POWER SYSTEM STABILITY IMPROVEMENT USING STATCOM

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
ELECTRICAL ENGINEERING
(With Specialization in Power Apparatus and Electric Drives)

By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled **POWER SYSTEM STABILITY IMPROVEMENT USING STATCOM** in partial fulfilment of the requirements for the award of the degree **Master of Technology** with specialization in **Power Apparatus and Electric Drives,** to the **Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee** is an authentic record of my own work carried out during a period from July 2007 to June 2008 under the supervision of Professor S.P. Gupta, Head of the Department, Electrical Engineering Department, Indian Institute of Technology Roorkee, Roorkee, Dr. G.N. Pillai, Assistant Professor, Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee and Dr. P. Balasubramanyam, Joint Director, CCAR, CPRI, Bangalore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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ABSTRACT

The static synchronous compensator (STATCOM) is being increasingly employed in modern power systems due to its capability to work as var generation and absorption systems. Besides the main task of voltage control, it is also applied to improve the transmission capability and power system stability.

STATCOM is mainly used to perform voltage or reactive power regulation. In general, a compensator maintaining constant terminal voltage is not effective in damping of power oscillations. To damp power oscillations a supplementary control signal should be added to the STATCOM Regulator. A multi objective comprehensive control system for the STATCOM combines the main control and supplementary control to hold constant bus voltage and improve power oscillation damping.

This work presents the detailed analysis of various 6-, 12-, 24-, and 48-pulse Voltage source Converters (VSC) and development of controller. A robust voltage controller is designed for a 48–pulse GTO based quasi harmonic neutralized voltage source converter based STATCOM. In addition to the main controller, a supplementary controller is designed to improve the small signal stability of a single machine infinite system.

Simulations carried out in PSCAD and RTDS® show the efficacy of the controller design.

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CHAPTER 1
INTRODUCTION

This chapter provides the concept FACTS, their advantages and their classification. It further compares the basic types of FACTS controllers.

1.1: Introduction to FACTS

The basic limitations of the classic ac power transmission are distance, stability and controllability of flow, which have resulted in the under-utilization of line and other assets. The potential of mitigating these limitations effectively by controlled compensation provided early incentives in the late 1970s. Power electronic control for reactive power compensation was introduced using FACTS controllers. The FACTS is a concept based on power-electronic controllers, which enhances the value of transmission networks by increasing their capacity. As these controllers operate very fast, they enlarge the safe operating limits of a transmission network without disturbing stability. The era of FACTS was triggered by the development of the new solid state electrical switching devices and more development in the utility industry. [1-3]

Flexible AC Transmission System (FACTS):

Flexible AC Transmission System is defined as "An Alternating current transmission system incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability of a power system". [3]

FACTS Controller:

FACTS controller is defined as "A power electronic-based system and other static equipment that provide control of one or more AC transmission system parameters". [3]

1.2: The Objectives of the FACTS Controllers

The main objectives of the FACTS controllers are

1. To increase the power transfer capability of transmission systems
2. To keep the power flows over designed routes

The first objective implies that power flow in a given line should be able to be increased up to the thermal limit by forcing the necessary current through the series line impedance. At the same time, stability of the system is maintained via appropriate real-time control of power flow during and following systems faults. By providing the necessary voltage stability via FACTS controllers, instead of large steady-state margins, the normal power transfer over the transmission lines is estimated to increase significantly.

The second objective implies that, by being able to control the current in a line, the power flow can be restricted to selected transmission corridors, while parallel and loop flows can be mitigated. [3]

1.3: Advantages of FACTS Controllers

The main advantages of the FACTS controllers are listed below:

- Rapid response to system disturbances
- Smooth voltage control over a wide range of operating conditions
- Automatic reconfiguration to handle certain equipment failures
- Expansion capability for future operation
- Provide increased capacity on the existing electrical transmission system
- Enhanced system reliability and improved system controllability
- Potential to control flows
- Less environmental impact than most alternative techniques of transmission reinforcement
- Less cost than alternatives techniques

1.4: Organization of FACTS Controllers

The advent of Flexible AC Transmission Systems (FACTS) is giving rise to a new family of power electronic equipment emerging for controlling and optimizing the performance of power system, e.g. STATCOM, SSSC and UPFC. The use of voltage-source converter (VSC) has been widely accepted as the next generation of reactive power controllers of power system to replace the conventional VAR compensation, such as the thyristor-switched capacitor (TSC) and thyristor controlled reactors (TCR). [2-3]

Essentially, FACTS Controllers are organized according to their respective connection to the controlled ac transmission system.

1. Shunt Connected Controllers
2. Series Connected Controllers
3. Combined Shunt and Series Connected Controllers

1.4.1: Shunt Connected Controllers

Shunt FACTS devices are connected to the power network in parallel and their main objective is to control the voltage at the point of common coupling (PCC). These are the some examples of shunt connected FACTS devices.

- **Battery Energy Storage System (BESS)**

  A chemical-based energy storage system using shunt connected, voltage sourced converters capable of rapidly adjusting the amount of energy which is supplied to or absorbed from an ac system.

- **Static Synchronous Compensator (SSC or STATCOM)**

  A static synchronous generator operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage.

- **Static Condenser (STATCON)**

  This term is deprecated in favor of the Static Synchronous Compensator (SSC or STATCOM).

- **Static Synchronous Generator (SSG)**

  A static, self-commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multi-phase output voltages, which may be coupled to an ac power system for the purpose of exchanging independently controllable real and reactive power.

- **Static Var Compensator (SVC)**

  A shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage).

- **Static Var Generator or Absorber (SVG)**

  A static electrical device, equipment, or system that is capable of drawing controlled capacitive and/or inductive current from an electrical power system and thereby generating or absorbing reactive power. Generally considered to consist of shunt connected, thyristor-controlled reactor(s) and/or thyristor-switched capacitors.

- **Static Var System (SVS)**

  A combination of different static and mechanically-switched var compensators whose outputs are coordinated.

- **Superconducting Magnetic Energy Storage (SMES)**

  A Superconducting electromagnetic energy storage device containing electronic converters that rapidly injects and/or absorbs real and/or reactive power or dynamically controls power flow in an ac system.

- **Thyristor Controlled Braking Resistor (TCBR)**

  A shunt-connected, thyristor-switched resistor, which is controlled to aid stabilization of a power system or to minimize power acceleration of a generating unit during a disturbance.

- **Thyristor Controlled Reactor (TCR)**

  A shunt-connected, thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor valve.

- **Thyristor Switched Capacitor (TSC)**

  A shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.

- **Thyristor Switched Reactor (TSR)**

  A shunt-connected, thyristor-switched inductor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.

- **Var Compensating System (VCS)**

  A combination of different static and rotating var compensators whose outputs are coordinated.

1.4.2: Series Connected Controllers

Series FACTS devices are inserted into the system in series with the transmission lines and are capable of regulating the active and reactive power flow through the line. These are the some examples of series connected FACTS devices.

- **Static Synchronous Series Compensator (SSSC or S^3C)**

  A static, synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power ..

- **Thyristor controlled Series Capacitor (TCSC)**

  A capacitive reactance compensator which consists of a series capacitor bank shunted by thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance.

- **Thyristor Controlled Series Reactor (TCSR)**

  An inductive reactance compensator which consists of a series reactor shunted by a thyristor controlled reactor in order to provide a smoothly variable series inductive reactance.

- **Thyristor Switched Series Capacitor (TSSC)**

  A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor switched rêactor to provide a stepwise control of series capacitive reactance.

- **Thyristor Switched Series Reactor (TSSR)**

  An inductive reactance compensator which consists of series reactor shunted by thyristor-switched reactor in order to provide a stepwise control of series inductive reactance.

1.4.3: Combined Shunt and Series Connected Controllers

Shunt-series devices are a combination of both shunt devices and series devices and are capable of functioning as both. These are the some examples of combined shunt and series connected FACTS devices.

- **Interphase Power Controller (IPC)**

  A series-connected controller of active and reactive power consisting, in each phase, of inductive and capacitive branches subjected to separately phase-shifted voltages. The active and reactive power can be set independently by adjusting the phase shifts and/or the branch impedances, using mechanical or electronic switches.

- **Thyristor Controlled Phase Shifting Transformer (TCPST)**

  A phase-shifting transformer, adjusted by thyristor switches to provide a rapidly variable phase angle.

- **Unified Power Flow Controller (UPFC)**

  A combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) which are coupled via a common dc link, to allow bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source. The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance, and angle or, alternatively, the real and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation.

1.5: Comparison of Different FACTS Device Categories

There is a main control objective associated with each of the FACTS device categories. But, adding auxiliary control signals to each device can widen their control capabilities. Table 1.1 summarizes the properties of the basic FACTS device categories in various applications in power systems. [3]

Application	FACTS Device Category		
	Shunt	Series	Shunt-Series
Voltage Control	High	Low	High
Load Flow Control	Low/Medium	Medium/High	High
Transient Stability	Medium	High	High
Oscillation Damping	Medium/High	High	High
Oscillation Damping	Low/Medium	Medium	High

Table 1.1: Comparison of Different FACTS Device Categories

1.6: Organization of Report

The rest of the report is organized give below:

Chapter 2 provides the concept of static shunt controller used in FACTS devices. This chapter describes the basic operating principles of static shunt compensators, characteristics of shunt compensators. It further compares the two main shunt compensators, the SVC and the STATCOM.

Chapter 3 deals with different types of voltage source converters and their advantages and disadvantages and it further deals with detailed analysis of various types of 6-, 12-, 24-, and 48- pulse voltage source converters and also presents the differences between the harmonic naturalized voltage source converter and quasi harmonic neutralized voltage source converters.

Chapter 4 deals the modelling of STATCOM in d-q reference frame model for finding the control parameters and it further deals with STATCOM controller for the voltage regulation.

Chapter 5 provides the concept of power system stability and its organization and it further deals with STATCOM controller for the power system stability improvement.

Chapter 6 provides RTDS® results for a 12-pulse VSC based STATCOM carried out at CPRI, Bangalore.

CHAPTER 2
INTRODUCTION TO STATCOM

This chapter provides the concept of static shunt controller used in FACTS devices, basic operating principles and characteristics of static shunt compensators. It further compares the two main shunt compensators; the SVC and the STATCOM.

2.1: Introduction

The most important shunt connected FACTS device, which has broad application in electric utility industry, is STATCOM (STATic synchronous COMpensator). STATCOM, also named ASVG (Advanced Static Var Generator) is one of the new-generation FACTS device, and recognized to be one of the key technologies in future power system. STATCOM has played an important role in power industry since 1980s. Kansai Electric Power Co., Inc. (KEPCO) and Mitsubishi Motors, Inc. developed the first STATCOM in the world, 20 Mvar STATCOM using force-commutated thyristor converters and put it into operation in Jan, 1980.

The STATCOM provides operating characteristics similar to a rotating synchronous compensator without the mechanical inertia. So, it is called as Static Synchronous Compensator. STATCOM employ solid state power switching devices so, it provides rapid controllability of the three phase voltages, both in magnitude and phase angle. [10-11]

2.2: The Principle of Operation of STATCOM

A STATCOM integrates the techniques of static var compensator and voltage source converter and is a new concept for reactive power control. The STATCOM basically consists of a coupling transformer with a leakage reactance, a three-phase GTO or IGBT voltage source converter (VSC) and a DC storage capacitor. The AC voltage difference across the leakage reactance produces reactive power exchange between the STATCOM and the power system, such that the AC voltage at the bus can be regulated to improve the voltage profile of the power system, which is the primary duty of the STATCOM. [3]

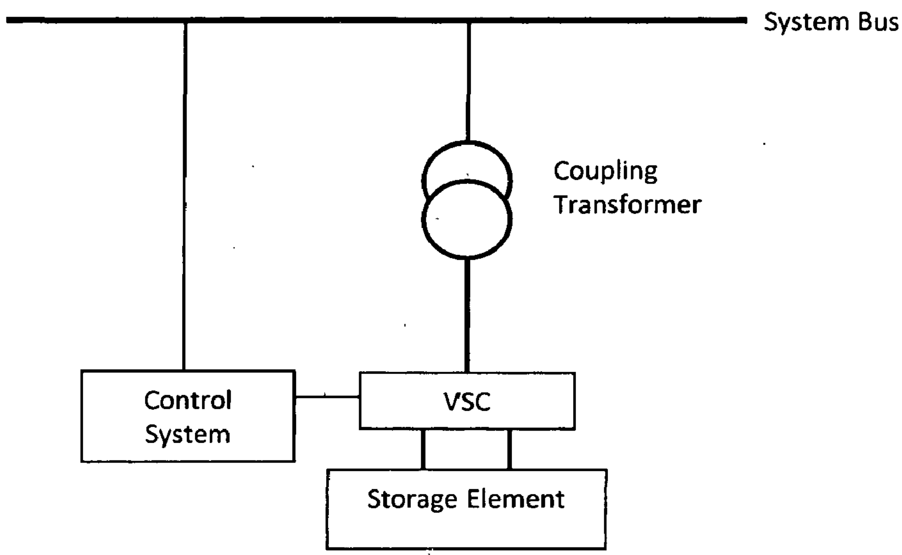


Figure 2.1: Schematic Diagram of a STATCOM

The basic STATCOM representation for reactive power generation is shown schematically in Figure 2.1.

A STATCOM is a controlled reactive-power source. It provides the desired reactive-power generation and absorption entirely by means of electronic processing of the voltage and current waveforms in a voltage-source converter (VSC). A single line STATCOM power circuit is shown in Figure 2.2 (a), where a VSC is connected to a utility bus through magnetic coupling. In Figure 2.2 (b) a STATCOM is seen as an adjustable voltage source behind a reactance.

The exchange of the reactive power between the converter and the ac system can be controlled by varying the amplitude of 3-phase output voltage, E_s, of the converter, as shown in Figure 2.2 (c). That is, if the amplitude of the output voltage is increased above that of the utility bus voltage, E_t, then current flows through the reactance from the converter to the AC system and the converter generates capacitive reactive-power for the ac system. If the amplitude of the output voltage is decreased below the utility bus voltage, then the current flows from the ac system to the converter and the converter absorbs inductive-reactance power from the ac system. If the output voltage equal to the ac system voltage, the reactive-power exchange becomes zero, in which case the STATCOM is said to be in a floating state.

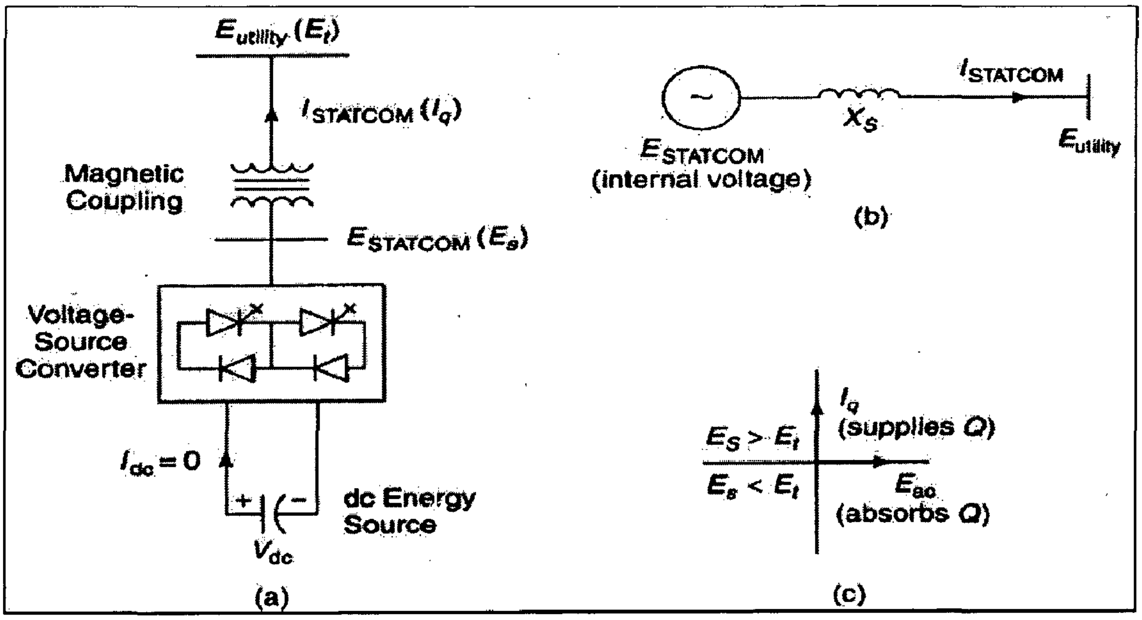


Figure 2.2: The STATCOM Principle Diagram (a) A Power Circuit (b) An Equivalent Circuit (c) A Power Exchange

Adjusting the phase shift between the converter output voltage and the ac system voltage can similarly control real power exchange between the converter and the ac system. In other words, the converter can supply real power to the ac system from its dc energy storage if the converter output voltage made to lead the ac system voltage. On the other hand, it can absorb real power from the ac system for the dc system if its voltage lags behind the ac system voltage.

STATCOM Losses:

Ideally, there are no losses in the STATCOM circuit; therefore, there is no active power exchange between it and the power system, and the capacitor voltage remains constant. However, in practice, the STATCOM has some switching losses associated with its semiconductor switches, and these are

supplied by the dc link capacitor. This will gradually discharge the capacitor voltage. Therefore, the angle of the converter output voltage α should be slightly lagging behind the angle of the voltage at the point of common coupling (PCC), i.e., the angle θ. The active power absorbed from the network as a result of this phase shift compensates for the STATCOM switching losses and maintains the dc link voltage at a constant value.

2.3: Reactive Power Compensation with STATCOM

VAR compensation is defined as the management of reactive power to improve the performance of ac power systems. In wide field of both system and customer problems, especially related with power quality issues the concept of VAR compensation embraces, since most of power quality problems can be eliminated or solved with an appropriate control of reactive power. The problem of reactive power compensation can be viewed from two aspects. [1] [5] [12]

- Load compensation
- Voltage support.

In load compensation the main objectives to increase the value of the system power factor, to balance the real power drawn from the ac supply, to compensate voltage regulation and to eliminate current harmonic components produced by large and fluctuating nonlinear industrial loads. Voltage support is generally required to reduce voltage fluctuation at a given terminal of a transmission line.

Series and shunt VAR compensators are used to modify the natural electrical characteristics of ac power systems. Series compensation modifies the transmission or distribution system parameters, while shunt compensation changes the equivalent impedance of the load. In both cases, the reactive power that flows through the system is effectively controlled and the performance of the overall ac power system can be improved.

Advantages of Reactive Power Compensation:

The main advantages of the reactive power compensation are listed below:

- Reactive power compensation in transmission systems improves the stability of the ac system by increasing the maximum active power that can be transmitted.
- It helps to maintain a flat voltage profile at all levels of power transmission
- It improves HVDC (High Voltage Direct Current) conversion terminal performance
- It increases transmission efficiency
- Controls the steady-state and temporary over voltages

Voltage control (keeping voltage within defined limits) in an electric power system is important for proper operation of electric power equipment to prevent damage such as overheating of generators and motors, to reduce transmission losses and to maintain the ability of the system to withstand disturbances and prevent voltage collapse.

In general terms, decreasing reactive power causes voltages to fall, while increasing reactive power causes voltages to rise. A voltage collapse occurs when the system is trying to serve much more load than the voltage can support. Inadequate reactive power supply lowers the voltage, as voltage drops, current must increase to maintain the power supplied, causing the lines to consume more reactive power and the voltage to drop further.

Voltage collapse occurs when an increase in load or loss of generation or transmission facilities causes dropping voltage, which causes a further reduction in reactive power in capacitors and line charging, and still further voltage reductions. If the declines continue, these voltage reductions cause additional elements to trip, leading to further reduction in voltage and loss of load. The result is a progressive and uncontrollable decline in voltage, all because the power system is unable to provide the reactive power required to supply the reactive power demand.

From last decade voltage source converter based static VAR compensators have been used for reactive power compensation. These compensators are known as Advanced Static VAR Generators (ASVG) or STATCOM.

Comparing to the traditional VAR compensators, the STATCOM has following features listed below:

- Since the bulky capacitors and the inductors are not required, the equipment is more compact.
- As the switching of the STATCOM to the system causes no inrush current, a large capacity STATCOM can be developed.
- The output VAR of the STATCOM can be controlled continuously and rapidly. With fast response, the STATCOM can increase the transmission capacity of the line and ensure the stable operation of the power transmission.
- STATCOM provides reactive power compensation without the dependence of the AC system voltage.

STATCOM is a controlled reactive power source. It provides voltage support by generating or absorbing reactive power at the point of common coupling without the need of large external reactors or capacitors. It is based on Voltage Source Converters (VSC) technology and gate turn off power electronics devices i.e., GTO, IGBT etc.

$$I_q = \frac{(V_S - V_t)}{jX_t} \tag{2.1}$$

In equation (1.1), *Vs* is the amplitude of the output voltage, *Vt* is the AC system voltage, X_t is the coupling transformer leakage reactance and, I_q is the current through STATCOM.

There are three possible cases:

Case 1: If $V_s = V_t$; $I_q = 0$, no reactive power exchange takes place.

Case 2: If $V_s > V_t$; I_q lags V_s by 90 degrees; the STATCOM operates in capacitive mode i.e. it generates var

Case 3: If $V_s < V_t$; I_q leads V_s by 90 degrees; the STATCOM operates in inductive mode i.e. it absorb var.

2.4: The *V-I* Characteristic of STATCOM

A typical *V-I* characteristic of a STATCOM shown in Figure 2.3 the voltage current characteristic at the terminals of a STATCOM is entirely dependent on the converter source voltage, V_S and on the coupling reactance, X_t. In general the coupling reactance as a value between 10% and 20%, i.e. the voltage drop (or rise) across it is about 10% to 20% of the nominal system voltage at the rated current of the STATCOM. The continuous current rating of a GTO, IGBT, or IGCT is almost independent of whether the current lags or leads the voltage. These devices usually also posses a short-time or transient, over current rating, which may exceed the safe turn-off (or turn-on) current for the STATCOM value components. If, by accident or design, the safe turn-off current is exceeded, then turn-off signals must be prevented from being issued until the current returns to below the safe switching level. [3]

$$I_q = \frac{(V_S - V_t)}{jX_t} \tag{2.2}$$

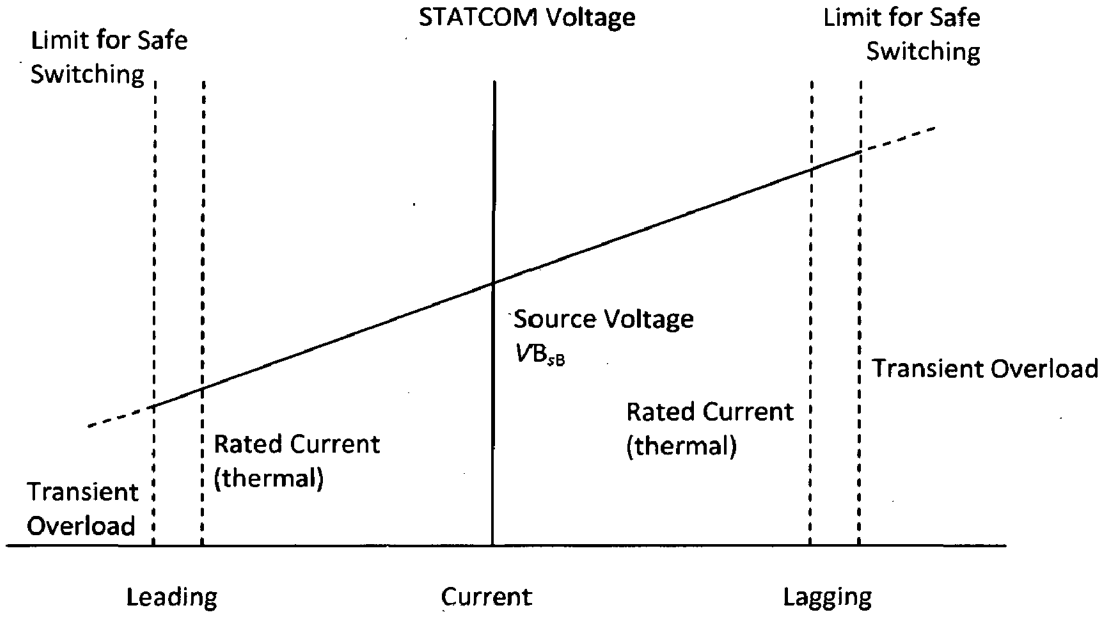


Figure 2.3: Natural *V-I* Characteristic of a STATCOM

As the STATCOM can supply both the capacitive and the inductive compensation and is able to independently control its output current over the rated maximum capacitive or inductive range irrespective of the amount of ac system voltage. That is, the STATCOM can provide full capacitive reactive power at any system voltage.

It is capable of yielding the full output of capacitive generation almost independent of the system voltage. This capability is particularly useful for situations in which the STATCOM is needed to support the system voltage during and after faults where voltages collapse.

