Enhancing Voltage Stability and Reactive Power Compensation by Replacing Mechanically Switched Capacitor Banks with Fuzzy Logic-Based DSTATCOM

(A Case Study of Bishoftu No.3 Substation)

Firaol Dadi Belda

A Thesis Submitted to the Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Electrical Power and Control Engineering (Power Engineering)

Office of Graduate Studies

Adama Science and Technology University

September, 2024

Adama, Ethiopia

Enhancing Voltage Stability and Reactive Power Compensation by Replacing Mechanically Switched Capacitor Banks with Fuzzy Logic-Based DSTATCOM

(A Case Study of Bishoftu No.3 Substation)

Firaol Dadi Belda

Advisor: Dr. CS Reddy

A Thesis Submitted to the Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Electrical Power and Control Engineering (Power Engineering)

Office of Graduate Studies

Adama Science and Technology University

September, 2024

Adama, Ethiopia

Declarations

I hereby declare that this Master Thesis entitled **"Enhancing Voltage Stability and Reactive Power Compensation by Replacing Mechanically Switched Capacitor Banks with Fuzzy Logic-Based DSTATCOM"** is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

___________________	______________	_____________
Name of Student	**Signature**	**Date**

Recommendation of Advisors

I/we, the advisor(s) of this thesis, hereby certify that I/we have read the revised version of the thesis entitled **"Enhancing Voltage Stability and Reactive Power Compensation by Replacing Mechanically Switched Capacitor Banks with Fuzzy Logic-Based DSTATCOM"** prepared under my/our guidance by Firaol Dadi submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electrical Power and Control Engineering. Therefore, I/we recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr. C S Reddy	____________________	____________________
Major Advisor	**Signature**	**Date**
____________________	____________________	____________________
Co- Advisor	**Signature**	**Date**

Approval Page of M.Sc. Thesis

I/we, the advisors of the thesis entitled **"Enhancing Voltage Stability and Reactive Power Compensation by Replacing Mechanically Switched Capacitor Banks with Fuzzy Logic-Based DSTATCOM"** and developed by Firaol Dadi, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr.C S Reddy	__________________	__________________
Major Advisor	Signature	Date
_________________	__________________	__________________
Co- Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Firaol Dadi have read and evaluated the thesis entitled **"Enhancing Voltage Stability and Reactive Power Compensation by Replacing Mechanically Switched Capacitor Banks with Fuzzy Logic-Based DSTATCOM"** and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electrical Power and Control Engineering.

Dr.Tafesse Asrat	__________________	__________________
Chair Person	Signature	Date
Dr. Kena Likassa	__________________	__________________
Internal Examiner	Signature	Date
Dr.Yeshitela Shiferaw	[signature]	09/23/2024
External Examiner	Signature	Date

Final approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

________________	__________________	__________________
Department Head	Signature	Date
_______________	__________________	________________
School Dean	Signature	Date
______________	_________________	_______________
Office of Post Graduate Studies, Dean	Signature	Date

Acknowledgments

First and foremost, I would like to thank Almighty God for his grace, which has helped me overcome trials and temptations throughout this journey. I am especially grateful to my advisor, Dr. CS Reddy, for his expert guidance, constructive feedback, and unwavering encouragement. His motivation and dynamic suggestions were invaluable in overcoming the challenges I faced during my research.

I also want to extend my gratitude to the members of the Electrical Power and Control Engineering department for their continuous encouragement during the thesis progress. Additionally, I appreciate the staff at Ethiopian Electric Power (EEP), particularly Ato Sisay Ayichew, the substation manager of Bishoftu No. 3, for providing me numerous valuable data and for his hospitable service.

Finally, I would like to express my gratitude to my family and friends, whose support and encouragement have been instrumental in helping me completing my work.

Table of Contents

Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVATIONS

AC	Alternating Current
DG	Distributed Generation
DSTATCOM	Distribution Static Synchronous Compensator
EMC	Electro Magnetic Compatibility
FLC	Fuzzy Logic Controller
MSC	Mechanically Switched Capacitor
PF	Power Factor
PI	Proportional Integral
SVC	Static Var Compensator
MVAR	Mega Volt-ampere
PLL	Phase Locked Loop
SVC	Static Var Compensator
GTO	Gate Turn off
VSC	Voltage Source Converter
FACTS	Flexible AC transmission System
IGBT	Insulated Gate Bipolar Transistor
PWM	Pulse Width Modulation
VAR	Volt Ampere Reactive

Abstract

Reactive power can cause voltage drops, inefficient power transmission, increased line losses and reduced system stability. To mitigate such kinds of power quality issues a mechanically switched capacitor bank is installed at Bishoftu No 3 substations. Mechanically switched capacitor banks, despite their economic advantage, are associated with several drawbacks. These includes large transient, switching time delay, wear and tear of contacts and limited switching frequency. This study analyzes the transient effects associated with the switching operations of the capacitor bank. The existing mechanically switched capacitor bank is designed according to the specifications of its component. Simulations were conducted using Matlab/Simulink tool to assess the bank's performance, first by switching in a single stage and subsequently all the three stages. The simulation revealed that during the switching of the first stage at 0.08seconds, a total harmonic distortion (THD) of voltage reached 16.48%, exceeding the acceptable standard of 5%. Furthermore, switching in all the three stages, each with a capacity of 1.2 MVAr totaling 3.6MVAr, resulted in a THD of 17.03%. These findings indicate mechanically switched capacitor bank poses a significant power quality challenges when frequently switched to meet reactive power demands. To mitigate these issues, this study proposes fuzzy logic-controlled DSTATCOMs as a replacement for the existing capacitor bank. The proposed system employs fuzzy logic controller techniques to regulate reactive power compensation and maintain voltage stability within acceptable levels. A DSTATCOM is designed having a capacity of 3.6MVAr. The controller measures the variation in source voltage and makes the decision based on rule base we set. It controls the firing angle of the DSTATCOM to either absorb or inject the required compensation reactive power from or to the distribution bus bar. The simulation result of FLC based DSTATCOM demonstrate its effectiveness in maintaining voltage stability within a range of 0.955 pu to 1.045 pu. The findings of this study contributes valuable insights into the efficacy of fuzzy logic controller based DSTATCOMs for voltage stability in substation, paving the way for future research and development in this area.

Key words: - *DSTATCOM, Matlab/Simulink, Capacitor bank, mechanically switched capacitor (MSC)*

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The area of focus for this case study is Bishoftu No3 Substation, which is recognized for its significant power delivery capacity. Situated approximately 53KM southeast of Addis Ababa, it plays a crucial role in the power distribution network. The substation receives a power supply of 400KV from Gelan substation through double circuit. The substation utilizes a three-stage voltage transformation process to facilitate efficient powerdelivery. Initially, the incoming 400KV voltage is reduced to 230KV using two 200MVA transformers. This 230KV voltage is then transmitted to other nearby substations such as Dukem and Modjo Substation.

To supply power to consumers in the vicinity of Bishoftu town, the 230KV voltage is further stepped down to 33KV and 15KV levels for distribution through the local system. This reduction to 33KV is achieved by employing two 50MVA transformers, which cater to the electricity needs of high-demand industries. Additionally, the voltage is further reduced to 15KV using two 50MVA transformers, completing the series of transformations necessary for effective distribution within the local area.

There are 16 distribution feeder lines in the system. From the 33KV busbar, there are six feeder lines that receive power. Additionally, from 15KV busbar, there are 10 feeder distribution lines. These 10 feeder lines provide power at the 15 KV voltage level to various locations within the distribution network.

To address voltage regulation and reactive power compensation, a capacitor bank has been installed on the 15KV busbar. The primary purpose of this capacitor bank is to compensate for reactive power, which refers to the power that alternates between the source and the load without being consumed.

The capacitor bank used in this system is a mechanically switched type, employing relays for its operation. This means that the switching of the capacitors within the bank is performed by circuit breaker, which are triggered based on certain predefined conditions or parameters.

By strategically switching the capacitors within the bank, we can adjust the reactive power and keep the voltage levels in the distribution network steady. This is important for maintaining stable voltage conditions and ensuring the efficient operation of electrical equipment and devices connected to the systems.

The capacitor bank is very important for managing reactive power and voltage regulation, enhancing the whole distribution network and dependability of the 15KV.

A vacuum switch breaker is used to insert in and out the capacitor bank. The capacitor bank has three stages where each stage has a capacity of 1200KVAR. The relay will decide whether to insert the first, second or third stage of the bank based on load demand. The first stage has only 1200KVAR reactive power compensating capability. The second stage has 2400KVAR capacity.And the final third stage has a total of 3600KVAR reactive power compensating capacity.

When the capacitors are switched on one after the other, the sudden surge of current (inrush current) is mainly caused due by the electrical resistance and between the first and second capacitor banks. To reduce this surge, a current limiting reactor is used.

It is not feasible for three stages of mechanically switched capacitor banks to be inserted simultaneously in practice, due to switching delays arising from the varying mechanical properties of VCB (Timo Wenzel and Thomas Leibfried, 2015).There will be rather a short time delay.

For addressing the challenges associated with mechanically switched capacitor bank, a power electronics-based solution like DSTATCOM is preferable option. In this study a fuzzy logic based DSTATCOM is presented as a replacement for the mechanically switched capacitor bank.

1.2 Problem of Statement

In power systems, maintaining voltage stability and compensating for reactive power are essential for ensuring reliable and efficient operation. To do this task a mechanically switched capacitor bank is installed at Bishoftu No3 Substation.

Despite their widespread use, mechanically switched type of capacitor bank configuration encounter several challenges that affect their operation and performance. The problems with this kind of configurations are: -

i) Switching Transients: When the relay switches the capacitors on or off, it can generate high-voltage transients due to the sudden change in the circuit's impedance. These transients can cause voltage spikes, which will damage the capacitors and other connected devices.

ii) Contact Wear and Tear: Mechanical relays have moving parts that experience wear and tear over time. The repetitive switching operations can lead to contact degradation, resulting in increased resistance and poor contact reliability. This can cause overheating, voltage drops, and potential failure of the relay or the capacitor bank.

iii) Switching Time and Delay: Mechanical relays typically have a finite switching time, which may result in delays between the desired switching operation and the actual response. This delay can impact the dynamic compensation capability of the capacitor bank, affecting the power factor correction and voltage regulation.

iv) Maintenance and Service: Relay-based capacitor banks require regular maintenanceto ensure proper operation. This includes inspecting and cleaning contacts, adjustingrelay settings, and replacing worn-out components. The mechanical nature of the relays makes them more prone to failures compared to solid-state switching devices,requiring more frequent maintenance.

v) Noise and Harmonics: The switching of capacitor banks can introduce electrical noise and harmonics into the power system. The sudden charging and discharging of the capacitors can generate high-frequency components that may interfere with sensitive equipment and cause electromagnetic compatibility (EMC) issues.

vi) Limited Switching Frequency: Mechanical relays have a limited switching frequency due to their physical constraints. Excessive switching operations beyond their rated capacity can lead to premature wear and failure. This limitation restricts the flexibility of the capacitor bank to respond quickly to dynamic load changes or power factor variations.

To address these challenges this thesis explores the integration of fuzzy logic-based DSTATCOM as a replacement for mechanically switched capacitor bank. Fuzzy logic controller utilizes a fuzzy inference system to determine reactive power compensation on real time voltage and current measurements. It also adapts to changing load conditions without the need for a detailed mathematical model. So this study has a target of investigating the capabilities of the integrated system in enhancing voltage stability and reactive power compensation, providing a more intelligent, adaptable, and precise solution for power system operation.

1.3 Objectives

1.3.1 General Objectives

The goal of this study is to evaluate the effectiveness of integrating fuzzy logic-based DSTATCOM as a replacement for mechanically switched capacitor bank in enhancing voltage stability and reactive power compensation in power systems.

1.3.2 Specific Objectives

- ✓ Studying the limitations with the existing mechanically switched capacitor bank.
- ✓ Evaluate the performance of a fuzzy logic-based DSTATCOM in dynamically regulating voltage and compensating reactive power in real-time.
- ✓ Analyze the integrated fuzzy logic- based DSTATCOM and its ability to maintain voltage stability.
- ✓ Assess the adaptability and flexibility of the fuzzy logic-based DSTATCOM in responding to changes in system parameters and load variations.
- ✓ Provide insights and recommendations for power system operators and engineers regarding the potential benefits and considerations when adopting fuzzy logic-based DSTATCOM as a replacement for mechanically switched capacitor banks.

1.4 Significance of the study

This study is important as it investigates the integration of fuzzy logic-based DSTATCOM as a replacement for mechanically switched capacitor banks, contributing to advancements in power system control, enhanced voltage stability, improved reactive power compensation, and the practical implementation of intelligent control solutions.

1.5 Expected Outcomes of the Study

The anticipated outcome of this study is to demonstrate that the integration of fuzzy logic-based DSTATCOM as a replacement for mechanically switched capacitor banks results in enhanced voltage stability, improved reactive power compensation, and practical insights for the implementation of intelligent control solutions in power systems.

1.6 Scope of the study

This study has a scope to comprehensively examine the integration of a fuzzy logic-based DSTATCOM as a replacement for mechanically switched capacitor bank in power systems. The study aims to analyze the impacts of this integration on enhancing voltage stability. It encompasses the design and also simulation of a fuzzy logic control strategy for DSTATCOM, considering linguistic variables, membership functions, and rule- based inference systems. It further explores the real time operation of the DSTATCOM, its adaptability to changing system conditions, and a potential comparative analysis with mechanically switched capacitor banks.

CHAPTER TWO

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

This chapter offers a thorough overview of the theoretical foundations and existing research that underpin our study.

2.2 Electric Power Distribution System

The electrical system that supplies power has three main parts: generation, transmission, and distribution. Of these, distribution is the final stage, delivering power from distribution substations to individual users, industries, and other consumers.

The main power lines that carry electricity to distribution transformers are called primary distribution lines. These lines connect distribution substation to transformers, creating the primary distribution system.

An interconnected system forming electrical grid comprises of generating stations, high-transmission lines, and distribution lines. Transmission lines are dedicated to transport electricity from power plants to load centers, while distribution lines connect the grid to individual consumers. Together, these components form a power grid that delivers electricity from generation to consumption. Within substation, high voltage power lines run through step down transformers, resulting in a usable voltage that is divided and delivered in various directions through low voltage power feeders (Desta, 2019).

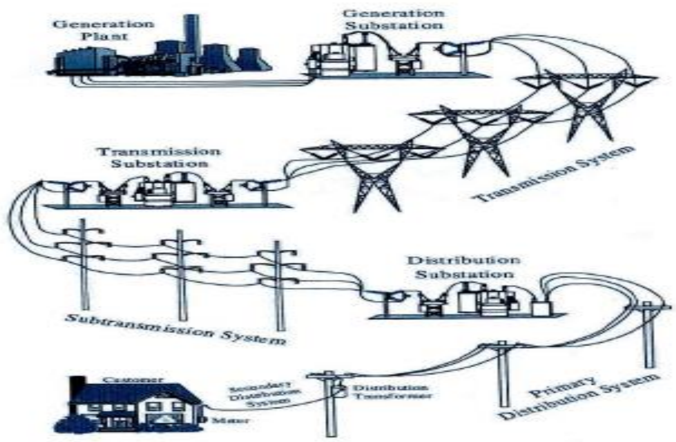

Figure 2.1 Electric power distribution system *(E.Brown)*

Conventionally, losses in the distribution networks are divided into two (Andreas.B, Raphael.C, Damien.J, 2017). They are Technical and Non-Technical Losses

Technical Losses:

Power losses in electrical system occur due to energy that dissipates in components like lines, transformers, and other equipment involved in power transfer. These losses, also known as 'physical losses,' are converted to noise and heat at the time of electricity distribution. The physical characteristics of distribution network equipment, such as design, voltage levels, and line length, directly contribute to these technical losses. Technical losses can be further classified into variable losses and fixed losses (Andreas.B, Raphael.C, Damien.J, 2017)

i) Variable losses

All conductors, including those in transformers, overhead lines, cables, and other electrical equipment, have internal resistance. When electricity flows through these conductors, their resistance causes them to heat up. Since energy is lost as heat, these losses depends on how much current is flowing through the conductors. And these losses are called 'variable losses' because they change as the current varies. They are also known as 'copper losses,' 'ohmic losses,' or 'resistive losses.'

The amount of variable loss is less in transmission networks at higher voltages because less current is needed to transmit a power of the same amount. However, distribution networks, operating at lower voltages, suffer from higher losses. Factors like network power factor, imbalance, and power quality can also influence variable losses. Additionally, the length and cross-sectional area of conductors affect these losses.

ii) Fixed losses

Even when no power is being delivered to customers, electrical networks still experience losses due to the energy dissipated by components like transformers and cables. These losses, known as 'fixed losses,' are not affected by changes in current but are influenced by the voltage applied. Since the applied voltage remains fairly constant when the network is energized, fixed losses are essentially fixed.

Non-Technical Losses:

Besides technical losses, energy delivered through the distribution network may not be accurately measured because of misallocated, misidentified, or incorrect energy flows. These discrepancies are referred to as 'non-technical losses.' It's essential to differentiate non-technical losses from the other two scenarios which are the energy that is accounted for but not invoiced, and energy that is billed but not paid. Non-technical losses, on the other hand, have an unknown end user or an unknown amount of energy utilized (Andreas.B, Raphael.C, Damien.J, 2017)

Non-technical losses include

Here is some of non-technical losses that happens in power supply system

Measurement errors:

Measurement errors occur when the recorded energy consumption differs from the actual energy delivered. These errors can be caused by factors such as inaccuracies in manual or automatic meter readings, faulty equipment, uncertainties in measurement equipment, and improper installation or configuration of meters.

