus Bar Performance

Figure 6.3 shows the bus bar voltages of all three phases. It can be seen that all the phases are 120°apart from each other. The system is operating on $690V_{LL,rms}$, where as single phase to ground rms voltage is $\sqrt{\frac{2}{3}}.V_{LLrms}$ which is 563V. It can be seen from the figure that all three phases have 563V. Figure 6.3 illustrates voltages of phases **a**, **b** and **c** respectively.

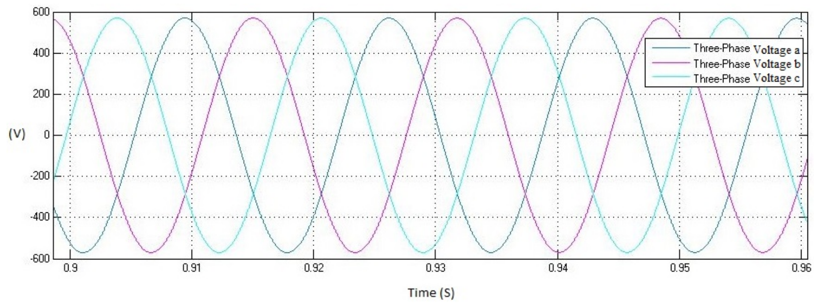

Figure 6.3: Bus bar voltages without connecting the VFD

6.2 Harmonics Compensation with Ideal Power Supply

This simulation was performed to compensate the harmonics in the system with the ideal power supply by using VSC converter. This technique is then implemented in the ship power system. Figure 6.4 represents the power system with ideal power supply, connected with the non-linear load, constant power load and dc load connected through the VSC converter.

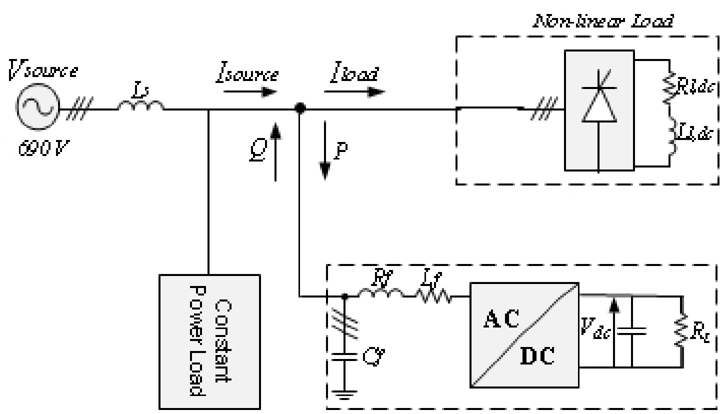

Figure 6.4: Power system with ideal supply and non-linear load

The harmonics are produced in the system because of the non-linear load, and it is compensated with the help of converter. The VSC converter is connected with the circuit breaker in the system. The simulation are carried out by using the converter control explained in chapter 5.

6.2.1 Harmonics Compensation with Converter

Figures 6.5 and 6.6 show the source current for three phase and single phase respectively, before and after connecting the converter in the circuit. The simulations were carried out for the time *t*=0.5 sec. The non-linear load as described in chapter 5 is connected in the circuit, which produces harmonics in the system. The control scheme for the thyristor bridge rectifier is shown in the appendix B. The converter is out of the circuit before time *t*=0.3 sec, harmonics can be seen during that time in Figure 6.5. After time *t*=0.3 sec the converter starts supplying the current and also compensates the harmonics, which is quite visible in the figure.

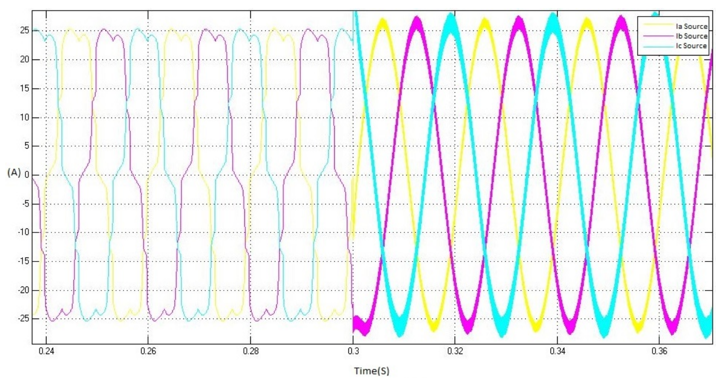

Figure 6.5: Three phase source current before and after connecting the converter

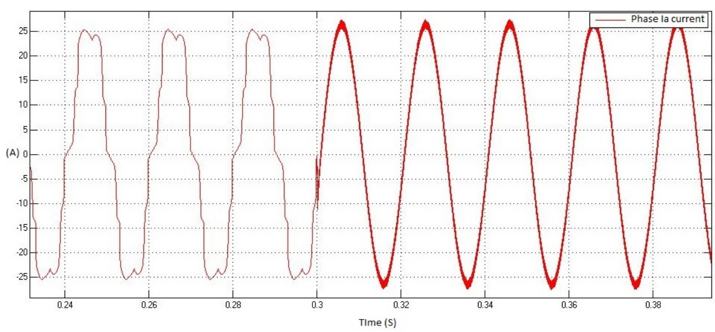

Figure 6.6: Single phase source current before and after harmonics compensation

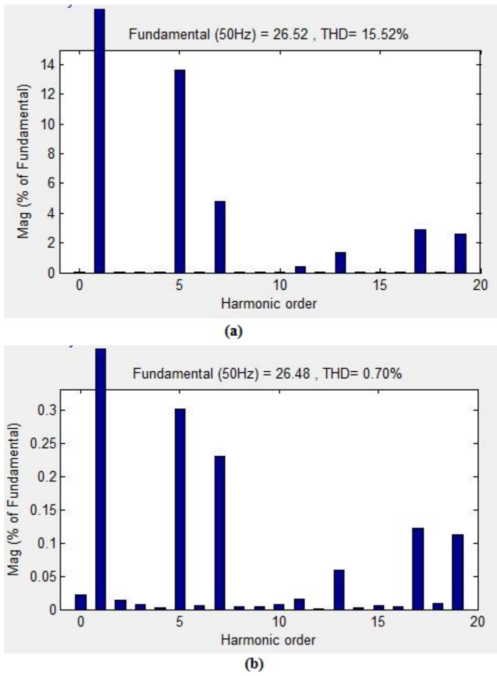

Figure 6.7: (a) FFT analysis before connecting the converter (b)FFT analysis after connecting the converter

Because of the ideal power supply all three phases are same. Study can be carried out with only one phase and it will stand true for all the other phases as well. Figure 6.6 shows the single phase current before and after the connection of VSC. The VSC is connected in the system at time *t*=0.3 sec. The harmonic current is visible before the time *t*=0.3 sec because of non-linear load, but right after the connection of converter distorted waveform changes into the pure sinusoidal waveform. The results from Figure 6.5 and 6.6 tell us that control for the converter in case of ideal power supply is working.

6.2.2 FFT Analysis

To find out the harmonics in the current Fast Fourier Transform (FFT) analysis were performed. The grid voltage was 690 V_{rms} and frequency was 50 HZ to perform the simulation. Figure 6.7 (a) and Figure 6.7 (b) represent the THD in the source current before and after the connection of converter in the system. It is quite visible from the figure that THD is reduced from 15.52 to 0.70 %.

Table 6.1 shows the harmonics in current before and after the connection of converter in the system. It can be seen that the THD is significantly reduced from 15.52% to 0.71%, when converter is supplying current. It can also be seen from the table that I_{5th}, I_{7th},

I_{11th}, I_{13th}, I_{17th} and I_{19th} order harmonic current components plays a vital role in the THD when the converter is not connected. These components are reduced significantly when the converter is connected in the system.

Table 6.1: Fast Fourier Transform analysis of the current with ideal power supply

Components	Harmonics before converter	Harmonics after converter
Fundamental	100%	100%
I_{5th}	13.63%	0.29%
I_{7th}	4.79%	0.24%
I_{11th}	0.38%	0.01%
I_{13th}	1.34%	0.06%
I_{17th}	2.89%	0.12%
I_{19th}	2.61%	0.12%
THD	15.52%	0.71%

The reduction in harmonics after connection of converter in the system shows that control is working according to the settings. The converter is successfully compensating the harmonics from the source current, THD is reduced with in the allowable limits of the IEEE standards.