At, reduced voltage the STATCOM can continue to be operated at rated leading (or lagging) current, with a constant transient overload current margin. These capabilities are available down to very low voltages. In contrast, the current limits for conventional SVCs are proportional to voltage. A STATCOM is better able to provide reactive/current support for a supply system whose voltage is severely depressed, whereas a conventional SVS can generally do more than a STATCOM to limit dynamic over voltage. [14]

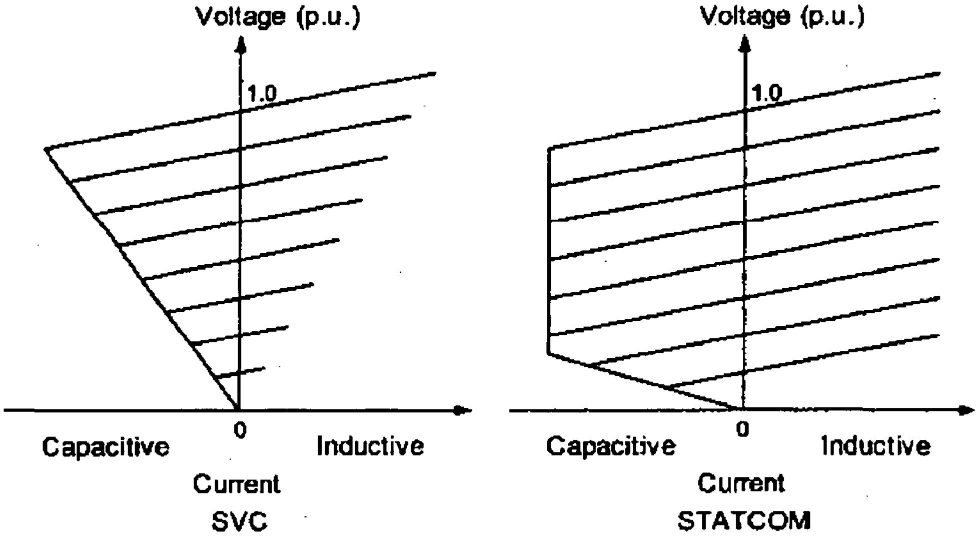


Figure 2.4: Family of *V-I* Characteristics for a SVC and STATCOM

Figure 2.3 shows that the STATCOM controller is normally set to have a regulation slope, Instead of performing as a perfect terminal voltage regulator, the device is now allowed to vary the terminal voltage in proportion with the compensating current. This regulation droop extends the linear operating range of the compensator and tends to enforce the automatic load sharing between the STATCOMs and other voltage regulating devices in the network. Moreover, without this regulation droop, the system is prone to having a poorly defined operating point, as well as a tendency of oscillation.

2.5: Applications of STATCOM

A STATCOM can improve the performance in such areas as the following: [14-16]

- Dynamic voltage regulation in transmission and distribution lines
- Reduction of temporary over voltages
- Improvement of steady-state power transfer capacity
- Improvement of transient stability margin

- Damping of power system oscillations
- Damping of subsynchronous power system oscillations
- Power quality improvement
- Distribution system applications

Other applications of the smaller STATCOMs, in service are for reduction of lamp flicker due to electric arc melting furnaces, for voltage control of wind farms and for balancing of single-phase traction loads.

Aspect	Synchronous Condenser	Static Compensator		Self-Commutated Compensator (STATCOM)
		TCR(with Shunt Capacitors if Necessary)	TSC (with TCR if necessary)	
Accuracy of Compensation	Good	Very Good	Good, very good with TCR	Excellent
Control Flexibility	Good	Very Good	Good, very good with TCR	Excellent
Reactive Power Capability	Leading/Lagging	Lagging/Leading Indirect	Leading/Lagging Indirect	Leading/Lagging
Control	Continuous	Continuous	Discontinuous (Continuous with TCR)	Continuous
Response Time	Slow	Fast, 0.5 to 2 cycles	Fast, 0.5 to 2 cycles	Very fast (but depends upon switching frequency and control system)
Harmonics	Very Good	Very high (large size filters are needed)	Good (filters are needed with TCR	Good but depends on switching pattern
Losses	Moderate	Good(less) but increase in lagging mode	Good(less) but increases in leading mode	Very good (least) but increases with switching frequency
Phase Balancing Ability	Limited	Good	Limited	Very good with 1-phase units, limited with 3-phase units
Cost	High	Moderate	Moderate	Low to moderate

Table 2.1: Comparisons of Basic Types of Shunt Compensators

2.6: Benefits of the STATCOM System

A STATCOM does have the following:

- It occupies small space, because it replace the passive banks of circuit elements by compact electronic converters.
- It offers modular, factory-built equipment, thereby reducing the site work and time.
- It uses encapsulated electronic converters, thereby minimizing its environmental impact

Table 2.1 summarizes the comparative merits of the main types of shunt VAR compensators. The significant advantages of self-commutated compensators make them an interesting alternative to improve compensation characteristics and also to increase the performance of AC power systems.

CHAPTER 3
MULTIPULSE CONVERTERS FOR STATCOM

This chapter deals with different types of voltage source converters, their advantages and it further deals with detailed analysis of various types of 6-, 12-, 24-, and 48-pulse voltage source converters and also presents the concepts of quasi harmonic neutralized voltage source converters.

3.1: Introduction

The basic requirement of the STATCOM is a converter that generates a sinusoidal voltage. Converter may be a voltage source converter (VSC) or current source converter (CSC). Generally in FACTS controllers employ voltage source converters over current source converters because of the below reasons. [16]

- CSC requires power semiconductors with the bidirectional voltage blocking capability. The available high power semiconductors with the gate turn off capability (GTO, IGBT) either cannot block reverse voltage at all or can only do it with detrimental effect on the other important parameters.
- Practical current source termination of the converter DC terminals by the charged reactor have much losses than the complimentary voltage source termination by VSC.
- The CSC requires a voltage source termination at the AC terminals usually in the form of a capacitive filter. The VSC requires a current source termination at the AC terminal that is naturally provided by the leakage reactance of the coupling transformer.
- CSC may require additional over voltage protection of higher rating of the semiconductors.

In voltage source converters the DC voltage always has one polarity and power reversal takes place through reversal of DC current polarity. Basically a voltage-sourced converter generates AC voltage from a DC voltage. It is referred to as an Converter, even though it has the capability to transfer power in either direction. Voltage source converter is made up of an asymmetric turn off device with a parallel diode connected in reverse. On the DC side voltage is unipolar and is supported by a capacitor. The basic objective of VSC is to produce a sinusoidal AC voltage with minimum harmonic distortion from the DC voltage.

3.2: Main Circuit Topologies of STATCOM

There are mainly two types of STATCOM circuit configurations:

1. Multipulse Converter
2. Multilevel Converter

3.3: Multipulse Converter

In the multipulse converter, the 3-phase bridges are connected in parallel on the DC side, as shown in Figure 3.1. The bridges are magnetically coupled through a zigzag transformer, and the transformer is usually arranged to make the bridges appear in series viewed from the AC sides. Each winding of the transformer is phase-shifted to eliminate selected harmonics and produce a multipulse output voltage. Pulse Width Moderation (PWM) can be applied to improve the harmonics content, at the expense of higher switching and snubber loss, plus reduced fundamental var rating. [3]

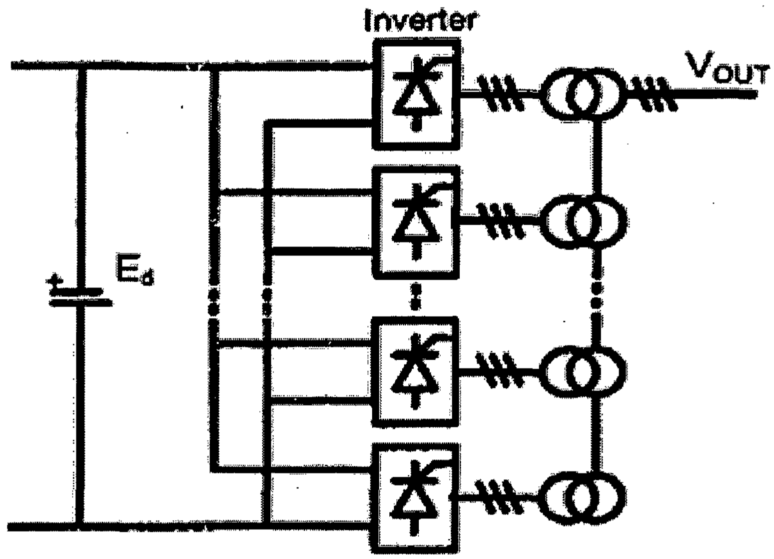


Figure 3.1: Multipulse Converter Diagram

The main disadvantages of multipulse converter configuration are:

- The phase-shift transformer makes the system complex and bulky
- There will be a unique transformer design for each STATCOM installation

3.4: Six Pulse Converter

The static synchronous voltage source can be implemented by various switching power converters. An elementary 6-pulse, voltage sourced converter is shown in Figure 3.2. It consists of six self-commutated semiconductor devices, each of which is shunted by a reverse-parallel connected diode. It should be noted that in a high power converter each switching device is consist of a string of series connected semiconductors to yield the required voltage rating. With a DC voltage source (which may be a charged capacitor) the converter can produce a balanced set of three quasi-square voltage waveforms of a given frequency, as shown in Figure 3.3, by connecting the dc source sequentially to the three output terminals via the appropriate converter switches. [6]

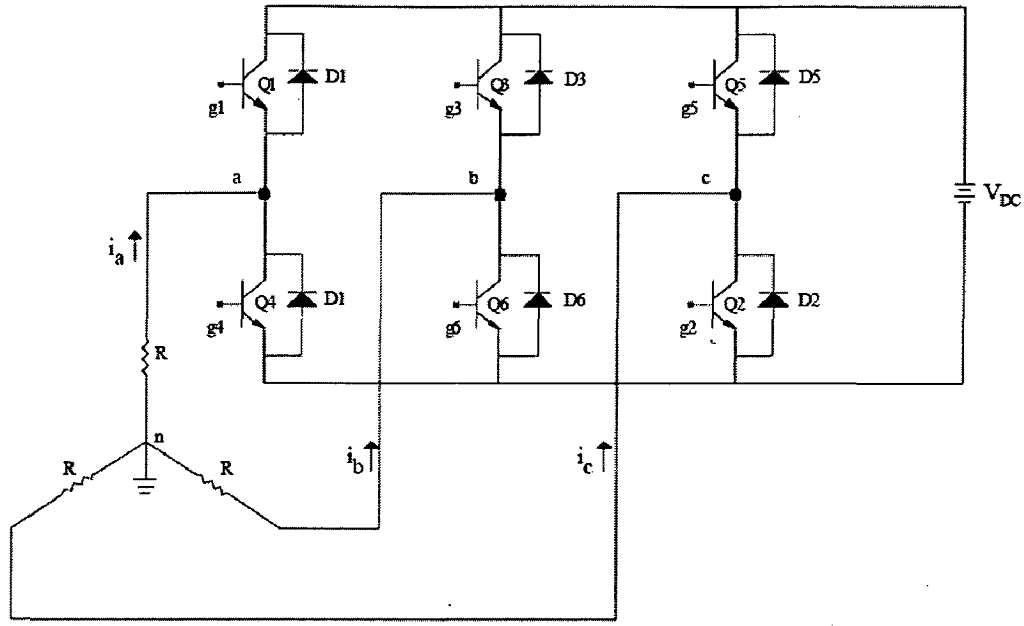


Figure 3.2: Elementary 6-Pulse, Voltage Source Converter

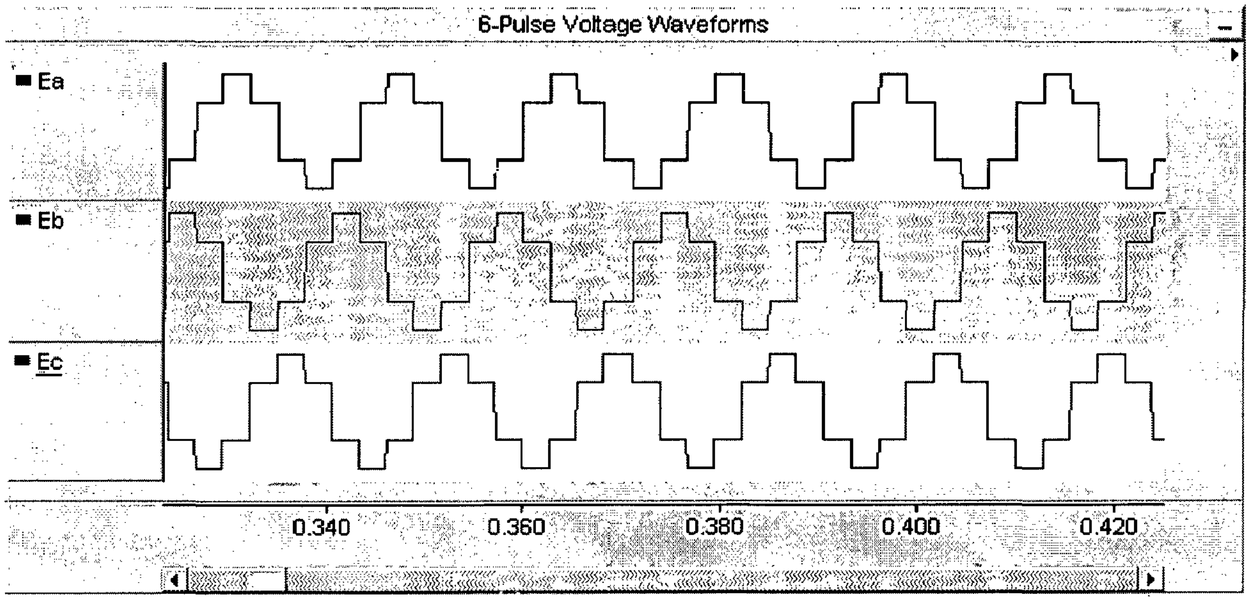


Figure 3.3: 6-Pulse Converter Output Voltage Waveforms

X axis: Time in sec.

Y axis: Voltage (kV)

Harmonic Analysis of Six Pulse Converter:

The harmonic content of the line-to-line and line-to-neutral voltages can be obtained applying a Fourier analysis to the waveforms shown in Figure 3.3. Therefore the instantaneous value of the voltage waveform based on Fourier analysis is given by [6]

$$v_{ab}(t) = \sum_{n=1}^{\infty} v_{ab_n} \sin(nwt + \frac{\pi}{6}n) \qquad (3.1)$$

Where,

$$v_{ab_n} = \frac{4}{T} \int_{\pi/6}^{5\pi/6} V_{dc} \sin(nwt) dwt \qquad (3.2)$$

T=2π

So that,

$$v_{ab_n} = \frac{2}{n\pi} V_{DC} \left(\cos\left(\frac{\pi}{6}n\right) - \cos\left(\frac{5\pi}{6}n\right) \right) \qquad (3.3)$$

From eq. (3.3) it is worth to note that only the *6r ± 1 (n = 6r ± 1)* terms exist, where *r* is any positive integer, that is, *n* = 1^{st}, 5^{th}, 7^{th}, 11^{th}, 13^{th}.....

Therefore eq. (3.3) can be reduced to

$$v_{ab_n} = \frac{4}{n\pi} V_{DC} \left(\cos\left(\frac{\pi}{6}n\right) \right) \forall n = 6n \pm 1, r = 0,1,2... \qquad (3.4)$$

Eq. (3.5) gives rise to the fundamental and harmonic components of the line-to-line voltages,

$$\left. \begin{aligned} v_{ab_1} &= 1.1026 V_{DC} peak \\ v_{ab_1} &= 0.7797 V_{DC} RMS \\ v_{ab_n} &= \frac{1.1026}{n} V_{DC} peak \\ v_{ab_n} &= \frac{0.7797}{n} V_{DC} RMS \end{aligned} \right\| \qquad (3.5)$$

Finally, voltage $v_{ab}(t)$ is expressed by eq. (3.7). Voltages $v_{bc}(t)$ and $v_{ca}(t)$ have a similar pattern except phase shifted by 120°and 240°, respectively, from $v_{ab}(t)$.

$$v_{ab}(t) = \frac{4}{\pi} V_{DC} \sum_{n}^{\infty} \frac{1}{n} \cos\left(\frac{\pi}{6}n\right) \sin\left(n\omega t + \frac{\pi}{6}n\right) \qquad (3.6)$$

$$v_{bc}(t) = \frac{4}{\pi} V_{DC} \sum_{n}^{\infty} \frac{1}{n} \cos\left(\frac{\pi}{6}n\right) \sin\left(n\omega t - \frac{\pi}{2}n\right) \qquad (3.7)$$

$$v_{ca}(t) = \frac{4}{\pi} V_{DC} \sum_{n}^{\infty} \frac{1}{n} \cos\left(\frac{\pi}{6} n\right) \sin\left(n\omega t - \frac{7\pi}{6} n\right) \quad (3.8)$$

$$\forall n = 6r \pm 1, r = 0,1,2......$$

In a similar way the harmonic content of the line-to-neutral voltages $v_{an}(t)$, $v_{bn}(t)$ and $v_{cn}(t)$ was obtained; analyzing $v_{an}(t)$ a half-odd wave symmetry is found, thus

$$v_{an}(t) = \sum_{n=1}^{\infty} v_{an_n} \sin(n\omega t) \quad (3.9)$$

Where,

$$v_{an_n} = \frac{4}{3T} V_{DC} \left(\int_0^{\pi/3} \sin(n\omega t) d\omega t + 2 \int_{\pi/3}^{2\pi/3} \sin(n\omega t) dwt + \int_{2\pi/3}^{\pi} \sin(n\omega t) d\omega t \right) \quad (3.10)$$

T=2π

So that,

$$v_{an_n} = \frac{2}{3n\pi} V_{DC} \left(\cos\left(\frac{\pi}{3} n\right) - \cos\left(\frac{2\pi}{3} n\right) + 1 - (-1)^n \right) \quad (3.11)$$

Although the waveforms of the line-to-line voltages and the line-to-neutral voltages are different, they present a similar harmonic content, the line-to-neutral voltages also have $6r \pm 1$ $(n = 6r \pm 1)$ order terms, where r is any positive integer, that is, $n = 1^{st}, 5^{th}, 7^{th}, 11^{th}, 13^{th}, ...$, there by eq. (3.11) is expressed by,

$$v_{an_n} = \frac{4}{3n\pi} V_{DC} \left(\cos\left(\frac{\pi}{3} n\right) + 1 \right) \quad (3.12)$$

$$\forall n = 6r \pm 1, r = 0,1,2......$$

Eq. (3.13) gives rise to the fundamental and harmonic components of the line-to-ground voltages,

$$\begin{aligned}
v_{an_1} &= 0.6366 V_{DC} peak \\
v_{an_1} &= 0.4502 V_{DC} RMS \\
v_{an_n} &= \frac{0.6366}{n} V_{DC} peak \\
v_{an_n} &= \frac{0.4502}{n} V_{DC} RMS
\end{aligned} \tag{3.13}$$

The following equations describe the line-to-neutral voltages based on Fourier analysis.

$$v_{an}(t) = \frac{4}{3\pi} V_{DC} \sum_{n}^{\infty} \frac{1}{n} \left(\cos\left(\frac{\pi}{3} n \right) + 1 \right) \sin(n\omega t) \tag{3.14}$$

$$v_{bn}(t) = \frac{4}{3\pi} V_{DC} \sum_{n}^{\infty} \frac{1}{n} \left(\cos\left(\frac{\pi}{3} n \right) + 1 \right) \sin\left(n\omega t - \frac{2\pi}{3} \right) \tag{3.15}$$

$$v_{cn}(t) = \frac{4}{3\pi} V_{DC} \sum_{n}^{\infty} \frac{1}{n} \left(\cos\left(\frac{\pi}{3} n \right) + 1 \right) \sin\left(n\omega t - \frac{4\pi}{3} \right) \tag{3.16}$$

$$\forall n = 6r \pm 1, r = 0,1,2......$$

It is worth noting that the fundamental component and the harmonic components of the line-to-line voltages and the line-to-neutral voltages are phase shifted by 30°from each other. The amplitude of the line-to-line voltages is $\sqrt{3}$ times the line-to-neutral voltage amplitude and the harmonics components not included in the set $n = 6r \pm 1$are in phase opposition. This is illustrated by the following expression:

$$v_{ab_n} = (-1)^n \sqrt{3} v_{an_n} \tag{3.17}$$

Where, $n = 6r \pm 1, r = 0,1,2......$

Figure 3.9 depicts the Fourier spectrum for voltage $V_{an}(t)$

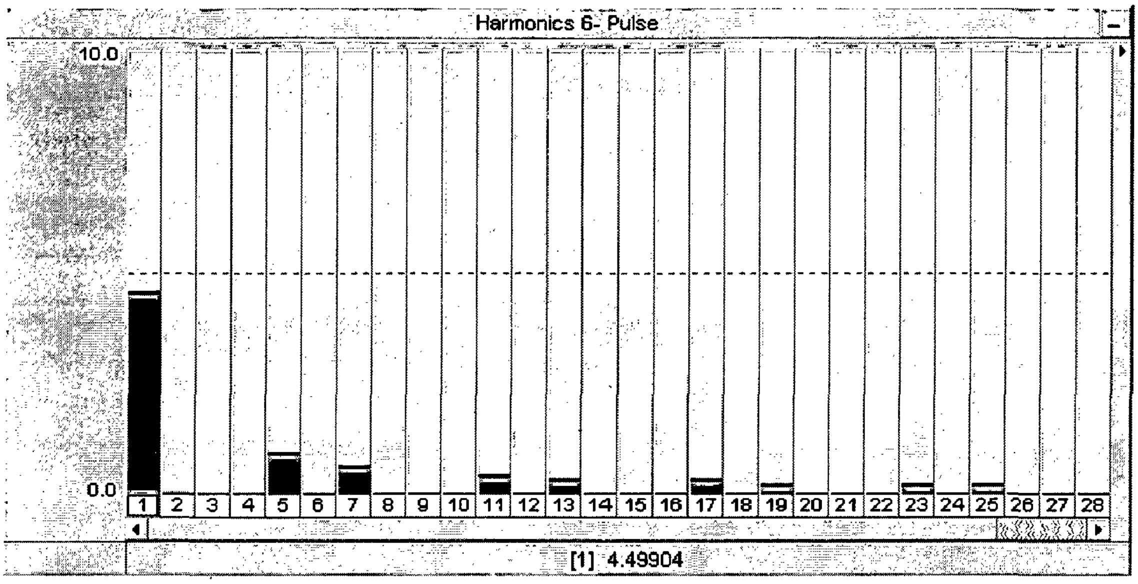


Figure 3.4: Voltage Fourier Spectrum for a 6-Pulse Converter

X axis: Harmonic Order

Y axis: Voltage Magnitude (kV)

3.5: Multipulse Converters

As mentioned earlier, a 6-pulse converter contains a voltage harmonics of the order given by

$h= 6k\pm 1, k= 1, 2, 3.....$ (3.18)

The 6-pulse converter is the simplest arrangement used in FACTS devices in high power applications it does not offer a good performance, due to the high harmonic content. Combining two or more six-pulse converters, a better performance is obtained. This new configuration is called multipulse converter. The twelve-pulse circuit is the lowest practical pulse-numbered circuit for power system application to achieve a satisfactory harmonic behavior.

3.5.1: 12-Pulse Converter

The 12-pulse converter is obtained by combining two 6-pulse VSC with its firing pulse shifted by 30° from each other. A 12-pulse VSC employs two 6-pulse converters and a magnetic circuit. It is assumed that all the 6-pulse converters are supplied by a common dc storage capacitor. Figure 3.5 shows the schematic diagram for a 12-pulse converter. The magnetic circuit contains 6 single-phase transformers (or two three-phase transformers). Three identical transformers single-phase transformers are used for each converter. The main purpose of the magnetic circuit is to provide a phase shift of 30° between the successive converter voltages. [11] [18]

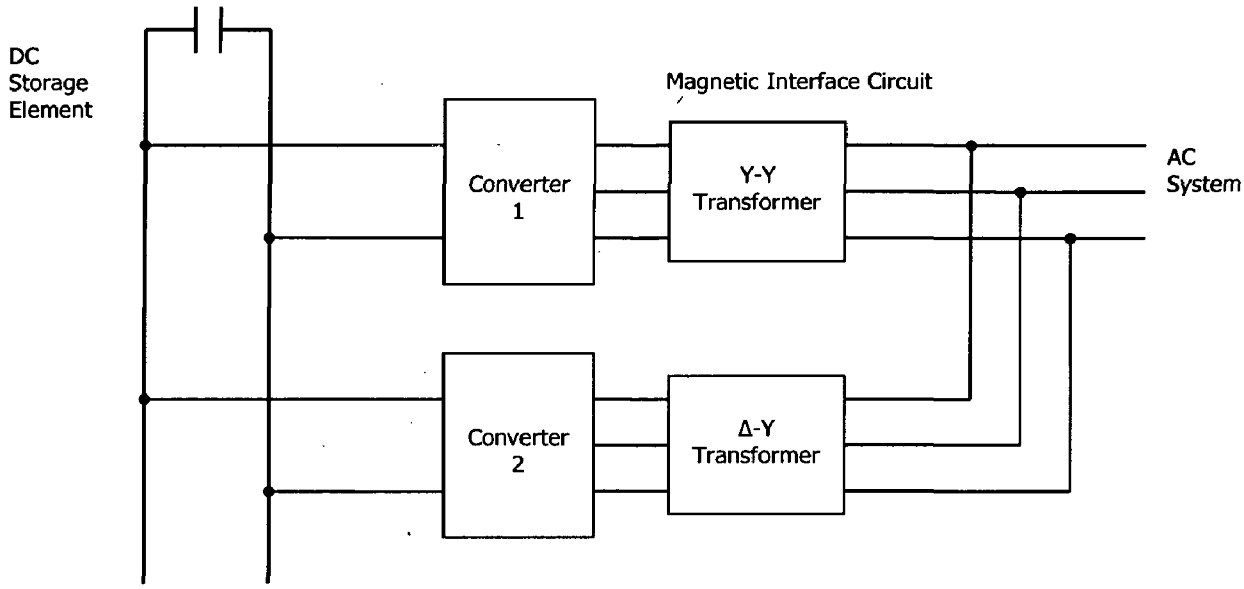


Figure 3.5: Schematic Diagram for a 12-Pulse Converter

Figure 3.6 shows the 12-pulse converter output voltage waveforms and Figure 3.7 shows the voltage Fourier spectrum for a 12-pulse Converter. From Figure 3.7 it can be observed that the twelve-pulse voltage waveforms holds only harmonics of order $n = 12r \pm 1$, where r is any positive integer, that is, $n = 11^{th}, 13^{th}, 23^{rd}, 25^{th}$..., order harmonics with amplitudes $1/11^{th}, 1/13^{th}, 1/23^{rd}, 1/25^{th}$..., respectively.