Other Factors:

- ✓ Imbalance of phases
- ✓ Harmonic distortions
- ✓ Power factor

Imbalance of phases: It’s when an electrical load lacks an even distribution of loads among all the three phases experiencing increased currents in at least one phase, which indicates that it is not optimized for minimized losses. This will lead to currents to flow in the neutral conductor, if they exists. It will result in currents flowing in the neutral conductors if they are present. As the loss is quadratic dependent on the current, this imbalance in the load through the three phases will lead to increase of losses.

Imbalances can be observed at various points of the low voltage (LV) networks, primarily caused by customers who utilize one or two phases with varying load condition.

Harmonic distortion: Harmonic effects are distortions in the AC waveform. They can arise in transformer windings due to the non-sinusoidal nature of the AC magnetizing current. While harmonics can occur at various frequencies, triple harmonics (3^{rd}, 6^{th}, 9^{th} etc.) are particularly common in three-phase systems because they are in phase and don't cause significant harmonic voltages**.**

However, harmonics can still lead to increased losses. The formula for calculating losses becomes $I^2R + \sqrt{H}$, where H is harmonics in the network. The equation shows that harmonics will result in overall load increase to the network, leading to higher losses

Power Factor: Power in a network can be defined as real power and reactive power. The power factor is defined as the ratio of real power to apparent power. When the power factor becomes lower than, the current must increase to supply the needed real power, resulting in increased losses.

2.3 Introduction to FACTS Technology

When it comes to electrical power transmission and distribution, nowadays power system operators are faced with a multitude of challenges. While standard issues persist, recent years have witnessed the emergence of new reconstructing trends that demand a fresh approach. To address future challenges and ensure resilience of power systems, operators must adopt innovative strategies and prepare for evolving conditions. The following key issues will significantly impact power systems.

- ✓ The global demand for electrical energy is steadily increasing, pushing transmission lines closer to their operational and safety limits. Since installing new transmission and distribution lines is highly difficult due to escalating cost, environmental constraints, and public regulations, it is vital to explore possibilities of using the existing structure in a more efficient manner (Kalyan K. and Mey Ling , 2009).
- ✓ The increasing complexity of power transmission systems, due to frequent interconnections, expansions, and changes in generation and load patterns, has made them more vulnerable to faults and instability. This complexity can lead to inadequate control of large power flows, excessive reactive power, voltage variations, increased losses, limiting the maximum potential of transmission interconnections.

- ✓ Integrating of large-scale renewable energy to the existing power grids is a significant trend driven by global environmental concerns. While renewable energy offers environmental benefits, it can also pose technical challenges, such as harmonic distortion and voltage regulation. Ensuring stable voltage levels and waveforms in the presence of fluctuating renewable energy sources is crucial, especially without modifying existing voltage and reactive power control mechanisms.

FACTS devices are valuable tools for enhancing power system efficiency and avoiding costly infrastructure upgrades, such as building new substations or power lines. By implementing FACTS devices, operators can optimize existing installations and improve system performance. Here are the applications of FACTS devices in power transmission networks (Xiao-Ping , Christian Rehtanz, Bikash Pal):

1) Power flow control: FACTS devices enable the dynamic control of power flow in transmission and distribution lines.
2) Voltage control: FACTS devices facilitate precise control of voltage levels, ensuring optimal conditions for power transmission and distribution. They maintain voltage stability and mitigate voltage fluctuations.
3) FACTS devices enhance transient by reducing overload and short-circuit currents, and by damping electromechanical oscillations.
4) Improvement of power quality via flicker mitigation and power conditioning.
5) Interconnecting renewable distributed generation and storages.

The emergence of FACTS devices has been propelled by the rapid advancement in power electronics technology and the availability of various types of high power semiconductor switches. These developments are complemented by ongoing progress in microelectronics technology, enabling the implementation of advanced control strategies and signal processing, along with associated algorithms, to a variety of applications.

According to an internal construction perspective, FACTS devices are classified based on variable impedance elements, such as capacitors and reactors, or a power electronics based variable source. Regardless of their internal construction, FACTS device can also be classified based on their connection to power system network into four types, as outlined below. The table below summarizes the most common FACTS devices classified by type.

Series FACTS devices

The basic principle of all series FACTS devices involves the injection of voltage in series with the transmission line, as illustrated in figure below. When injected voltage in phase quadrature with the line current, the series FACTS device primarily interacts with the transmission line by exchanging variable reactive power.

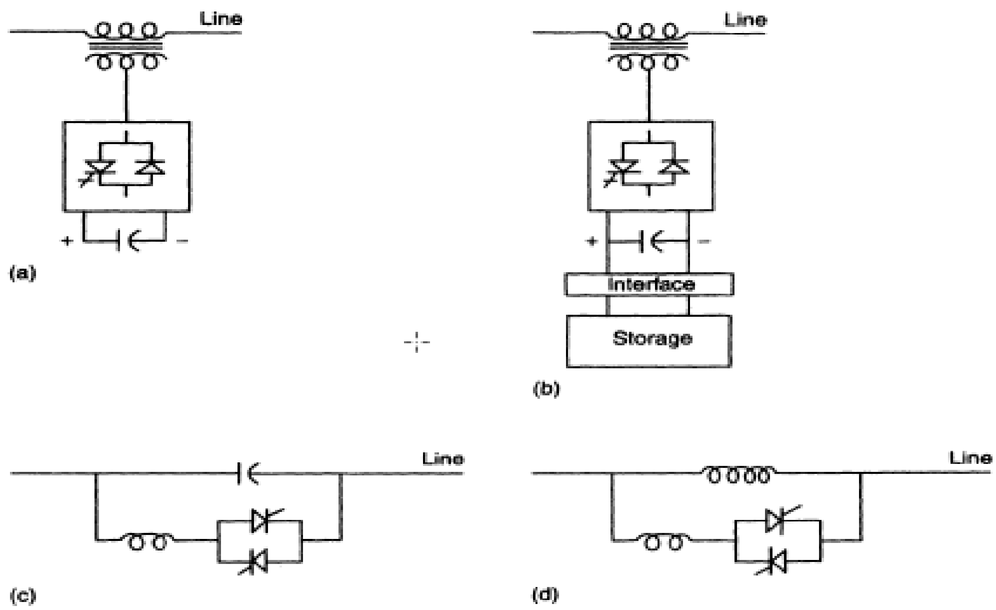

Figure 2.2 Series connected FACTS devices *(Narain G. Hingorani, Laszlo Gyugyi, 2000)*

✓ Shunt FACTS Devices

As illustrated in the figure below, Shunt FACTS device operate by injecting current into the system at the point of connection. When the injected current is in phase quadrature with the line voltage, the shunt FACTS devices primarily interacts with the transmission network by exchanging reactive power. However, if the current and voltage have any other phase relationship, the shunt FACTS device will also affect the handling of the real power. This makes shunt FACTS device an effective means of controlling voltage at and around point of connection by injecting reactive current, which is either leading or lagging.

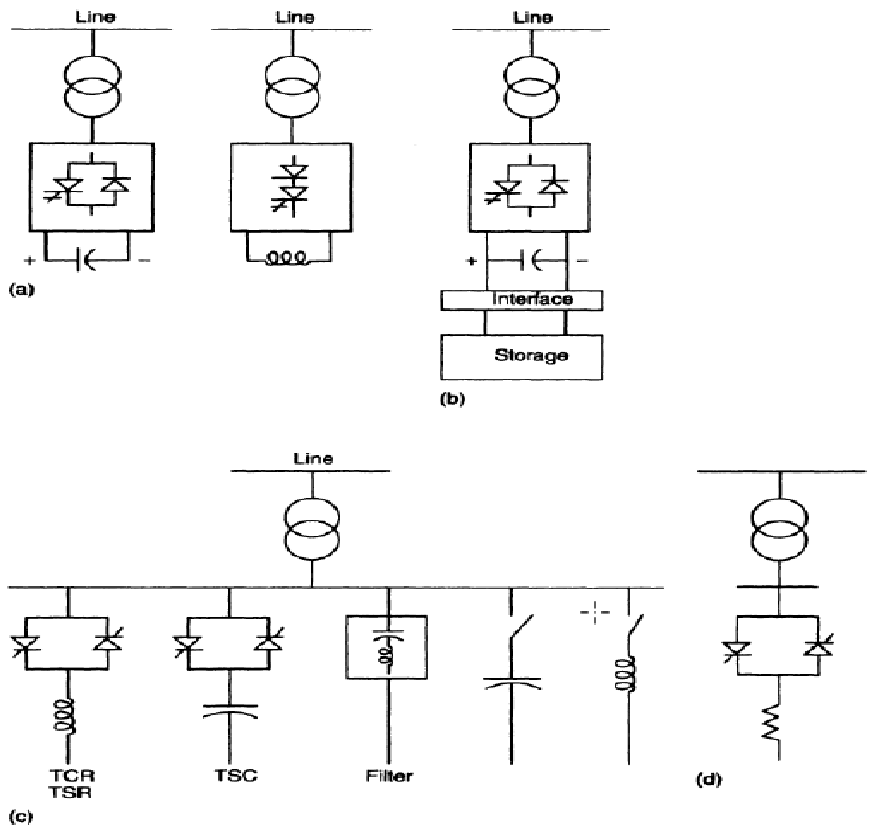

Figure 2.3 Shunt connected FACTS devices *(Narain G. Hingorani, Laszlo Gyugyi, 2000)*

✓ Combined series-series FACTS devices.

These are a configuration where separate series FACTS devices are combined and controlled in a coordinated manner. Alternatively, a unified FACTS devices can be employed, where independent series FACTS devices are installed on each line and real power is transferred among the lines through a power link. This setup enables the balancing of both real power and reactive power flow in the lines and thereby maximize the utilization of the transmission system.

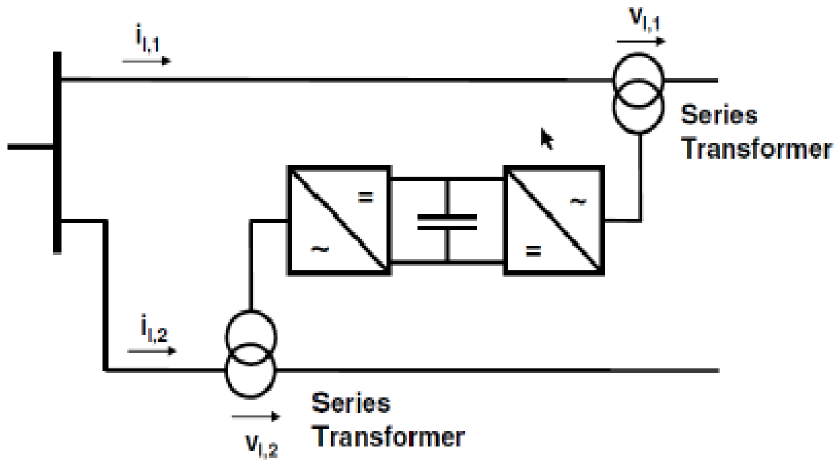

Figure 2.4 Combination of series-series based FACTS devices

- ✓ Hybrid of series-shunt based FACTS devices.

  Hybrid FACTS devices combine shunt and series elements, offering greater flexibility and control. Shunt elements inject current into the system, while series elements inject voltage. A power link enables the exchange of real power between the shunt and series parts, allowing for precise control of reactive power flow.

  Figure 2.6 depicts the configuration of series-shunt FACTS device

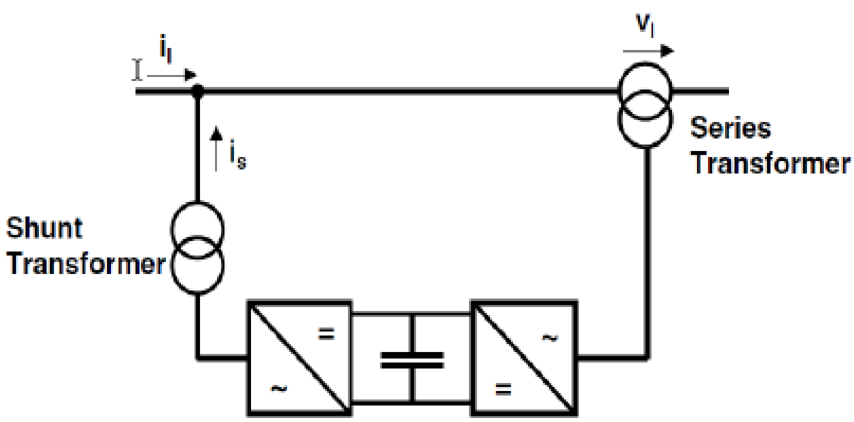

Figure 2.5 Combination of series-shunt based FACTS device

Many FACTS devices incorporate energy storage elements like capacitors, batteries, or superconducting magnets. This combination enhances their effectiveness by allowing for dynamic real power exchange with the system. This capability improves the device's ability to regulate and stabilize power system dynamics.

Table 2.1 Overview of major FACTS devices

Type	Reactor Based	Converter Based
Series	TCSR(Thyristor Controlled Series Reactor) TCSC(Thyristor Controlled Series Capacitor)	SSSC (Static Synchronous Series Compensator).
Shunt	TCR(Thyristor Controlled Reactor) TSC(Thyristor Switched Capacitor) SVC(Static VAR Compensator)	STATCOM(Static Synchronous Compensator)
Combined Series-Series	-	IPFC(Interline Power Flow Controller)
Combined Series-Shunt	-	UPFC (Unified Power Flow Controller).

This thesis focuses on integration of DSTATCOM to the existing power network as a replacement of mechanically switched capacitor bank.

Now let's delve into the concept of DSTATCOM deeply

2.4 DSTATCOM

DSTATCOM is a power electronics device designed to address various power quality issues. By inserting in a shunt connection configuration to the system, it can effectively control reactive power, stabilize voltage, and suppress flicker noises. Additionally, it provides compensation for power system imbalances.

The DSTATCOM can function in two modes: voltage control and current control. The specific compensation effect is determined by the control algorithm governing the voltage source inverter (VSI) switching. The effectiveness of the DSTATCOM ultimately depends on the quality of the control algorithms used to generate the source current. (G.Gupta, W.Fritz, M.T.E , 2017).

DSTATCOM regulates reactive power demand of the load by giving a relief to the grid and it includes a shunt connected VSC and a DC capacitor, enabling it to inject or absorb reactive power. Thisideal device has no inertia and provides immediate response. It may not adjust the device's impedances but can internally generate reactive power, including both capacitive and inductive power. No reactive power is supplied to the device if the output voltage of VSC is equivalent to AC terminal voltage (Mr. Amit , Mr. Vinayak K U, 2021).

The DSTATCOM used for voltage control at the point of PCC should be configured so that the injected current contributes to the source voltage and in phase with it, facilitating improvement in power factor.

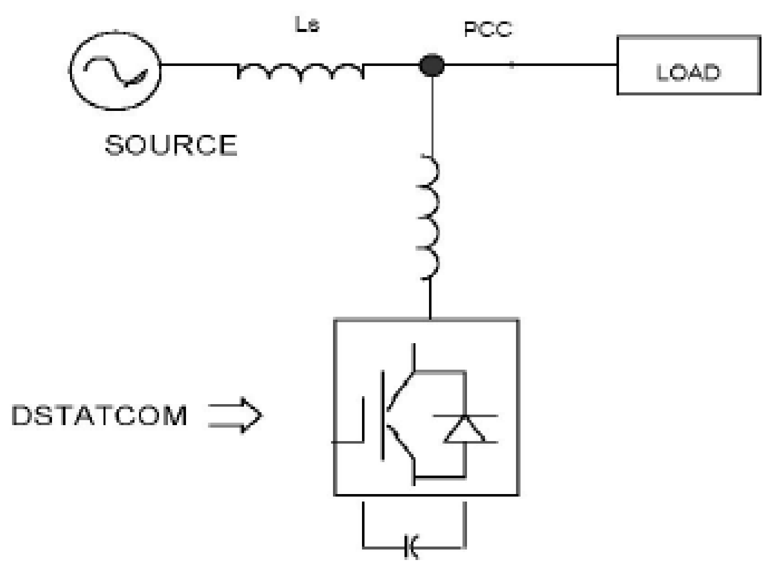

Figure 2.6 Schematic of DSTATCOM

2.4.1 Power Electronics Devices

DSTATCOMs primarily utilize DC/AC converters with high-power AC switches. The converter consists of valves where each containing power electronic devices and gate drive circuits arranged in a back-to-back configuration. High-power electronic devices are rapid switches designed to exhibit a variety of switching characteristics. In their forward-conducting direction, the devices may have control to turn on and turn off the current flow when ordered to do so by means of gate control (Narain G. Hingorani, Laszlo Gyugyi, 2000).

Power electronics have diverse applications, including electrical machine drives, excitation systems, and industrial rectifiers. FACTS devices are one such application, benefiting from advancements in power semiconductor technology. Since the invention of the thyristor in 1957, the focus has been on reducing switching and conduction losses in power semiconductors, driving innovation in the FACTS domain.

Currently, there are two technologies used in power electronics: thyristor and transistor. These technologies cater to a wide range of power and voltage requirements in various applications. Figure below illustrates the power and voltage ranges for specific semiconductor applications, providing an overview of these semiconductors in different scenarios (Narain G. Hingorani, Laszlo Gyugyi, 2000).