6.3 Harmonics Compensation with One VFD Installed

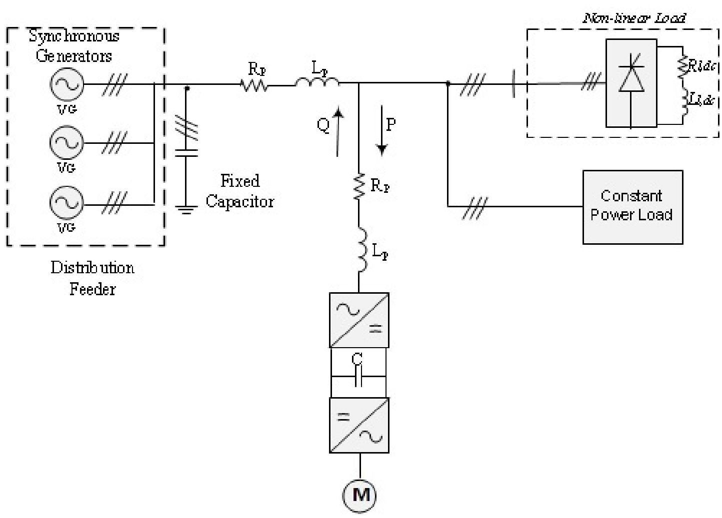

Figure 6.8: Power system on ship with one VFD and non-linear load

Figure 6.8 represents the ship power system connected with one VFD and non-linear load. Three parallel operating synchronous generators are supplying the load, the grid voltage is $690V_{rms}$ and frequency is 60 HZ. The non-linear load connected through the thyristor bridge is producing harmonics in the system, which is mitigated using the converter in the VFD. The constant load is in form of parallel RLC load, which represents the loads like lightning, computer load and cooling system. The control scheme explained in chapter 5 is implemented in the VFD, to remove the harmonics from the source current and following results were obtained. The control blocks for the this case are shown in appendix B.2.

6.3.1 Harmonics Compensation with Converter

The simulation model for the ship power system was built in MATLAB/SIMULINK™ to compensate the harmonics components from the source current. Figures 6.9 and 6.10 illustrated the three phase and the single phase source current with and without harmonics compensation respectively. The non-linear load as explained in chapter 5 is connected with the system, which is main cause of harmonics production here. The circuit breaker for the VFD is connecting at the time *t*=0.2 sec and it is disconnecting at time *t*=2.1 sec. The total simulation time for this case is 2.5 sec.

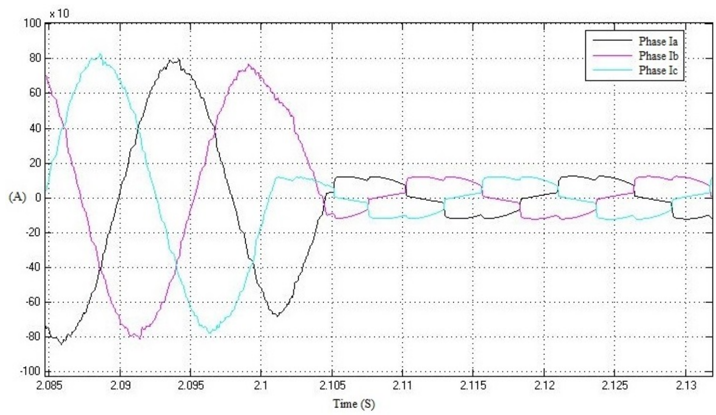

Figure 6.9: Three phase source current with and without connecting the VFD

The propulsion motor is connected with the VFD as load. The VSC converter in this case not only compensates the harmonics but also supply power to the motor. Figure 6.9 illustrates the three phase source current of the system. It can be seen from the figure that when converter supplies the current, it compensates the harmonics and when the converter stop supplying the current after the time *t*=2.1 sec harmonics appears again in the source current. The high value of current in the figure before time *t*=2.1 sec is because of the propulsion motor load, this converter not only compensates the harmonics from the system but also supplies current to the propulsion motor through inverter.

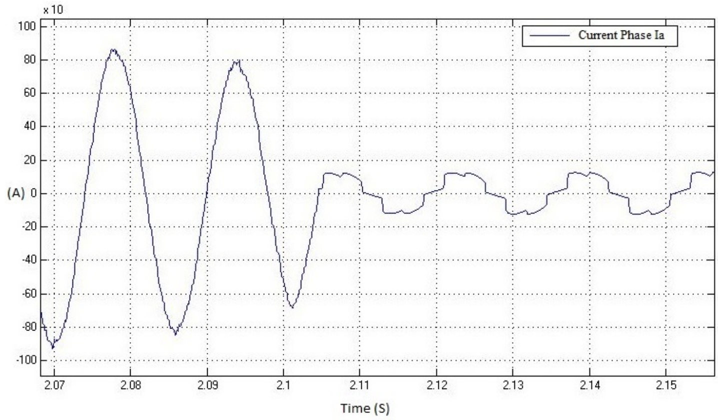

Figure 6.10: Single phase source current with and without connecting the VFD

When the breaker turns off at time t=2.1 sec, the propulsion motor load is also removed from the system which can be seen in Figure 6.9. After time t=2.1 sec, there is abrupt change in the magnitude of the current. The simulation results for the source current when breaker is turned on at time t=0.2 sec are not shown because motor drags huge amount of current in starting which makes it difficult to show the results in one frame. The single phase in this case has the same characteristics as three phase, studies can be carried out with only the single phase current only and implemented on the three phase. Figure 6.10 illustrates the single phase source current of the system, the figure shows compensation of harmonics in that case also. The simulation results show that control for the converter is working accordingly and compensating the harmonics.

6.3.2 FFT Analysis

Table 6.2: FFT analysis of the current in case of one VFD installed

Components	Harmonics without converter	Harmonics with converter
Fundamental	100%	100%
I_{3rd}	3.29%	1.21%
I_{5th}	17.65%	1.24%
I_{7th}	6.41%	0.26%
I_{9th}	1.86%	0.20%
I_{11th}	6.23%	0.36%
I_{13th}	2.33%	0.16 %
I_{15th}	1.72%	0.10%
THD	23.16%	4.05%

To find out the harmonics in the current FFT analysis were performed. The grid voltage in this case was 690 V_{rms} and frequency was 60 Hz to perform the simulations. Table 6.2 shows the harmonics in current without and with the connection of converter in the system. It can be seen that the THD is significantly reduced from 23.16% to 4.05%, when converter is supplying current. It can also be seen from the table that I_{3rd}, I_{5th}, I_{7th}, I_{9th}, I_{11th}, I_{13th} and I_{15th} order harmonic current components play a vital role in the THD, when converter is not connected. These components are reduced significantly when converter is connected in the system. These values of harmonics for the different order are with in the allowable limits in [1].

6.4 Harmonics Compensation with Two VFDs Installed

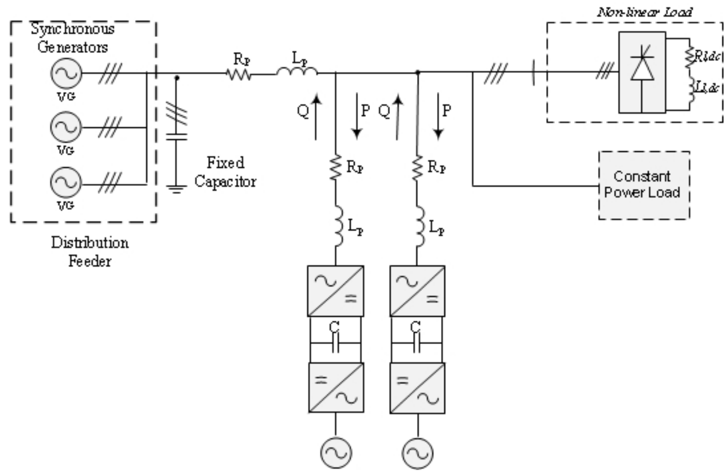

Figure 6.11: Power system on ship with two VFDs and non-linear load

In the previous case simulations were done by using only one VFD in the power system on ship, here we use the power system connected with two VFDs. Figure 6.11 represents the ship power system connected with two VFDs and non-linear load. The non-linear load connected through the thyristor bridge is producing the harmonics in the system, which is mitigated using the converters in the VFDs. Three parallel operating synchronous generators are supplying the load, the grid voltage and frequency in this case are $690V_{rms}$ and 60 HZ respectively. The non-linear load is producing harmonics in the system, which is mitigated using the converter in the VFD. The control scheme explained in chapter 5 is implemented in the VFDs and the following results were obtained.

6.4.1 Harmonics Compensation with Converter

Figures 6.12 and 6.13 illustrate the three phase and the single phase source current with and without harmonics compensation respectively. The non-linear load as explained in chapter 5 is connected with the system, which is main cause of harmonics production here. The circuit breaker for the VFD is connected at the time *t*=0.2 sec and is disconnected at time *t*=1.45 sec. The total simulation time for this case is 2.5 sec.