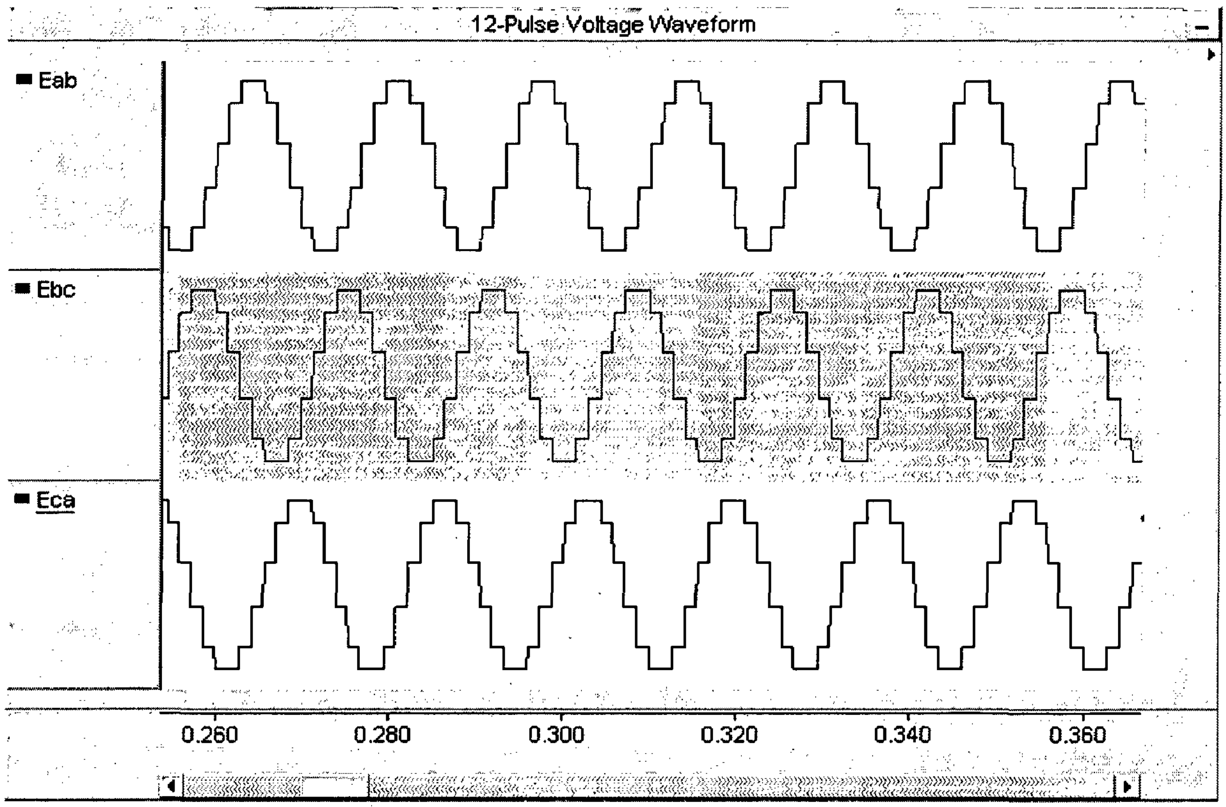


Figure 3.6: 12-Pulse Converter Output Voltage Waveforms

X axis: Time in sec.

Y axis: Voltage (kV)

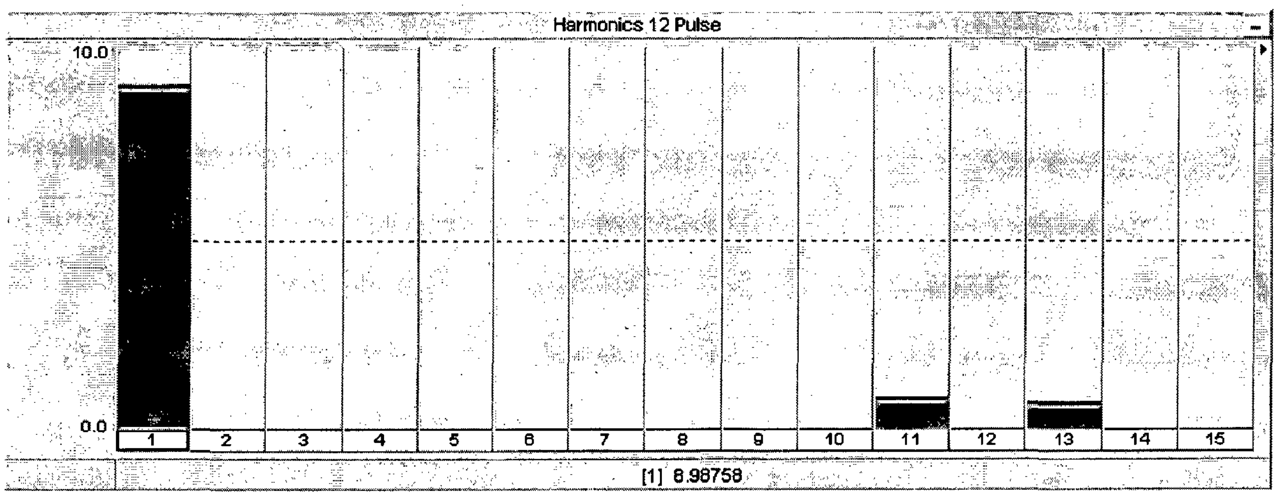


Figure 3.7: Voltage Fourier Spectrum for a 12-Pulse Converter

X axis: Harmonic Order

Y axis: Voltage Magnitude (kV)

3.5.2: 24-Pulse Harmonic Neutralized Converter

The 24-pulse converter is obtained by combining two 12-pulse VSC with its firing pulse shifted by 7.5° from each other. A 24-pulse VSC employs four 6-pulse converters and a magnetic circuit. It is assumed that all the six- pulse converters are supplied by a common dc storage capacitor. Figure 3.8 shows the schematic diagram for a 24-pulse converter. The magnetic circuit contains 12 single-phase transformers of which 6 are 3-winding transformers. Three identical transformers are used for each converter. The use of three-winding transformer is to provide the necessary phase shift. The primary sides of these transformers are connected in delta. The secondary side connection is hybrid one as some of them are connected in delta while the rest are connected in wye.

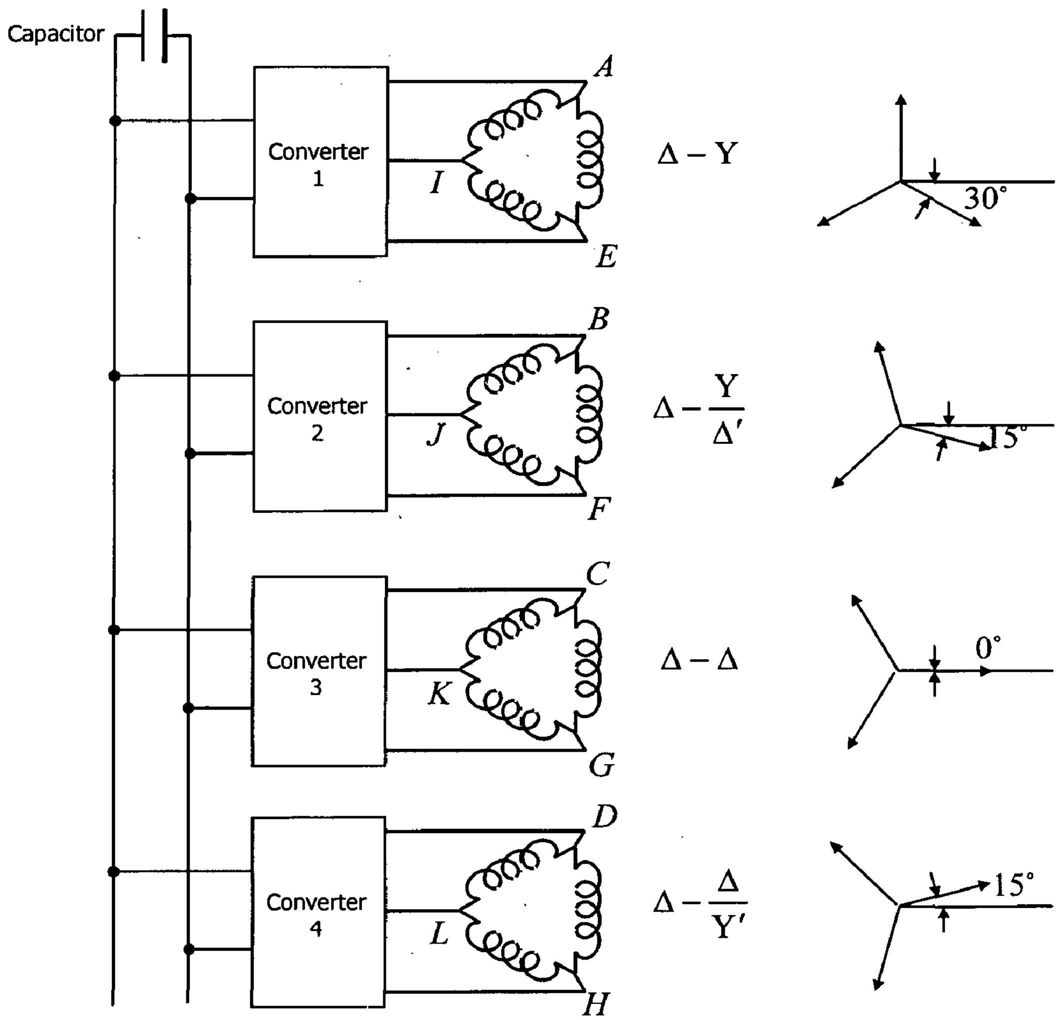


Figure 3.8: Schematic Diagram for a 24-Pulse Converter

The main purpose of the magnetic circuit is to provide a phase shift of 15° between the successive converter voltages. [19]

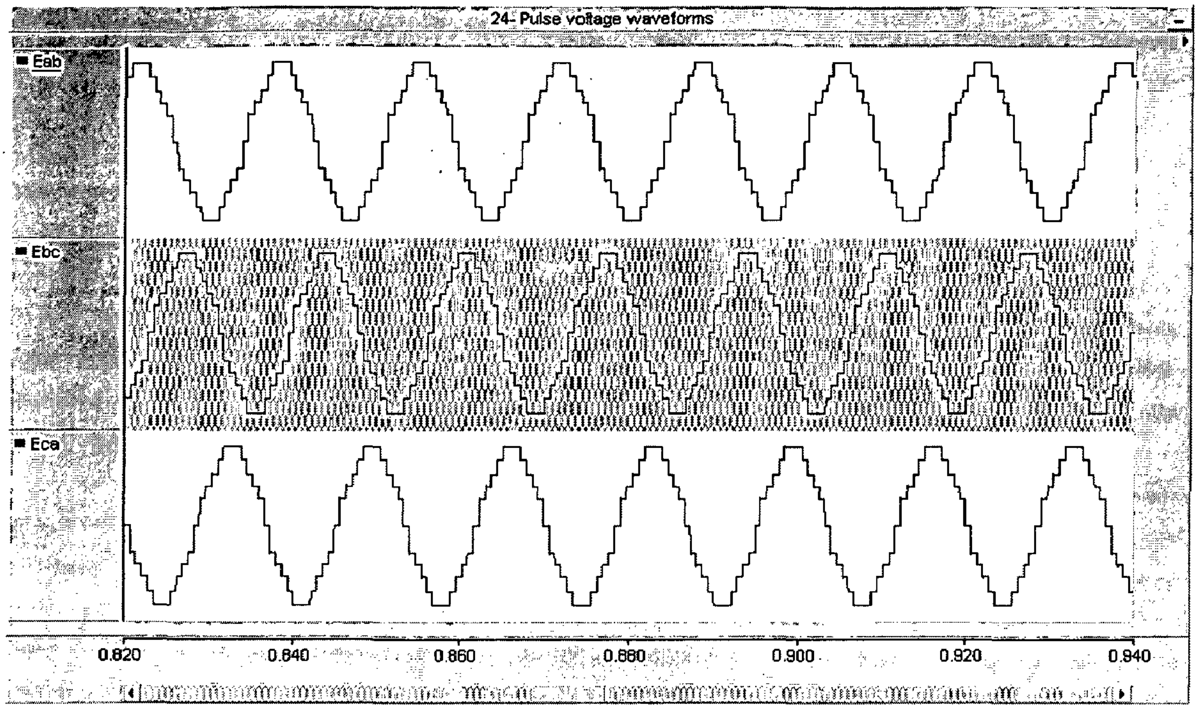


Figure 3.9: 24-Pulse Converter Output Voltage Waveforms

X axis: Time in sec.

Y axis: Voltage (kV)

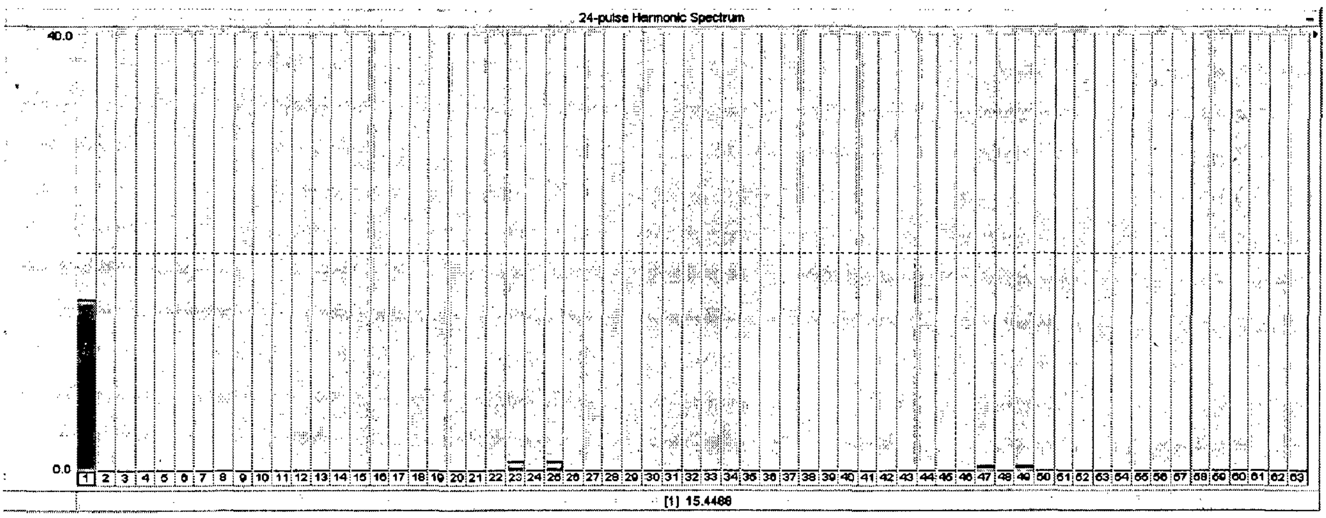


Figure 3.10: Voltage Fourier Spectrum for a 24-Pulse Converter

X axis: Harmonic Order

Y axis: Voltage Magnitude (kV)

Figure 3.9 shows the 24-pulse converter output voltage waveforms and Figure 3.10 shows the voltage Fourier spectrum for a 24-pulse Converter. From Figure 3.10 it can be observed that the 24-pulse voltage waveforms holds only harmonics of order $n = 24r \pm 1$, where r is any positive integer, that is, $n = 23^{rd}, 25^{th}, 47^{th}, 49^{th}...$, order harmonics with amplitudes $1/23^{rd}, 1/25^{th}, 1/47^{th}, 1/49^{th}...$, respectively.

3.5.3: 48-Pulse Harmonic Neutralized Converter

The 48-pulse converter is obtained by combining two 24-pulse VSC with its firing pulse shifted by 7.5° from each other. A 48-pulse VSC employs eight 6- pulse converters and a magnetic circuit. It is assumed that all the six- pulse converters are supplied by a common dc storage capacitor. Figure 3.11 shows the schematic diagram and transformer configuration for a 48-pulse converter. The magnetic circuit contains 24 single-phase transformers of which 18 are 3-winding transformers. Three identical transformers are used for each converter. The use of three-winding transformer is to provide the necessary phase shift. The primary sides of these transformers are connected in delta. The secondary side connection is hybrid one as some of them are connected in delta while the rest are connected in wye. The main purpose of the magnetic circuit is to provide a phase shift of 7.5° between the successive converter voltages. [20]

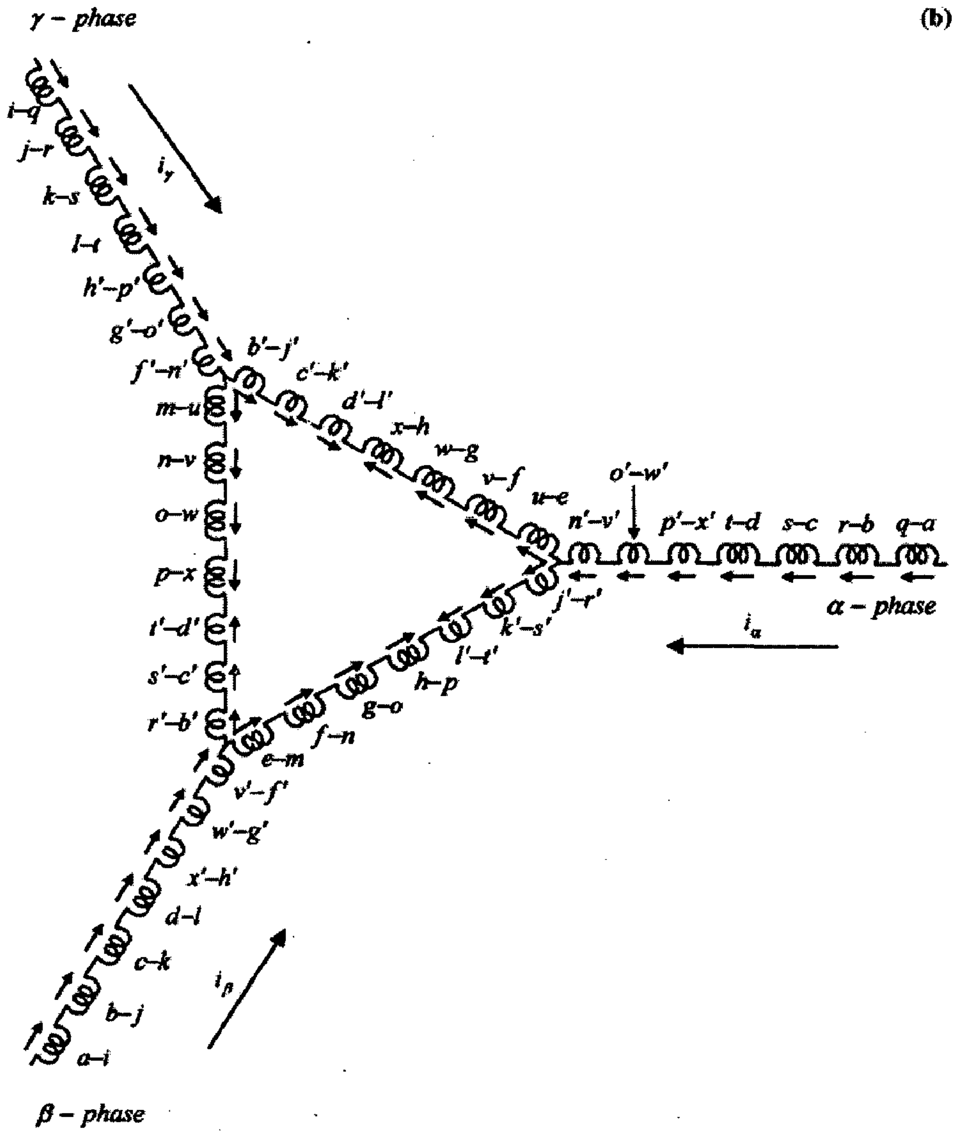


Figure 3.11: 48-Pulse Converter (a) Schematic Diagram (b) Transformer Configuration

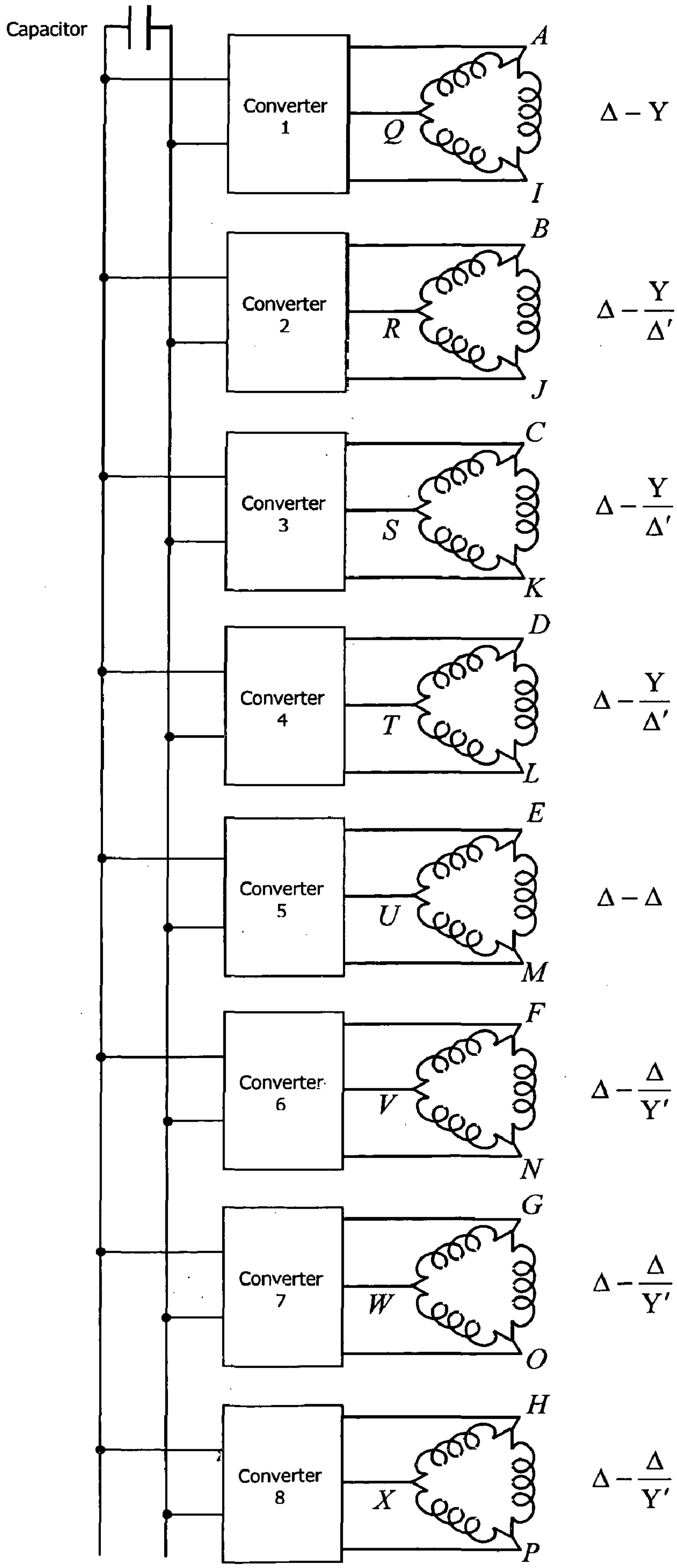


Figure 3.11: *(Continued)*

Figure 3.12 shows the 48-Pulse converter output voltage waveforms and Figure 3.13 shows the voltage Fourier spectrum for a 48-Pulse Converter. From Figure 3.13 it can be observed that the 48-pulse voltage waveforms holds only harmonics of order $n = 48r \pm 1$, where r is any positive integer, that is, $n = 47^{th}, 49^{th}, 95^{th}, 97^{th}$..., order harmonics with amplitudes $1/47^{th}, 1/49^{th}, 1/95^{th}, 1/97^{th}$..., respectively.

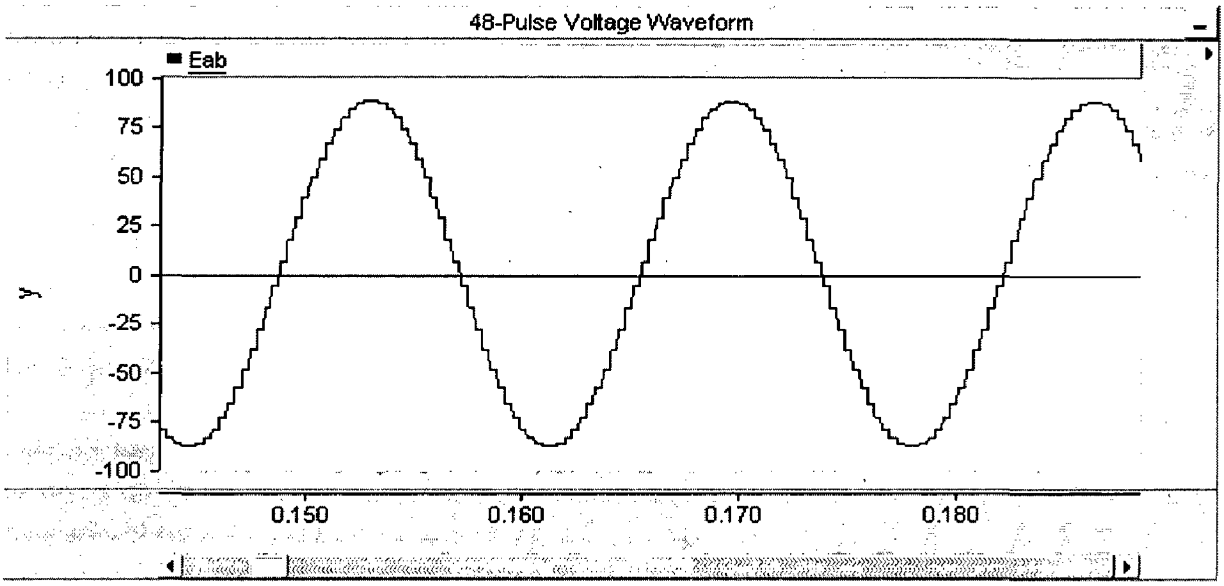


Figure 3.12: 48-Pulse Converter Output Voltage Waveform

X axis: Time in sec.