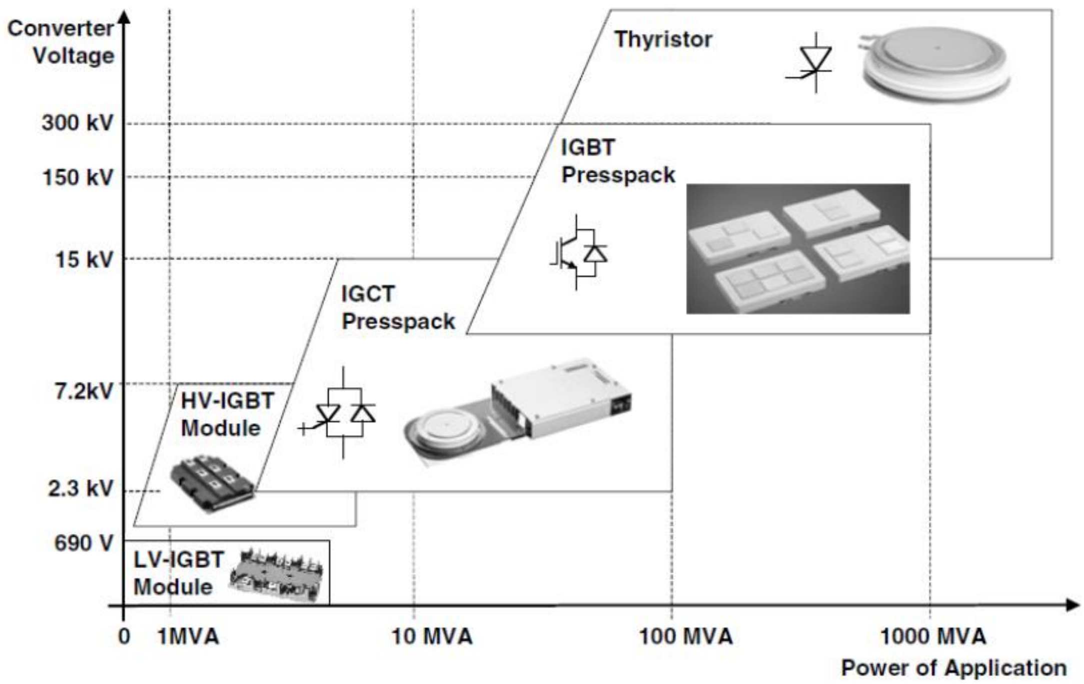

Figure 2.7 Power semiconductor application, voltages and power levels

Power electronic device can be classified to three major categories which are diodes, transistors and thyristors.

The conduction of current in the diode is forward direction which is from its anode to its cathode, when the anode is positively biased compared to the cathode. Diodes do not possess a get that controls conduction. Conversely, diodes block current flow in the reverse direction during the cathode is made positive compared to the anode.

Transistors, on the other hand, conduct current in their forward direction when a particular electrode known as the collector is positively biased with respect to another electrode known as the emitter. To enable this conduction, a turn-on voltage or current signal must be applied to a third electrode known as the base. Transistors are widely applied to low and medium power application.

One specific type of transistor is Insulated Gate Bipolar Transistor (IGBT), which is very common in applications going up to several megawatts and even a few ten of megawatts (Amirnaser.Y, Reza Iravani, 2010).

Thyristors are essential components in FACTS devices. They conduct current in the forward direction when a trigger signal is applied to the gate. Once triggered, thyristors latch on and maintain conduction with a low voltage drop. Unlike transistors, thyristors cannot actively turn off; they rely on circuit conditions to reduce current to zero.

Gate turn-off thyristors (GTOs) offer improved controllability compared to conventional thyristors. Like thyristors, GTOs conduct when a trigger signal is applied to the gate. However, GTOs can be turned off by applying a negative gate current. However, GTOs also possess the ability to be turned-off when a turn-off pulse is applied to the gate in the reverse direction (Naser Mahdavi , Ali Jafari , Nicu Bizon, Frede Blaabjerg, 2017).

When comparing thyristors and transistors, transistors typically exhibit better switching efficiency, characterized by fast switching speeds and lower switching losses. In contrast, thyristors have lower on-state conduction losses and higher power handling capabilities compared to transistors (Naser Mahdavi , Ali Jafari , Nicu Bizon, Frede Blaabjerg, 2017).

2.4.1.1 Converter operation in DSTATCOM

A voltage-sourced converter (VSC) converts DC voltage into AC. VSCs provide precise control over the phase angle, magnitude, and frequency of the output AC voltage. They are the core component of DSTATCOMs and many other FACTS devices, with various converter concepts and topologies available.

As the direct current in a VSC can flow in both directions, the converter valves must be bidirectional. Additionally, because the DC voltage do not reverse, the turn-off devices do not require capability of reverse voltage. These types of turn-off devices are referred to as asymmetric turn-off devices. Traditional thyristor devices only turn-on control, relying on the current to naturally reach zero based on circuit and system conditions for turn-off.

While traditional thyristors lack active turn-off capability, devices like IGBTs, GTOs, MOS turn-off thyristor (MTOs), and IGCTs offer both turn-on and turn-off control. These turn-off devices, although more costly and with higher losses compared to thyristors, it allows converter concepts that can provide major system benefits in terms of cost and performance.

Voltage-sourced converter valves typically consist of an asymmetric turn-off device (like an IGBT or GTO) connected in parallel with a reverse-biased diode. On the DC side, a large capacitor supports the unipolar voltage. This capacitor must be able to handle the charging and discharging currents associated with the converter's switching sequence and phase angle shifts without significant voltage fluctuations. On the AC side, a coupling transformer or reactor isolates the DC capacitor from the AC system, preventing it from being short-circuited by a capacitive load like a transmission line. (Nan, 2018).

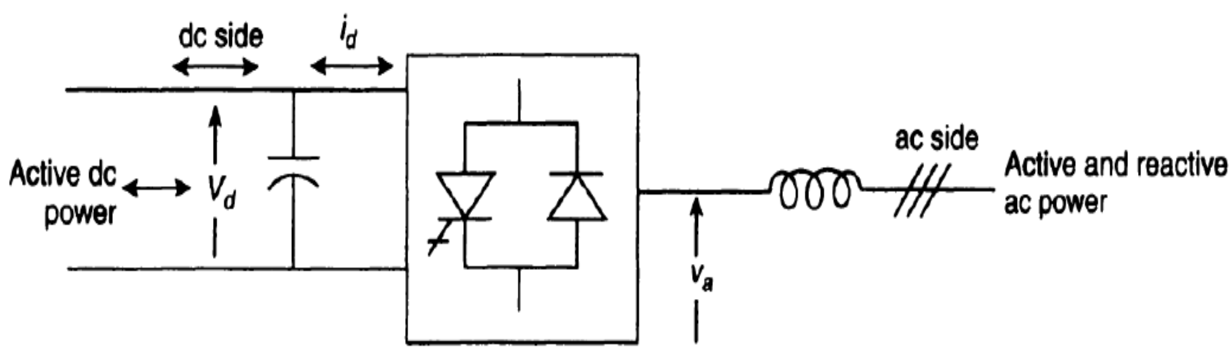

Figure 2.8 VSC operation

Two common converter topologies for DSTATCOM applications are multi-pulse and multi-level converters. Multi-pulse converters are created by combining multiple 6 pulse converters with phase shifting transformer and they are 12-pulse, 24-pulse, and 48-pulse. Multi-level converters, a more recent alternative, offer several advantages including improved waveforms, harmonic reduction, lower electromagnetic interference, and enhanced correction of power factor. Multi-level converters can be designed using flying capacitor diode-clamped, or cascaded H-bridge configurations. Furthermore, each switch can be controlled individually to robustly tackle the unbalanced load operations even in higher switching frequencies relatively to the multi-pulse configuration (Bjarne R. Andersen, Stig L. , 2020)

2.4.1.2 Multi-pulse Converters

Early DSTATCOM applications often used multi-pulse converters due to their lower losses and harmonic content. A basic 6-pulse VSC DSTATCOM configuration consists of six GTOs or other self-commutated devices like IGBTs, MCTs, or IGCTs, along with anti-parallel diodes. These switching devices enable the converter to generate balanced three-phase AC output voltages from a DC capacitor. The frequency of the output voltage is adjusted by the modulating frequency of GTO switches and the phase voltages are coupled to the AC grid through an interconnection transformer (R. Mohan, Rajiv K., 2002)

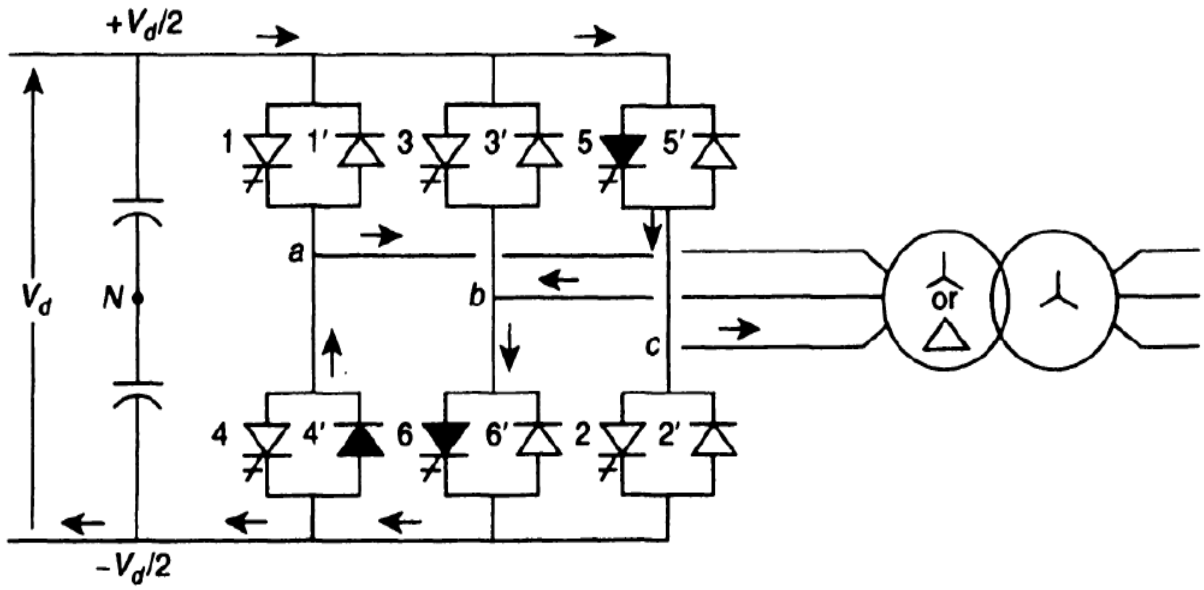

Figure 2.9 VSC DSTATCOM with 6-pulse

DSTATCOMs operate by synthesizing a staircase waveform through controlled DC voltage level generation. The sequential operation of valves, numbered 1 to 6, determines the waveform shape. A DSTATCOM comprises three phase legs that work in unison, each with a 120-degree phase shift. These phase legs works in square wave mode, where each valve are alternately closing for 180 degrees. It is depicted by the wave forms V_a, V_b and V_c as in the figure below. The square waves represent the AC bus voltages a, b, and c relative to the DC capacitor's midpoint, N. Note that peak voltages of $+V_d/2$ and $-V_d/2$ in the DC bus. The timing of the three phase legs is staggered by 120 degrees, similar to a 6-pulse converter.

Figure 2.11 illustrates the three phase-to-phase voltages of V_{ab}, V_{bc}, and V_{ca}, calculated as the differences between the individual phase voltages, where $V_{ab} = V_a - V_b$, $V_{bc} = V_b - V_c$, and $V_{ca} = V_c - V_a$. The phase-to-phase voltages exhibit a pulse width of 120 degrees and a peak magnitude of V_d. In case of two valves appearing on the same side of the DC bus are closed, phase-to-phase voltage becomes zero for 60 degrees. The switching of devices determines the AC bus voltage waveforms relative to the DC voltage, and the resulting current flow is a consequence of the interaction between the AC voltage and the AC system. Each phase leg of the converter can handle bidirectional current flow.

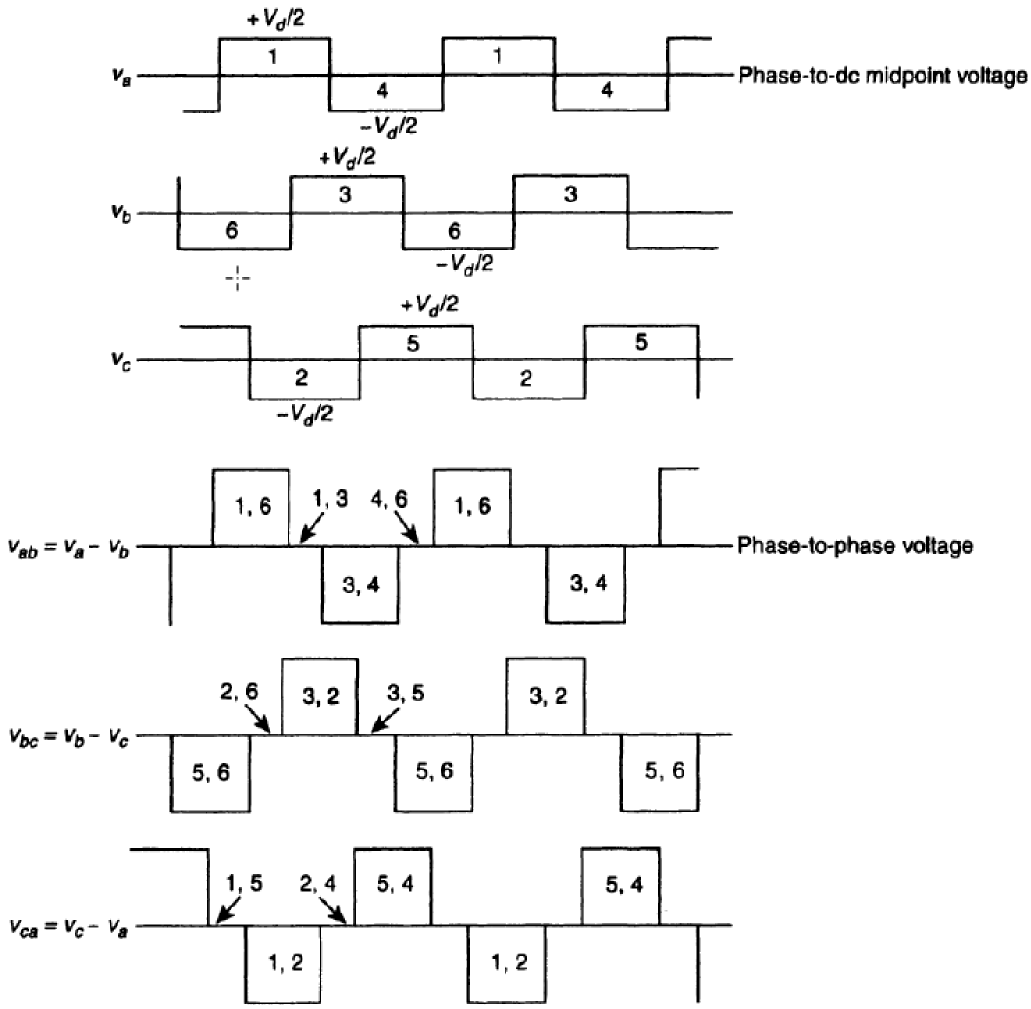

Figure 2.10 VSC Operation with three-phase full-wave *(Narain G. Hingorani, Laszlo Gyugyi, 2000)*

To examine the correlation between the AC waveform generated and the AC grid system, we focus on the independent operation of a one leg. This analysis allows us to understand the power flow dynamics. When power flows happens from the AC system toward the DC side, current in the voltage source converter (VSC) passes through the diode. Conversely, when power flows happens from the DC to the AC system, the current from the VSC flows through the turn off devices. Figure below illustrates the relationship between an AC current waveform and the corresponding generated AC voltage of a single phase-leg. The phase angle of the generated AC voltage is adjusted to showcase how the controlling of the waveform enables the regulation of power flow direction in DSTATCOM.