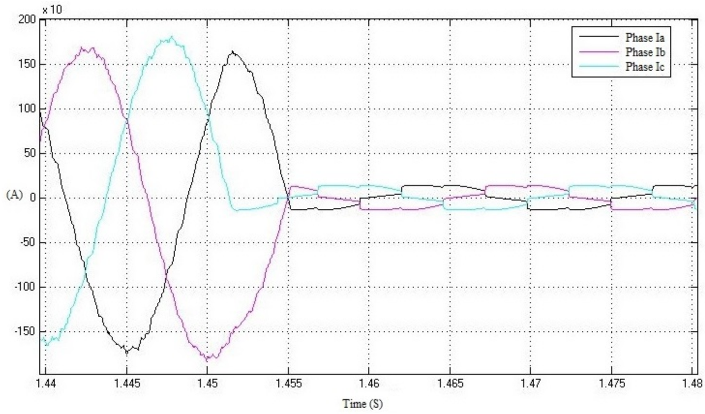

Figure 6.12: Three phase source current with and withou connecting the VFDs

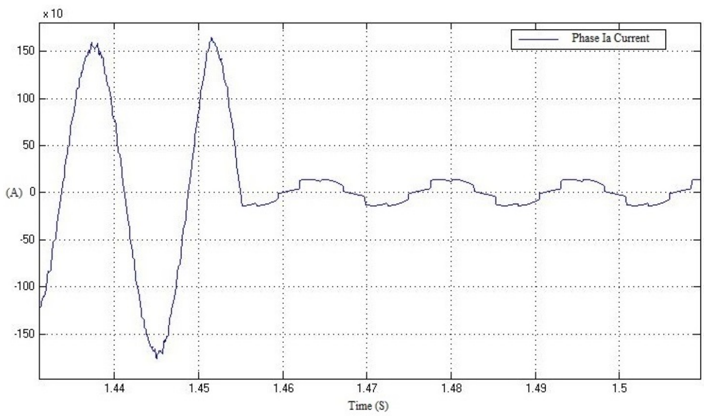

Figure 6.13: Single phase source current with and without connecting the VFDs

Figure 6.12 shows the three phase source current of the system. It can be seen from the figure that when the converter supplies the current it compensates the harmonics and when converter stop supplying the current after the time *t*=1.45 sec, harmonics appears again in the source current. The high value of current in the figure is because of the propulsion motor loads. The value of the current in Figure 6.12 is almost double as compare to the value of current in Figure 6.9, because of the two VFDs connected in the system. These converters are not only compensating the harmonics from the system but also supply current to the propulsion motors through inverter.

When the breaker turns off at time *t*=1.45 sec, the propulsion motor loads are also removed from the system which can be seen in Figure 6.12. After time *t*=1.45 sec, there is an abrupt change in the magnitude of the current. Figure 6.13 shows the single phase source current of the system. The figure illustrates compensation of harmonics in that case also. This shows that control for the converters are working accordingly and compensating the harmonics.

6.4.2 FFT Analysis

To find out the harmonics in the current FFT analysis were performed. The grid voltage in this case was 690 V_{rms} and frequency was 60 Hz to perform the simulation. Table 6.3 shows the harmonics in current without and with the connection of converter in the system. It can be seen that the THD is significantly reduced from 26.03% to 3.87%, when converter is supplying current. It can also be seen from the table that I_{3rd}, I_{5th}, I_{7th}, I_{9th}, I_{11th}, I_{13th} and I_{15th} order harmonics are reduced from 7.3%, 15.22%, 3.93%, 2.43%, 2.38%, 0.19%, 0.62% to 2.27%, 0.49%, 0.31%, 0.33%, 0.24%, 0.22% and 0.14% respectively. These components are reduced significantly when converters are connected in the system. The simulation results show that control is working accordingly and keeping the harmonics level with in the allowable limits. The value of the THD with converter connected in the system is well with in the range of IEEE and IEC standards.

Table 6.3: FFT analysis of the current in case of two VFDs installed

Components	Harmonics without converter	Harmonics with converter
Fundamental	100%	100%
I_{3rd}	7.37%	2.27%
I_{5th}	15.22%	0.49%
I_{7th}	3.93%	0.31%
I_{9th}	2.43%	0.33%
I_{11th}	2.38%	0.24%
I_{13th}	0.19%	0.22%
I_{15th}	0.62%	0.14%
THD	26.03%	3.87%

6.5 Voltage Support with Reactive Power Compensation

The VFDs in the ship power system can be used for the improvement of voltage in case of fault. It will not only supply the power to the thruster motor, but also improve the stability by supporting the voltage in faulted condition. The VFD improves the voltage by injecting the reactive power in case of fault. In this case the vector control scheme is used to provide the reactive current during fault. The reactive power is supplied by keeping the value of i_{dref} zero in the control of VSC converter.

6.5.1 Voltage Support with one VFD Installed

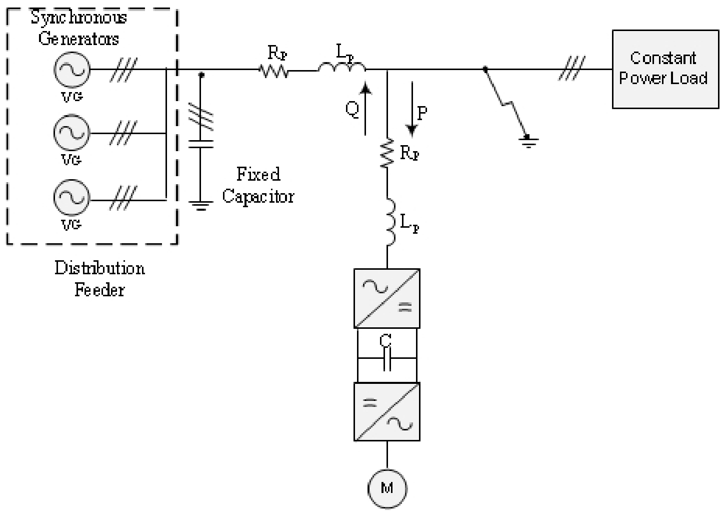

Figure 6.14: The power system with one VFD installed

The symmetrical three phase to ground fault was implemented on the system, with fault resistance $R_f = 0.02\Omega$. The system was connected with one VFD and the fault was implemented at time *t*=2.1 sec. The simulations were carried out for time *t*=4 sec. The reactive power was injected during the fault time *t*=2.1 sec to *t*=2.3 sec for the sake of voltage support in faulted condition.

Figure 6.15 shows the voltages before and after the connection of VFD in faulted condition. Figure 6.15(a) shows that the voltage of the system goes down when three phase to ground fault was implemented during time *t*=2.1 to *t*=2.3 sec. The voltages reduce from 563V to 350V approximately, which is quite a high reduction. Figure 6.15 (b) shows the voltage waveform of the system, when the VFD was supplying the reactive power. The control of the VSC converter was built in such a manners that it provides the reactive power in the interval time *t*=2.1 to *t*=2.3 sec. It can be seen from the figure that there is a rise in the voltage of the system during that period.

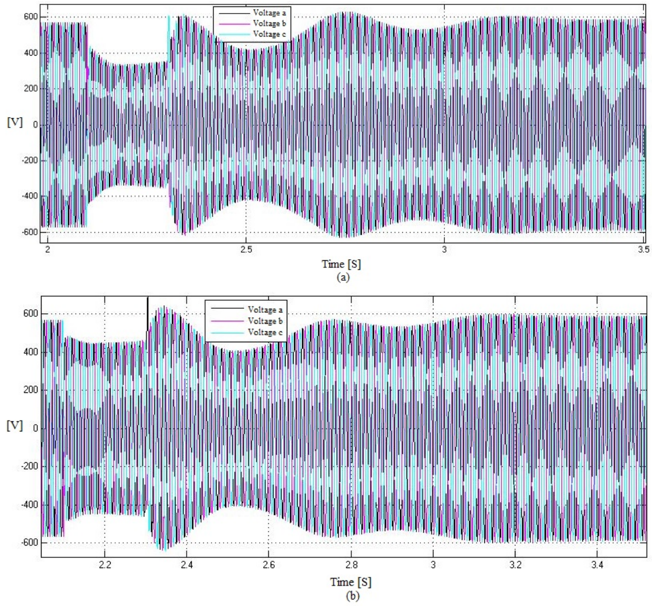

Figure 6.15: (a) Three phase to ground fault with no reactive power compensation (b)Three phase to ground fault with reactive power compensation by one VFD