Y axis: Voltage (kV)

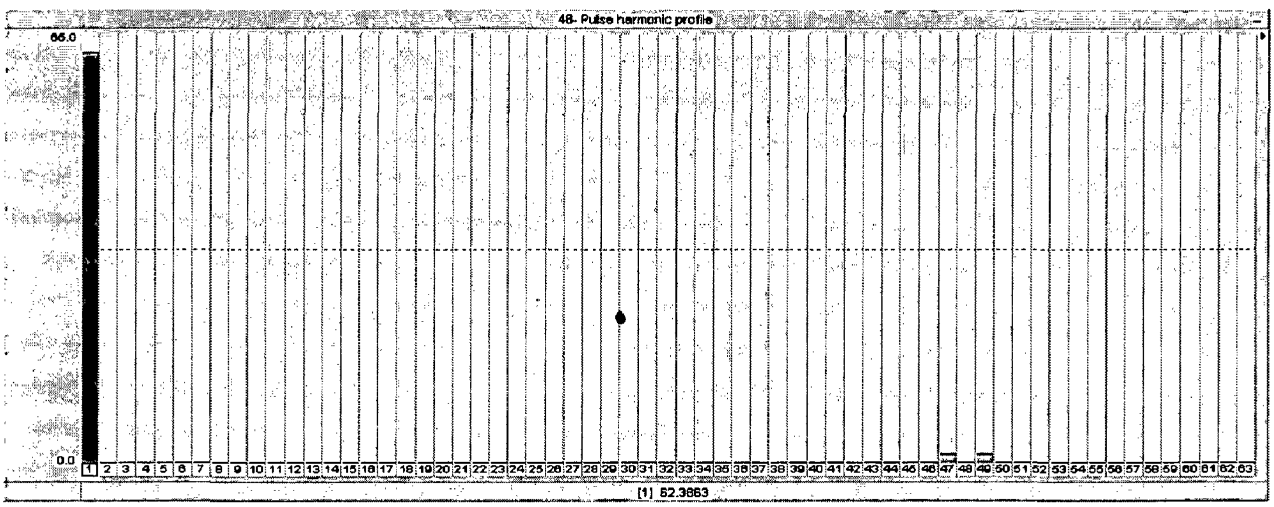


Figure 3.13: Voltage Fourier Spectrum for a 48-Pulse Converter

X axis: Harmonic Order

Y axis: Voltage Magnitude (kV)

3.5.4: 24-Pulse Quasi Harmonic Neutralized Converter

In the past, 24-pulse voltages are provided by transformer connection. These transformers are connected in zigzag, which produce phase displacements of 15 degrees between each transformer. Therefore, each transformer must have a tertiary winding with different turn ratio and leakage reactance. This leads to high construction cost of transformers. A quasi 24-pulse converter (shown in Figure 3.14) uses the principle of superposition. The circuit configuration can be viewed as two 12-pulse converters, which are connected in series. The 15 degrees phase displacements between two 12-pulse converters must be produced among four VSCs. The firing angle of the first 12-pulse converter (VSC_1 and VSC_2) is set at 7.5 degrees advanced, which gives the phase angles of -7.5 degrees for VSC_1 and 22.5 degrees for VSC_2, respectively. The firing angle of the second 12-pulse converter (VSC_3 and VSC_4) is set at 7.5 degrees delayed, which gives the phase angles of 7.5 degrees for VSC_3 and 37.5 degrees for VSC_4, respectively. Consequently, the waveform of phase voltage of each VSC has 15 degrees phase displacement from each other. [9] [19] [21]

Primary windings of each stage are connected in wye (T_1), delta (T_2), wye (T_3), and delta (T_4) respectively. The primary sides of the transformers of each stage are connected to a VSC. A Voltage Source Converter (VSC) consists of GTOs and diodes, which are arranged as six bidirectional valves. All four VSCs are connected in parallel to a common DC bus, which in turn connected to a DC capacitor. According to this arrangement, transformer T_1 is similar to T_3 and T_2 is similar to T_4, so the transformer cost of quasi multi-pulse converter is less than conventional multi-pulse converter. This is a great advantage of quasi multi-pulse converter.

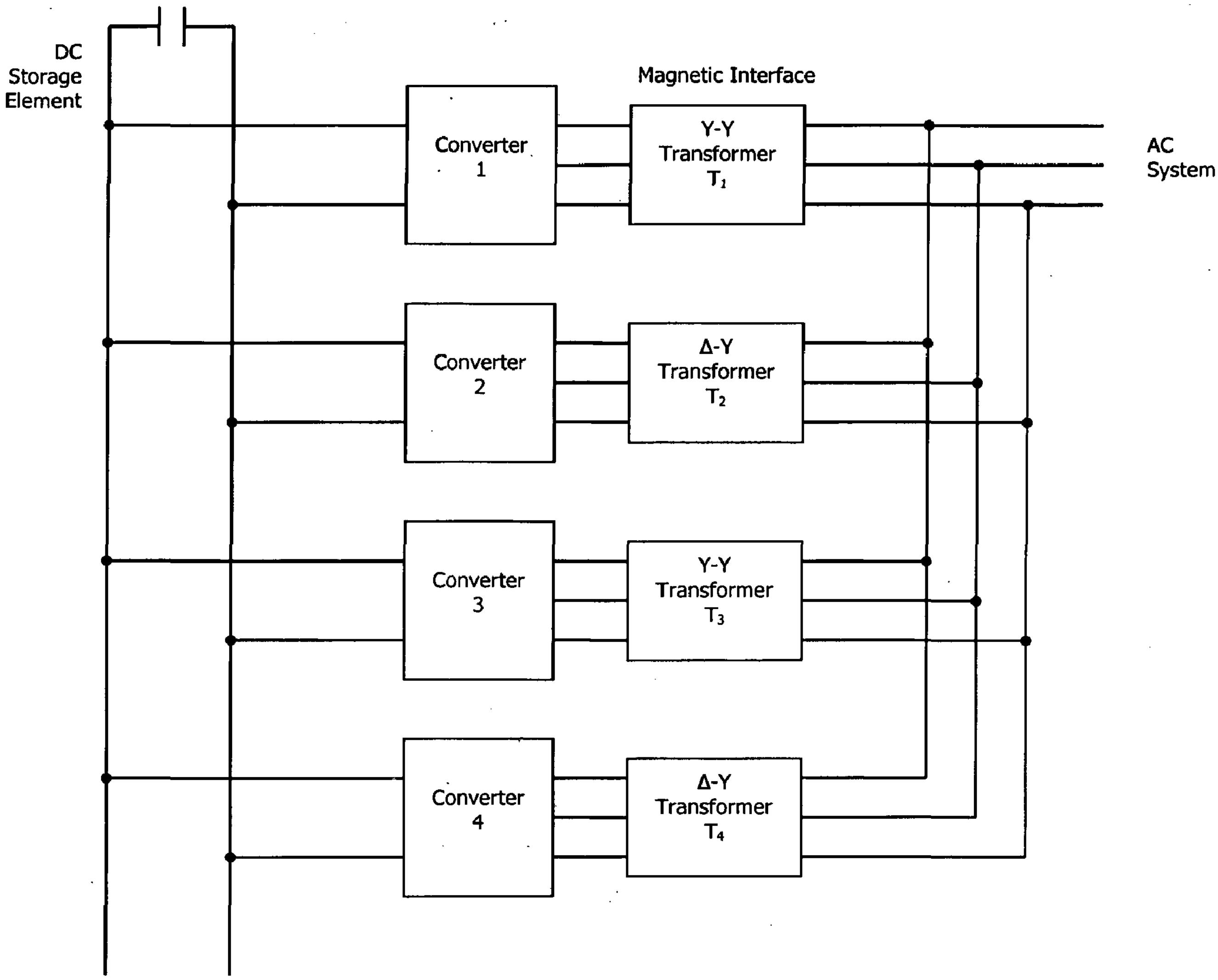


Figure 3.14: Schematic Diagram for a 24-Pulse Quasi harmonic Neutralized Converter

Figure 3.15 shows the 24-Pulse converter output voltage waveforms and Figure 3.16 shows the voltage Fourier spectrum for a 24-pulse converter. From Figure 3.19 it can be observed that the 48-pulse voltage waveforms holds harmonics of order $n = 12r \pm 1$, where r is any positive integer. This is due to the fact that quasi 24-pulse is made of four series 12-pulse VSCs. But, the dominant harmonics are 23rd and 25th because the 11th and 13th order harmonics are very small in magnitude. Hence harmonic filters may not be necessary to eliminate those harmonics

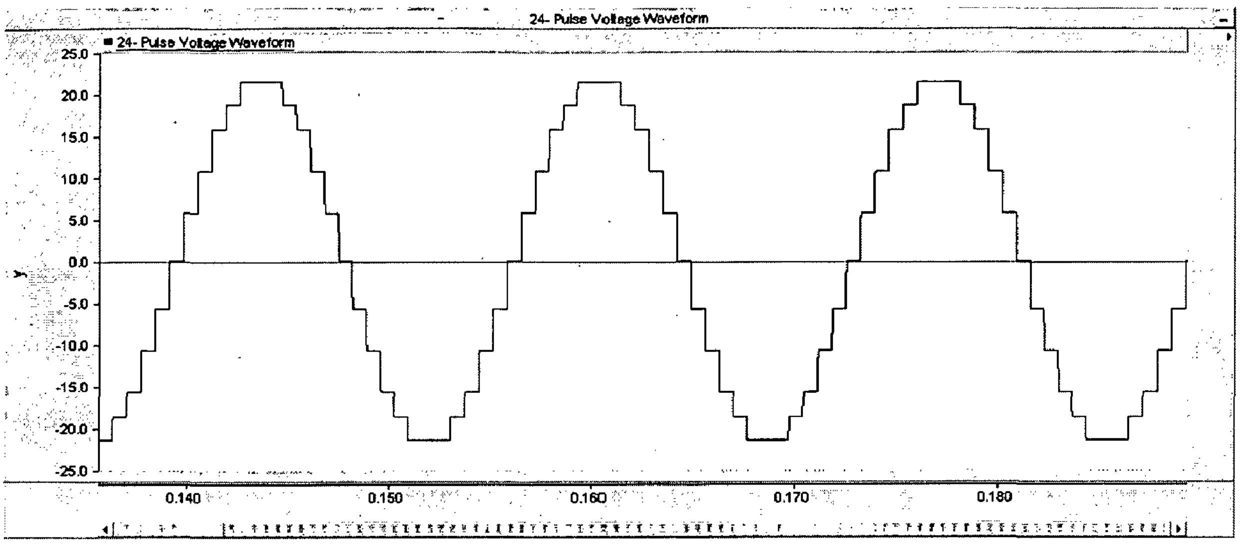


Figure 3.15: 24-Pulse Quasi Harmonic Naturalized Converter Output Voltage Waveforms

X axis: Time in sec.

Y axis: Voltage (kV)

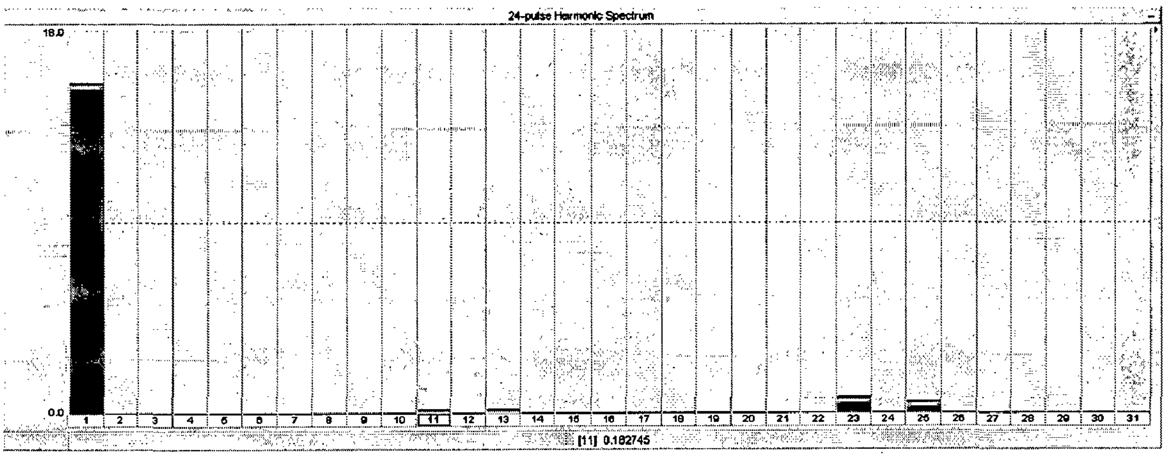


Figure 3.16: Voltage Fourier Spectrum for a 24-Pulse Quasi Harmonic Naturalized Converter

X axis: Harmonic Order

Y axis: Voltage Magnitude (kV)

3.5.4: 48-Pulse Quasi Harmonic Neutralized Converter

A quasi 48-pulse converter shown in Figure 3.17 uses the principle of superposition. The circuit configuration can be viewed as four 12-pulse converters, which are connected in cascade. The 7.5 degrees phase displacement between two 12-pulse converters must be produced by the eight 6 pulse VSCs. The firing angle of the first 12-pulse converter (VSC_1 and VSC_2) is set at 11.25 degrees advanced, which gives the phase angles of -11.25 degrees for VSC_1 and 18.75 degrees for VSC_2, respectively. The firing angle of the second 12-pulse converter (VSC_3 and VSC_4) is set at 3.75 degrees advanced, which gives the phase angles of -3.75 degrees for VSC_3 and 26.25 degrees for VSC_4, respectively. The firing angle of the third 12-pulse converter (VSC_5 and VSC_6) is set at 3.75 degrees delayed, which gives the phase angles of +3.75 degrees for VSC_5 and 33.75 degrees for VSC_6 respectively. The firing angle of the last 12-pulse converter (VSC_7 and VSC_8) is set at 11.25 degrees delayed, which gives the phase angles of +11.25 degrees for VSC_7 and 41.25 degrees for VSC_8, respectively. Consequently, the waveform of phase voltage of each VSC has 7.5 degrees phase displacement from each other. Primary windings of each stage are connected in wye (T_1), delta (T_2), wye (T_3), delta (T_4) wye (T_5), delta (T_6), wye (T_7) and delta (T_8) respectively. The primary sides of the transformers of each stage are connected to a VSC. All eight VSCs are connected in parallel to a common DC bus, which in turn connected to a DC capacitor.

According to this arrangement, transformer T_1, T_3, T_5 and T_7 are similar and also transformers T_2, T_4, T_6 and T_8 are similar. So, the transformer cost of quasi multi-pulse converter is less than conventional multi-pulse converter. This is a great advantage of quasi multi-pulse converter. Similarly a quasi 48-pulse converter (shown in Figure 3.15) uses the principle of superposition. The circuit configuration can be viewed as four 12-pulse converters, which are connected in series. The 7.5 degrees phase displacements between two 12-pulse converters must be produced among eight VSCs. [9] [19] [21-22].

Figure 3.18 shows the 48- Pulse converter output voltage waveforms and Figure 3.19 shows the voltage Fourier spectrum for a 48-Pulse Converter. From Figure 3.19 it can be observed that the 48-pulse voltage waveforms holds harmonics of order $n = 12r \pm 1$, where r is any positive integer. This is due to the fact that quasi 48-pulse is made of four series 12-pulse VSCs. But, the dominant harmonics are 47^{th} and 49^{th} because the 11^{th} and

13^{th} order harmonics are very small in magnitude. Hence harmonic filters may not be necessary to eliminate those harmonics.

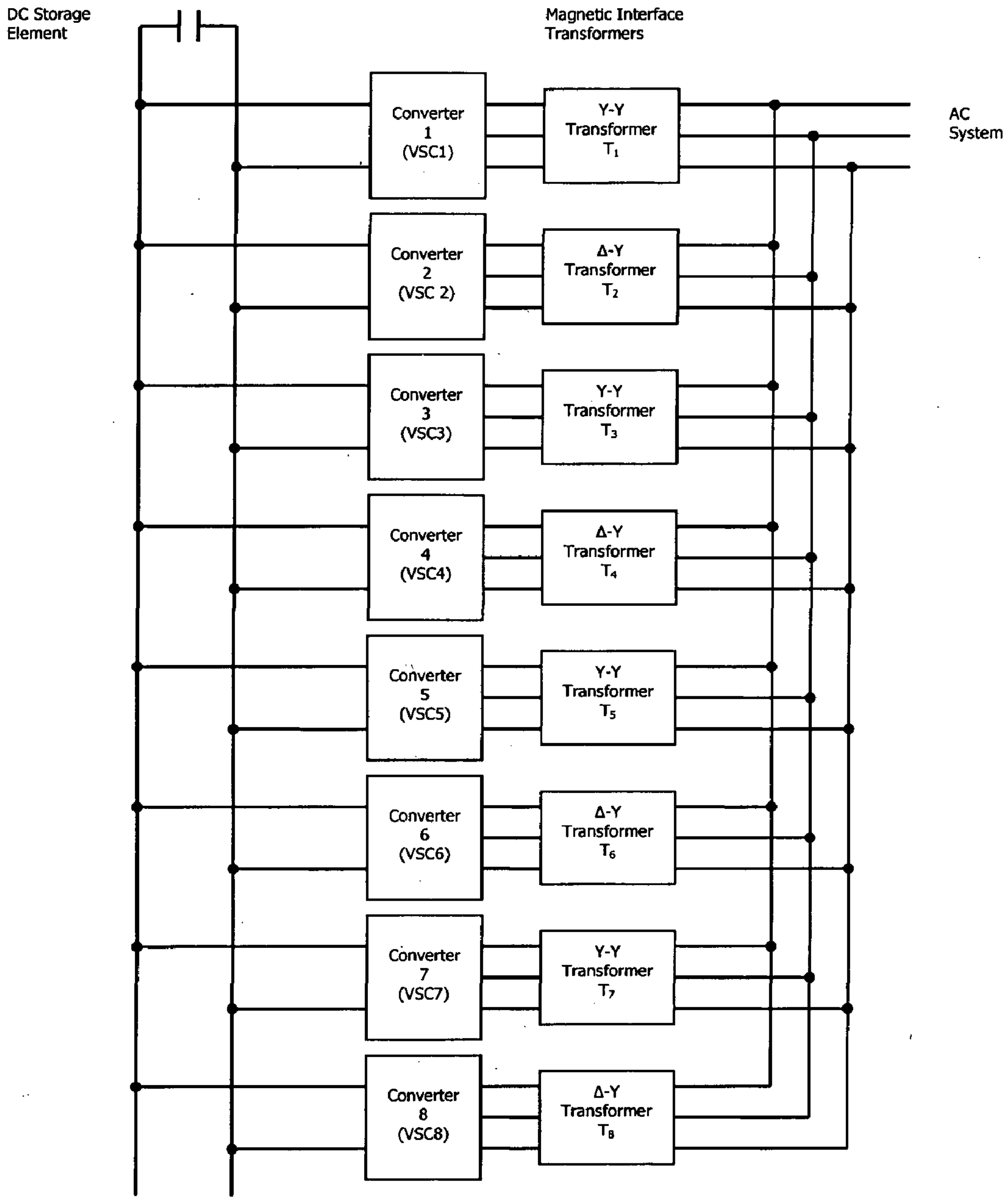


Figure 3.17: Schematic Diagram for a 48-Pulse Quasi Harmonic Neutralized Converter

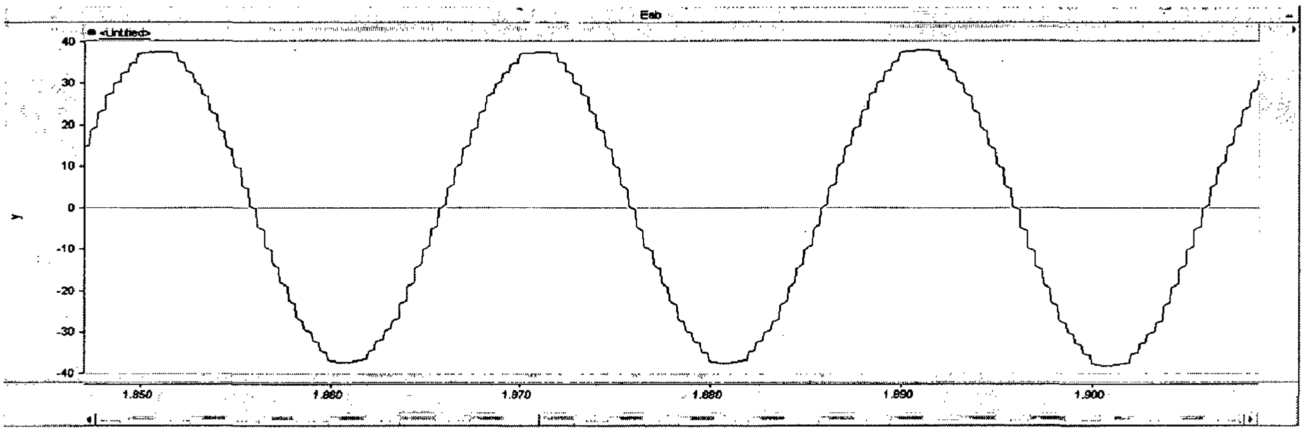


Figure 3.18: 48-Pulse Quasi Harmonic Naturalized Converter Output Voltage Waveforms

X axis: Time in sec.

Y axis: Voltage (kV)

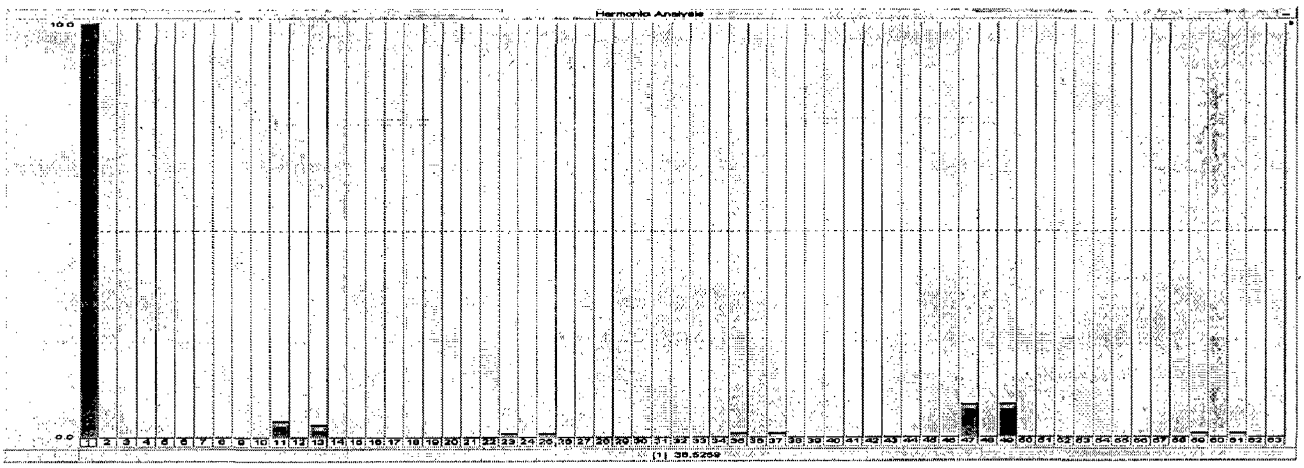


Figure 3.19: Voltage Fourier Spectrum for a 48-Pulse Quasi Harmonic Naturalized Converter

X axis: Harmonic Order

Y axis: Voltage Magnitude (kV)

Table 3.1 summarizes the percentage harmonic contents for a 48-pulse harmonic naturalized converter.

Harmonic Order	11th	13th	23rd	25th	35th	37th	47th	49th
Percentage	0.0	0.0	0.0	0.0	0.0	0.0	2.105	2.019

Table 3.1: Harmonic Contents for a 48-Pulse Harmonic Naturalized Converter

Table 3.2 summarizes the percentage harmonic contents for a 48-pulse quasi harmonic naturalized converter.

Harmonic Order	11th	13th	23rd	25th	35th	37th	47th	49th
Percentage	0.892	0.662	0.282	0.259	0.246	0.265	2.105	2.019

Table 3.2: Harmonic Contents for a 48-Pulse Quasi Harmonic Naturalized Converter

The voltage THD obtained in the 48-pulse quasi harmonic naturalized topology 3.199% is almost the same as one obtained using a 48-pulse harmonic naturalized topology 2.948%.

CHAPTER 4
STATCOM MODELLING AND CONTROL

This chapter deals the modelling of STATCOM in d-q reference frame for finding the control parameters and STATCOM controller for the voltage regulation.

4.1: Introduction

The main function of the STATCOM is to regulate the transmission line voltage at the point of connection. It achieves this objective by drawing a controlled reactive current from the line. In contrast with a conventional static VAR generator, the STATCOM also has the intrinsic ability to exchange real power with the line. As there are no sizeable power sources or sinks associated with the converter and its DC side components, the real power must be actively controlled to a value which is zero on average and which departs from zero only to compensate for the losses in the system. [23-24]

The notation of reactive power is well known in the phasor sense. However, to study and control the dynamics of the STATCOM within a sub cycle time frame and subject to line distortions, disturbances and unbalance, it needs a broader definition of reactive power, which is valid on an instantaneous basis. The instantaneous real power at a point on the line is given by

$$P = v_a i_a + v_b i_b + v_c i_c \tag{4.1}$$

The instantaneous reactive current is conceptually as that part of the three-phase current set that could be eliminated at any instant without altering *P*. The algebraic definition of instantaneous reactive current is obtained by means of a vectorial interpretation of the instantaneous values of the circuit variables, as explained in the following section

4.2: Vector Representation of Instantaneous Three-Phase Quantities

A set of three instantaneous phase variables that sum to zero can be uniquely represented by a single point in a plane, as illustrated in Figure 4.1.