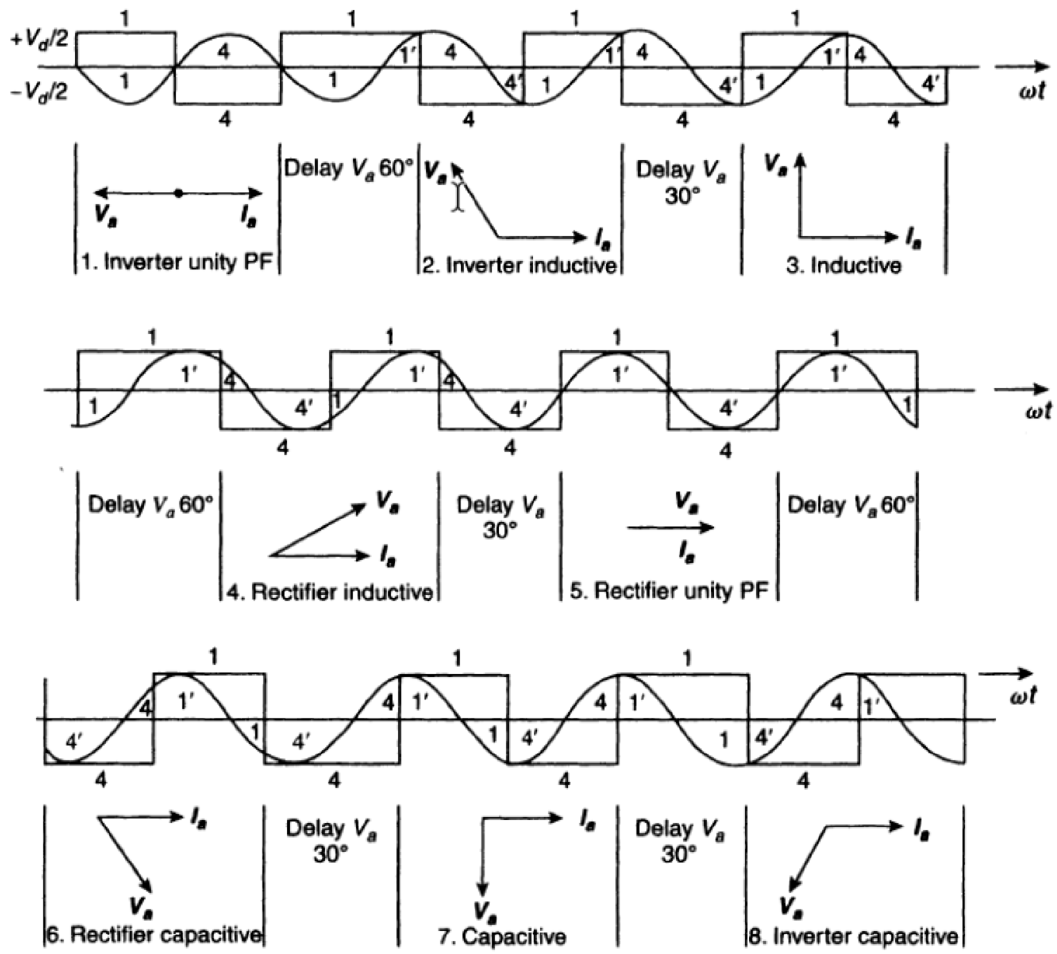

Figure 2.11 Phase-leg operation through four quadrants *(Narain G. Hingorani, Laszlo Gyugyi, 2000)*

In the first one-cycle segment, the phase leg functions as an inverter with a power factor of unity. Current flows exclusively through turn-off devices 1 and 4, while diodes remain non-conductive. The transfer of current in between turn-off devices takes place during natural current zero, a process referred to as soft switching. Soft switching reduces stress on the turn-off devices and minimizes switching losses as compared to switching at high current levels.

The phase angle is adjusted for the next one-cycle segment by delaying device 1 by 60 degrees, while device 4 is turned on earlier. As the current experiences change of polarity, it transfers from the turn-off device to its corresponding diode. This configuration results in inverter operation with the current lagging behind the voltage by 120 degrees, indicating the presence of inductive reactive power. During the switches in this part of the cycle turn off, the exhibit it smoothly. But when they turn on, they do so forcefully, causing a large voltage drop and significant energy loss. This happens when the current is at its highest.

By adding a delay of 30 degrees, the current lags behind the voltage by 90 degrees. This makes the VSC act like a pure inductor. Like before, the switches turn off smoothly but turn on hardly.

With an additional 60-degree delay, the VSC functions as a rectifier in an inductive mode, where the current lags behind the voltage by 30 degrees. A further 30-degree delay causes the VSC to operate as a rectifier with unity power factor. During this cycle, only diodes are active, and current naturally shifts between diodes when polarity reverses. This concludes the inductive modes of operation in the DSTATCOM.

A 60-degree delay shifts the Voltage Source Converter (VSC) into capacitive mode, allowing it to operate as a rectifier with the current leading the voltage. In contrast to inductive mode, turn-on occurs softly, whereas turn-off is hard. An extra 30-degree delay leads to pure capacitive operation. With another 30-degree delay, the VSC functions as an inverter in capacitive mode, encompassing all possible operating modes for a DSTATCOM.

It's important to highlight that the transition from pure inductive to pure capacitive mode requires a 180-degree phase delay. Moreover, due to losses in power devices and transformers, these losses must be supplied from the DC side during inverter operation or the AC side during rectifier operation. However, in full inductive or capacitive operation, losses can be supplied from either side by operating the system slightly in rectifier or inverter mode.

To analyze the harmonic content of the generated AC waveform in power electronics-based devices connected to the grid, it's crucial to examine the Fourier transform of the voltage waveforms:

$$V_a = \frac{4}{\pi}\left(\frac{V_d}{2}\right) \left[\cos(\omega t) - \frac{1}{3}\cos(3\omega t) + \frac{1}{5}\cos(5\omega t) - \frac{1}{7}\cos(7\omega t) + \ldots\right] \quad (2.1)$$

These equations will help identify and quantify the harmonic components present in the generated AC voltage

Where V_b is obtained by replacing ωt by (ωt-2π/3), and V_c is obtained by replacing ωt by (ωt+2π/3). All 3n harmonics (3rd, 9th, 15th, etc.) are in phase. Due to the floating AC neutral, it's essential to calculate phase-to-neutral voltages across the transformer secondaries. Assuming a wye transformer secondary with a floating neutral, the neutral acquires a voltage relative to the hypothetical DC midpoint. Applying Kirchhoff's current law to the three phases reveals that this voltage equals ($V_a + V_b + V_c$)/3. Figure 2.13 illustrates that V_n is a square wave with a magnitude of $V_d/6$ and a frequency three times the fundamental frequency, containing all 3n harmonics of the terminal voltages.

In order to determine the phase voltages across the secondary of the transformer, the value of V_n is subtracted from each phase V_a, V_b and V_c. The outcome, as described in equation 2.2 is illustrated in figure 2.13. This figure represents only the V_{an} component which exhibits a waveform composed of steps with and amplitude of $V_d/3$. This waveform is from 3n harmonics, and instead, it contains harmonics of the form $6n\pm1$ (such as the 5th, 7th, 1th, 13th, etc.). The waveforms V_{bn} and V_{cn} are similar to V_{an}, with the only difference being a phase shift of 120° and 240° from V_{an}, respectively. It is important to highlight that the phase-to-neutral voltages of the transformer remain aligned with the phase-to-DC midpoint voltages, but they no longer contain the 3n harmonics.

2.5 Literature Review

The work of this study is necessarily based on what has been already done by other researchers on topics related to the work. So as to look in to works of these scholars and get necessary and important information related to the topic; different literature will be referred from different available sources such as books, papers, journals, internets, and others.

In this section, a review of related literature focusing on the mechanically switched capacitor bank and application of fuzzy logic controller for power quality are reviewed. Additionally, a literature on modelling fuzzy logic based DSTATCOM are also reviewed.

(R. C. , D. O. Lacerda., 2010)The paper discusses the application, design, and protection of the Mechanically Switched Capacitor with Damping Network (MSCDN), which is a cost-effective solution for reactive compensation and harmonic control in transmission systems. It provides relevant information and recommendations for specifying the filter components, including the use of harmonic filters, component parameters, and protection relays.The paper does not provide any analysis or evaluation of the performance or efficiency of the MSCDN system, nor does it discuss any potential challenges or limitations that may arise in different operating conditions or scenarios.

(A. L. de Oliveira, A. L. Pereira., 2010)The paper discusses the application of Mechanically Switched Capacitors (MSCs) in Power Transmission Systems, highlighting theirrole in stabilizing system voltage, improving power factor, and reducing voltage fluctuations caused by load variations and disturbances. The paper also emphasizes the importance of MSCsin maintaining system stability under fault conditions and reducing voltage dips caused by network disturbances. The paper does not discuss the specific limitations of the MSCs or the challenges faced in their application in Power Systems.

(Amoozegar.D, 2016) Presents a novel and robust control strategy for a power quality device called D-STATCOM, which can improve the reactive power compensation and damping of power systems. The article shows that the fuzzy -PI controller provides a better response in changes of reference reactive current and eliminates the steady state error, without requiring a complex mathematical model of the system.

(Prerna.J, R. J, 2021) Proposes a fuzzy logic controller (FLC) based distributed static compensator (DSTATCOM) to improve the power quality in a distributed generation (DG) system that uses renewable energy sources such as solar, wind and biomass. D-STATCOM is a shunt connected device that can regulate the voltage and current by generating or absorbing reactive power. It can correct power quality issues like as harmonics, unbalance, and voltage sags or swells. The paper uses a fuzzy inference system to control the reference current of the D-STATCOM based on the error and change of error between the output and reference signals. The paper presents the mathematical equations and parameters for the proposed system, and shows the simulation results using MATLAB/Simulink. The paper demonstrates that the proposed system can effectively mitigate the voltage sags and harmonicsin the DG system under different fault conditions, and improve the voltage profile, stability, andreliability.

(Arati, Dr. G.. Jayaramaiah, 2022) The paper introduces a distribution static compensator (DSTATCOM) to address power quality issues in an electrical network, specifically related to non-linear and unbalanced loads. The performance of the electrical network is compared underthe Proportional Integral (PI) controller and the Fuzzy Logic Controller (FLC) in terms of powerquality improvement. The paper does not discuss the impact of the proposed FLC-based controlstrategy on other aspects of the electrical network, such as system stability or efficiency.

(Garima S, Pankaj.K , Sudhir .K, 2018) The paper compares fuzzy logic and PI controllers for regulating the DC output voltage of a shunt active power filter. The simulation results show that the fuzzy logic controller and PI controller successfully control the dc output voltage of the shunt active powerfilter, resulting in harmonic reduction and improved power quality in the presence of nonlinearloads. The paper does not provide any comparative analysis or evaluation of the proposed controller strategies with other existing methods or techniques for power quality control.

(T. Varadharaj, S. Krishna.K, 2014) The paper proposes a fuzzy logic-based supervision ofa PI regulator to regulate the DC capacitor voltage and improve transient performance during load changes. Additionally, the paper aims to reduce harmonic content of the load current belowthe standard value. The paper does not provide a detailed analysis of the performance of the proposed fuzzy logic-based supervision and its effectiveness in improving transientperformance of the DC link during load changes.

(C.S. Sai , K.Harinath, P.Suresh Babu, 2014) The paper aims to improve thequality of power distribution systems by using a Distributed Static Compensator (D-STATCOM) with a fuzzy controller. The proposed approach is found to be effective in enhancing power quality in distribution systems as revealed by extensive simulations conducted in Matlab's SIMULINK. The paper does not provide any comparative analysis or evaluation of the proposedapproach against other existing methods or technologies for power quality enhancement in distribution systems.

From the reviewed literature, studies focus on various techniques for improving power quality, particularly focusing on DSTATCOM and mechanically switched capacitor bank. They lack comprehensive performance evaluations or comparisons with conventional methods. Additionally, there is a limited exploration of the real world application of these systems in specific contexts, such as the unique challenges faced by the Bishoftu No 3 substation. By implementing a tailored FLC based DSTATCOM solution, this thesis aims to fill these gaps by assessing on voltage stability and reactive power compensation, and evaluating its effectiveness against the mechanically switched capacitor bank. Furthermore, the research will investigate the adaptability of the fuzzy logic controller in dynamic operational conditions, contributing to a deeper understanding of its potential in enhancing power quality in the substation.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

This chapter provides a comprehensive explanation of the materials and methodologies employed in the development of the systems model.

This work has a target of analyzing the effect fuzzy logic based DSTATCOM as a replacement for mechanically switched capacitor on the power quality at a selected substation of Bishoftu No3 substation. The substation is supplied by a 400KV transmission line from Gelan substation. This 400KV is further reduced to 230 KV voltage level and transmitted to a nearby substation. And also this 230KV is further reduced to 33KV and 15KV to supply a surrounding community and industries. There are a total of ten 15KV outgoing feeder which is feed by two transformer of a capacity of 50MVA in which each transformer feeds five feeders. The following figure depicts the configuration of the substation.

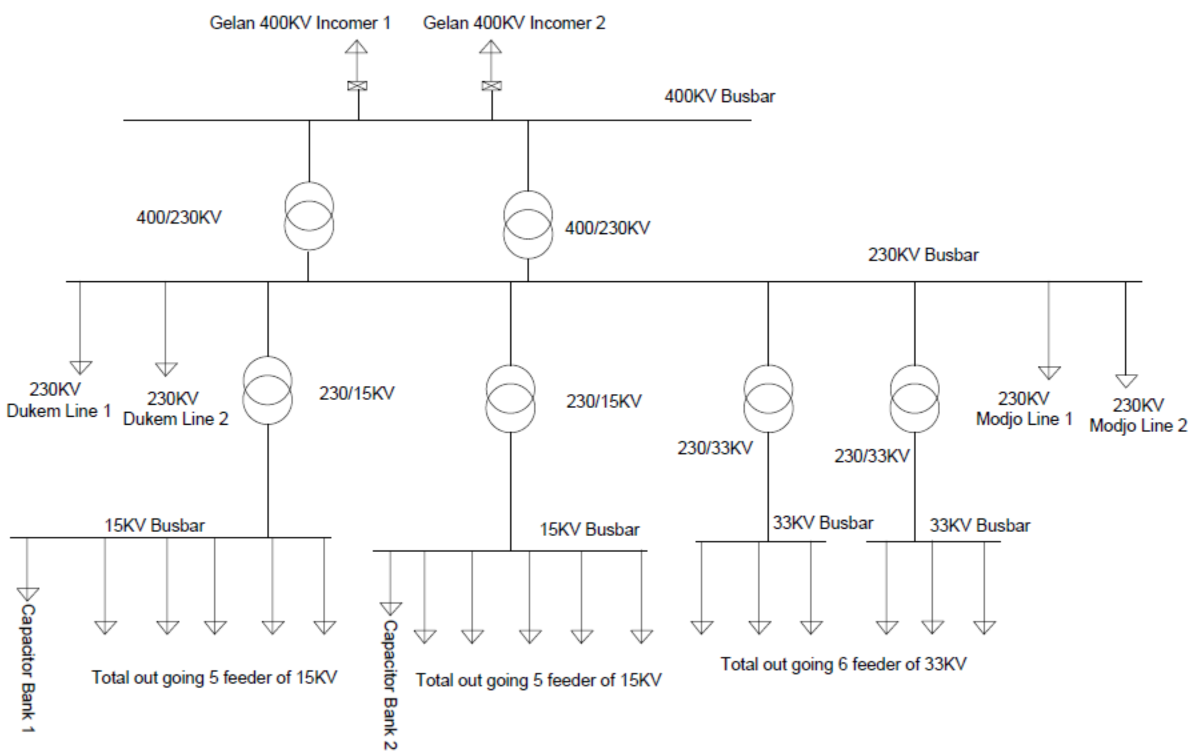

Figure 3.1 SLD of Bishoftu No3 Substation

A mechanically switched capacitor bank is connected to a busbar of 15KV to compensate for reactive power and power factor correction. The switching mechanism of the capacitor bank is a mechanical system which is known for its cost effective but has also a drawback in using for a multiple time of switching to compensate the varying load nature.

3.1.1 Software Tools

To achieve the goal of this thesis, various software tools are used. Primarily, by taking into account existing configuration, an AutoCAD software is used to depict the single line diagram of the substation. Subsequently, a Matlab/Simulink software tool is used to simulate the designed mechanically switched capacitor bank and also the proposed system Fuzzy logic based DSTATCOM. For the proposed system a fuzzy toolbox from Matlab is used to realize the control system. Finally all this document is arranged and grouped together in an understandable way using Microsoft software.

Steps followed in the process of accomplishing this thesis work is as follows:

To accomplish the objective of this thesis, the following methods are applied:

Step 1: Data Collection for the substation under consideration which is Bishoftu No3 Substation which includes transformer data, number of feeders,

Step 2: Studying of the power quality mitigating techniques currently employed at the substation, which is a mechanically switched capacitor bank.

Step 3: Modelling of the mechanically switched capacitor bank.

Step 4: Studying of the response of the system by switching in the capacitor bank

Step 5: Modelling of the proposed fuzzy logic based DSTATCOM

Step 6: Analyzing the response of the proposed system

Step 7: Making conclusion based on the result obtained

3.2 Methods

3.2.1 Modelling of Mechanically Switched Capacitor Bank

Capacitor banks at the substation is connected in shunt through mechanically switched circuit breaker to a busbar of 15KV. Its target is to compensate the reactive power demand of load and correcting the power factor. The main components used in the connection are vacuum switches, current transformer (CT), series reactor and capacitor bank.

i) Vacuum Switches: offer an optimal switching environment for capacitors, providing the necessary high dielectric strength to prevent arcing and ensure reliable operation. It switches in and out between capacitor banks.

ii) Current Transformer: are applied to measure the current through the shunt capacitor bank. A relay is used with it.

iii) Series Reactor: is used to limit the inrush current and protects the capacitor bank.