6.5.2 Voltage Support with two VFDs Installed

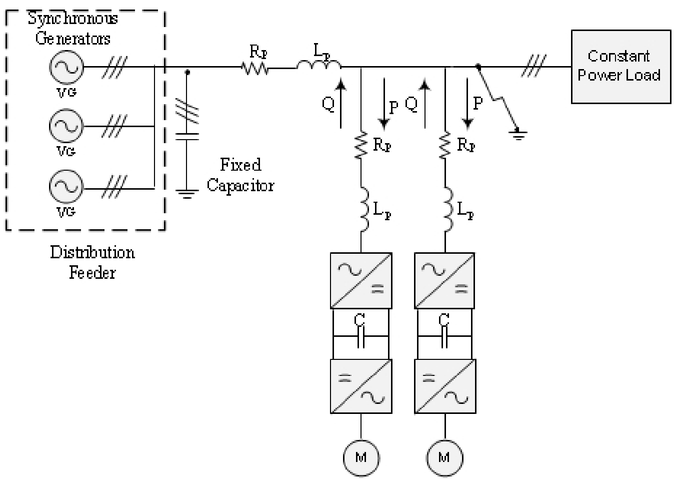

Figure 6.16: The power system with two VFDs installed

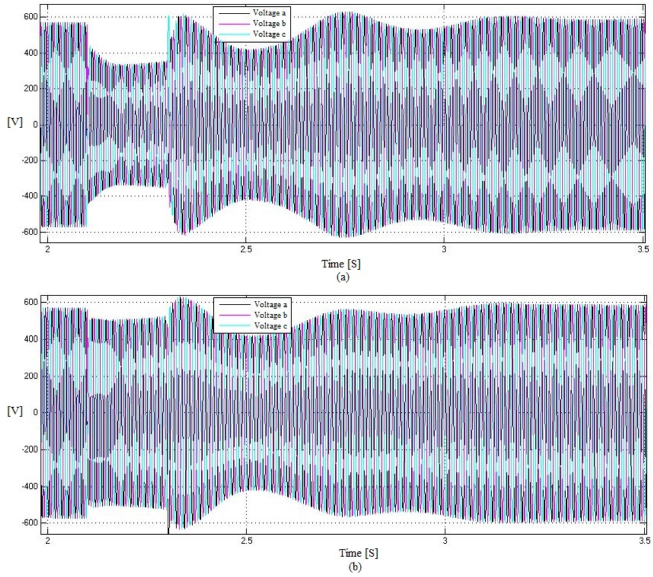

Figure 6.17: (a) Three phase to ground fault with no reactive power compensation (b)Three phase to ground fault with reactive power compensation by two VFDs

The symmetrical three phase to ground fault was implemented on the system with two VFDs, the fault resistance was $R_f = 0.02\Omega$. The fault was implemented at time *t*=2.1 sec and removed at time *t*=2.3 sec. The simulations were carried out for time *t*=4 sec. The reactive power was injected during the fault time *t*=2.1 sec to *t*=2.3 sec for the sake of voltage support in faulted condition.

Figure 6.17 shows the voltages before and after the connection of VFDs in the faulted condition. Figure 6.17(a) represents that the voltage of the system goes down when three phase to ground fault was implemented during time *t*=2.1 to *t*=2.3 sec. The voltages reduce from 563V to 350V approximately, which is quite high reduction. Figure 6.17 (b) shows the voltage waveform of the system, when the two VFDs were supplying the reactive power. The control of the VSC converters was built in such a manners that they provide the reactive power in the interval time *t*=2.1 sec to *t*=2.3 sec. It can be seen from the figure that there is a rise in the voltage of the system during that period. It can be seen from Figure 6.17 (b) that voltage during fault is now approximately 510V which is within the allowed limits of ship power system.

7

Discussion and Comparison

From the theoretical review of the system, it can be seen that harmonics and reactive power consumption produce fluctuations in the voltage. These scenarios add up in the power quality problems which lead the whole power system towards instability in worse situation. The generator connected in the autonomous grid, if reaches its limit of reactive power, then the system get unstable and due to voltage break, blackout can take place.

In case of fault on the lines, the grid faces voltage dip and the SG start consuming the reactive power. Ever increasing non-linear loads, the switching devices and the load variations produce harmonics in the system. The harmonics causes fluctuation in the grid voltage, which may lead to the instability of the grid.

The thesis studies the power system on ships and use of the VFD in isolated systems. For the control operation of motors and to meet the power quality standards, the VFDs are used in the ship power systems. The parallel operation of synchronous generators have been performed and observed during operation. The control for VFD is designed and evaluated with the help of simulation results from MATLAB/SIMULINK™. The converter used in the variable frequency drive is working as bi-directional converter, which can transfer the power in both directions. The simulations were carried out by using one and then two VFDs connected in the system.

Parallel Operation fo Generators

This case is performed to see the behaviour of generators in case of parallel operation. Three SGs were installed in parallel with ratings mentioned in chapter 5. The total load of 4Mw was connected with the main grid and all the generators were supplying load of 1.33Mw. It is quite visible from simulation results that all the SGs are operating in parallel and sharing the load. The bus bar performance was also observed and it was found that all the three phase are 120°apart from each other with voltages 563V.

Harmonics Compensation with Ideal Power Supply

The system with the ideal power supply was built which was connected with non-linear load, constant power load and VSC converter. The converter was connected with the constant DC load. This simulation was carried out to check the control of the VSC on ideal system and then it is further implemented in the ship power system. The harmonics were produced in the source current by non-linear load, which were successfully removed with minor changes in the control of converter.

The simulation results illustrate the source current signal before and after connection of converter in the system. It can be seen from the results that harmonics are removed from the system when converter start supplying the current. The FFT analysis were also performed to see the percentage of harmonics content in the source current. By FFT analysis it is found that THD is reduce from 15.52% to 0.70%, which is with in the IEEE standards.

Harmonics Compensation with One VFD Installed

The simulations are now carried out with the power system model same as on the ship but with only one VFD installed in the system. The converter in this case is not connected with the constant power load. It is connected with the inverter which is supplying power to the thruster motor. The power is now supplied by the three parallel operating generators instead of ideal power supply, discussed in the first case. The constant power load and non-linear load are also connected with the system.

The harmonics are produced in the source current, which produce fluctuation in the voltage. Now, the harmonics are removed from the ship power system with the control of the converter. In this case, the motor is also connected in the system which takes very high current during start up. The simulation results are shown when converter is disconnected from the system rather then when it is connected. The simulation results show the removal of harmonics from the source current. The FFT analysis shows that THD is reduced from 23.16% to 4.05%, which is according to the standards.

Harmonics Compensation with Two VFDs Installed

The same simulations are performed with two VFDs installed in the system instead of one. There was no big change in the ratings of other components of the power system. The harmonics are also compensated in this case with the help of two VFDs. The simulation results are shown when the converters stop supplying the current in the system. In this case current is almost double as compare to the last case where only one VFD was installed. This time two thruster motors are connected in the system. The FFT analysis shows that THD in this case is reduced from 26.03% to 3.87% which is quite an improvement in harmonics compensation.

Voltage Support with Reactive Power Compensation

In this case, reactive power compensation technique is implemented to support the voltage in case of symmetrical three phase to ground fault. The system with parallel operating generators, and constant power load is used here. The simulations were first carried out with one VFD and then it was extended to two VFDs installed in the system.

The symmetrical three phase to ground fault was implemented, the voltage dip can be seen in all the voltages during that time. The reactive power was injected from the converter during this interval to support the voltages. The process is first tested with one VFD, which improves the voltage from 350V to 430V approximately. When two VFDs were installed in the system the voltages of the system were improved, which is around 510V and it is well in the range of ship power system standards.

8 Conclusion

The control in this thesis is performed using the vector control scheme, through which both active and reactive power can be controlled. It was observed that by injecting the measured current components at point of common coupling harmonics can be removed from the source current. This also helps the system to maintain the voltage with in the limits during fault.

In this thesis, work has been done to remove the harmonics from the source current. The harmonics are first compensated in the system with ideal power supply using the converter control, the THD is reduced from 15.52% to 0.7 %. This scheme is then implemented on the ship power system model with one VFD installed and the THD was reduced from 23.16% to 4.06%. The same procedure is applied on the system having two VFDs installed and harmonics were reduced from 26.03% to 3.87%. These values of THD are well with in the range of limits set by IEEE.

The voltage support is also provided by injecting the reactive power from the converter in case of fault. The symmetrical three phase to ground fault was implemented in the system, which causes voltage dip in all the three phases. The voltage of the system was supported during fault by keeping the voltage with in +6 %, -10% which is IEC standard 6002-101 .

The rapidly increasing PE devices into the ship power system are causing complexities in it. These devices produce harmonics and consumes reactive power from the AC mains which cause fluctuations in the voltage of the system. The stable operation of the ship power system is only possible if these PE devices work as active filters. The VFD in this thesis is bi-directional, which removes the harmonics and support the voltage in case of faulted condition.

Through the knowledge gained from this work, further improvement can be made in the existing VFDs in the ship power system. The stability can be improved by making the converter as active filter, which will not only compensate the harmonics but also provide the support to the voltage during fault.

9 Recommendations for Future Work

This master thesis studies the ship power system and some of the power quality problems associated with it. Lots of benefits can be taken, by getting the information from the work done in this thesis. Although the proposed ship power system works successfully, there are still many things which can be done to improve the power quality. Some of the recommended tasks which can be done are as follows:

- The power system on ship in this thesis is limited to two drives, which can be further extended to more drives.
- The work done in the MATLAB/SIMULINK™ can be implemented in the lab using real models.
- The voltage support was performed only for the symmetrical faults in this work. The further extension of the work could include the asymmetrical fault ride through by incorporation of both the positive and negative sequence voltage controller using multi drive system.
- A comprehensive stability analysis of the system can be performed to design the filter components with both single and multi-drive systems.
- The overall switching losses of both the converter and inverter side can be calculated, because the proposed system with VSC-based converter can have more switching losses.