By definition, the vector drawn from the origin to this point has a vertical projection onto each of three symmetrically disposed phase axes, which corresponds to the instantaneous value of the associated phase variable. This transformation of phase variables to instantaneous

vectors can be applied to voltages as well as to currents. As the values of the phase variables change, the associated vector moves around the plane describing various trajectories. The vector contains all the information on the three-phase set, including steady-state unbalance, harmonic waveform distortions, and transient components. [24]

In Figure 4.2, the vector representation is extended by introducing an orthogonal co-ordinate system in which each vector is described by means of its d_s- and q_s- components. The transformation from phase variables to d_s and q_s co-ordinates is as follows:

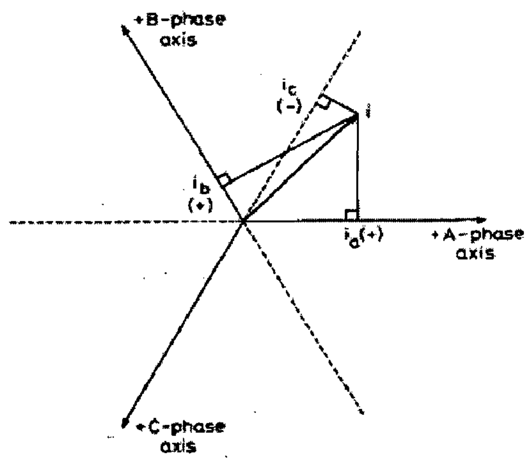


Figure 4.1: Vector Representations of Instantaneous Three-Phase Variables

$$[c]=\frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}, \qquad [c]^{-1}=\frac{3}{2}[c]$$

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ 0 \end{bmatrix} = [c]\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}, \qquad \begin{bmatrix} v_{ds} \\ v_{qs} \\ 0 \end{bmatrix} = [c]\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad (4.2)$$

Figure 4.3 shows how the vector representation leads to the definition of instantaneous reactive current. In the diagram, two vectors are drawn, one to represent the transmission line voltage at the point of connection and the other to describe the current in the STATCOM lines.

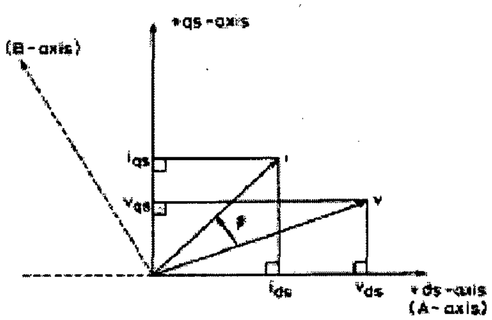


Figure 4.2: Definition of Orthogonal Co-ordinates

Using equations (4.2), the instantaneous power given by equation (4.1) can be written as follows:

$$P=\frac{3}{2}\left(v_{ds}i_{ds}+v_{qs}i_{qs}\right)=\frac{3}{2}|v||i|\cos(\phi) \qquad (4.3)$$

Where Ø is the angle between the voltage and the current vectors. Clearly, only that component of the current vector which is in phase with the instantaneous voltage vector contributes to the instantaneous power. The remaining component could be removed without changing the power, and this is component is therefore the instantaneous reactive current. These observations can be extended to the following definition of instantaneous reactive power:

$$Q = \frac{3}{2}|v||i|\sin(\phi) = \frac{3}{2}\left(v_{ds}i_{qs} - v_{qs}i_{ds}\right) \tag{4.4}$$

where the constant 3/2 is chosen so that definition coincides with the classical phasor definition under balanced steady-state conditions.

Figure 4.3 shows how further manipulation of the vector co-ordinate frame leads to a useful separation of variables for power control purposes. A new co-ordinate system is defined where the *d*-axis is always coincident with the instantaneous voltage vector and the *q*-axis is in quadrature with it. The *d*-axis current component, i_d, accounts for the instantaneous power and the *q*-axis current, i_q is the instantaneous reactive current.

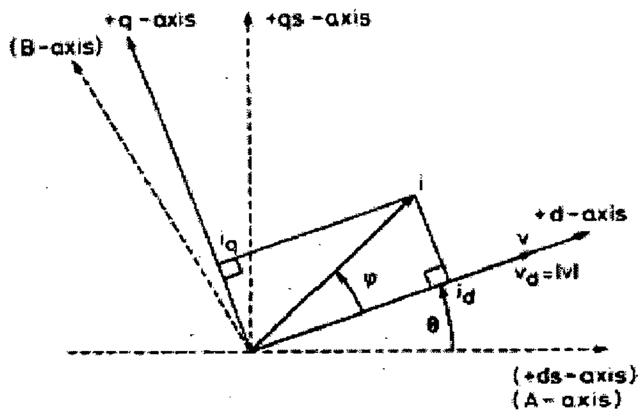


Figure 4.3: Definition of Rotating Reference Frame

The *d* and *q* axes are not stationary in the plane. They follow the trajectory of the voltage vector, and the d and q coordinates within this synchronously rotating reference frame are given by the following time-varying transformation: [15]

$$[c_1] = \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

$$\theta = \tan^{-1}(\frac{v_{qs}}{v_{ds}})$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = [c_1]^{-1} \begin{bmatrix} i_d \\ i_q \\ 0 \end{bmatrix} \qquad \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = [c_1]^{-1} \begin{bmatrix} |v| \\ 0 \\ 0 \end{bmatrix} \tag{4.5}$$

and substituting in equation (4.1) will give

$$P = \frac{3}{2}|v|i_d \qquad Q = \frac{3}{2}|v|i_q \tag{4.6}$$

Under balanced steady-state conditions, the co-ordinates of the voltage and current vectors in the synchronous reference frame are constant quantities. This feature is useful for analysis and for decoupled control of the two current components.

4.3: Equivalent Circuit and Equations

Fig. 3.4 shows a simplified representation of the STATCOM, including a DC side capacitor, an converter, and series inductance in the three lines connecting to the transmission line. This inductance accounts for the leakage of the actual power transformers. The circuit also includes resistance in shunt with the capacitor to represent the switching losses in the converter, and resistance in series with the AC lines to represent the converter and transformer conduction losses. The converter block in the circuit is treated as an ideal, lossless power transformer. [15]

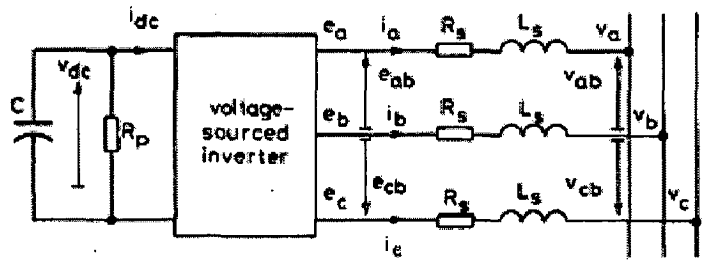


Figure 4.4: Equivalent Circuit of STATCOM

In terms of the instantaneous variables shown in Figure 4.4, the AC side circuit equations can be written as follows:

$$p\begin{bmatrix} i_a' \\ i_b' \\ i_c' \end{bmatrix} = \begin{bmatrix} \frac{-R_s'\omega_b}{L'} & 0 & 0 \\ 0 & \frac{-R_s'\omega_b}{L'} & 0 \\ 0 & 0 & \frac{-R_s'\omega_b}{L'} \end{bmatrix} \begin{bmatrix} i_a' \\ i_b' \\ i_c' \end{bmatrix} + \frac{\omega_b}{L'} \begin{bmatrix} (e_a' - v_a') \\ (e_b' - v_b') \\ (e_c' - v_c') \end{bmatrix} \tag{4.7}$$

where p = d/dt, and a per-unit system has been adopted according to the following definitions:

$$L' = \frac{\omega_b L_s}{Z_{base}}, \quad C' = \frac{1}{\omega_b C Z_{base}}, \quad R_s' = \frac{R_s}{Z_{base}}, \quad R_p' = \frac{R_p}{Z_{base}}$$

$$i_x' = \frac{i_x}{i_{base}}, \quad v_x' = \frac{v_x}{v_{base}}, \quad e_x' = \frac{e_x}{v_{base}}, \quad Z_{base} = \frac{v_{base}}{i_{base}} \tag{4.8}$$

Using the transformation of variables defined in equation (4.5), equation (4.7) can be transformed to the synchronously rotating reference frame as follows:

$$p\begin{bmatrix} i_d' \\ i_q' \end{bmatrix} = \begin{bmatrix} \frac{-R_s'\omega_b}{L'} & \omega \\ -\omega & \frac{-R_s'\omega_b}{L'} \end{bmatrix} \begin{bmatrix} i_d' \\ i_q' \end{bmatrix} + \frac{\omega_b}{L'} \begin{bmatrix} (e_d' - |v'|) \\ e_q' \end{bmatrix} \tag{4.9}$$

where $\omega = d\theta/dt$.

Figure 4.5 illustrates the AC side circuit vectors in the synchronous frame. When i_q' is positive, the STATCOM is drawing inductive vars from the line, and for negative i_q' it is capacitive.

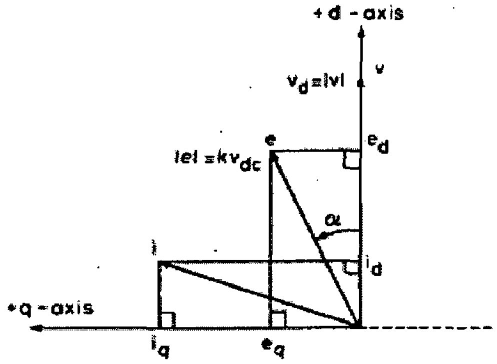


Figure 4.5: STATCOM Vectors in Synchronous Frame

4.4: Types of Voltage-Sourced converter Control

Neglecting the voltage harmonics produced by the converter, we can write a pair of equations for $e_d^{'}$ and $e_q^{'}$. [9]

$$e_d^{'} = kV_{dc}^{'}\cos(\alpha) \tag{4.10}$$

$$e_q^{'} = kV_{dc}^{'}\sin(\alpha) \tag{4.11}$$

where *k* is a factor for the converter, which relates the DC side voltage to the amplitude (peak) of the phase-to-neutral voltage at the converter AC-side terminals, and α is the angle by which the converter voltage vector leads the line voltage vector. It is important to distinguish between two basic types of voltage-sourced converter that can be used in STATCOM systems.

Converter Type I Control:

Allows the instantaneous values of both α and *k* to be varied for control purposes. Provided that $V_{dc}^{'}$ is kept sufficiently high, $e_d^{'}$ and $e_q^{'}$ can be independently controlled. This capability can be achieved by various pulse-width modulation (PWM) techniques.

Converter Type II Control*:* In this case, *k* is a constant factor, and the only available control input is the angle α, of the converter voltage vector. For Type I converter control it is necessary to include the converter and DC-side circuit equation in the model. The instantaneous power at the AC- and DC-terminals of the converter is equal, giving the following power balance equation:

$$v'_{dc}\, i'_{dc} = 3/2(e'_d\, i'_d + e'_q\, i'_q) \tag{4.12}$$

and the DC-side circuit equation is

$$pv'_{dc} = -w_b C'(i'_{dc} + \frac{v'_{dc}}{R_p}) \tag{4.13}$$

Combining equations (4.9), (4.10), (4.11), (4.12), and (4.13), following state equations of the STATCOM is obtained:

$$p\begin{bmatrix} i'_d \\ i'_q \\ v'_{dc} \end{bmatrix} = [A]\begin{bmatrix} i'_d \\ i'_q \\ v'_{dc} \end{bmatrix} - \begin{bmatrix} \frac{w_b}{L'}|v'| \\ 0 \\ 0 \\ \end{bmatrix}$$

$$[A] = \begin{bmatrix} -\frac{R'_s w_b}{L'} & w & \frac{kw_b}{L'}\cos(\alpha) \\ -w & -\frac{R'_s w_b}{L'} & \frac{kw_b}{L'}\sin(\alpha) \\ -\frac{3}{2}kC'w_b\cos(\alpha) & -\frac{3}{2}kC'w_b\sin(\alpha) & -\frac{w_b C'}{R'_p} \end{bmatrix} \tag{4.14}$$

4.5: STATCOM Controller for Voltage Regulation:

The controller of a STATCOM is used to operate the converter in such a way that the phase angle between the converter voltage and the line voltage is dynamically adjusted so that the STATCOM generates or absorbs desired VAR at the point of connection. [25]

Figure 4.6 shows the voltage control block diagram of the STATCOM. Here Vpu is the voltage measured at the BUS of the ac system at which the STATCOM was connected and the V_{ref} is the desired Voltage and these two are compared and the error signal is generated.

The total error signal is fed to a lead-lag compensator, then to the Proportional plus Integral PI controller in order to control the control angle order (i.e. alpha_ord as shown in the in Figure 4.6) which is converted into electric degrees, this phase angle order is sent directly to the firing sequence of GTO's switches of the converter. The phase locked loop is then used to provide the required reference signal of the terminal voltage at the bus. The generation of firing pulses is based on the comparison of the reference modulated signal to triangular modulating signals. Two sets of signals (reference and triangular ones) are needed. One set for turning on and the second one (a negative of the first set of signals) for turning off. Two signals are being sent to each switch. The first one tells to turn on or off; the second one determines an exact moment of switching and is used by interpolation procedure which allows for switching between timesteps.

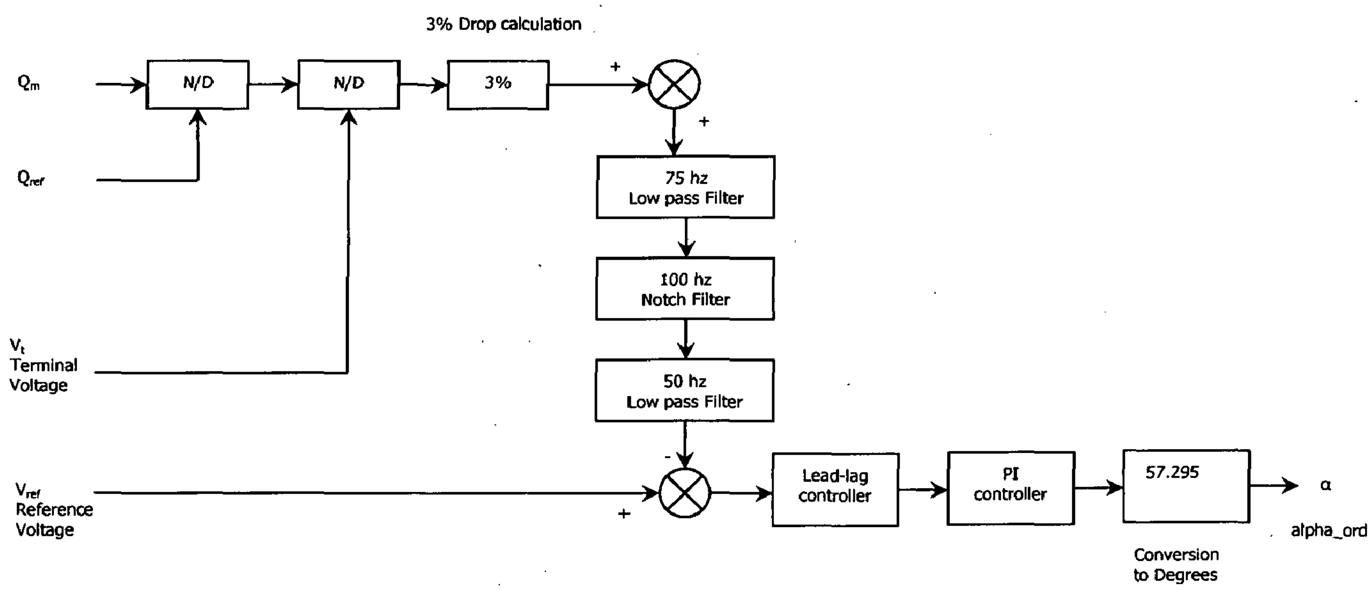


Figure 4.6: Voltage Controller for the STATCOM

4.6: PSCAD/EMTDC Results:

From Figure 4.7 to Figure 4.13 will summarize the results of the voltage regulation controller of the STATCOM [27]

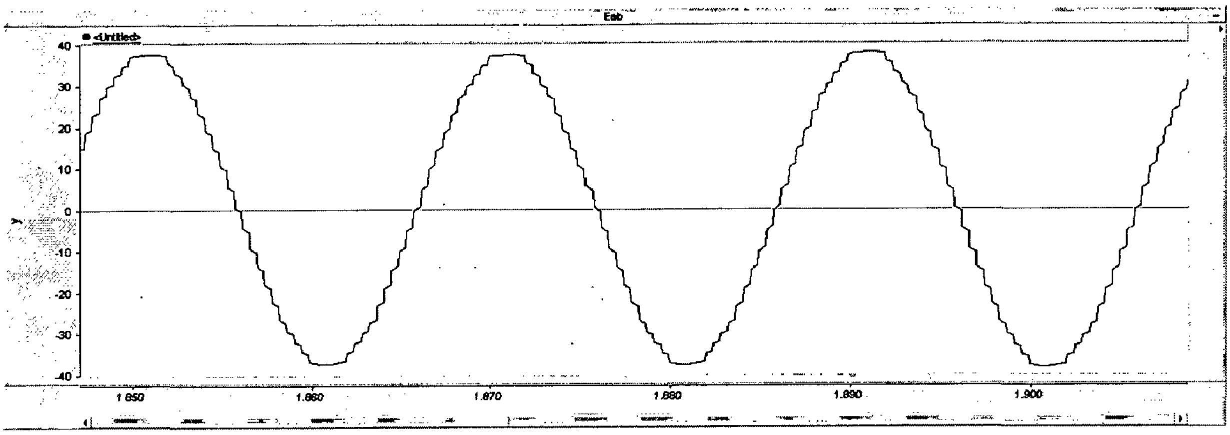


Figure 4.7: Voltage Waveform of 48-Pulse Quasi Harmonic Neutralized (QHN) Voltage Source Converter

X axis: Time in sec.

Y axis: Voltage (kV)

Figure 4.7 shows the near sinusoidal output of the 48-pulse quasi harmonic neutralized (QHN) voltage source converter.

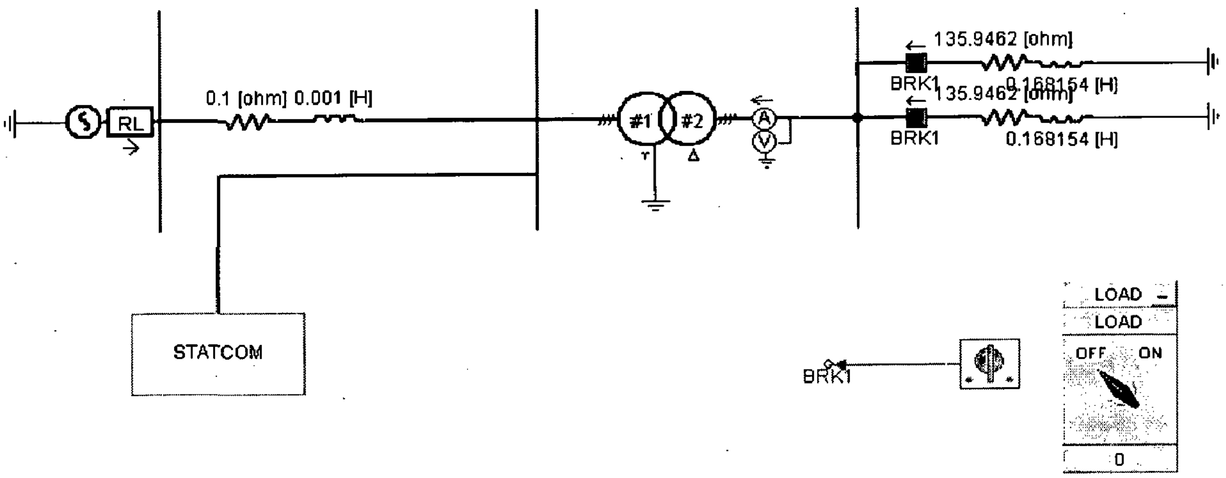


Figure 4.8: Test System

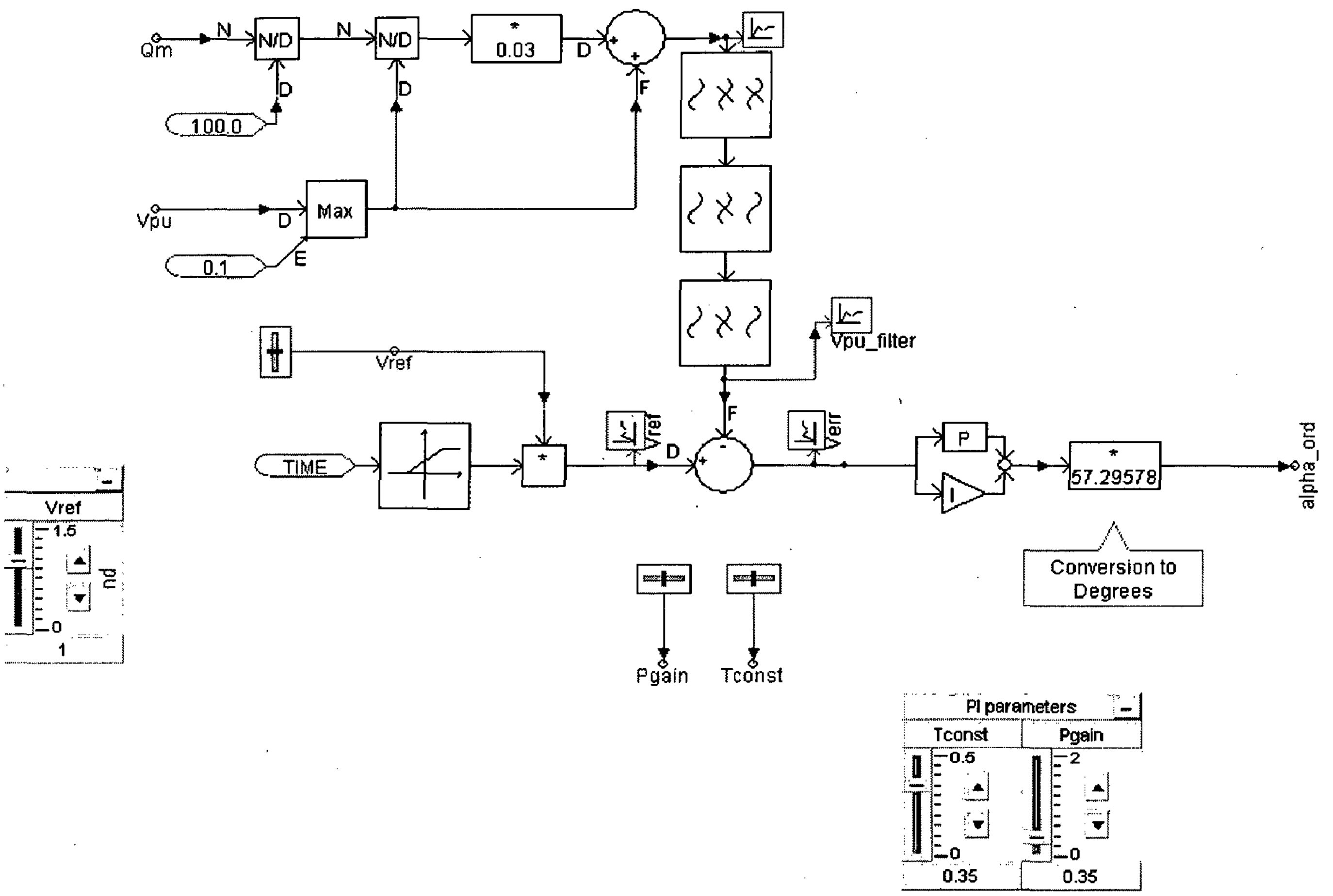


Figure 4.9: Voltage Controller of the STATCOM

Figure 4.9 shows PSCAD view of the STATCOM controller for voltage regulation.

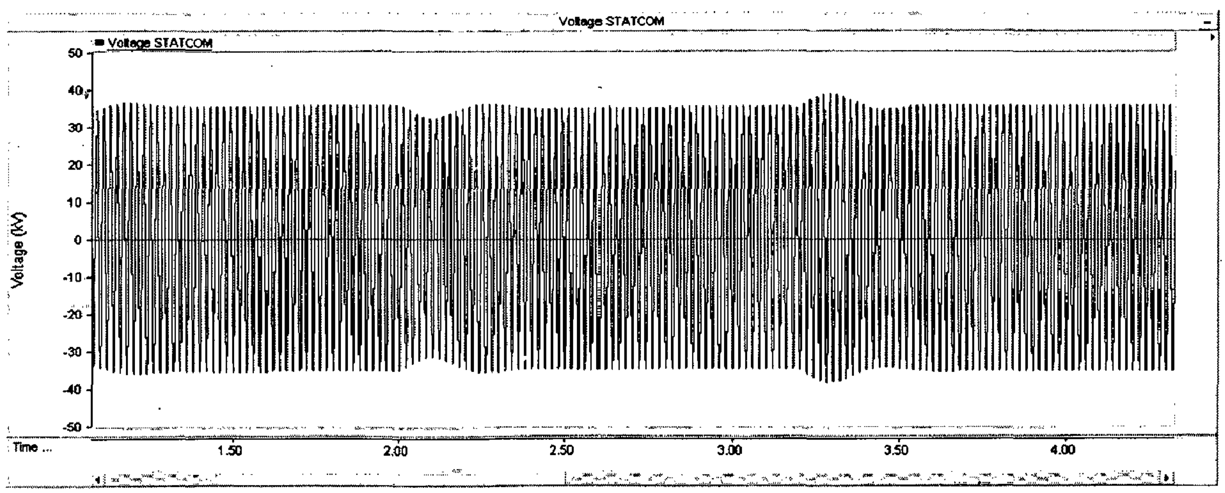


Figure 4.10: Variations in STATCOM Voltage

X axis: Time in sec.