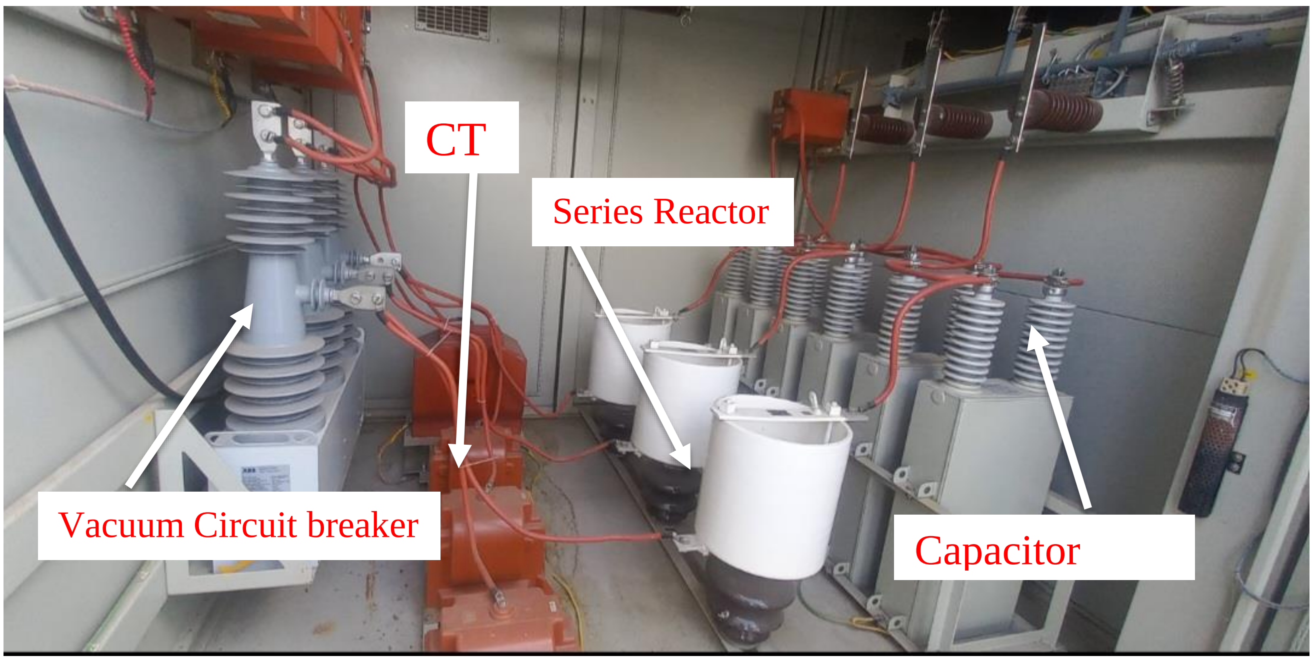

Figure 3.2 Mechanically Switched Capacitor Bank (Source: Substation)

3.2.1.1 Matlab Model of MSC

By considering the configuration and the component of the existing capacitor bank, it is modelled as follows

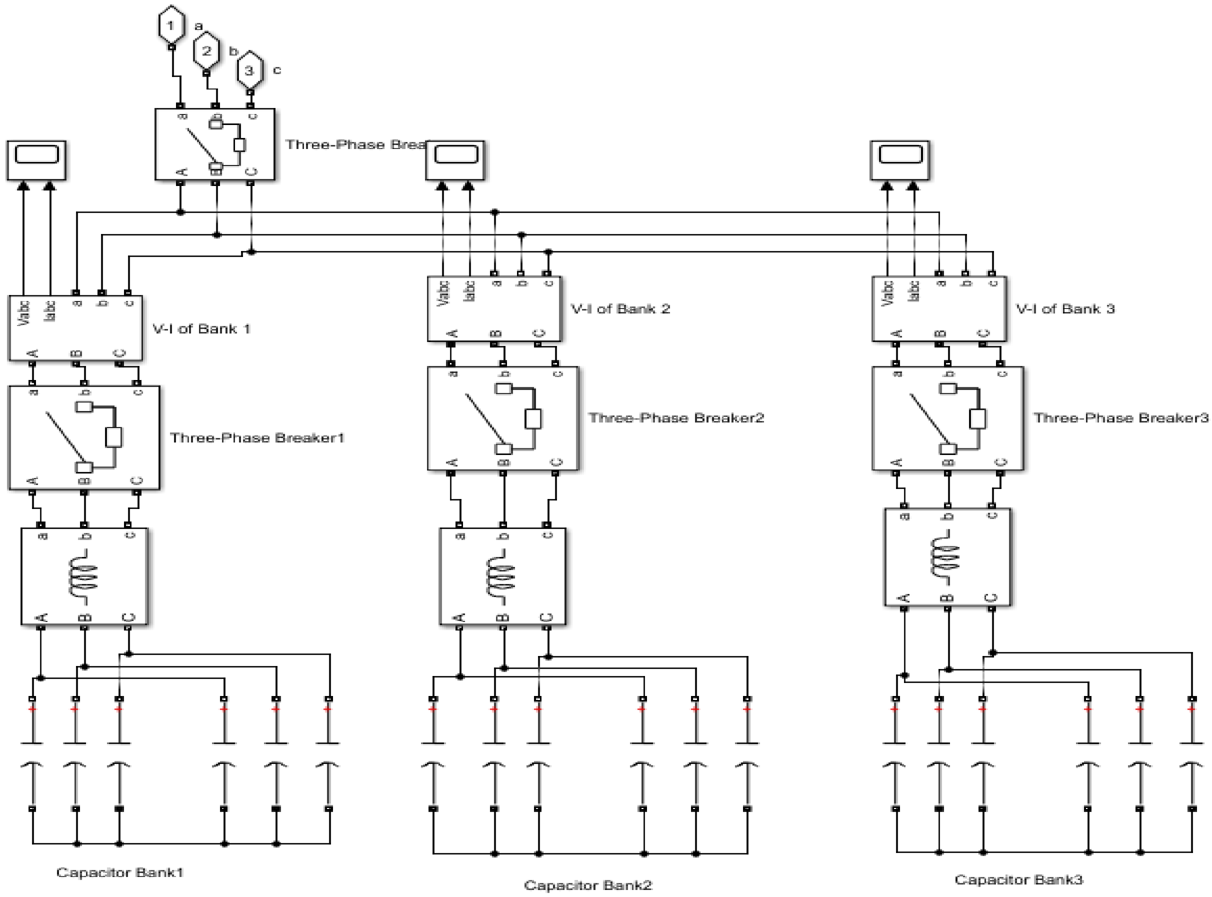

Figure 3.3 Matlab model of the Capacitor Bank

3.2.2 Mathematical Modelling of DSTATCOM

To analyze DSTATCOM dynamics and formulate a mathematical model using state-space equations, we'll simplify the design process by converting the three-phase model into α-β coordinate system and then then into the rotating d-q coordinate system. In the subsections, we will explain how to derive the three-phase model for both the AC and DC sides of the DSTATCOM, and then how to change it into d-q rotating coordinates for designing the controller.

3.2.2.1 Mathematical Model of Three Phase DSTATCOM

The main part of a DSTATCOM is a VSC connected to the distribution busbar via a coupling reactance. The equivalent circuit of a DSTATCOM is shown in the figure below. The DSTATCOM can be modeled as an AC voltage source with controllable magnitude, phase, and frequency. In a derivation that follows, we'll use a per-unit (pu) system, with i_B and v_B as the base values and ω_B as the angular frequency of the system frequency.

$i'_{pa}=\frac{i_{pa}}{i_B}$ $i'_{pb}=\frac{i_{pb}}{i_B}$ $i'_{pc}=\frac{i_{pc}}{i_B}$

$v'_{pa}=\frac{v_{pa}}{v_B}$ $v'_{pb}=\frac{v_{pb}}{v_B}$ $v'_{pc}=\frac{v_{pc}}{v_B}$

$v'_{ia}=\frac{v_{ia}}{v_B}$ $v'_{ib}=\frac{v_{ib}}{v_B}$ $v'_{ic}=\frac{v_{ic}}{v_B}$

$z_B=\frac{v_B}{i_B}$ $L'_p=\frac{\omega_B L_p}{Z_B}$ $R'_p=\frac{R_p}{Z_B}$

$v'_{dc}=\frac{v_{dc}}{v_B}$ $i'_{dc}=\frac{i_{dc}}{i_B}$ $C'=\frac{1}{Z_B C\omega_B}$ $R'_c=\frac{R_c}{Z_B}$

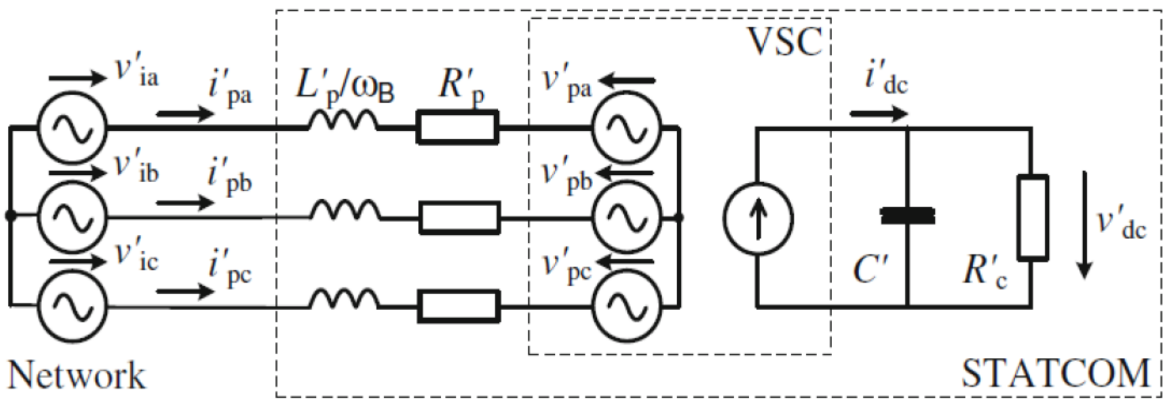

Figure 3.4 DSTATCOM equivalent circuit

As shown in the DSTATCOM circuit, the device is modelled as a voltage source (voltages v'_{pa},v'_{pb},v'_{pc}) connected to the network through the inductance L'_p/ω_B and the resistance R'_p which represents the coupling circuit losses. The DSTATCOM current is denoted as i'_p. The DC circuit is modeled as a current source (i'_{dc}) connected to the capacitor C' and the resistance R'_c. The resistance R'_c accounts for losses in the semiconductor. Using the three-phase equivalent circuit illustrated in Figure 3.1, we can formulate differential equations for the DSTATCOM currents. The disparity between the network voltages (via', vib', $'$) and the DSTATCOM voltages (vpa', vpb', vpc') will result in the DSTATCOM current (ipa', ipb', ipc') flowing through the coupling circuit

$$\frac{d}{dt}\begin{bmatrix} i'_{pa} \\ i'_{pb} \\ i'_{pc} \end{bmatrix}=\frac{-R'_p\omega_B}{L'_p}\begin{bmatrix} i'_{pa} \\ i'_{pb} \\ i'_{pc} \end{bmatrix}+\frac{\omega_B}{L'_p}\begin{bmatrix} (v'_{ia}-v'_{pa}) \\ (v'_{ib}-v'_{pb}) \\ (v'_{ic}-v'_{pc}) \end{bmatrix} \quad (3.1)$$

For an accurate modelling of DSTATCOM, the DC side circuit must also be characterized, as the

DC side voltage is not entirely constant. The DC side current can be expressed as

$$i'_{dc} = \frac{1}{\omega_B C'}\frac{d\,v'_{dc}}{dt}+\frac{v'_{dc}}{R'_c} \tag{3.2}$$

To describe the relationship between the AC and DC sides, we can examine the instantaneous power of VSC. Namely, the instantaneous power on the DC side of the converter is always equal to the power on the AC side:

$$v'_{dc}i'_{dc} = v'_{pa}i'_{pa} + v'_{pb}i'_{pb} + v'_{pc}i'_{pc} \tag{3.3}$$

The connection between the VSC AC and DC side voltages can be described with the switching function (signals S_a, S_b, S_c), describing the generation of AC voltages from DC voltage:

$$\begin{bmatrix} v'_{pa} \\ v'_{pb} \\ v'_{pc} \end{bmatrix} = K_p \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} v'_{dc} \tag{3.4}$$

The factor K_p is dependent on the type of converter. Although it can be excluded from the derivations, including it allows for consideration of different converter topologies with varying DC-side to AC-side voltage amplitude ratios. Considering equations (3.3) and (3.4), we obtain the expression for the DC-side current:

$$i'_{dc} = K_p S_a i'_{pa} + K_p S_b i'_{pb} + K_p S_c i'_{pc} \tag{3.5}$$

The DC current in equation (3.5) is incorporated into equation (3.2), offering a comprehensive description of the DC-side circuit. Below is the complete set of equations detailing the operation of the DSTATCOM, including the DC-side circuit. The equivalent block diagram of the three-phase DSTATCOM model is presented in Figure 3.2.

$$\frac{d}{dt}\begin{bmatrix} i'_{pa} \\ i'_{pb} \\ i'_{pc} \\ v'_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R'_p\omega_B}{L'_p} & 0 & 0 & -\frac{k_p\omega_B}{L'_p}S_a \\ 0 & -\frac{R'_p\omega_B}{L'_p} & 0 & -\frac{k_p\omega_B}{L'_p}S_b \\ 0 & 0 & -\frac{R'_p\omega_B}{L'_p} & -\frac{k_p\omega_B}{L'_p}S_c \\ k_p\omega_B C' S_a & k_p\omega_B C' S_b & k_p\omega_B C' S_c & -\frac{\omega_B C'}{R'_c} \end{bmatrix} \begin{bmatrix} i'_{pa} \\ i'_{pb} \\ i'_{pc} \\ v'_{dc} \end{bmatrix} + \frac{\omega_B}{L'_p}\begin{bmatrix} v'_{ia} \\ v'_{ib} \\ v'_{ic} \\ 0 \end{bmatrix} \tag{3.6}$$

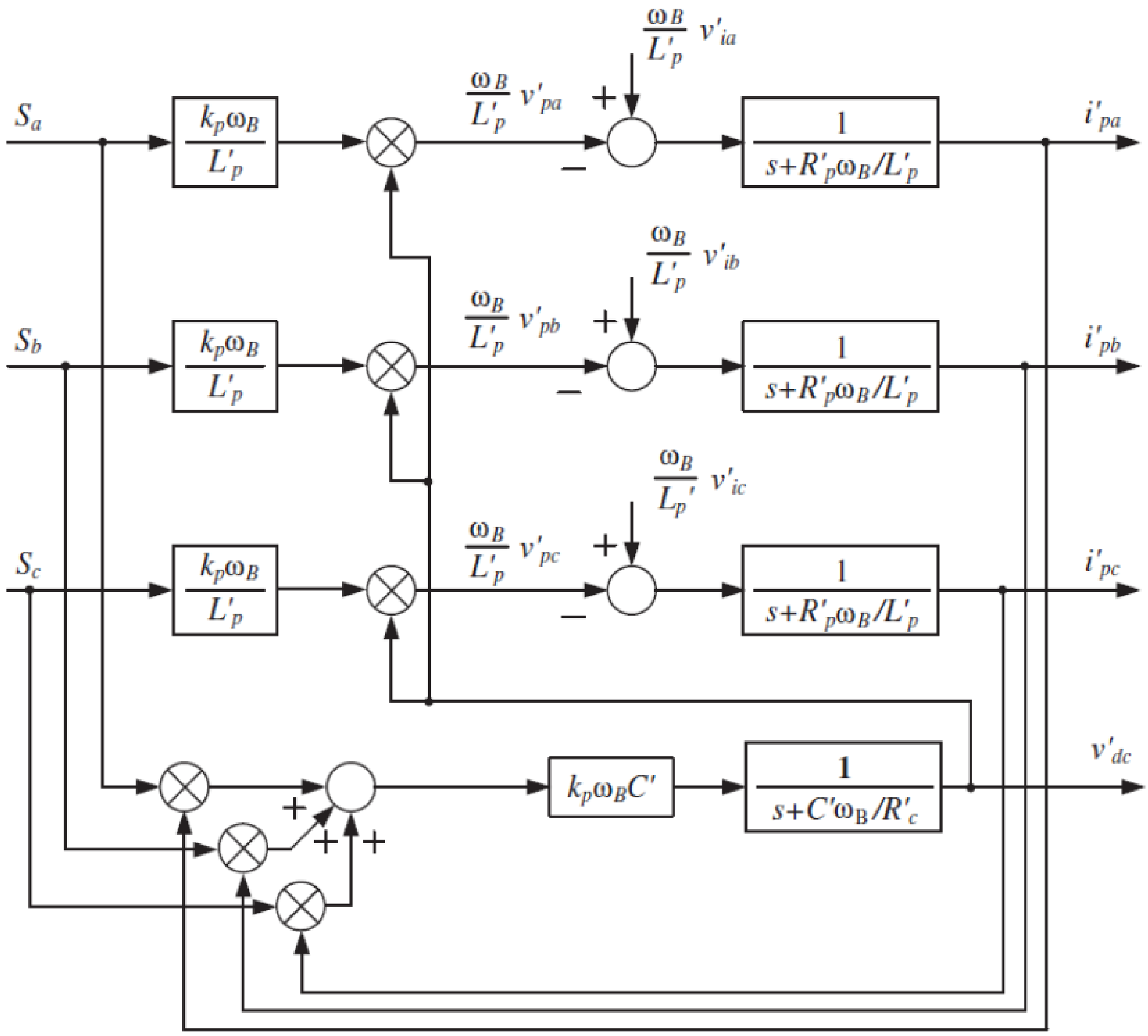

Figure 3.5 Mathematical model block diagram of the three-phase DSTATCOM

3.2.2.2 α-β Coordinate System Mathematical Model

The main goal of creating a system model is to design a controller. So, we need to make the model as simple as possible while still being helpful for designing the controller. To make the DSTATCOM work really well, its control system needs to follow a specific kind of wave called a sinusoidal reference input.

Based on the three-phase system model we created earlier, a controller that can follow three sinusoidal reference inputs without having big errors would need to be quite complex and might be difficult to use. Also, we would need three separate control loops for each phase.

A common approach to simplify system models for various power system control tasks is to derive the mathematical model in the α-β coordinate system rather than the three-phase phasor representation.

A common way to make system models easier to work with for different power system control tasks is to create the mathematical model using the α-β coordinate system instead of the three-phase phasor representation.

$$f_a(t) = \hat{f}\cos(\omega t + \theta_0) \quad (3.7)$$

$$f_b(t) = \hat{f}\cos(\omega t + \theta_0 - \frac{2\pi}{3}) \quad (3.8)$$

$$f_c(t) = \hat{f}\cos(\omega t + \theta_0 - \frac{4\pi}{3}) \quad (3.9)$$

Here $\hat{f}$ is the amplitude, θ_0 is the initial phase angle, and ω the angular frequency, respectively. For this three-phase sinusoidal function, the three components can be represented in a space phasor form expressed as,

$$\vec{f}(t) = \frac{2}{3}\left[e^{j0}f_a(t) + e^{\frac{j2\pi}{3}}f_b(t) + e^{\frac{j4\pi}{3}}f_c(t)\right] \quad (3.10)$$

$$\vec{f}(t) = (\hat{f}e^{j\theta_0})\, e^{j\omega t} = \underline{f}e^{j\omega t} \quad (3.11)$$

Where $f = \hat{f}\, e^{j\theta_0}$.