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Appendix

9.1 Appendix A

9.1.1 Block Diagram of Parallel Operation of Generators

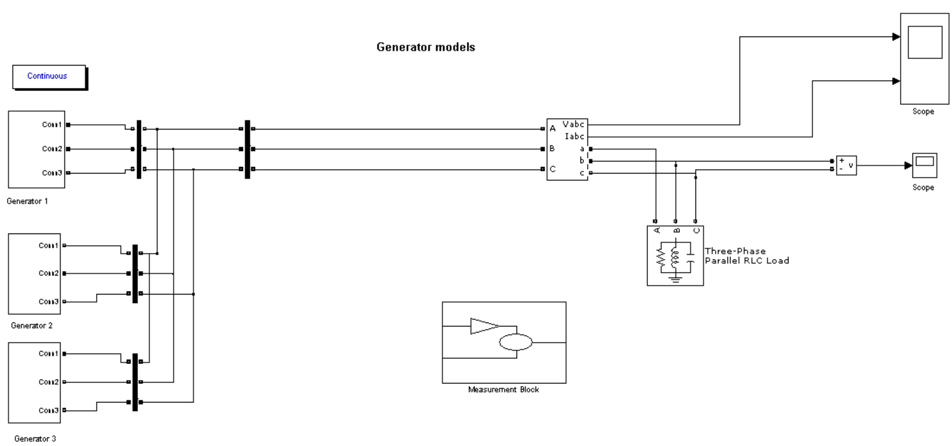


Figure 9.1: Block diagram of parallel operating synchronous generators with parallel RLC load

9.1.2 Block Diagram of System with Ideal Power Supply and Non-linear Load

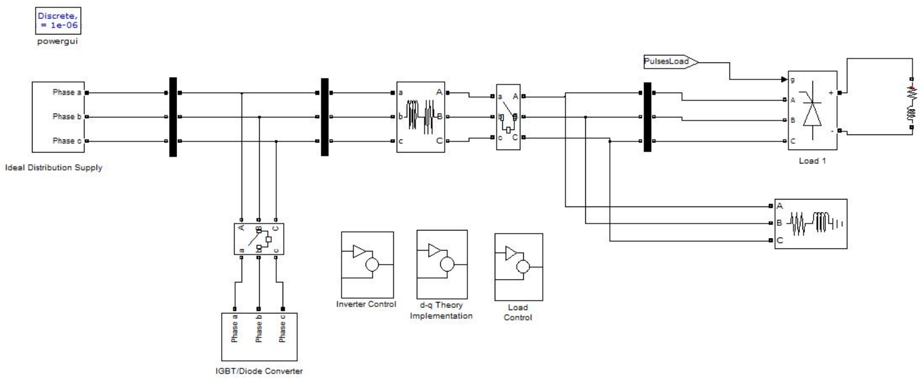


Figure 9.2: Simulink model of the system with ideal power supply and non-linear load

9.1.3 Block Diagram of System with one VFD and Non-linear Load

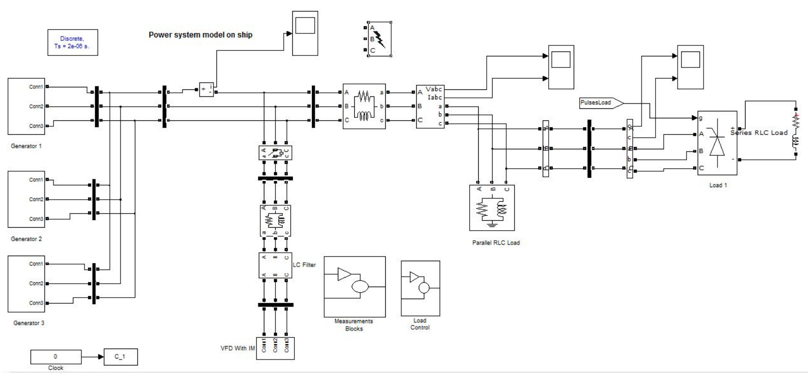


Figure 9.3: Power system on ship with parallel operating generators, one VFD and non-linear load

9.1.4 Block Diagram of System with two VFDs and Non-linear load

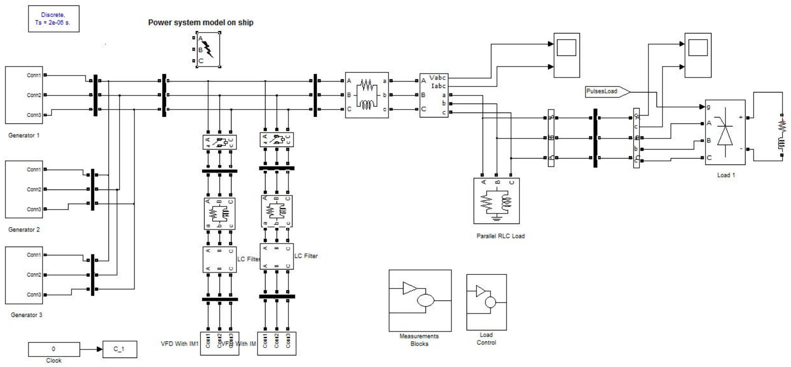


Figure 9.4: Power system on ship with parallel operating generators, two VFDs and non-linear load

9.1.5 Block Diagram of System with one VFD for Reactive Power Compensation

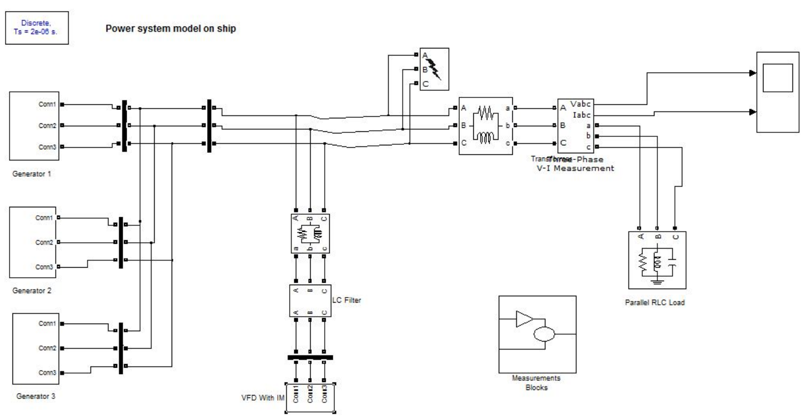


Figure 9.5: Power system on ship with parallel operating generators, one VFD for reactive power control

9.1.6 Block Diagram of System with two VFDs for Reactive Power Compensation

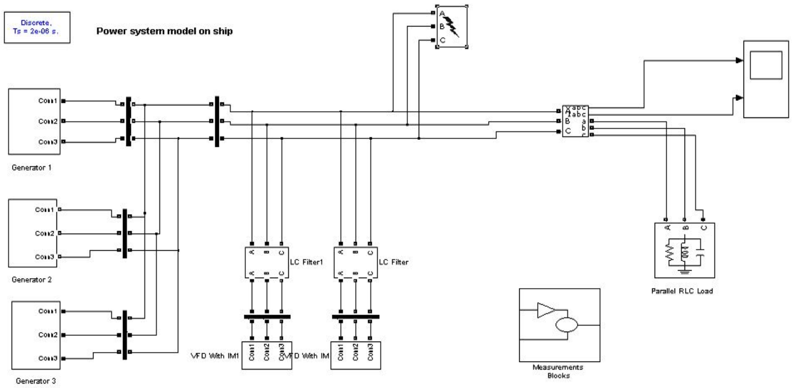


Figure 9.6: Power system on ship with parallel operating generators, two VFDs for reactive power control