Y axis: Voltage (kV)

Figure 4.10 shows the variations in the STATCOM voltage. Here load was on at 2.0sec and removed at 3.17sec.

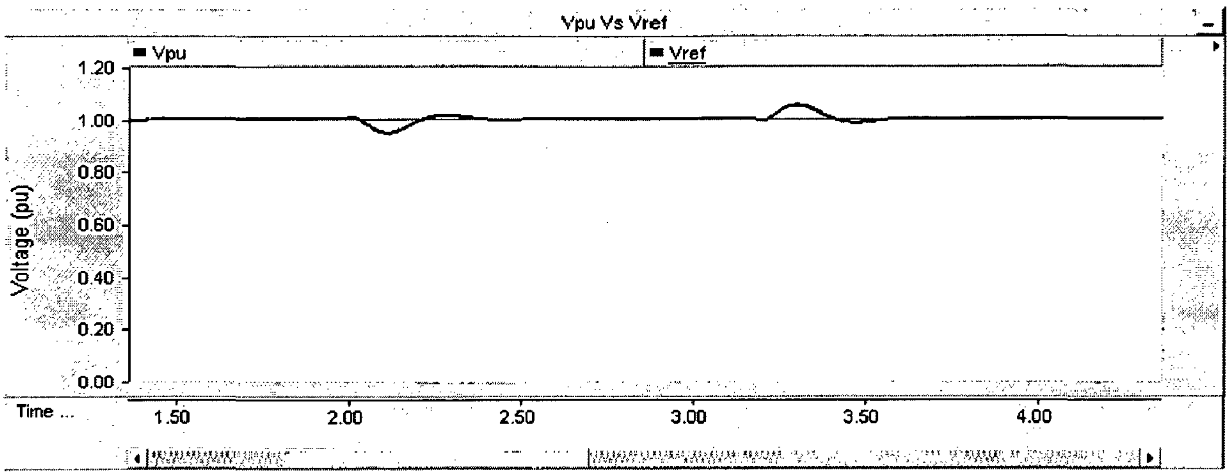


Figure 4.11: variations in BUS Voltage

X axis: Time in sec.

Y axis: Voltage (pu)

Figure 4.11 shows the variations in the bus voltage. Here load was on at 2.0sec and removed at 3.17sec. From the figure it can be observed that STATCOM is maintaining the system voltage.

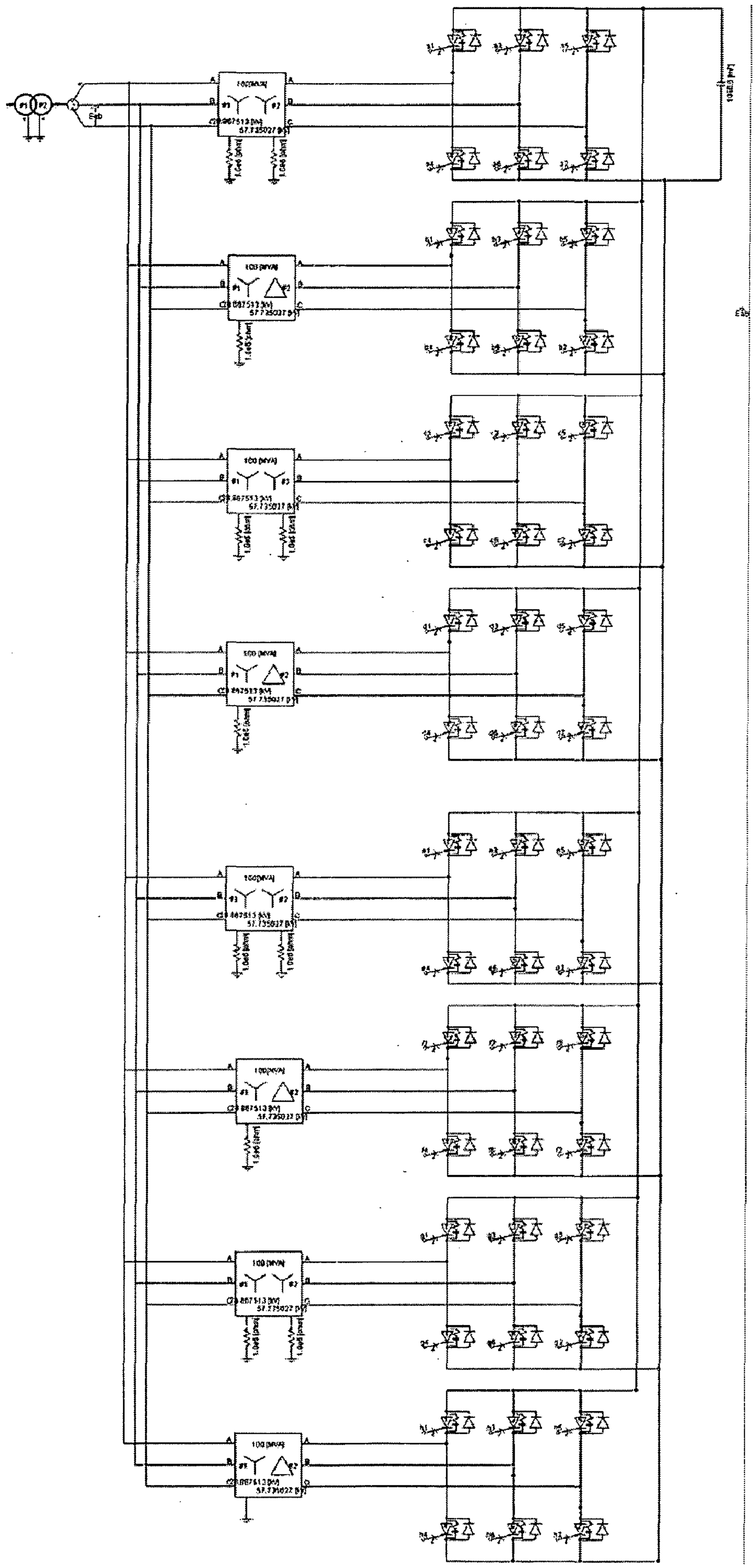


Figure 4.12: 48-Pulse VSC Based STATCOM

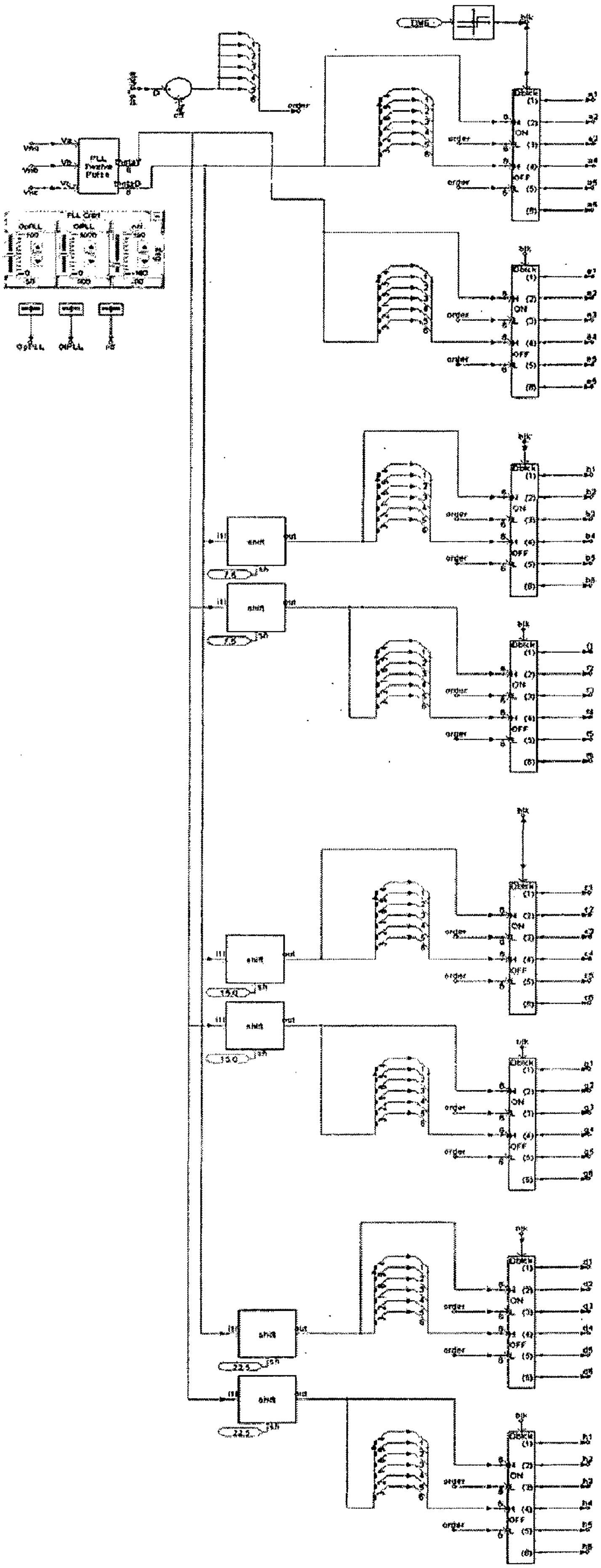


Figure 4.13: Interpolated Firing Angle Control for the 48- Pulse QHN Converter

CHAPTER 5
POWER SYSTEM STABILITY IMPROVEMENT USING STATCOM

This chapter provides the concept of power system stability and its organization and it further deals with STATCOM controller for the power system stability improvement.

5.1: Power System Stability

Power system stability denotes the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that system integrity is preserved. Integrity of the system is preserved when practically the entire power system remains intact with no tripping of generators or loads, except for those disconnected by isolation of the faulted elements or intentionally tripped to preserve the continuity of operation of the rest of the system. Stability is a condition of equilibrium between opposing forces; instability results when a disturbance leads to a sustained imbalance between the opposing forces. [1] [7-8]

The power system is a highly nonlinear system that operates in a constantly changing environment; loads, generator outputs, topology, and key operating parameters change continually. When subjected to a transient disturbance, the stability of the system depends on the nature of the disturbance as well as the initial operating condition. The disturbance may be small or large. Small disturbances in the form of load changes occur continually, and the system adjusts to the changing conditions. The system must be able to operate satisfactorily under these conditions and successfully meet the load demand. It must also be able to survive numerous disturbances of a severe nature, such as a short circuit on a transmission line or loss of a large generator.

Traditionally, the stability problem has been one of maintaining synchronous operation. Since power systems rely on synchronous machines for generation of electrical power, a necessary condition for satisfactory system operation is that all synchronous machines remain in synchronism or, colloquially, "in step." This aspect of stability is influenced by the dynamics of generator rotor angles and power angle relationships.

Instability may also be encountered without the loss of synchronism. For example, a system consisting of a generator feeding an induction motor can become unstable due to collapse of load voltage. In this instance, it is the stability and control of voltage that is the issue, rather than the maintenance of synchronism. This type of instability can also occur in the case of loads covering an extensive area in a large system.

Because of the high dimensionality and complexity of stability problems, it is essential to make simplifying assumptions and to analyze specific types of problems using the right degree of detail of system representation. The following subsection describes the classification of power system stability into different categories.

5.2: Classification of Power System Stability

Power system stability is a single problem; however, it is impractical to deal with it as such. Instability of the power system can take different forms and is influenced by a wide range of factors. Analysis of stability problems, including identifying essential factors that contribute to instability and devising methods of improving stable operation is greatly facilitated by classification of stability into appropriate categories. These are based on the following considerations

- The physical nature of the resulting instability related to the main system parameter in which instability can be observed.

- The size of the disturbance considered indicates the most appropriate method of calculation and prediction of stability.
- The devices, processes, and the time span that must be taken into consideration in order to determine stability.

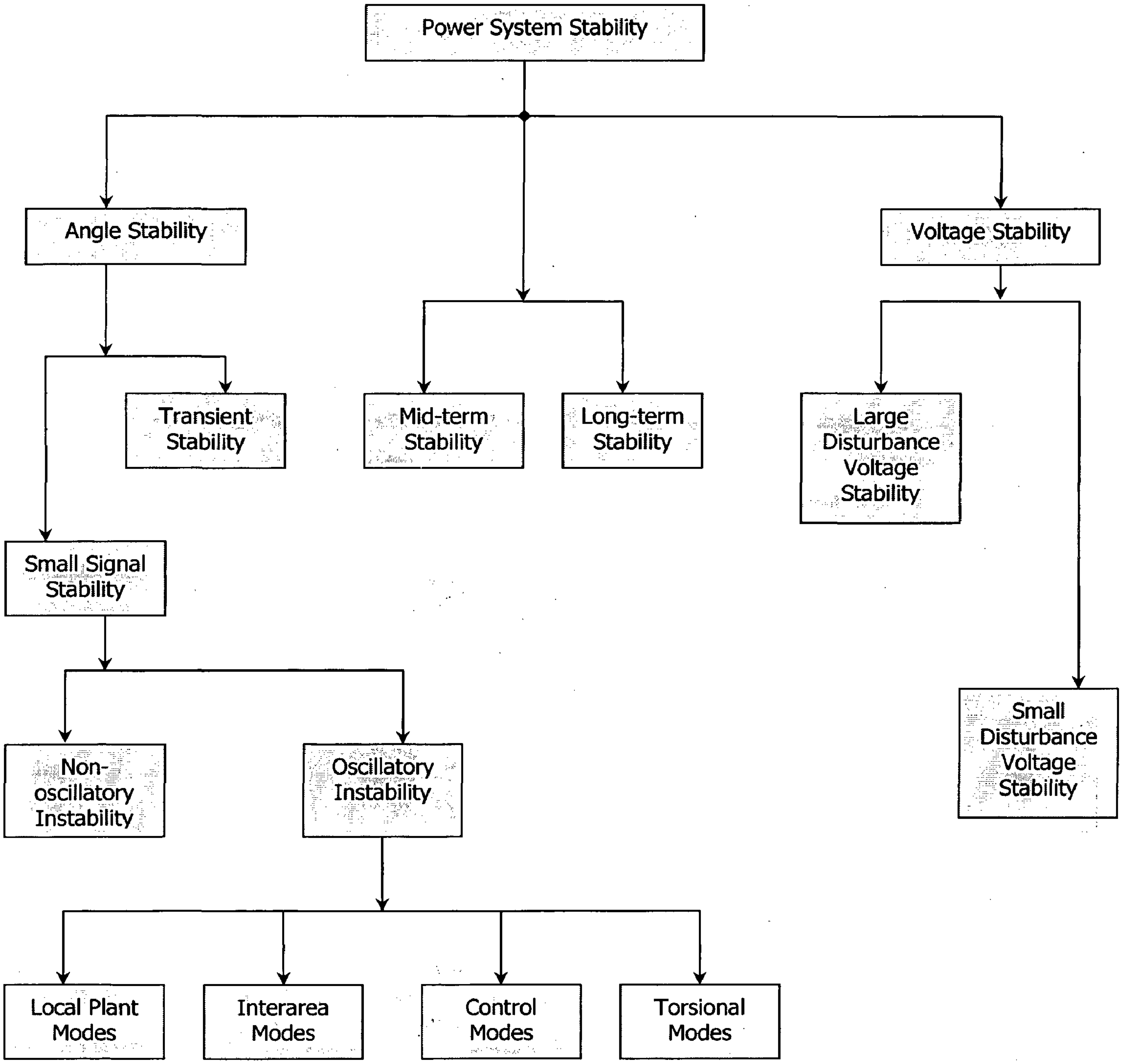


Figure 5.1: Classification of Power System Stability

5.2.1: Rotor Angle Stability

Rotor angle stability is concerned with the ability of interconnected synchronous machines of a power system to remain in synchronism under normal operating conditions and after being subjected to a disturbance. It depends on the ability to maintain or restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system. Instability that may result occurs in the form of increasing angular swings of some generators leading to their loss of synchronism with other generators.

The rotor angle stability problem involves the study of the electromechanical oscillations inherent in power systems. A fundamental factor in this problem is the manner in which the power outputs of synchronous machines vary as their rotor angles change. The mechanism by which interconnected synchronous machines maintain synchronism with one another is through restoring forces, which act, whenever there are forces tending to accelerate or decelerate one or more machines with respect to other machines.

Under steady-state conditions, there is equilibrium between the input mechanical torque and the output electrical torque of each machine, and the speed remains constant. If the system is perturbed, this equilibrium is upset, resulting in acceleration or deceleration of the rotors of the machines according to the laws of motion of a rotating body. If one generator temporarily runs faster than another, the angular position of its rotor relative to that of the slower machine will advance. The resulting angular difference transfers part of the load from the slow machine to the fast machine, depending on the power-angle relationship. This tends to reduce the speed difference and hence the angular separation. The power-angle relationship, as discussed above, is highly nonlinear. Beyond a certain limit, an increase in angular separation is accompanied by a decrease in power transfer; this increases the angular separation further and leads to instability. For any given situation, the stability of the system depends on whether or not the deviations in angular positions of the rotors result in sufficient restoring torques.

It should be noted that loss of synchronism can occur between one machine and the rest of the system, or between groups of machines, possibly with synchronism maintained within each group after separating from each other.

The change in electrical torque of a synchronous machine following a perturbation can be resolved into two components:

- Synchronizing torque component, in phase with a rotor angle perturbation
- Damping torque component, in phase with the speed deviation

System stability depends on the existence of both components of torque for each of the synchronous machines. Lack of sufficient synchronizing torque results in aperiodic or non-oscillatory instability, whereas lack of damping torque results in oscillatory instability.

Small signal (or steady state) stability is concerned with the ability of the power system to maintain synchronism under small disturbances. The disturbances are considered to be sufficiently small that linearization of system equations is permissible for purposes of analysis. Such disturbances are continually encountered in normal system operation, such as small changes in load. Small signal stability depends on the initial operating state of the system.

Instability that may result can be of two forms:

1. Increase in rotor angle through a non-oscillatory or aperiodic mode due to lack of synchronizing torque, or
2. Rotor oscillations of increasing amplitude due to lack of sufficient damping torque.

In today's practical power systems, small signal stability is largely a problem of insufficient damping of oscillations. The time frame of interest in small-signal stability studies is on the order of 10 to 20 sec following a disturbance.

The stability of the following types of oscillations is of concern:

- Local modes or machine-system modes, associated with the swinging of units at a generating station with respect to the rest of the power system. The term "local" is used because the oscillations are localized at one station or a small part of the power system.
- Interarea modes, associated with the swinging of many machines in one part of the system against machines in other parts. They are caused by two or more groups of closely coupled machines that are interconnected by weak ties.
- Control modes, associated with generating units and other controls. Poorly tuned exciters, speed governors, HVDC converters, and static var compensators are the usual causes of instability of these modes.
- Torsional modes, associated with the turbine-generator shaft system rotational components. Instability of torsional modes may be caused by interaction with excitation controls, speed governors, HVDC controls, and series-capacitor-compensated lines.

5.2.2: Large Disturbance Rotor Angle Stability or Transient Stability

Large disturbance rotor angle stability or transient stability, as it is commonly referred to, is concerned with the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship. Transient stability depends on both the initial operating state of the system and the severity of the disturbance. Usually, the disturbance alters the system such that the post-disturbance steady state operation will be different from that prior to the disturbance. Instability is in the form of aperiodic drift due to insufficient synchronizing torque, and is referred to as first swing stability.

In large power systems, transient instability may not always occur as first swing instability associated with a single mode; it could be as a result of increased peak deviation caused by superposition of several modes of oscillation causing large excursions of rotor angle beyond the first swing. The time frame of interest in transient stability studies is usually limited to 3 to 5 sec following the disturbance. It may extend to 10 sec for very large systems with dominant inter-area swings. Power systems experience a wide variety of disturbances. It is impractical and uneconomical to design the systems to be stable for every possible contingency. The design contingencies are selected on the basis that they have a reasonably high probability of occurrence.

Small signal stability as well as transient stability are categorized as short term phenomena.

5.3: Small Signal Stability Enhancement using STATCOM

The problem of small signal stability is usually one of insufficient damping of system oscillations. The use of power system stabilizers to control generator excitation systems is the most cost effective method of enhancing the small signal stability of power systems. Additionally, supplemental stabilizing signals may be used to modulate HVDC converter controls, static var compensator and STATCOM to enhance the damping of system oscillations.

The controls used for rotor angle stability enhancement should perform satisfactorily under severe transient disturbances. Therefore, while the controls are designed using linear techniques, their overall performance is assessed by considering small as well as large signal responses.

FACTS (Flexible AC Transmission System) technology offers an alternative way in improving the power system stability. Among STATCOM has been employed to an increasing extent in modern power systems due to its capability to work as var generation and absorption systems. Besides the main task of voltage control, it may also be applied to improve the transmission capability and power system stability.

5.4: STATCOM Controller for Small Signal Stability Improvement

STATCOM is mainly used to perform voltage or reactive power regulation. In general, a compensator maintaining constant terminal voltage is not effective in damping of power oscillations. To damp power oscillations a supplementary control signal should be added to the STATCOM Regulator. The Figure 5.2 shows the multi objective comprehensive control system for the STATCOM, which combines the main control and supplementary control to hold constant bus voltage and improved power oscillation damping.

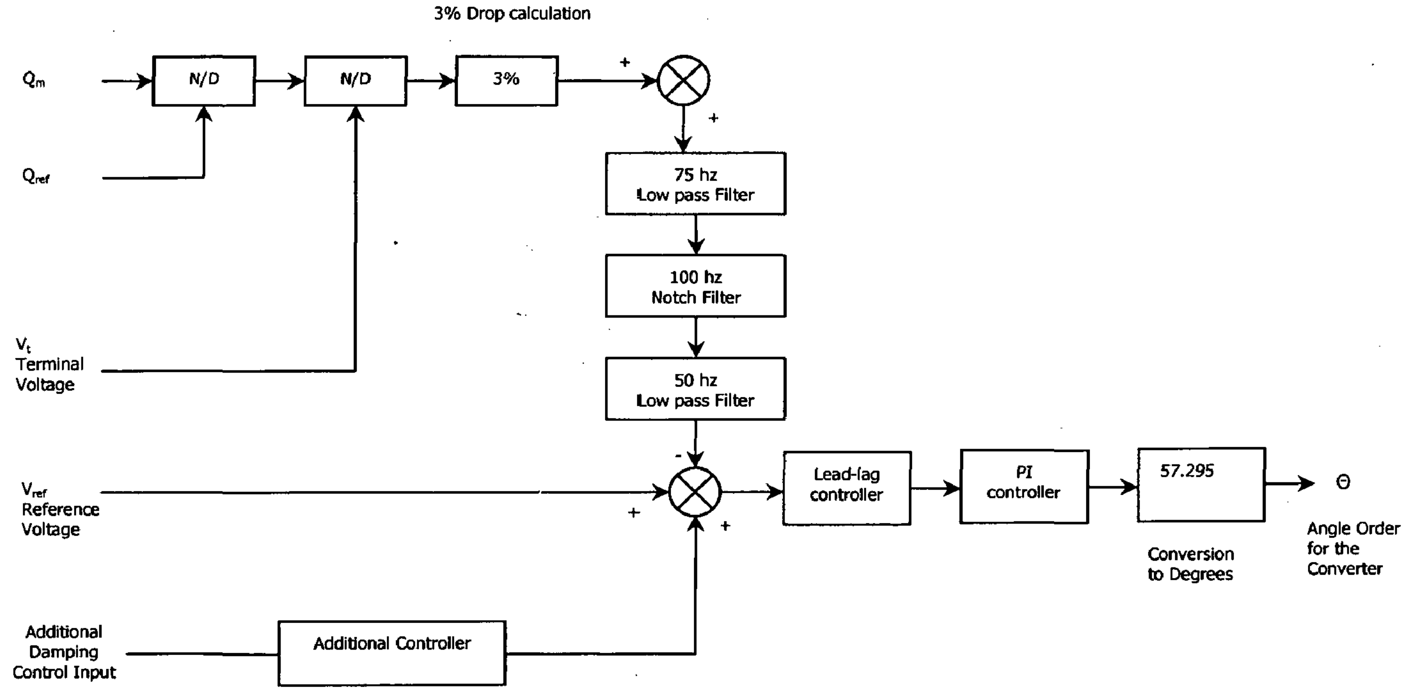


Figure 5.2: Schematic Diagram of STATCOM Controller for Small Signal Stability

In the schematic diagram, main controller realizes desired voltage regulation and the output of the supplementary controller, which will be sent to the main controller to modulate certain reference value for improving small signal stability. The desired additional control input signal should be preferably local to avoid problems associated with remote signal control. Typical choices of local signals are real/reactive power flows and line currents in the adjacent lines. Among these the best input signal can be determined based on their performance. An additional lead-lag control block is used to improve dynamic system response. For example if we take tie line power as additional input then the additional controller is in the form below: [26-28]

$$V_{add} = K_A \frac{T_w s}{1+T_w s}\left(\frac{1+T_1 s}{1+T_2 s}\right)^m P_L \tag{5.1}$$

Where m is usually 1 or 2. T_w is called as the washout circuit time constant. The transfer function of the washout circuit is $\frac{T_w s}{1+T_w s}$ and it is used primarily to eliminate steady state bias in the output of the controller. The washout circuit can be generally ignored in the controller design. Thus, there are only three tunable parameters in the controller transfer function if m specified. The controller essentially consists of m stages of lead-lag network. The objective of the lead-lag network is to introduce a phase advance (ϕ) at the center frequency (ω_c) given by

$$\phi = \tan^{-1}\sqrt{n} - \tan^{-1}\left(\frac{1}{\sqrt{n}}\right) \tag{5.2}$$

Where, $n = \frac{T_1}{T_2}$. The center frequency (ω_c) is defined as $\omega_c = \frac{1}{\sqrt{T_1 T_2}}$ and the phase lead of the transfer function $\left(\frac{1+sT_1}{1+sT_2}\right)$ is maximum at this frequency. Generally, ω_c is chosen as the frequency of the critical electromechanical mode that requires damping.