The complex quantity f is represented as a vector in the complex plane. When $\hat{f}$ is constant, this vector is similar to the conventional phasor used in the analysis of linear circuits under steady-state sinusoidal conditions. In this case, the tip of $\hat{f}(t)$ moves along the circumference of a circle centered at the origin of the complex plane (see Figure 3.6).

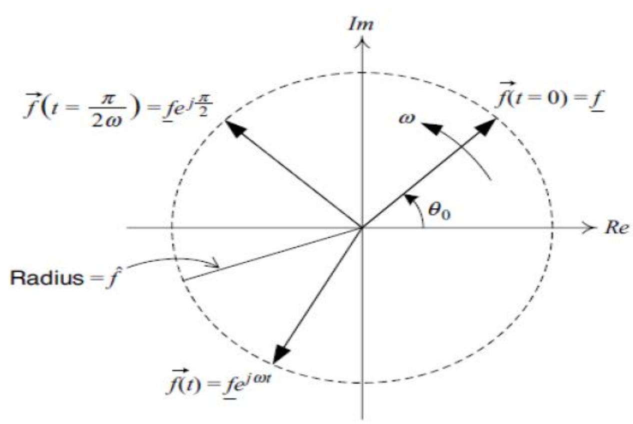

Figure 3.6 Complex plane representation of space phasor

Clarke transformation involves decomposing the given space phasor $\vec{f}(t)$ into its real and imaginary components, as illustrated in Figure 3.7. This process translates the three-phase quantities from the three-phase reference frame to a two-axis orthogonal stationary reference frame

$$\vec{f}(t) = f_\alpha(t) + jf_\beta(t) \tag{3.12}$$

Substituting (3.12) into (3.11) and equating the corresponding real and imaginary parts of both sides of the resulting equation, we deduce

$$\begin{bmatrix} f_\alpha(t) \\ f_\beta(t) \end{bmatrix} = \frac{2}{3} C \begin{bmatrix} f_a(t) \\ f_b(t) \\ f_c(t) \end{bmatrix} \tag{3.13}$$

Where

$$C = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{3.14}$$

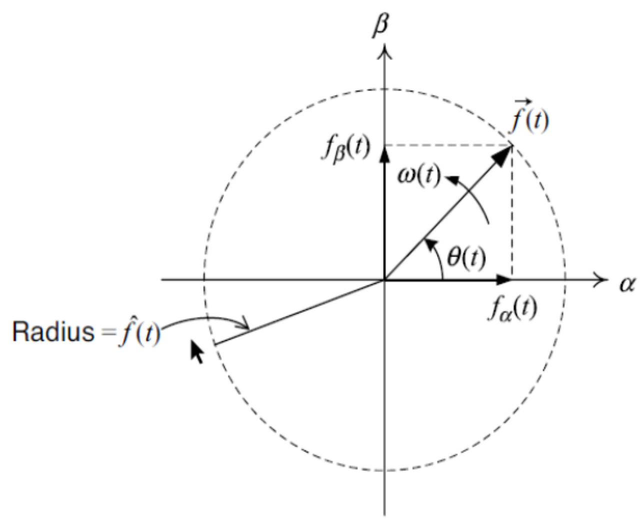

Figure 3.7 Representation of α-β frame in space phasor

Applying (3.13) to the three-phase model (3.1) yields the DSTATCOM AC side mathematical model in the α-β frame:

$$\frac{d}{dt}\begin{bmatrix} i'_{p\alpha} \\ i'_{p\beta} \end{bmatrix} = \begin{bmatrix} -\frac{R'_p\omega_B}{L'_p} & 0 \\ 0 & -\frac{R'_p\omega_B}{L'_p} \end{bmatrix}\begin{bmatrix} i'_{p\alpha} \\ i'_{p\beta} \end{bmatrix} + \frac{\omega_B}{L'_p}\begin{bmatrix} v'_{i\alpha} - v'_{p\alpha} \\ v'_{i\beta} - v'_{p\beta} \end{bmatrix} \tag{3.15}$$

The zero sequence component has been omitted due to the three phase, three wire DSTATCOM topology. To incorporate the DC side circuit into the mathematical model, expressions (3.4) and (3.5) are transformed into α-β frame equations.

$$v'_{p\alpha} = K_p S_\alpha v'_{dc} \tag{3.16}$$

$$v'_{p\beta} = K_p S_\beta v'_{dc} \tag{3.17}$$

$$i'_{dc} = \frac{3}{2}(K_p S_\alpha i'_{p\alpha} + K_p S_\beta i'_{p\beta}) \tag{3.18}$$

The complete set of equations in α-β coordinates describing DSTATCOM model is given below.

$$\frac{d}{dt}\begin{bmatrix} i'_{p\alpha} \\ i'_{p\beta} \\ v'_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R'_p\omega_B}{L'_p} & 0 & -\frac{k_p\omega_B}{L'_p}S_\alpha \\ 0 & -\frac{R'_p\omega_B}{L'_p} & -\frac{k_p\omega_B}{L'_p}S_\beta \\ \frac{3k_p\omega_B C'}{2}S_\alpha & \frac{k_p\omega_B C'}{2}S_\beta & -\frac{\omega_B C'}{R'_c} \end{bmatrix}\begin{bmatrix} i'_{p\alpha} \\ i'_{p\beta} \\ v'_{dc} \end{bmatrix} + \frac{\omega_B}{L'_p}\begin{bmatrix} v'_{ia} \\ v'_{ib} \\ v'_{ic} \\ 0 \end{bmatrix} \tag{3.19}$$

3.2.2.3 d-q Rotating Coordinate System mathematical model

The Clarke transformation makes the three-phase mathematical model of a DSTATCOM simpler by changing it into a two-axis α-β coordinate system. This makes the control system design easier because we only need two control loops instead of three. However, the wave-like nature of the reference, feedback, and feed-forward signals in the original three-phase system can make the compensator designs complicated if we want good performance and small errors. By changing the mathematical model and controller design into the rotating d-q coordinate system, we can solve these problems.

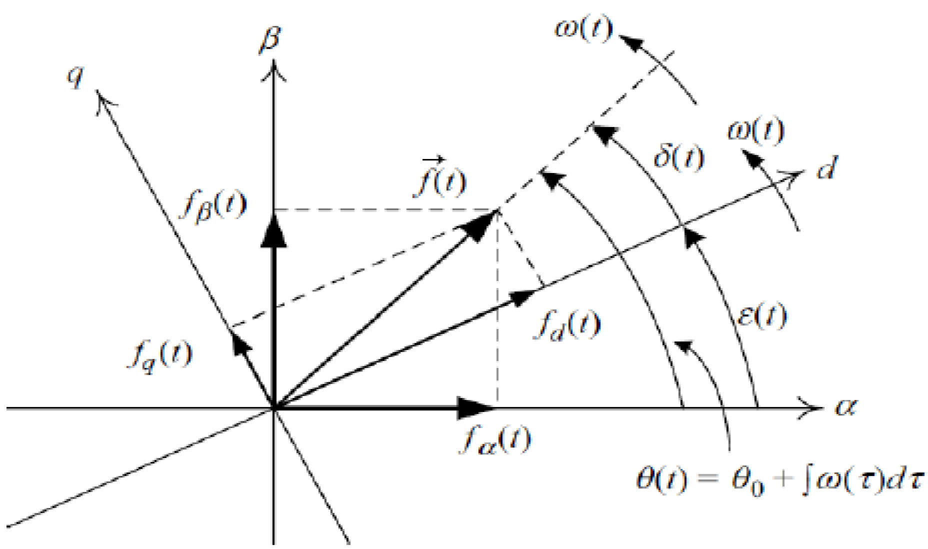

Figure 3.8 d-q rotating coordinate systems

The rotating d-q coordinate system, known as the Park transformation, was developed by Robert H. Park. This coordinate system is based on the concept of $\alpha - \beta$ rotating axes that align with a space phasor at the same angular speed. The d-axis represents one of these rotating axes, as illustrated in Figure 3.5. Because the coordinate system rotates at the same frequency as the space phasor, the d-component and q-component values remain constant over time, effectively becoming DC quantities. For a given space phasor $\vec{f} = f_\alpha(t) + jf_\beta(t)$, the transformation from the $\alpha - \beta$ coordinate system to the d-q coordinate system is defined by

$$f_d + jf_q = \left(f_\alpha + jf_\beta\right)e^{-j\varepsilon(t)} \quad (3.20)$$

Its equivalent to a phase shift in $\vec{f}(t)$ by the angle -$\varepsilon(t)$. To see the usefulness given by (3.20), assume that $\vec{f}$ has the following form:

$$\vec{f}(t) = f_\alpha + jf_\beta = \hat{f}(t)\, e^{-j[\theta_0 + \int \omega(\tau)d\tau]} \quad (3.21)$$

Where $\omega(\tau)$ is the frequency and θ_0 is the initial phase angle of the three-phase signal corresponding to $\hat{f}(t)$. If $\varepsilon(t)$is chosen as

$$\varepsilon(t) = \varepsilon_0 + \int \omega(\tau)d\tau \quad (3.22)$$

Then based on (3.20), the d-q coordinate system representation of $\vec{f}(t)$ becomes

$$f_d + jf_q = \hat{f}(t)\, e^{j(\theta_0 - \varepsilon_0)} \quad (3.23)$$

This system is stationary and, as a result, the constituent of its corresponding three-phase signal are DC quantities. Highlight that $\theta(t)$ and $\varepsilon(t)$are not necessarily equal, but $\frac{d\theta\,(t)}{dt} = \frac{d\varepsilon(t)}{dt}$ must be ensured (usually by using Phase locked Loop). Using Euler's identity $e^{-j(.)} = \cos(.) + j\sin(.)$, (3.20) can be written as

$$\begin{bmatrix} f_d(t) \\ f_q(t) \end{bmatrix} = R[\,\varepsilon(t)] \begin{bmatrix} f_\alpha(t) \\ f_\beta(t) \end{bmatrix} \quad (3.24)$$

Where,

$$R[\,\varepsilon(t)] = \begin{bmatrix} \cos\varepsilon(t) & \sin\varepsilon(t) \\ -\sin\varepsilon(t) & \cos\varepsilon(t) \end{bmatrix} \quad (3.25)$$

A direct way of transforming the three phase coordinate system into the rotating d-q coordinate system can be found by substituting (3.13) in (3.23)

$$\begin{bmatrix} f_d(t) \\ f_q(t) \end{bmatrix} = \frac{2}{3}\mathbf{T}[\varepsilon(t)] \begin{bmatrix} f_a(t) \\ f_b(t) \\ f_c(t) \end{bmatrix} \tag{3.26}$$

$$\mathbf{T}[\varepsilon(t)] = R[\varepsilon(t)]\mathbf{C} = \begin{bmatrix} \cos\ \varepsilon(t) & \cos\ (\varepsilon(t) - \frac{2\pi}{3}) & \cos\ (\varepsilon(t) - \frac{4\pi}{3}) \\ \sin\ \varepsilon(t) & \sin\ (\varepsilon(t) - \frac{2\pi}{3}) & \sin\ (\varepsilon(t) - \frac{4\pi}{3}) \end{bmatrix} \tag{3.27}$$

Now to transform the mathematical model presented in (3.5) into the d-q synchronous frame we use the transformation matrix (3.26). The zero sequence component is excluded, as a three wire DSTATCOM cannot generate zero sequence currents.

$$\mathbf{T_{dq}} = \frac{2}{3} \begin{bmatrix} \cos\ (\omega t) & \cos\ (\omega t - \frac{2\pi}{3}) & \cos\ (\omega t + \frac{2\pi}{3}) \\ -\sin\ (\omega t) & -\sin\ (\omega t - \frac{2\pi}{3} & -\sin\ (\omega t + \frac{2\pi}{3} \end{bmatrix} \tag{3.28}$$

Applying the transformation, yields the following mathematical model of the DSTATCOM's AC side

$$\frac{d}{dt} \begin{bmatrix} i'_{pd} \\ i'_{pq} \end{bmatrix} = \begin{bmatrix} -\frac{R'_p \omega_B}{L'_P} & \omega \\ -\omega & -\frac{R'_p \omega_B}{L'_P} \end{bmatrix} \begin{bmatrix} i'_{pd} \\ i'_{pq} \end{bmatrix} + \frac{\omega_B}{L'_P} \begin{bmatrix} v'_{id} - v'_{pd} \\ v'_{iq} - v'_{pq} \end{bmatrix} \tag{3.29}$$

The DC side current equation is already represented in (3.6). To the calculate the DC side current, we again use the power balance equation, this time expressed in the d-q coordinate system as follows:

$$v'_{dc} i'_{dc} = \frac{3}{2}(v'_{pd} i'_{pd} + v'_{pq} i'_{pq}) \tag{3.30}$$

The relation between the AC and DC side voltages is expressed in (3.31) in the d-q frame. Where S_d And $S_q$represent the switching function. The factor $k_p$is dependent upon the converter type.

$$\begin{bmatrix} v'_{pd} \\ v'_{pq} \end{bmatrix} = k_p \begin{bmatrix} S_d \\ S_q \end{bmatrix} v'_{dc} \tag{3.31}$$

The relation between AC and DC currents, taking into account (3.30) and (3.31), is given in (3.32) as:

$$i'_{dc} = \frac{3}{2}(k_p S_d i'_{pd} + k_p S_d i'_{pq}) \tag{3.32}$$

The overall mathematical model in the d-q coordinate system is presented in (3.33). The constant ω represents the angular speed of the fundamental frequency voltage component. Since the d-q transformation is frequency-dependent, the derived mathematical model is applicable solely to the fundamental component. Figure 3.9 illustrates the block diagram of the DSTATCOM model in the rotating d-q frame.

$$\frac{d}{dt}\begin{bmatrix} i'_{pd} \\ i'_{pq} \\ v'_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R'_p\omega_B}{L'_P} & \omega & -\frac{k_p\omega_B}{L'_p}S_d \\ -\omega & -\frac{R'_p\omega_B}{L'_P} & -\frac{k_p\omega_B}{L'_p}S_q \\ \frac{3k_p\omega_B C'}{2}S_d & \frac{3k_p\omega_B C'}{2}S_q & -\frac{\omega_B C'}{R'_c} \end{bmatrix} \begin{bmatrix} i'_{pd} \\ i'_{pq} \\ v'_{dc} \end{bmatrix} + \begin{bmatrix} \frac{\omega_B}{L'_p}v'_{id} \\ \frac{\omega_B}{L'_p}v'_{iq} \\ 0 \end{bmatrix} \tag{3.33}$$

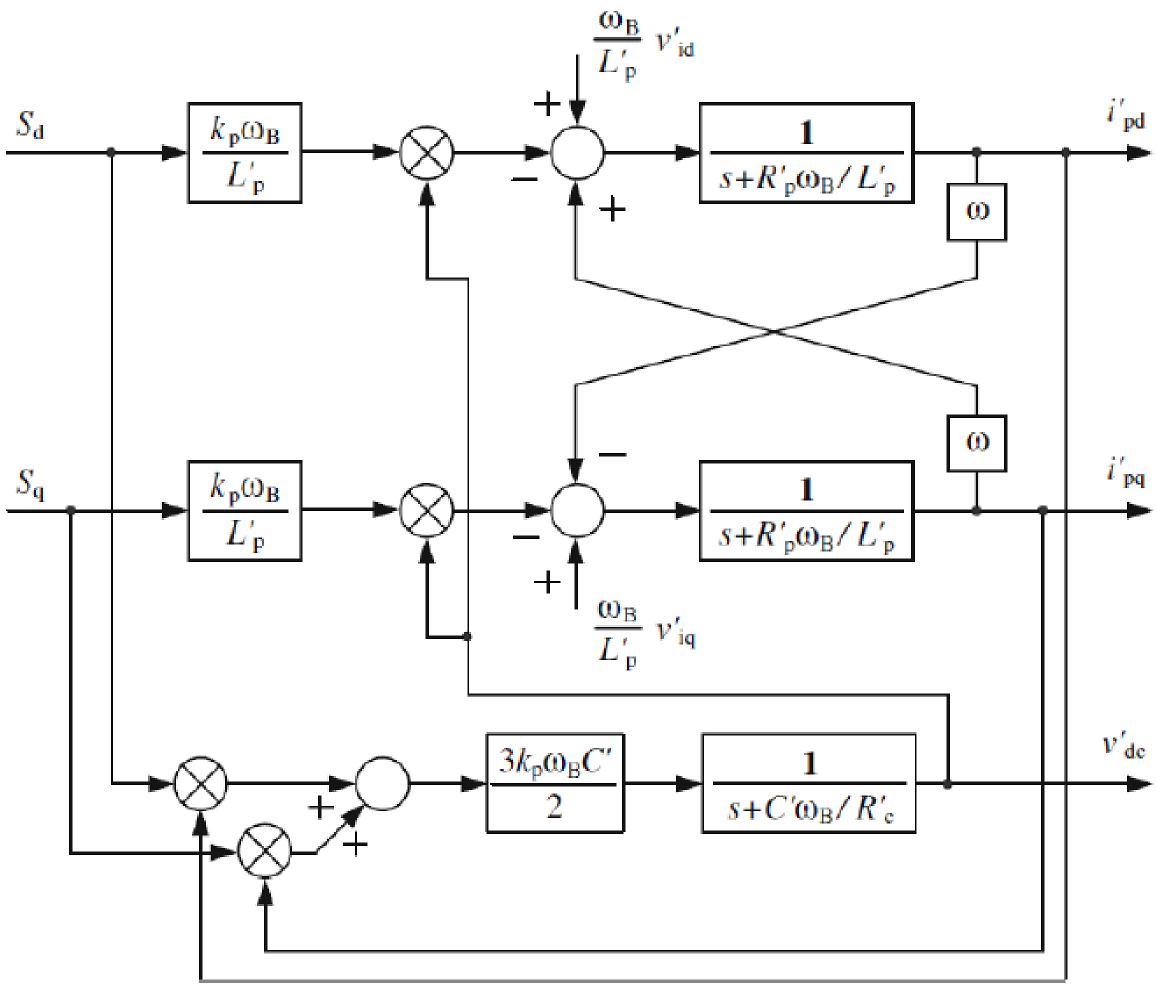

Figure 3.9 DSTATCOM mathematical representation block diagram model in the d-q frame

3.2.3 Introduction to Fuzzy Logic

Fuzzy logic control relies on the fuzzy logic, which is more akin to natural language and human reasoning. Such method enables the approximation of the imprecise conditions found in the real world (Tomohiro.T and Michio.S, 1985).