9.1.7 Block Diagram of VFD with Induction Motor

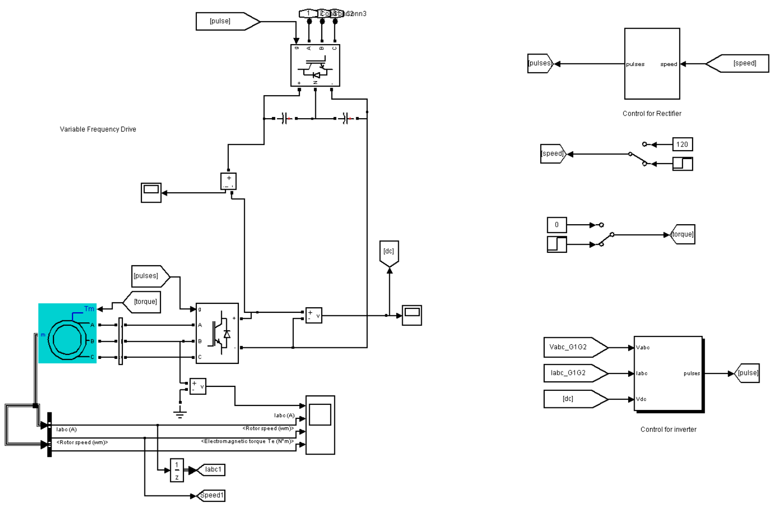


Figure 9.7: Block diagram of VFD with induction motor as load

9.2 Appendix B

9.2.1 Control of Harmonics Compensation with Ideal Power Supply

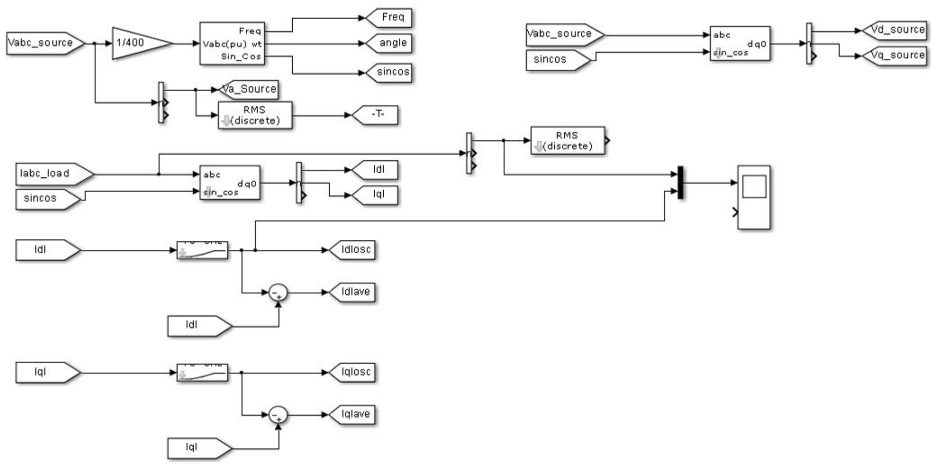


Figure 9.8: Block diagram of implementation of Clark and Park Theory

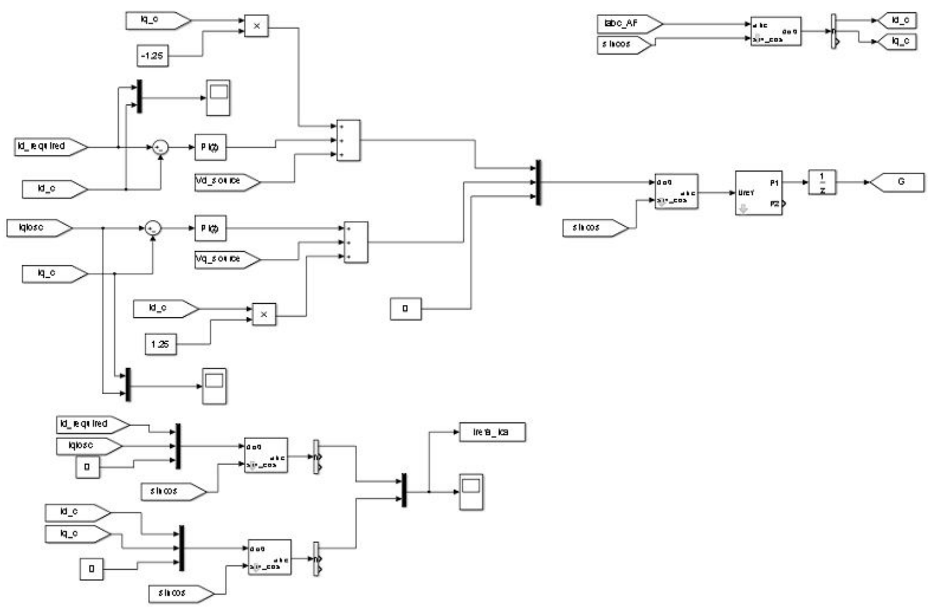


Figure 9.9: The current controller for the harmonics compensation

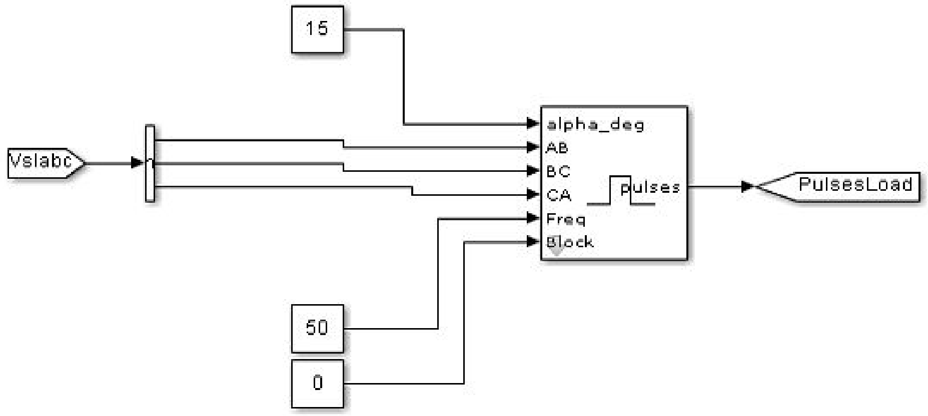


Figure 9.10: The control Block for Thyristor bridge

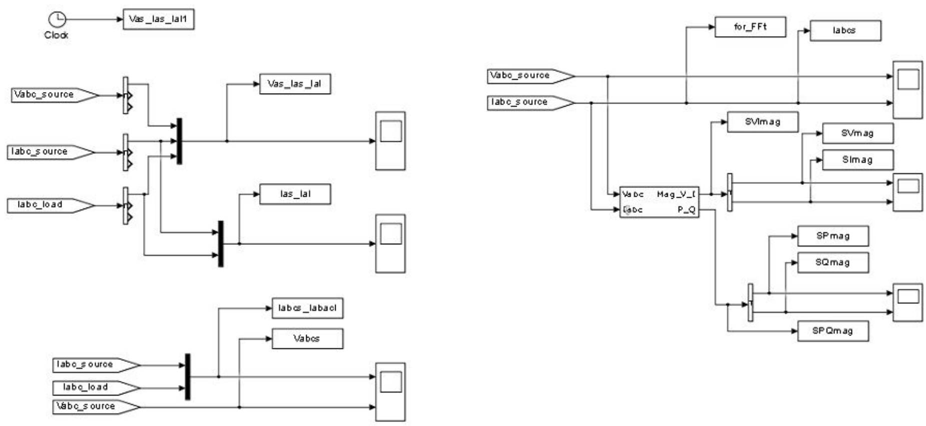


Figure 9.11: The measurements blocks in case of ideal power supply

9.2.2 Control of Harmonics Compensation In Ship Power System

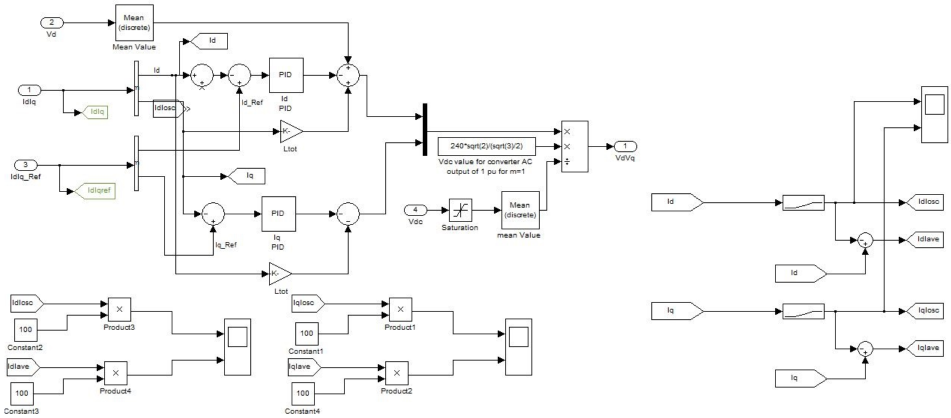


Figure 9.12: The current controller of VSC converter

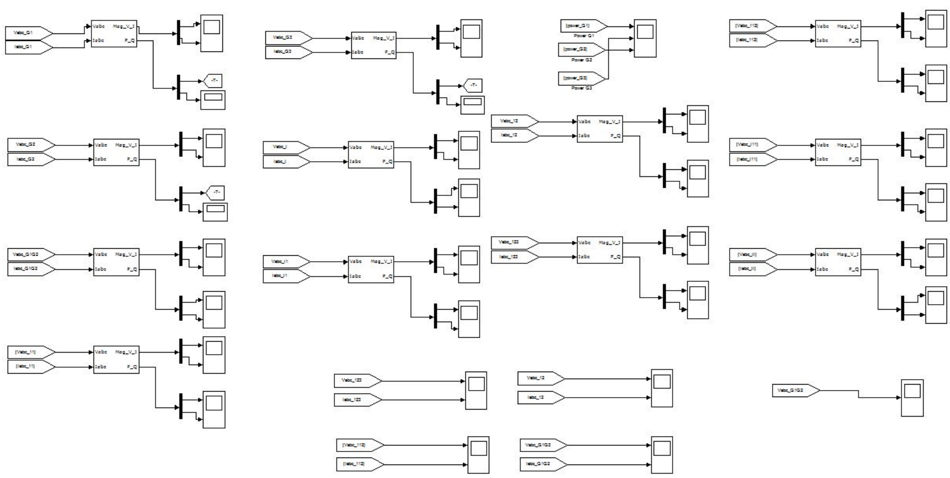


Figure 9.13: The measurement blocks in case of real ship power system

9.3 Appendix C

This section is demonstrating some of the useful waveform obtained from the thesis work.