5.5: Test System

The here study system consists of only a generator, a transmission line and a load as depicted in Figure 5.3. The load bus is modeled as an infinite bus, which is normally used to replace a stiff large system with a constant voltage magnitude and angle. This system can be used to investigate the behavior of a generator labeled as G_1 with respect to the infinite bus.

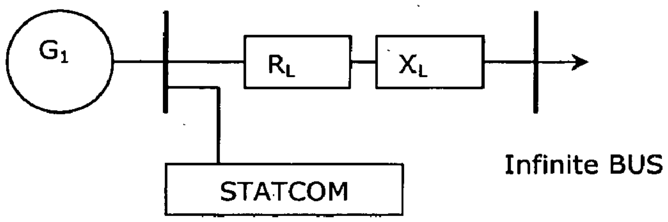


Figure 5.3: SMIB Test System

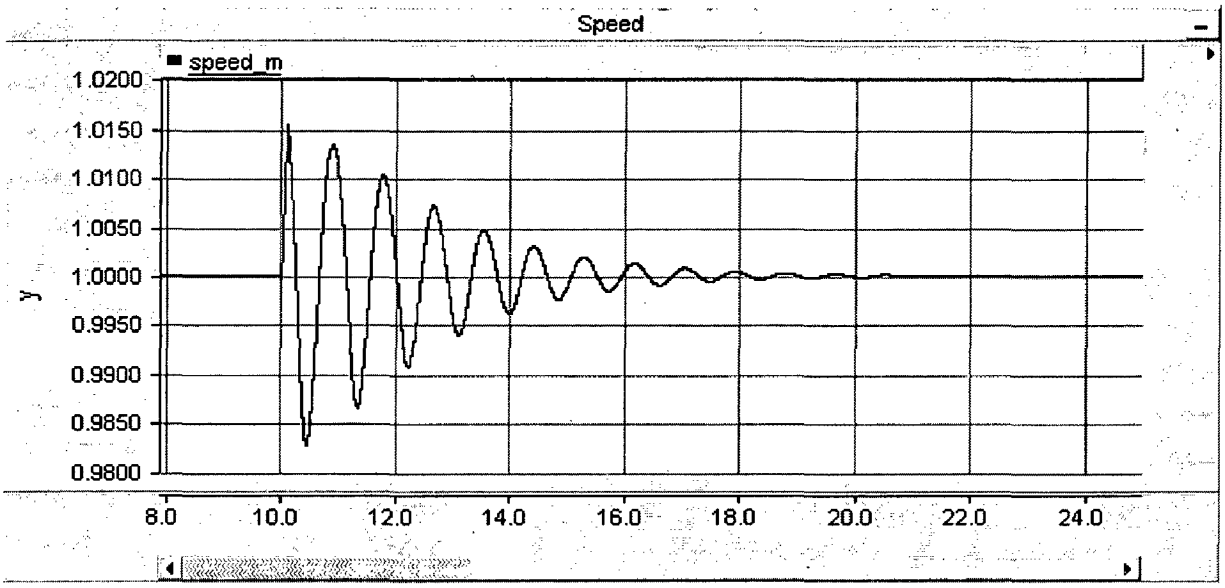
5.6: Results and Discussion

The robustness of the small signal stability improvement controller of the STATCOM is verified by conducting simulations on the test system shown in the Figure 5.3. Here the generator is modeled in turbine-governor model and the infinite bus is modeled in the form of an ideal voltage source. A three phase line to ground fault is applied at the terminal of the generator and variations of the load angle and speed are observed with and without additional controller of the STATCOM.

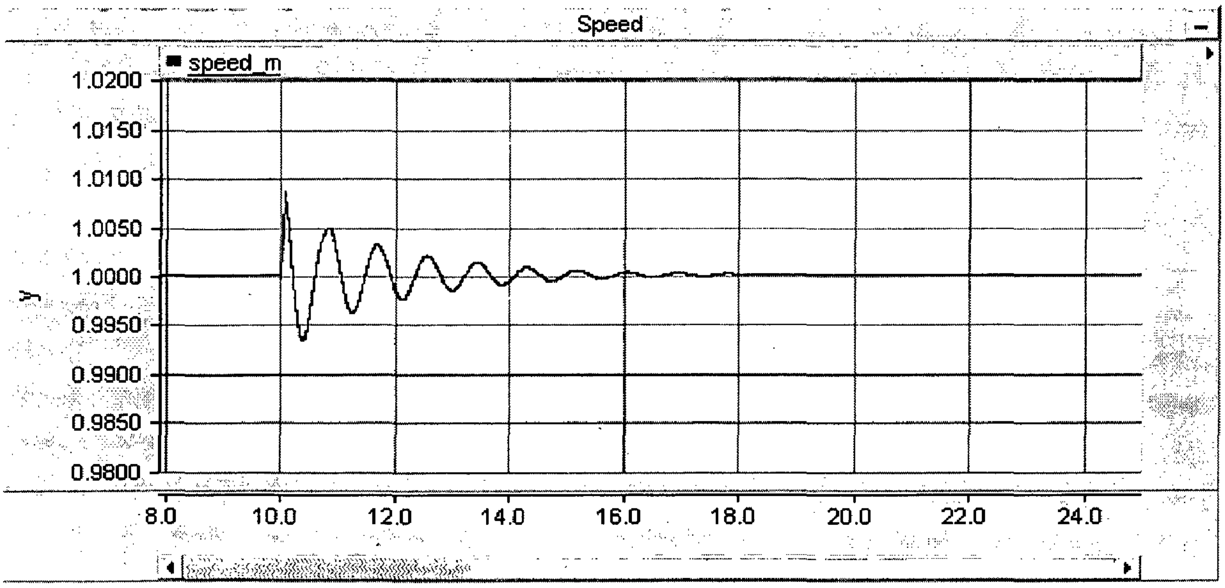
Figures 5.4 and 5.8 will summarize the PSCAD results of the small signal stability improvement controller for a 48-pulse quasi harmonic neutralized converter based STATCOM. [29]

A 3 phase line to ground fault of 0.1 sec duration is introduced in each case, at the instant of t= 10 sec.

Figure 5.4 shows rotor speed oscillations resulting from the fault. Figure 5.4(a) shows the speed oscillations without additional controller of the STATCOM and Figure 5.4(b) shows the oscillations with additional controller.



(a)



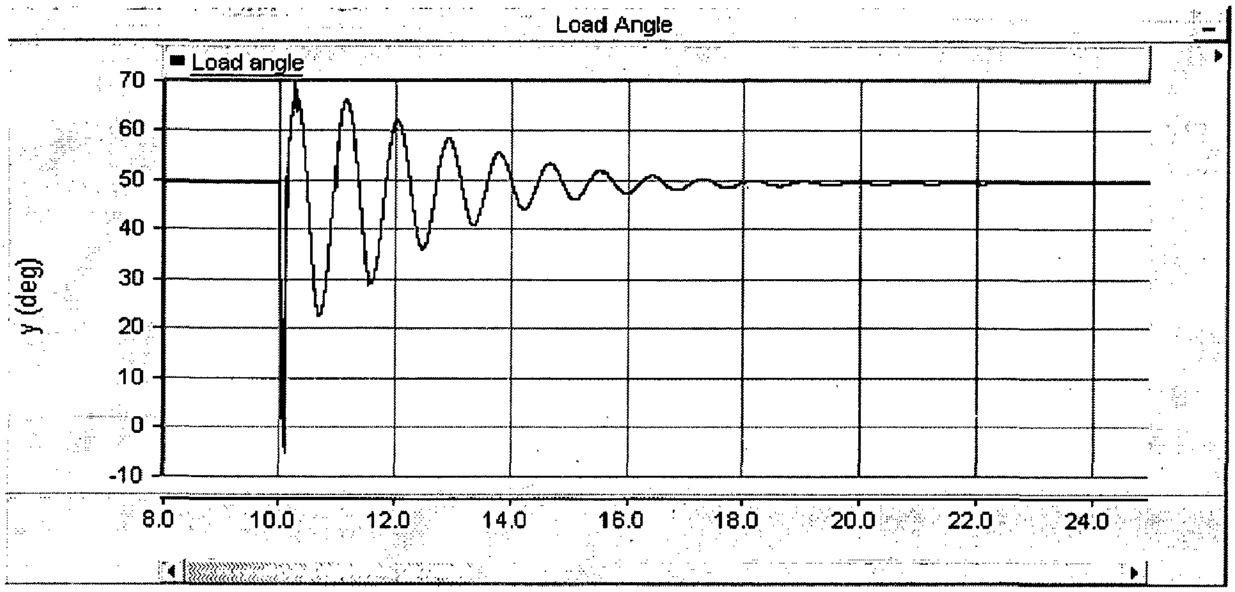
(b)

Figure 5.4: Rotor Speed Oscillations (a) Without Additional Controller (b) with Additional Controller [with Fault Resistance= 5Ω]

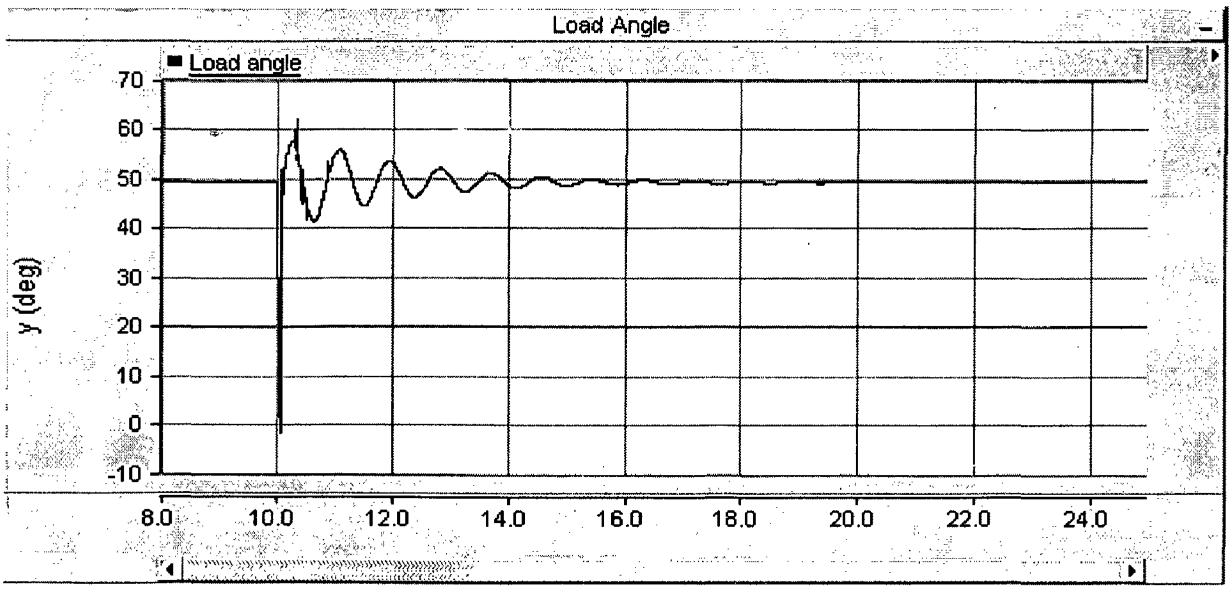
X axis: Time in sec.

Y axis: Rotor Speed (pu)

In Figure 5.4(a) the settling time and peak overshoot are 9.5 sec and 0.017 respectively. Similarly, in the Figure 5.4(b) settling time and peak overshoot are 6.2 sec and 0.008 respectively. So, it can be observed that the rotor speed oscillations and over shoots are very much reduced with the inclusion of the additional controller.



(a)



(b)

Figure 5.5: Load Angle Oscillations (a) Without Additional Controller (b) with Additional Controller [with Fault Resistance= 2Ω]

X axis: Time in sec.

Y axis: Load Angle (Deg.)

Figure 5.5 shows the variations in the load angle oscillations resulting from the fault. Figure 5.5(a) shows the load angle oscillations without additional controller of the STATCOM and Figure 5.5(b) shows the oscillations with additional controller.

In the Figure 5.5(a) the settling time and peak overshoot are 9.5 sec and 28.1 deg respectively. Similarly, in the Figure 5.5(b) Settling time and peak over shoot are 6.1 sec and 8.8 deg respectively. So, it can be observed again that the load angle oscillations and over shoots are very much reduced with the inclusion of the additional controller.

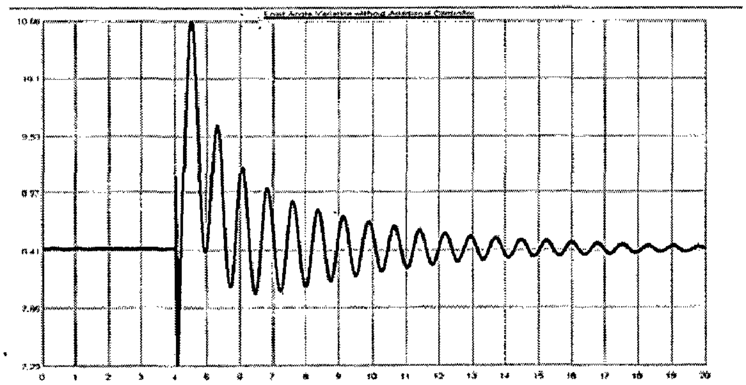
CHAPTER 6

RTDS® RESULTS OF 12-PULSE STATCOM

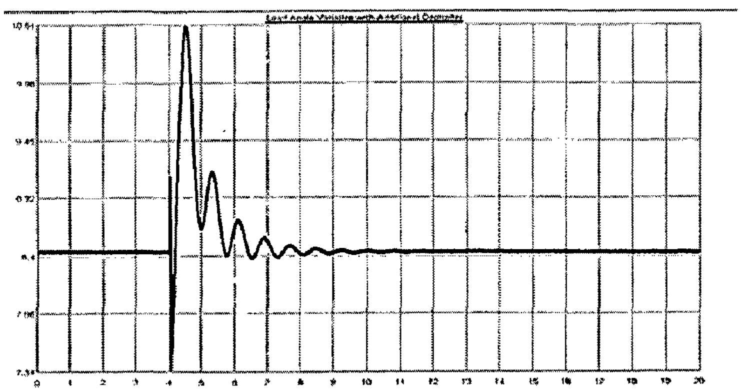
This chapter provides RTDS® results for a 12-pulse VSC based STATCOM carried out at CPRI, Bangalore.

6.1: RTDS® Results

Figures 6.1 to 6.9 will summarize the RTDS® results of the power system stability improvement controller for a 12-pulse STATCOM for the same test system as depicted in Figure 5.3. Due to the hardware limitation of RTDS®, it was not possible to model the 48-pulse voltage source converter hence, the work is restricted to 12-pulse only. [30]



(a)



(b)

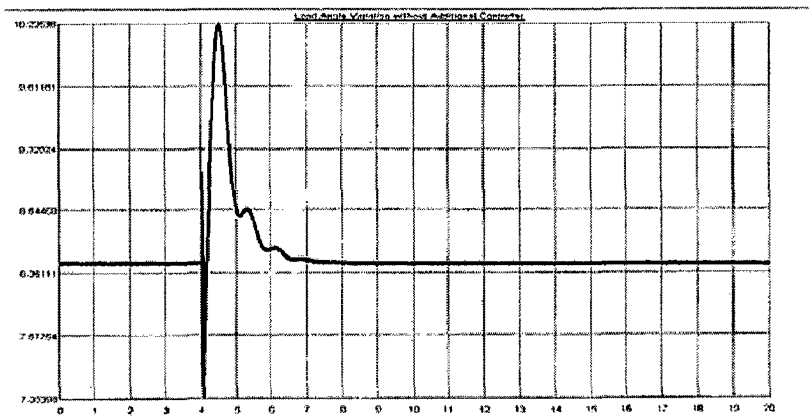
Figure 6.1: Load Angle Oscillations (a) Without Additional Controller (b) with Additional Controller [with Fault Resistance= 5Ω]

X axis: Time in sec.

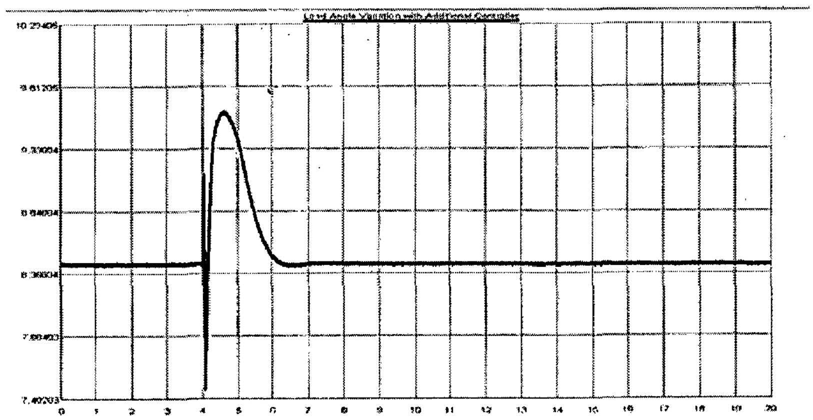
Y axis: Load Angle (Deg.)

Figure 6.1(a) shows the load angle oscillations without additional controller of the STATCOM and Figure 6.1(b) shows the oscillations with additional controller. Here also a 3 phase line to ground fault of 0.1 sec is introduced.

In the Figure 6.1(a) the settling time and peak over shoot are 17.2 sec and 2.25 deg respectively. Similarly, in the Figure 6.1(b) Settling time and peak over shoot are 6.8 sec and 2.11 deg respectively. So, it can be observed that that load angle oscillations and over shoots are very much reduced with the addition of the auxiliary controller.



(a)



(b)

Figure 6.2: Load Angle Oscillations (a) Without Additional Controller (b) with Additional Controller [with Fault Resistance= 2Ω]

X axis: Time in sec.

Y axis: Load Angle (Deg.)

Figure 6.2(a) shows the load angle oscillations without additional controller of the STATCOM and Figure 6.2(b) shows the oscillations with additional controller. Here a 3-phase line to ground fault of 0.01 sec is introduced.

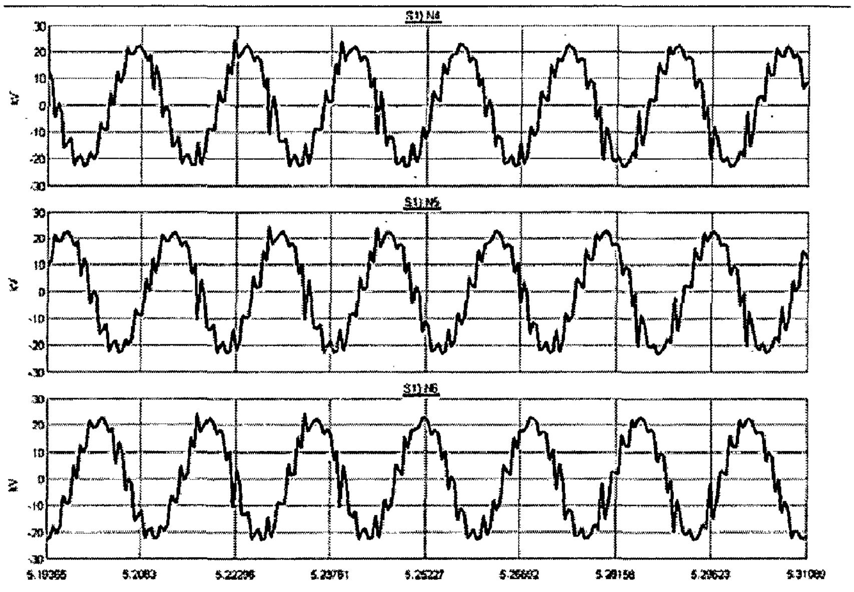


Figure 6.3: Voltage waveforms at the terminals of the STATCOM

X axis: Time in sec.

Y axis: Voltage (kV)

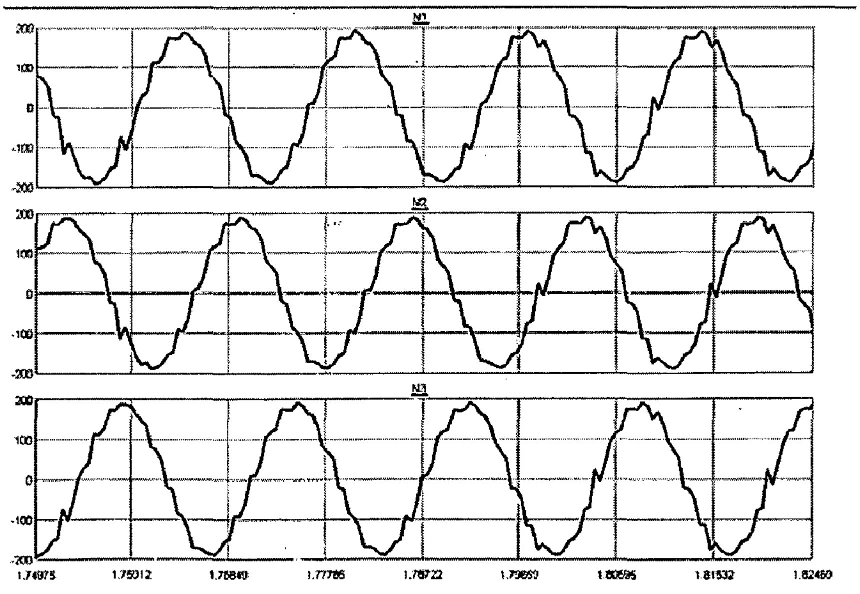


Figure 6.4: Voltage waveforms at the terminals of the AC System

X axis: Time in sec.

Y axis: Voltage (kV)

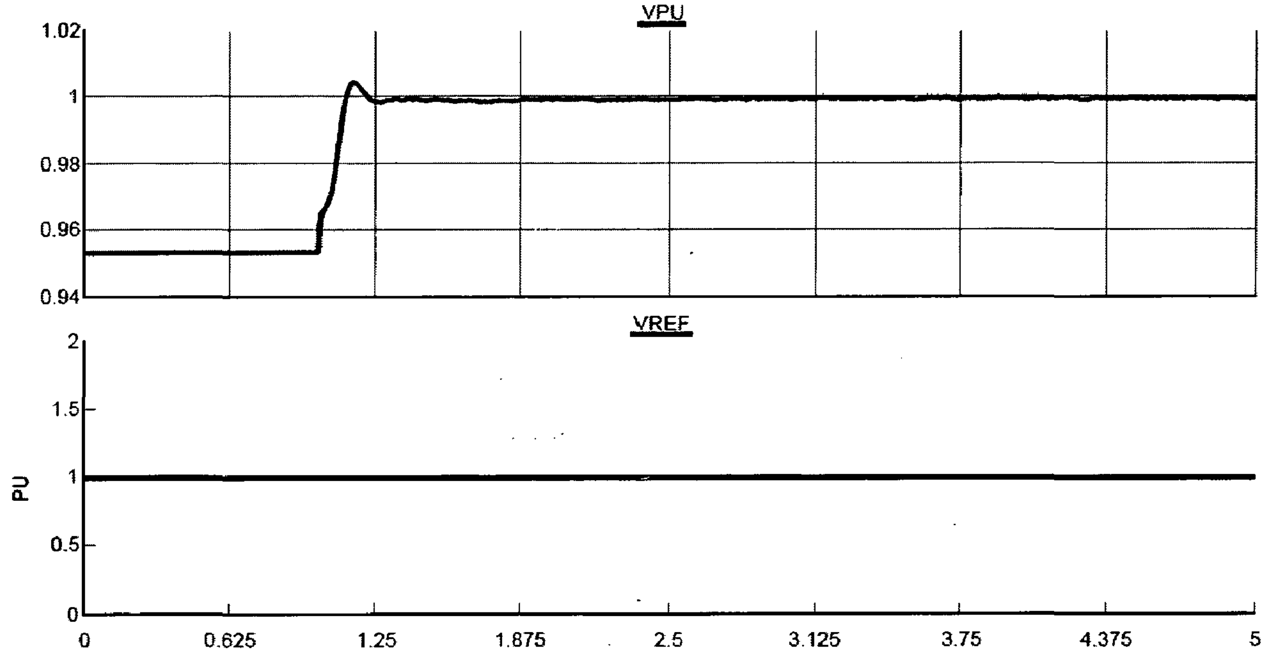


Figure 6.5: Bus Voltage when STATCOM ON with Load with Reference Voltage Setting

X axis: Time in sec.

Y axis: Voltage (pu)

Figure 6.5 shows the variations in bus voltage with the voltage reference setting. Here in the first one second shows the BUS voltage with out STATCOM, and the STATCOM was on at 1 sec and the BUS voltage immediately achieve the desired voltage setting.