Instead of using mathematical equations, fuzzy logic uses linguistic terms to express operational rules. Many systems are highly complicated to represent them correctly, even using complex mathematical expressions. As a result, old approaches are no longer viable. Fuzzy logic linguistic terms, on the other hand, provide a viable method for defining the operational characteristics of such a system and even perform well with only approximate data (Emer.B, Marylu L., 2020).

Fuzzy logic was chosen in this study for a variety of reasons.

- ✓ Designing without understanding the accurate model of the process is possible.
- ✓ Control simplicity and smooth functioning.
- ✓ Tolerance is quite high.
- ✓ The price is low.
- ✓ Non-linearity's influence is reduced.
- ✓ Approximation ability is inherent in the system.

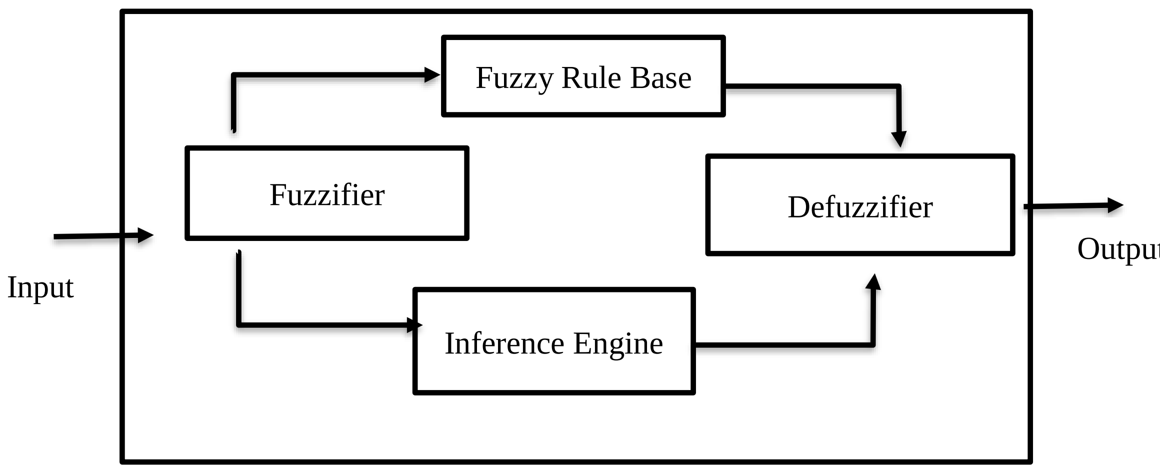

Figure 3.10 Fuzzy Inference System

Fuzzification:

Fuzzification is the process performed during run time and it converts a crisp input into a fuzzy set. The following functions will be performed in this step.

i) Several precise input measurements are transformed into fuzzy membership functions in a process known as fuzzification.

ii) Performing a scale mapping to convert the range of input variable values into corresponding universe of discourse.

iii) Excutes the fuzzification process by transforming input data into appropriate linguistic variables, which can be seen as labels for fuzzy sets. Logic implications, such as if then rules, are frequently used to convey fuzzy logic language words. Fuzzy membership function are defined by rules as a set of values. A triangular, trapezoidal bell or other suitable form can be used to represent a fuzzy membership function (Jinho Jung, Hong.H, David .S, 2019)

Rule Evaluation:

The rule evaluation process involves applying the fuzzy values obtained during fuzzification to the rule base to derive a fuzzy output value. This process follows the structure of "if (condition x) and (condition y) then (result z)" rules. By employing linguistic variables and fuzzy IF-THEN rules, the system can tolerate imprecision and uncertainty, mirroring the human mind's ability to distill information and concentrate on relevant decision-making factors. These rules are usually derived from expert knowledge.

Inference Engine

Fuzzy inference is a core component of fuzzy controllers, simulating human decision-making using fuzzy logic concepts. Its primary task is to identify fuzzy control actions by utilizing inference rules within the fuzzy logic framework. Within an inference engine, fuzzy "IF-THEN" rules derived from a fuzzy rule base are employed to establish mappings between fuzzy input sets and fuzzy output sets.

Defuzzification

Defuzzification is the process of taking the fuzzy sets created by the inference engine and turning them into a crisp value. This is done using the membership functions that define each output variable. There are different ways to do this, and the best method depends on the specific expert system and the goal of minimizing error.

3.2.3.1 Fuzzy Sets and Membership Functions

A fuzzy set is described by a membership function that tells you how much an element belongs to the set. This membership function can be either continuous or discrete. For example, a fuzzy set called A can be described by its membership function like this

$$A = \{(x; \mu\_A(x)); \text{such that } x \varepsilon X\} \tag{3.34}$$

Where $\mu\_A(x)$ is the membership value of the element x in fuzzy subsets

$$(\hat{f}e^{j\theta_0})\ e^{j\omega t}=\underline{f}e^{j\omega t} \quad (3.35)$$

3.2.4 Design of Fuzzy Logic Controller

The FLC for DSTATCOM operates within the rotating d-q frame, using measurements and control signals. It employs a current control scheme where the controller aims to track a specified quadrature current (I_q) by manipulating the switching functions. This control is achieved by adjusting the firing angle (α).

The architecture of the fuzzy logic controller (FLC) for reactive control is shown in the following figure. The controller operates in discrete samples and comprises several computational steps. At each sample, the error between the desired reference reactive current (I_q^*) and the measured reactive current (I_q) is calculated and sent to the FLC control block. Additionally, the rate of change of the reactive current error is determined and provided as an additional input to the FLC control block. Incorporating the rate of change of error significantly enhances the FLC's performance by providing information speed and direction of error. This results in decreased response time and less overshoot.

Since the fuzzy processor functions digitally, the crisp inputs, e(k) and Δe(k), are obtained from sampled data. As a result, the output Δα(k) is also a discrete value. The fuzzy processor uses a fuzzifier to convert the crisp inputs e(k) and Δe(k) into fuzzy membership values. The rule base system then activates relevant rules based on the fuzzy inputs, resulting in fuzzy consequents that produce a general fuzzy conclusion for the process. Finally, the defuzzifier converts the general fuzzy conclusion into a crisp output Δα(k), which serves as the final decision for the kth sample.

3.2.4.1 Reactive Current Control

Basically, the DSTATCOM adds the necessary reactive power to the distribution line. Since the controller is designed using the rotating d-q coordinate system, controlling reactive power is the same as controlling the quadrature current component (Iq).

The fuzzy logic controller works like an integral controller by adding the change in the control signal (Δα(k)) to the previous control signal value (Δα(k-1)). This results in the current output as the updated control signal (α(k)). This method is used because the control signal for the DSTATCOM, even when there's no change in voltage, is not exactly zero due to the power used to supply the internal reactance's of the coupling system.

The fuzzy processor uses the Mamdani reasoning method to take the inputs e(k) and Δe(k) and create the output Δα(k). Based on the size of the control signal α(k), the voltage source converter (VSC) makes the necessary voltage at the output of the DSTATCOM to match the desired reactive current. The decision made by the fuzzy processor, shown as Δα(k), can be to increase or decrease the control signal, or to do nothing if the system output Iq is following the reference (I_q^*) within a reasonable range.

To make sure the control signal is adjusted correctly, the fuzzy processor needs a rule base that is accurate and appropriate. The performance of the fuzzy logic controller (FLC) depends a lot on these rules, as they represent the knowledge and experience of the person who operates the system.

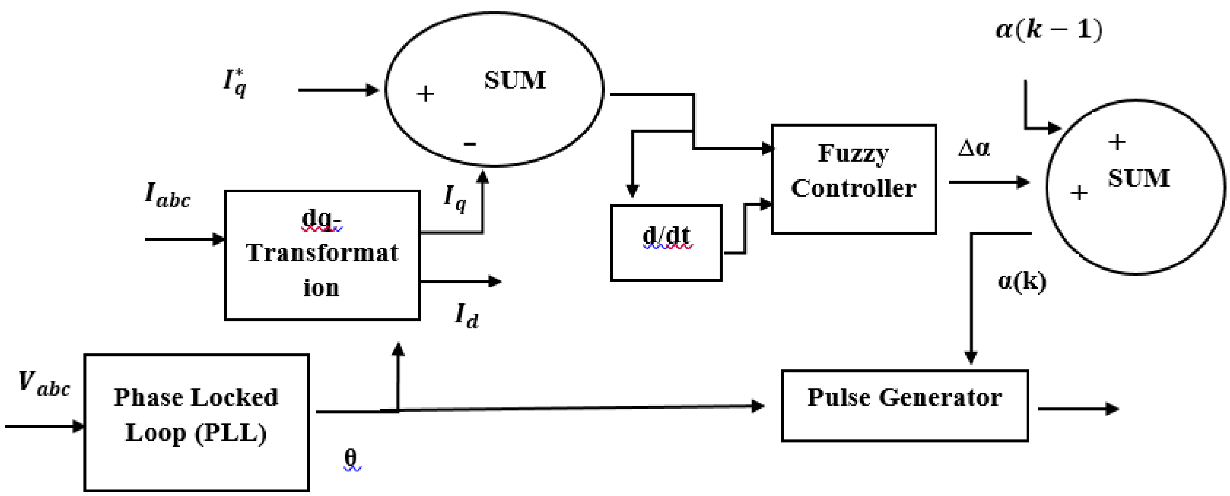

Figure 3.11 FLC model for Reactive current control

This control model depicts how the inner current looks and it regulates the reactive current flow through VSC regardless of the line voltage.

3.2.4.2 Line Voltage Control with DSTATCOM

The desired reactive current (I_q^*) flowing through the VSC depends on whether the DSTATCOM is providing reactive power to the line (positive) or taking reactive power from the line (negative). The voltage of the DC link capacitor is changed to match the voltage needed for compensation.

The reactive current control loop focuses on the internal current control mechanism that manages reactive current via the VSC, independent of the line voltage. If the goal is to control the line voltage, an external voltage control loop sets the reference reactive current for the inner current control loop, which subsequently adjusts the line voltage (Kalyan K. and Mey Ling , 2009).

The outer fuzzy logic based voltage controller is illustrated in figure below. The output of PLL is used in the dq transformation to convert the instantaneous three-phase measured line voltages into their direct component (V_d) and quadrature (V_q) component. The magnitude of V_{dq} is then computed and feed to fuzzy logic controller. This controller processes the rule base and maps the line voltage variations into a commanded reactive current, which serves as the reference quadrature current for the inner current controller.

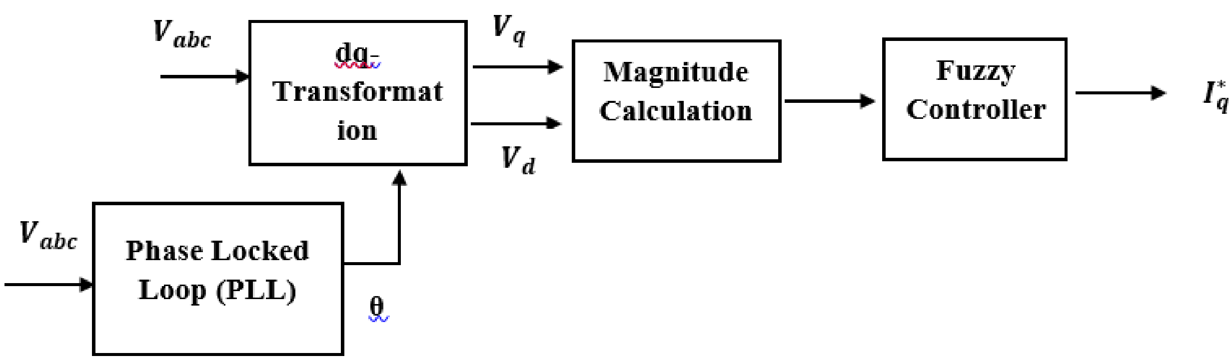

Figure 3.12 Model of Voltage Control

The controller is structured around the rotating dq coordinate frame system. Controlling reactive power is essentially the same as managing the quadrature current (Iq).

The fuzzy processor determines the control action by evaluating rules related to whether Iq is following the reference quadrature current (I_q^*).

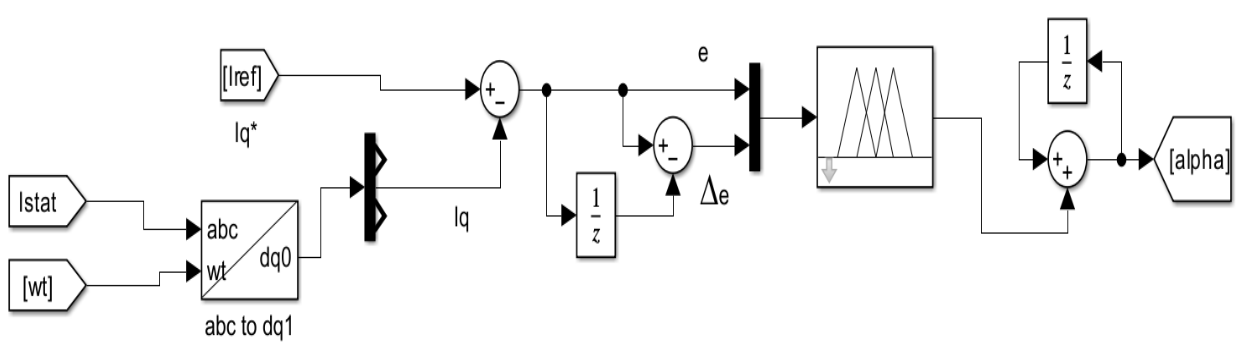

Figure 3.13 Quadrature DSTATCOM current control

3.2.5 Modelling of FLC in Matlab and Membership Function choice

The DSTATCOM, employing a fuzzy logic controller, is implemented in Matlab Simulink using the Simscape specialized power system library.

The FLC designed for both current and voltage controller are based on Mamdani fuzzy inference system type, utilizing the max-min aggregation method and centroid defuzzification.

The design of the fuzzy logic controller is depicted as below.

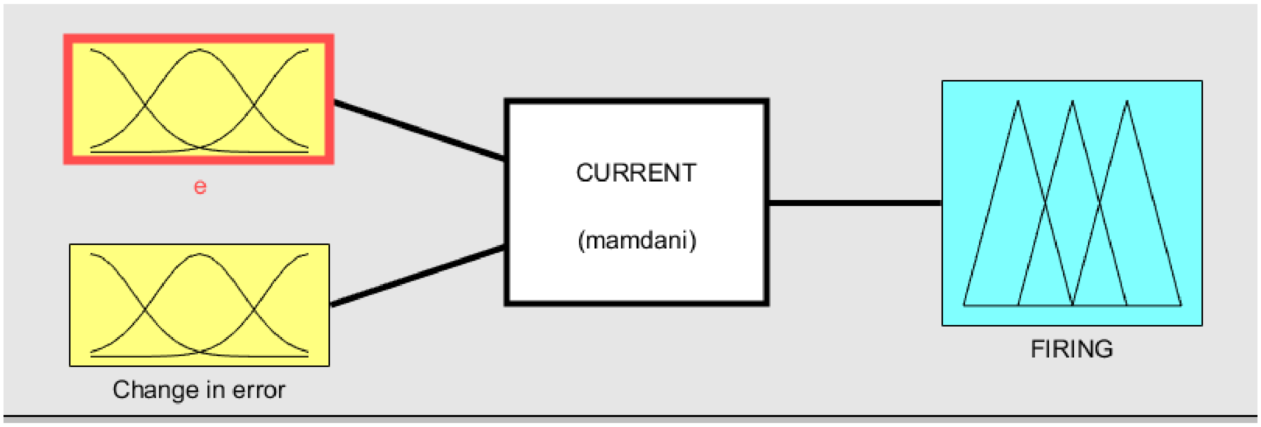

Figure 3.14 FLC for reactive current in Matlab

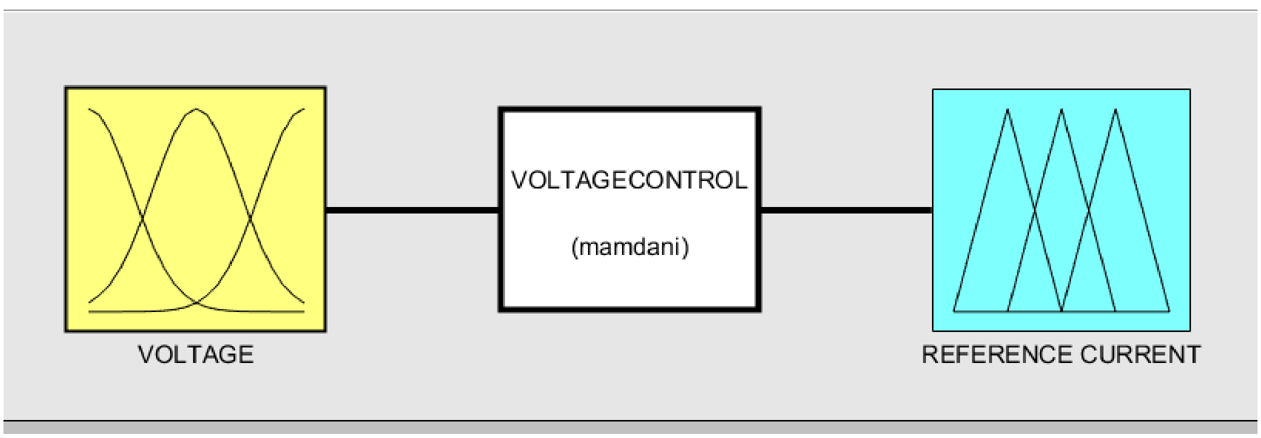

Figure 3.15 FLC for outer voltage control in Matllab

The voltage is regulated by an outer loop that sets the desired reactive current. This reference current is then used by the inner current control loop to manage the line voltage.