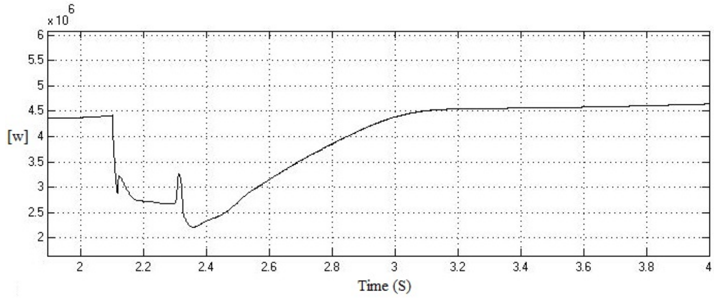


Figure 9.14: The power from the system in case of three phase to ground fault

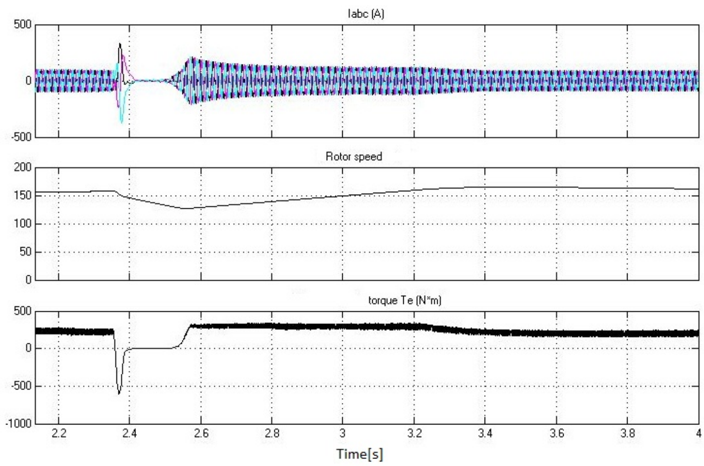


Figure 9.15: The impact of three phase to ground fault on the induction motor parameters

This section shows the reactive power compensation in case of ideal power supply. Figure 9.16 shows the real and reactive power drawn by the system in case of no VSC converter connected. Figure 9.17 shows the real and reactive power when converter starts supply the reactive power. From Figure 9.17(b) it can be seen then reactive power given by the source goes to zero. Its mean converter is compensating the reactive power.

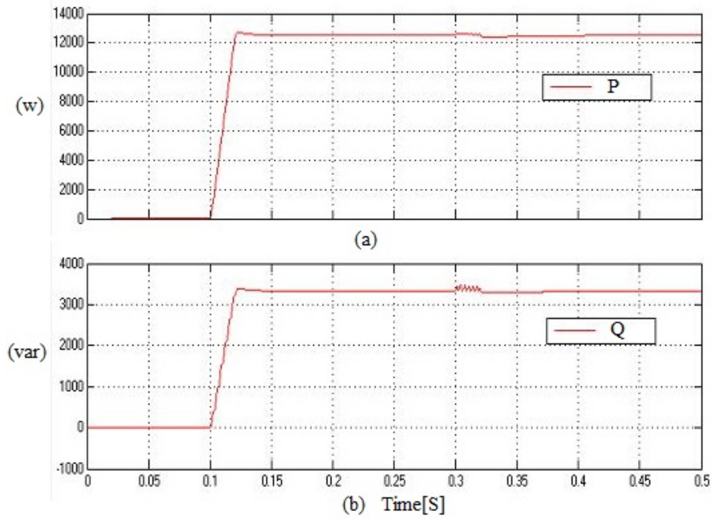


Figure 9.16: (a)The real power from the system connected with ideal power supply (b) Reactive power drawn from the system with ideal power supply

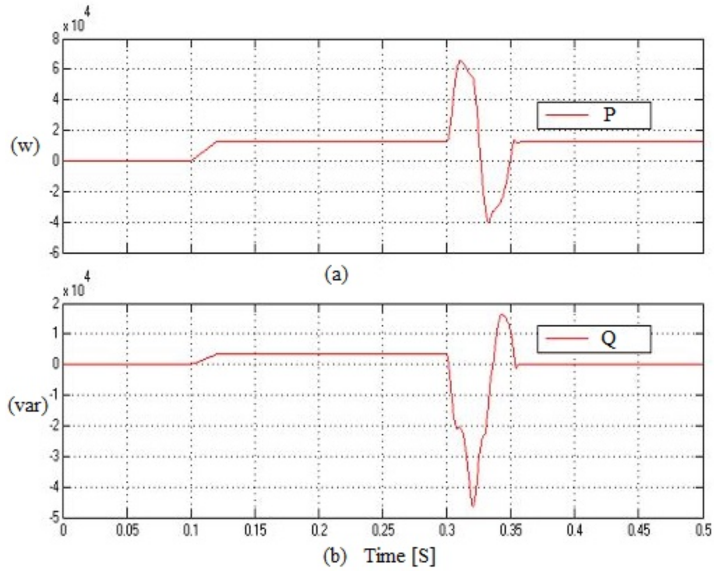
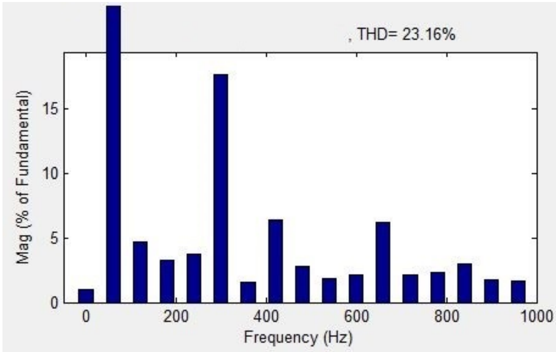
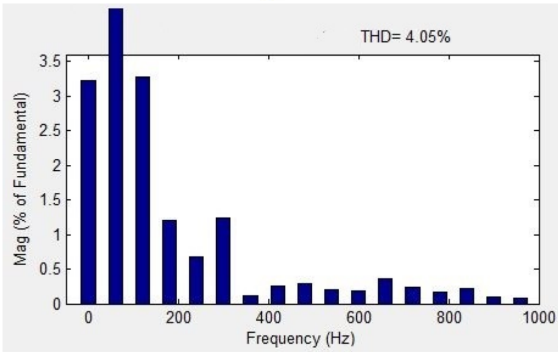


Figure 9.17: (a)The real power from the system connected with ideal power supply when converter start compensating the reactive power at t= 0.3 sec (b) Reactive power drawn from the system with ideal power supply when converter start compensating the reactive power at t= 0.3 sec



(a)



(b)

Figure 9.19: (a) The FFT analysis without connecting VFD in the system (b)The FFT analysis with one VFD connected in the system

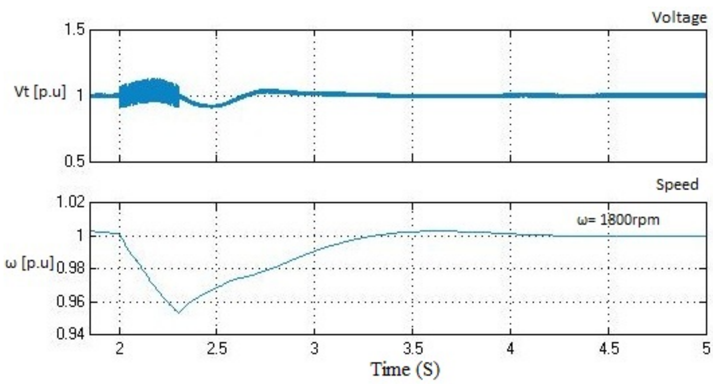


Figure 9.18: The impact of three phase to ground fault on SG parameters

9.4 Appendix D

9.4.1 Reactive Power Compensation Techniques

In this section all the possible methods to compensate the reactive power are explained, which can be utilized according to the situation. Some of the reactive power compensation methods are as follow:

9.4.2 Shunt Compensation

The figure 4.11 explains the shunt compensation principle. The figure 4.11(a) show the system where compensator is not installed, it can be seen in the phaser diagram that load needs reactive power for normal operation. By supplying the reactive power in form of current, can reduce the losses and regulate the voltage of the system. This is done in figure 4.11 (b) where current is injected just before the load and improvement can be seen in the phaser diagram.