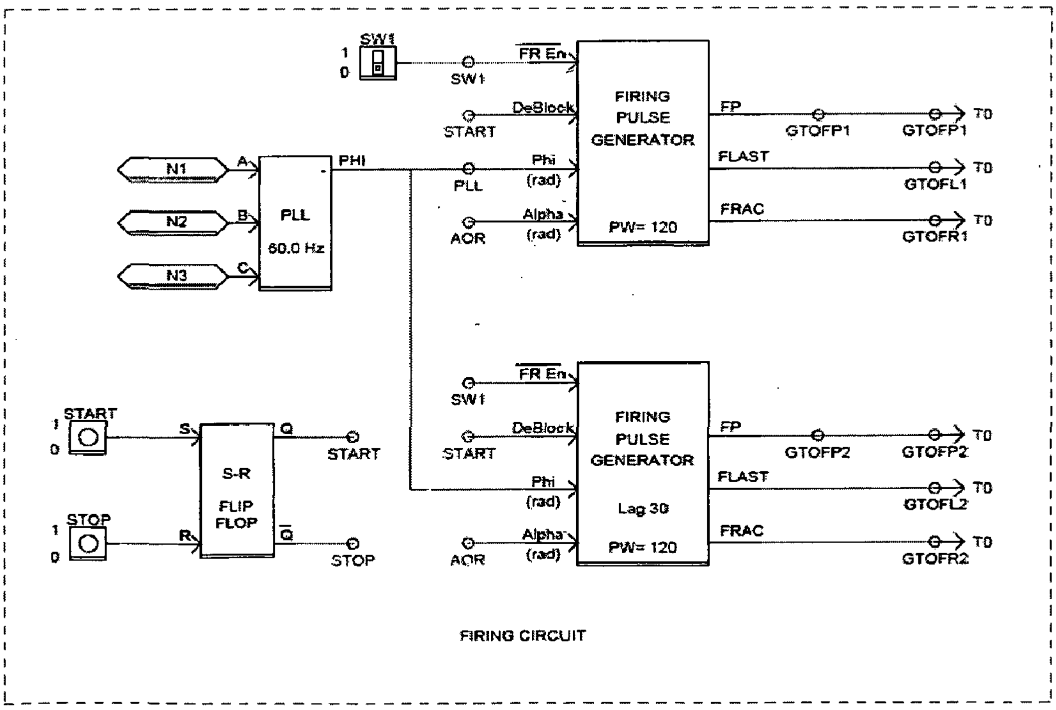


Figure 6.6: RSCAD View of Firing Circuit

Figure 6.6 shows the RSCAD view of the firing circuit of a 12-pulse STATCOM

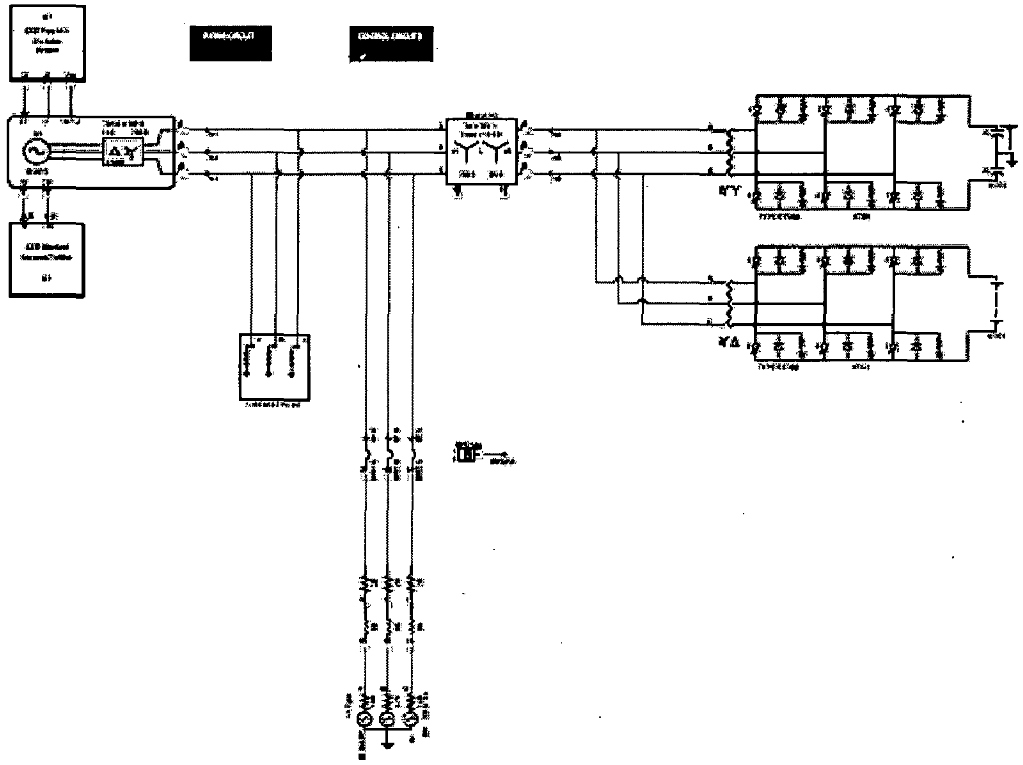


Figure 6.7: RSCAD View of STATCOM

Figure 6.7 shows the RSCAD view of the test system

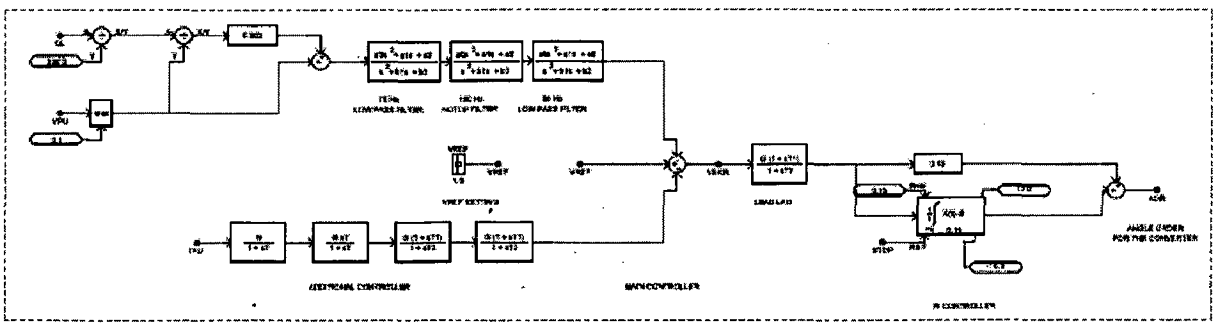


Figure 6.8: RSCAD view of the STATCOM Controller

Figure 6.8 shows the RSCAD view of the controller for the small signal stability improvement of a 12-pulse STATCOM.

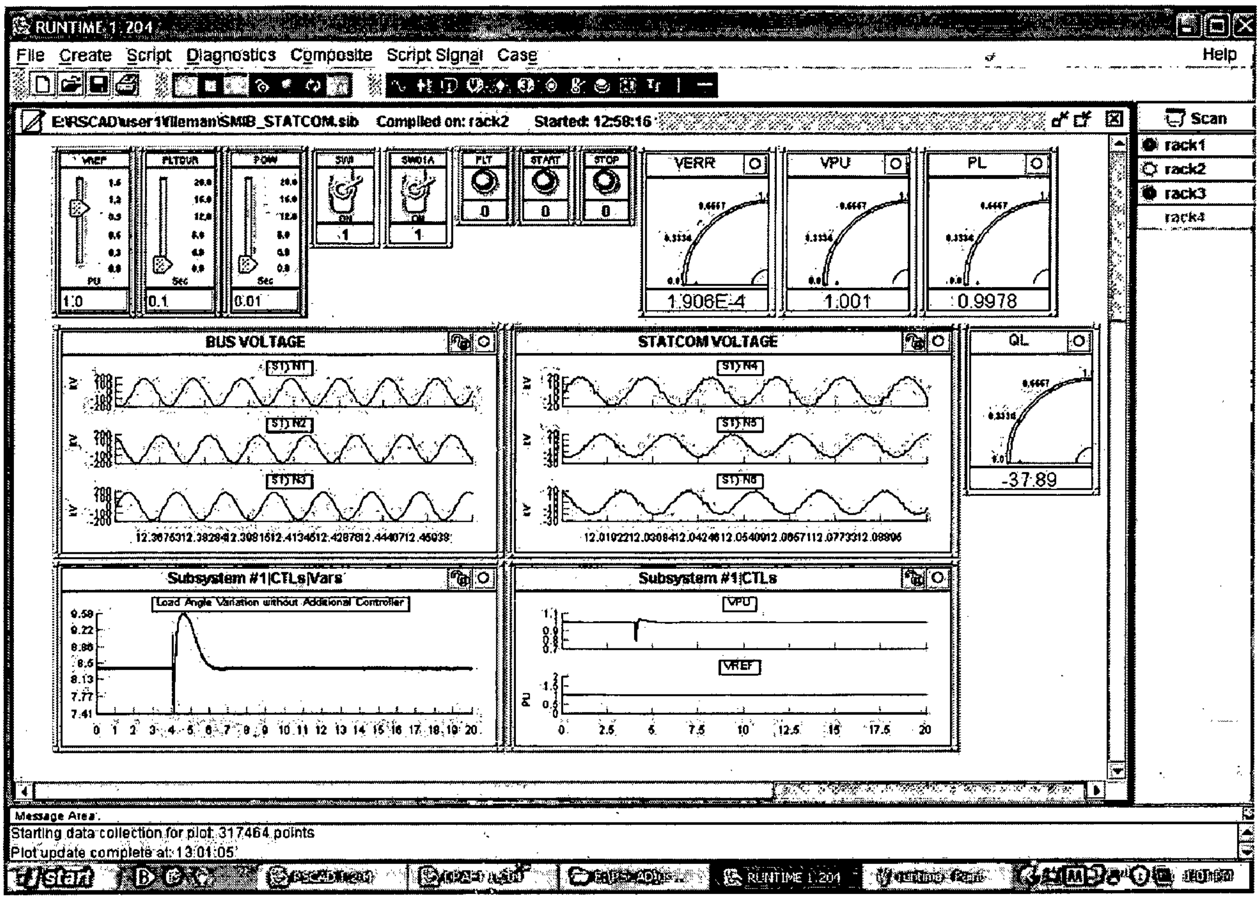


Figure 6.9: RSCAD View of Runtime

CONCLUSIONS

In this report the STATCOM and its operation, *V-I* Characteristics and advantages are widely discussed. From *V-I* Characteristics, it is observed that at reduced voltage the STATCOM can continue to be operated at rated leading (or lagging) current, with a constant transient overload current margin. So, STATCOM is better able to provide reactive/current support for a supply system whose voltage is severely depressed.

The basic requirement of for the development of STATCOM is a converter. It may be a multilevel or multipulse. Generally for high power applications multipulse type converter is preferred. The simplest three-phase converter is the 6-pulse converter. However simple six pulse converter is unlikely in high power applications due to its harmonic distortion. To reduce the harmonic distortion to an acceptable level the pulse order must be increased to 12, 24 or 48. Magnetic interface transformers are needed to obtain multi pulse structure. From simulation results it can be observed that the performance of the 48-pulse converter was better when compare with 24-, 12-, and 6- pulse because of the near sinusoidal voltage waveform. But, complex phase shifting transformers are needed to obtain 48-pulse output so, this will make the system bulky and complex. By using quasi harmonic neutralized converters almost similar waveform can be obtained without using complex phase shifting transformers. So, this will makes the system simple. The voltage THD obtained in the 48-pulse quasi harmonic naturalized topology 3.199% is almost the same as one obtained using a 48-pulse harmonic naturalized topology i.e. 2.948%. But in the output of quasi harmonic neutralized converter still containing 11^{th} and 13^{th} order harmonics but their magnitude are very low filters may not be required.

Besides the main task of voltage control, a STATCOM also improve the transmission capability and power system stability. In general, a compensator maintaining constant terminal voltage is not effective in damping of power oscillations. To damp power oscillations a supplementary control signal should be added to the STATCOM Regulator.

In this work, a control circuit is designed for 48-pulse quasi harmonic neutralized converter based STATCOM for the small signal stability improvement. This new controller is able to compensate the effects of uncertainties and disturbances of the power system network.

The results presented in the repot shows that inclusion of the additional controller the rotor speed and load angle oscillations are reduced.

Scope for Future Work:

Some of the improvements of the present work and future direction for further studies are listed below:

- Design of the voltage source converter using the combination of multi level and multi pulse converters.
- The STATCOM and its control can be implemented in a multi machine system.
- The 48-pulse converter and its model can be directly applied to construct an UPFC and its control system.

REFERENCES

Text Books:

1. C.L. Wadhwa, "Electric Power Systems," New Age International Limited Publishers, pp 226-232, 720-728, 1983.
2. Yong Hua Song, Allen T Jones, "Flexible AC Transmission System (FACTS)," IEEE Press, 2001.
3. Laszlo Gyugyi, Narain G. Hingorani, "Understanding FACTS Concepts and Technology of Flexible AC Transmission System," IEEE Press, 2002.
4. X.P. Zhang, B. Pal, "Flexible AC Transmission System Modelling & Control," Springer Press, 2006.
5. T. J. E. Miller, "Reactive Power Control in Electric System," John Wiley & Sons, pp 2-10, 51-56, 1982.
6. M.H. Rashid, "Power Electronics-Circuits, Devices and Applications," PHI, 2004.
7. P. Kundur, "Power System Stability & Control," Electric Power Research Institute Press, IEEE Press Power Engineering Series, Tata McGraw- Hill Publications, 1994.
8. Leonard L. Grigsby, "Power System Stability & Control," CRC Press, 2007.
9. K.R. Padiyar, "FACTS Controllers in Power Transmission and Distribution," New age International Publishers, 2007.

Research Papers:

10. L. Gyugi, "Power Electronics in Electric Utilities: Static VAR Compensators," Proceedings of the IEEE, Vol. 76, No.4, pp 483-494, April 1988.
11. K.K Sen, "STATCOM- STATic synchronous COMpensator: Theory, Modeling, and Applications," IEEE PES 1999 Winter Meeting Proceedings, pp 1177-1183, 1998.
12. CIGRE, "Static Synchronous Compensator," Working Group 14.19, September 1998.
13. L. Gyugyi, "Dynamic Compensation of AC transmission Lines by Solid-State Synchronous Voltage Source," IEEE Transaction on Power Delivery, Vol. 9, No. 2, pp 904-911, April 1994.

14. C.W. Edwards, P.R. Nannery, K.E. Mattern, J. Gubernick, "Advanced Static VAR Generator Employing GTO Thyristors," IEEE Transaction on Power Delivery, Vol. 3, No. 4, pp 1622-1627, October, 1988.

15. Qingguang Yu , Pei Li, Wenhua Liu,. Xiaorong Xie, "Overview of STATCOM Technologies," IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies, Hong Kong, Vol. 2, pp 647- 652, April 2004.

16. C. Schauder, M. Gernhardt, E. Stacey, T. Lemark, L. Gyugi, T.W. Cease, A.Edris, "Development of ± 100 MVAR Static Condenser for Voltage Control of Transmission System," IEEE Transactions on Power Delivery, Vol. 10, No. 3, pp 1486- 1496, July 1995.

17. Yang Ye, Mehrdad Kazerani and Victor H. Quintana, "Current-Source Converter Based STATCOM: Modeling and Control," IEEE Transactions on Power Delivery, vol. 20, no. 2, pp 795-800, April 2005.

18. Carlos A. C. Cavaliere, Edson H. Watanabe, Maurício Aredes, "Multi-pulse STATCOM Operation under Unbalanced Voltages," Power Engineering Society Winter Meeting, IEEE, Vol. 1, pp 567-572, 2002.

19. L. Gyugyi, Narain G. Hingorani, P.R. Nannery and N. Tai, "Advanced Static VAR Compensators Using Gate Turn Off Thyristors for Utility Applications," CIGRE, pp 1-7, August, 1990.

20. L. Sunil Kumar and A. Ghosh, "Modeling and Control Design of a Static Synchronous Series Compensator," IEEE Trans. Power Delivery, Vol. 14, No. 4, pp. 1448-1453, 1999.

21. N. Voraphonpiput, S. Chatratana "Analysis of Quasi 24-Pulse STATCOM Operation and Control using ATP-EMTP," IEEE Trans. Power Delivery, vol. 3, pp 359-362, 2004.

22. Carlos A.C. Cavaliere , Edson H. Watanabe and Maurício Aredes, "Analysis and Operation of STATCOM in Unbalanced Systems," IPST - International Conference on Power Systems Transients, Paper 207, 2001.

23. D. R. Trainer, S. B. Tennakoon, R. E.Morrison, "Analysis of GTO-based Static VAR Compensators," IEE Proc.-Elect. Power Appl., Vol. 141, No. 6, pp. 293-302, November 1994.

24. C.Schauder and H. Mehta, "Vector Analysis and Control of Advanced Static VAR Compensators," Proc. Inst. Elect. Eng., Vol. 140, No. 4, pp. 299–306, July 1993.

25. Mohamed S. ElMoursi and Adel M. Sharaf, "Novel STATCOM Controllers for Voltage Stabilization of Stand Alone Hybrid (Wind/Small Hydro) Schemes," International Journal of Emerging Electric Power Systems, Vol. 7, Issue 3, Article 5, pp. 1-25, 2006.
26. Masoud Zarringhalami and M.A.Golkar, "Coordinated Design of PSS and STATCOM Parameters for Power System Stability Improvement Using Genetic Algorithm," DRPT2008, Nanjing, China, pp 1453-1459, April 2008.
27. S. M. Muyeen, M. H. Ali, R. Takahashi, T. Murata, and J. Tamura, "Stabilization of Wind Farms Connected with Multi Machine Power System by Using STATCOM," PowerTech 2007, Paper ID 207, 2007.
28. Sun Qu and Chen Chen, "Low Frequency Oscillations Damping by STATCOM with a Fuzzy Supplementary Controller," Power System Technology Proceedings, Vol. 1, pp. 67–70, October 2002.

Simulation Software Manuals:

29. "EMTDC Transient Analysis for PSCAD Power System Simulation User's Guide," Manitoba Research Institute, Manitoba, Canada, 2005.
30. "Real Time Digital Simulator Power System Users Manual," RTDS Technologies Inc., Canada, Nov, 2006.

APPENDIX A

TEST SYSTEM DATA

Generator:

Name	Description	Value	Units
Vb	Rated RMS Phase Voltage	7.9677	kV
Xq	Q-axis Unsaturated Reactance	1.71	p.u.
Xq'	Q: Unsaturated Transient Reactance	0.228	p.u.
Xd	D-axis Unsaturated Reactance	1.63	p.u.
Xd'	D: Unsaturated Transient Reactance	0.228	p.u.
H	Inertia Constant	1.7	MWs/MVA
f	Base Frequency	50.0	Hz

Generator Transformer:

Name	Description	Value	Units
vtpri	Transformer Primary L-L RMS kV	230.0	kV
vtsec	Transformer Secondary L-L RMS kV	13.8	kV
dlagp	Delta Leads or Lags Primary 30 Deg.	Lags	
TMVA	Transformer MVA rating	100.0	MVA
trpos	Positive Sequence Resistance	0.0	pu
txpos	Positive Sequence Reactance	0.1	pu
trzro	Zero Sequence Resistance	0.0	pu
txzro	Zero Sequence Reactance	0.1	pu
tloss	Shunt Conductance at TRF Primary	0.0001	pu

Exciter: IEEE TYPE1

Name	Description	Value	Unit
Vb	Rated RMS Phase Voltage	7.9677	kV
Vi	Initial Terminal Voltage	1.0	pu
Tr	Time Constant Tr	0.0	sec
Tb	Time Constant Tb	1.0	sec
Tc	Time Constant Tc	1.0	sec
Ka	Gain Ka	20.0	
Ta	Time Constant Ta	0.05	sec
Te	Integrator Time Constant Te	0.4	sec
Kf	Feedback Gain Kf	0.06	
Tf	Feedback Time Constant Tf1	0.715	sec
Kc	Constant Kc	0.1	
Kd	Constant Kd	0.0	
Ke	Constant Ke	1.0	

Governor: IEEE TYPE1

Name	Description	Value	Unit
T1	Time Constant T1	1.0	sec
T2	Time Constant T2	1.0	sec
T3	Time Constant T3	0.02	sec
T4	Time Constant T4	0.673	sec
T5	Time Constant T5	3.0	sec
T6	Time Constant T6	0.45	sec
K1	Constant K1	14.3	
K2	Constant K2	0.7	
K3	Constant K3	1.0	

Coupling Transformer:

Name	Description	Value	Unit
YD1	Winding #1 Connection	Y	
YD2	Winding #2 Connection	Y	
Lead	Delta Lags or Leads Y	Lags	
Tmva	Transformer Rating (3 Phase)	100.0	MVA
f	Base Frequency	50.0	Hz
xl	Leakage Inductance of Tx	0.15	p.u.
NLL	No load Losses	0.001	p.u.
VL1	Base Primary Voltage (L-L RMS)	230.0	kV
Im1	Magnetizing Current	1.0	%
VL2	Base secondary Voltage (L-L RMS)	25.0	kV
Im2	Magnetizing Current	1.0	%

STATCOM:

No. of Pulses: 48

Capacitor: 300 μF

Interface Transformer #1:

Name	Description	Value	Unit
Tmva	Transformer MVA (3 phase)	100.0	MVA
Vac	Line Side Voltage (L-L, RMS)	25.0	kV
Vvlv	Valve Side Voltage (L-L, RMS)	12.5	kV
Xl	Transformer +ve Seq. Leakage Reactance	0.1	p.u.
Xr	Transformer +ve Seq. Resistance	0.01	p.u.
Xlz	Transfmr Zero Seq. Leakage Reactance	0.1	p.u.
Xrz	Transfmr Zero Seq. Resistance	0.01	p.u.
f	Base Frequency	50.0	Hz

Interface Transformer #2:

Name	Description	Value	Unit
Tmva	Transformer MVA (3 phase)	100.0	MVA
Vac	Line Side Voltage (L-L, RMS)	25.0	kV
Vvlv	Valve Side Voltage (L-L, RMS)	12.5	kV
Xl	Transformer +ve Seq. Leakage Reactance	0.1	p.u.
Xr	Transformer +ve Seq. Resistance	0.01	p.u.
f	Base Frequency	50.0	Hz

Snubber Circuit:

Name	Description	Value	Unit
SnR	Snubber Circuit Resistance	5000.0	Ohms
SnC	Snubber Circuit Capacitance	0.05	uF
Roff	GTO OFF State Resistance	1e8	Ohms

Main Controller Parameters:

PI Controller:

Proportional Gain= 1.3

Integral Time Constant= 0.015 sec

Lead- Lag Controller:

Name	Description	Value	Unit
T1	Lead Time Constant	0.007	sec
T2	Lag Time Constant	0.0001	sec
G	Gain	1.0	

Additional Controller Parameters:

Lead- Lag Controller# 1:

Name	Description	Value	Unit
T1	Lead Time Constant	5.0	sec
T2	Lag Time Constant	0.5	sec
G	Gain	1.0	

Lead- Lag Controller# 2:

Name	Description	Value	Unit
T1	Lead Time Constant	5.0	sec
T2	Lag Time Constant	0.5	sec
G	Gain	1.0	

Wash Out Circuit:

Time Constant= 0.25 sec

Gain= 2.0

Low Pass Filter:

Time Constant= 0.05 sec

Gain= 1.0

3- Phase Fault Parameters:

Type: 3-Phase to ground

Fault Resistance= 5.0 Ω

Load (for STATCOM Voltage Controller):

Resistance= 463 Ω

Reactance= 0.404 H

APPENDIX B
PSCAD/EMTDC

PSCAD:

PSCAD (Power Systems CAD) is a powerful and flexible graphical user interface to the world-renowned, EMTDC solution engine. PSCAD enables the user to schematically construct a circuit, run a simulation, analyze the results, and manage the data in a completely integrated, graphical environment. Online plotting functions, controls and meters are also included, so that the user can alter system parameters during a simulation run, and view the results directly.

PSCAD comes complete with a library of pre-programmed and tested models, ranging from simple passive elements and control functions, to more complex models, such as electric machines, FACTS devices, transmission lines and cables. If a particular model does not exist, PSCAD provides the flexibility of building custom models, either by assembling them graphically using existing models, or by utilizing an intuitively designed Design Editor.

EMTDC:

EMTDC (which stands for Electromagnetic Transients including DC) represents and solves differential equations (for both electromagnetic and electromechanical systems) in the time domain. Solutions are calculated based on a fixed time step, and its program structure allows for the representation of control systems, either with or without electromagnetic or electromechanical systems present.

The first lines of code were written in 1975, at Manitoba Hydro by Dennis Woodford (Technical Director of the Centre 1986 - 2001), out of a need for a simulation tool that was sufficiently powerful and flexible to study the Nelson River HVDC power system in Manitoba, Canada.

EMTDC serves as the electromagnetic transients solution engine for the PSCAD family of products. PSCAD is used extensively for many types of AC and DC power simulation studies, including: Power electronics (FACTS), sub-synchronous resonance and lightning over-voltages (to name a few).

APPENDIX C
RTDS®

RTDS Technologies Inc. provides Real Time Digital Simulators (RTDS®) and Simulation Services for the electrical power industry. The RTDS Simulator performs fully digital Electromagnetic Transient Power System Simulation in real time utilizing the Dommel Algorithm similar to non-real time EMTP type programs. The RTDS simulator is a modular, fully digital power system simulator that can be used for a wide range of studies, including:

- Performing analytical power system simulation
- Testing protective relay systems
- Testing control systems
- Education and training

The RTDS simulator performs simulations for the study and analysis of small or very large and complex electrical power networks. To date some applications include:

- ✓ Closed-loop testing of protective relays, and integrated protection and control schemes
- ✓ Closed-loop testing of control systems for HVDC, SVC, TCSC, and synchronous machines, including AVR and PSS
- ✓ studying general AC system operation including behavior of generation and transmission systems
- ✓ investigating power system equipment interaction
- ✓ Studying interaction between integrated AC/DC systems
- ✓ Developing FACTS devices and associated controls;
- ✓ Educating and training of power system personnel

The RTDS Simulator was the first of its kind and is the world's benchmark for performing real time simulations. Using the RTDS Simulator provides the link between theory and practical operation of the power system.