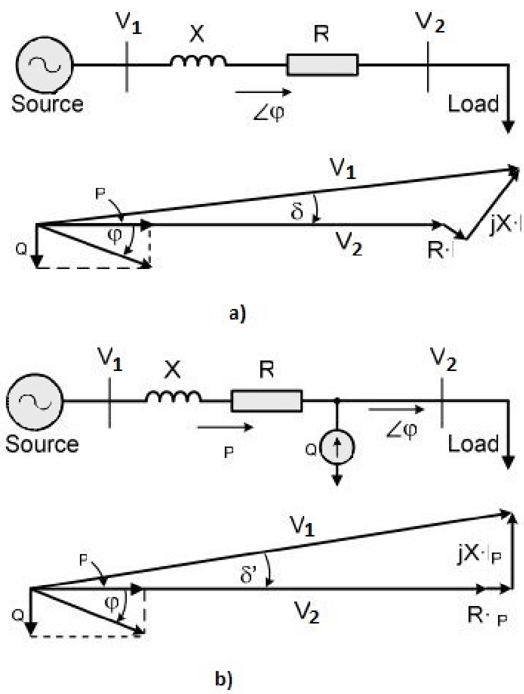


Figure 9.20: (a) The system with no compensation (b) The system with shunt compensation [14]

9.4.3 Series Compensation

The reactive power compensation can also be performed using series compensator. By this method angular stability, voltage fluctuation and load sharing of the system can be improved. The figure 4.12 (a) and figure 4.12 (b) shows the system without and with series compensator. In series compensator voltage is added in series to change the angle of voltage.

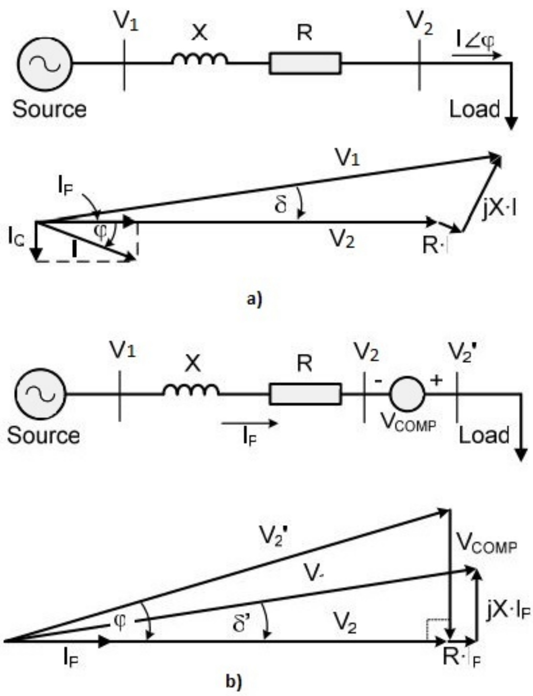


Figure 9.21: (a) The system with no compensation (b) The system with series compensation [14]

9.4.4 Fixed or Mechanically Switched Capacitors

By inserting the capacitor current in parallel, reduces the angle difference between current and voltage of the load. The value of capacitor bank is selected according to the value of reactive current drawn from the load. The value of reactive power keeps on varying in the system, that is why fixed capacitor is not a smart solution for the problem. In this type of compensation technique switching of capacitor banks is done with the help of relays and breakers [14].

9.4.5 Synchronous Condensers

In this technique a synchronous machine is connected with the system, which produce or absorb reactive power according to the system demand. This technique is used to stabilize the system and to get the regulated voltage, when load is changing continuously. Because of the complexities associated with its starting and running, this technique is not very often used today [14].

9.4.6 Thyristor Switched Capacitor (TSC)

The purpose of thyristor VAR compensator and synchronous condenser is same, but compensation is much faster in case of TSC because of faster switching. The figure 4.13(a) shows the TSC, in which capacitor is switching with the help of two way switches. In the technique one capacitor bank and two thyristor switches are attached with each phase of the power system. A small induction is also added in series with the switches to prevent the resonance.

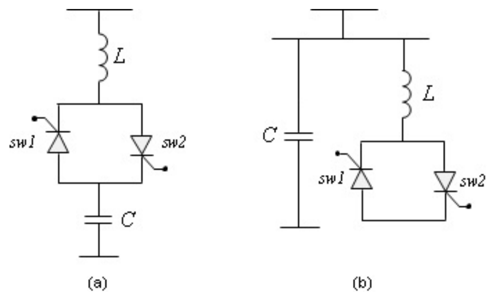


Figure 9.22: (a) Thyristor controlled capacitor circuit (b) Thyristor controlled reactor cicuit [29]

The value of current drawn from the capacitor can be calculated with the following expression:

$$i(t) = \frac{V_m}{X_c - X_L}\cos(\omega t+\alpha) - \frac{V_m}{X_c - X_L}\cos(\alpha)\cos(\omega_r t) + [\frac{X_c V_m \sin(\alpha)}{\omega_r L(X_c - X_L)} - \frac{V_{co}}{\omega_r L}]\sin(\omega_r t) \tag{9.1}$$

In this equation X_c and X_L are the capacitance and reactance of the of the capacitor and inductor respectively. Whereas V_m is the voltage and α is the phase angle at which capacitor is connected. The accurate results can be achieved from this expression by considering the resistance of the system negligible.

Though it is very simple in use for reactive power compensation but due to some disadvantages this technique is not very famous: the compensation process is not constant, for every capacitor a thyristor is required, voltage across the passive thyristors is almost double the source voltage and protection must be supplied to the thyristor to save it form heavy current.

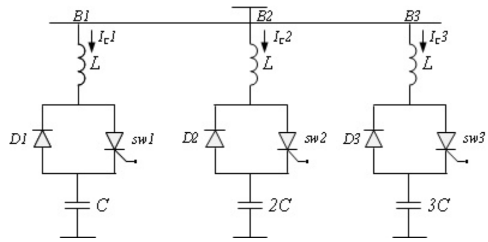


Figure 9.23: Thyristor-diode switched capacitor compensation [29]

The drawback of this technique is removed by adding one diode as shown in the figure 4.14. By doing so high value of current can be prevented, now the process will be continuous and thyristor firing timing can be controlled.

9.4.7 Thyristor Controlled Reactor (TCR)

The figure 4.13(b) shows the thyristor controlled reactor (TCR) circuit diagram. Sometimes for the removal of harmonics, capacitor bank is also used with this configuration. This figure represents the TCR for single phase, in three phase each branch has its own inductor and two switches. This technique consumes reactive power when thyristor switching is done by phase angle method. Which eventually ends up in producing harmonics in the system. The main drawback of this method is production of harmonics in the system.

9.4.8 Combination of TCR and TSC

The reactive power compensation can be done with TCR or TSC alone and also with the combination of both of them. The figure 4.15 shows the combination of both TCR and TSC, in this technique compensation is achieved with more accurate results. In case of reactive power absorption, capacitor bank is disconnected from the circuit and reactor circuit starts absorbing the reactive power.

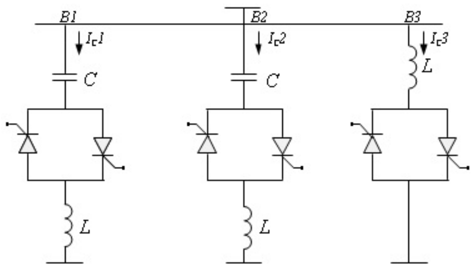


Figure 9.24: The combination of TCR and TSC

The method where we use combination of TCR and TSC gives us continuous control, with generation of almost no harmonics, with out transient and with simple control. The only drawback of this method is that it increases the cost.

9.4.9 VAR Compensation with Self Commutation

The self commutation is considered as an effective technique for reactive power compensation. After so much progress in commutation of semiconductor devices, new methods for compensation of reactive power has been developed. The figure 4.16 shows the current and voltage source converter, which are the different method used for the compensation. The reduction in price is the huge advantage of these techniques.

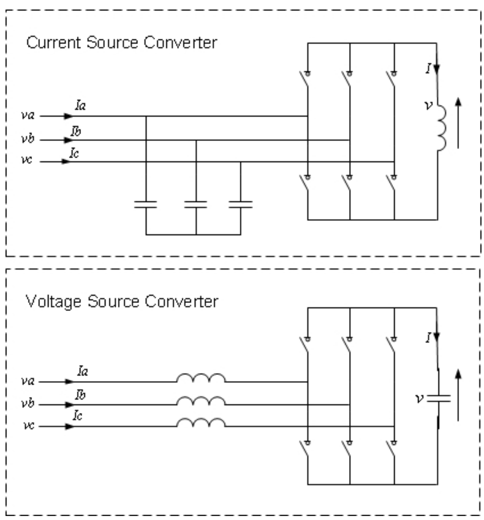


Figure 9.25: The VAR compensation with Current souce converter and voltage source converter

This method produce stability in the power system, regulates the voltage, improves the power factor and balance the load.