A PLL is utilized to convert the instantaneous three-phase voltage measurements into their direct (V_d) and quadrature (V_q) components through dq transformation.

The magnitude of $V_{dq}$is then calculated and fed into the fuzzy logic controller. Based on its rule base, the fuzzy logic controller translates line voltage variations into a reference quadrature reactive current for inner current control loop.

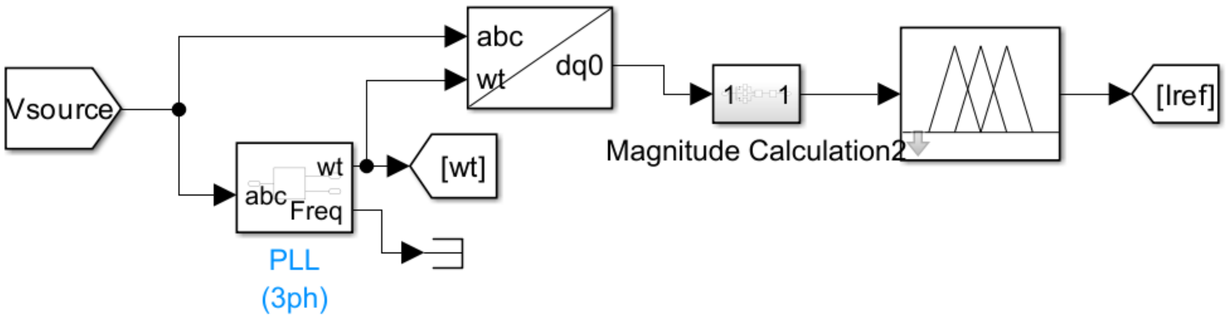

Figure 3.16 Outer voltage control loop

The following is the fuzzy membership for the input and output variables.

Table 3.1 Fuzzy Membership Functions and their symbols

Fuzzy membership function	**Symbol**
Negative Very Big	NVB
Negative Medium Big	NMB
Negative Small Big	NSB
Zero	Z
Positive Small Big	PSB
Positive medium Big	PMB
Positive Very Big	PVB

The membership function for error, change in error, change in firing angle, voltage and reference current are depicted in the following figure. For reactive current control, the first input is reactive current error (e). To ensure optimal tracking, the universe of discourse for this input is selected as [-0.1 0.1]. A combination triangular and trapezoidal membership functions is utilized to divide the universe of error into fuzzy sets, as illustrated below.

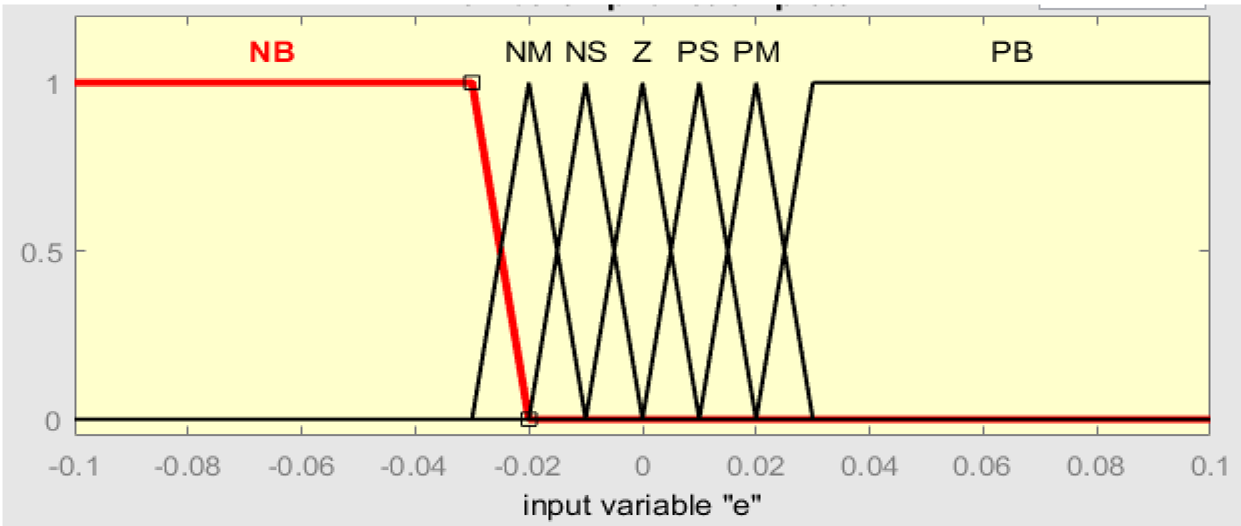

Figure 3.17 Reactive current error membership functions

The FLC will now use the rate at which the error is changing as its second input. This input ranges from -0.01 to 0.01, indicating how quickly the error is increasing or decreasing.

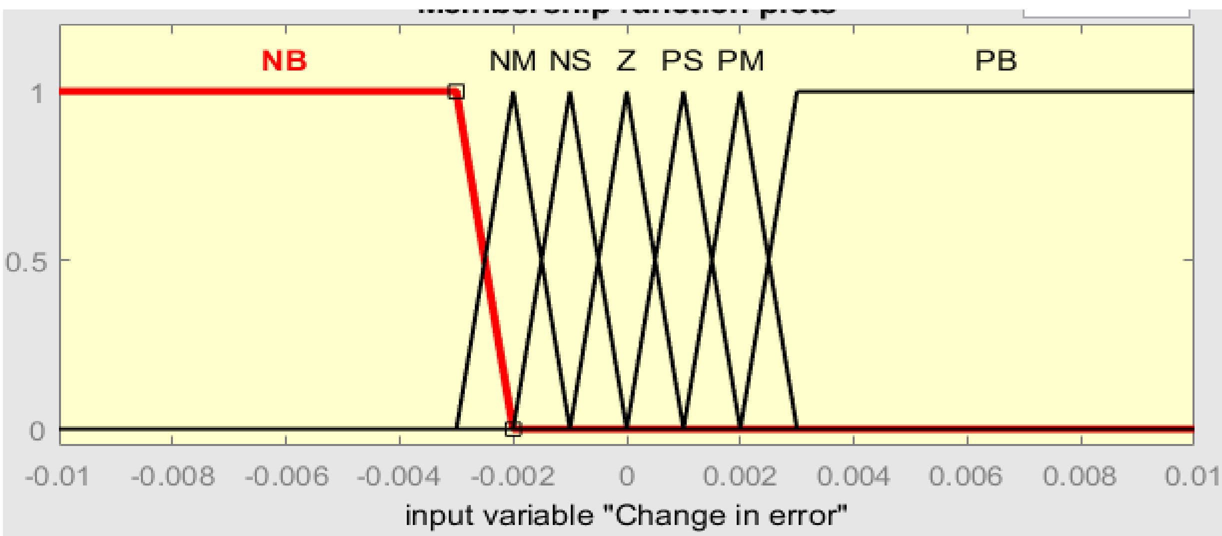

Figure 3.18 Change in reactive current membership

The reactive current control system produces an output called (Δα). This output determines how much to increase or decrease the angle α. The range of (Δα) is chosen carefully to avoid both slow responses and excessive oscillations. As a result, it's set to be between -0.1 to 0.1

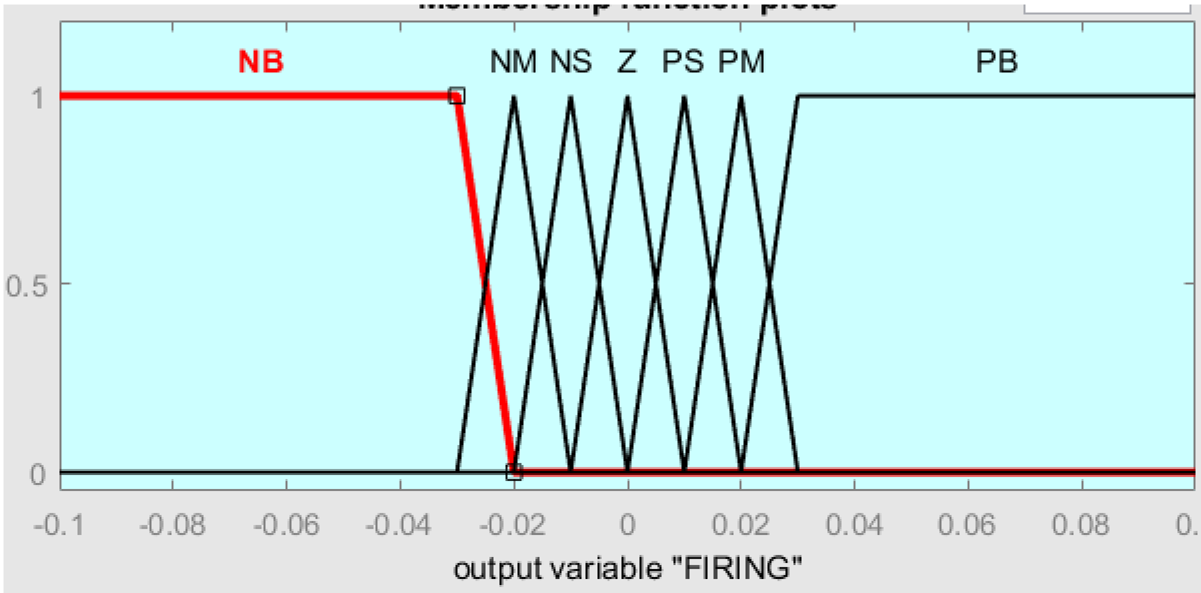

Figure 3.19 Change in firing angle membership functions

The outer voltage control system uses a DSTATCOM V-I characteristic to decide on the range and shape of the membership functions for both its input (voltage) and output reference current. This V-I depicts how the DSTATCOM should react to different line voltages. When the voltage is at its desired level of 1pu, the DSTATCOM should produce zero reactive current. If the voltage is lower, it should produce a capacitive current, and if it's higher, it should produce an inductive current. The amount of reactive current depends on how much the voltage deviates from the desired level.

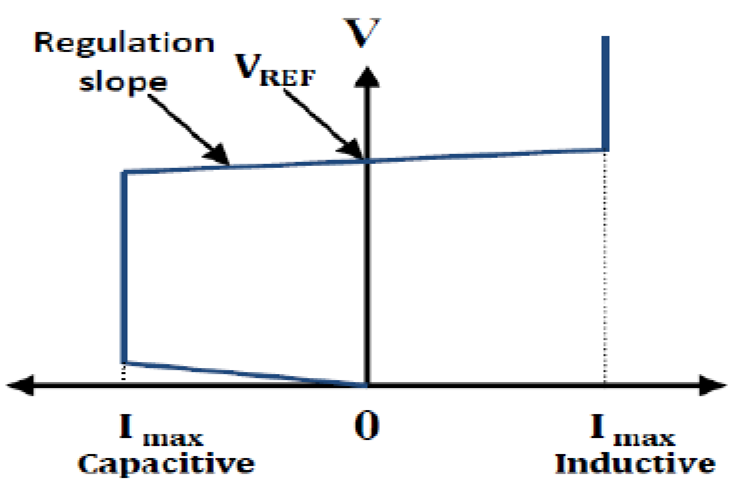

Figure 3.20 Typical V-I characteristic of DSTATCOM

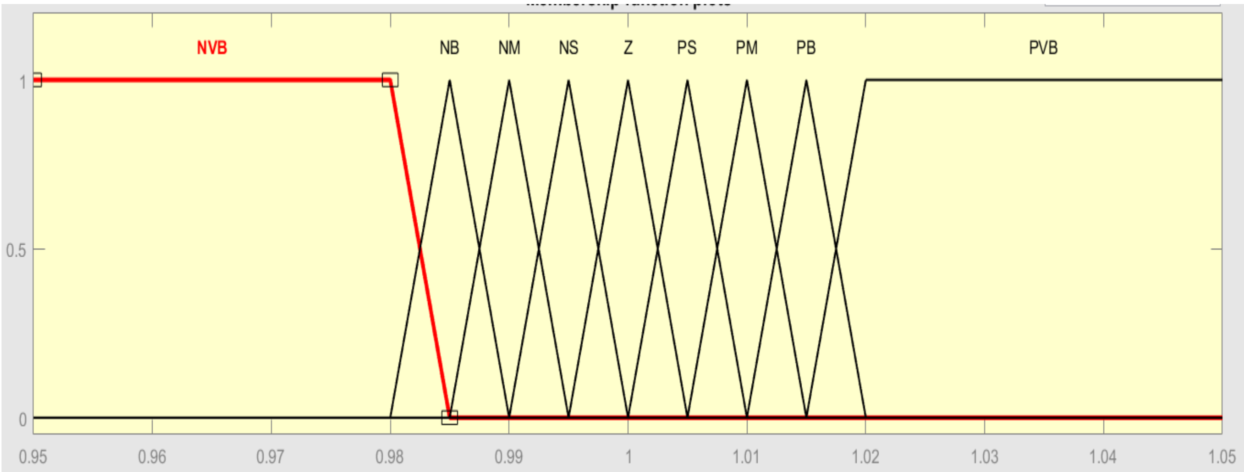

Figure 3.21 membership function of measured line voltage

The output of the voltage FLC which is the reference reactive is expected to be in the range of -1 to 1, because the DSTATCOM is expected to supply full capacitive reactive power when the current is at 1pu, and absorbs full inductive reactive power at -1pu.

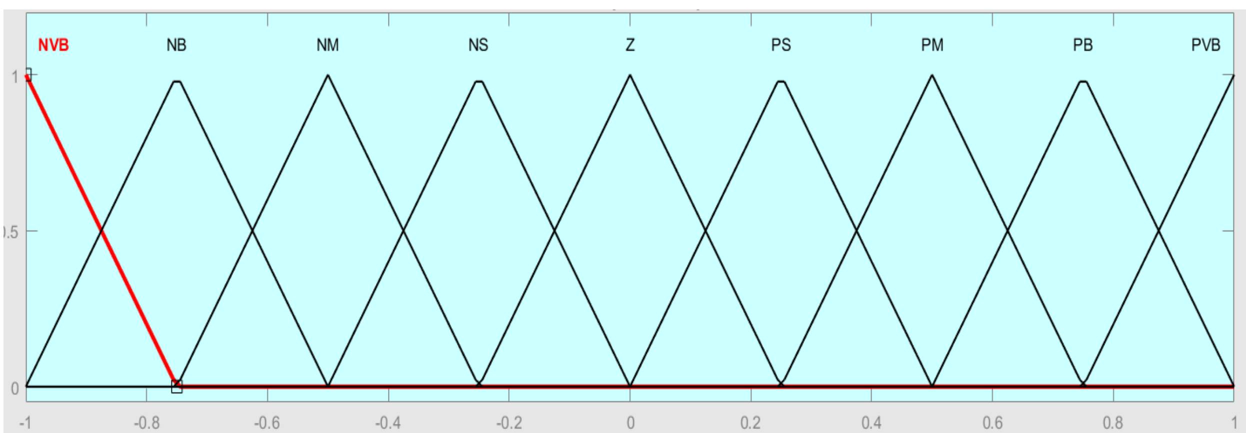

Figure 3.22 Membership function for Reference reactive current

3.2.5.1 Rule Base (Decision Making)

The inner reactive-current control has two inputs: error between the desired and actual quadrature current, and the rate at which this error is changing. These inputs are converted into fuzzy values using membership functions based on the rule base assigned.

They are defined as

$$e(k)= I_q^*(k)-I_q(k) \quad (3.36)$$

$$\Delta e(k)=e(k)-e(k-1) \quad (3.37)$$

The fuzzy rule base, which may also be called as the fuzzy decision table, is the engine mapping the two crisp input, e(k) and Δe(k) to the fuzzy output space defined on the universe of Δe(k). in order to intuitively generate the set of rules for the FIS, the system response is analyzed thoroughly first.

Each one of e(k), Δe(k), and Δα(k) has three different options for the signs to be assigned. They are either positive or negative if not zero. Therefore, the universe of error, change in error, and change in control signal can be partitioned into three categories as Negative (N), Zero (Z), and Positive (P), initially. Keeping in mind these three options, an initial rule decision table with nine rules can be formed as shown as below table.

Table 3.2 Initial 9 rule table

e(k)	Δe(k)		
	N	Z	P
N	P	P	P
Z	P	Z	N
P	N	N	N

To quantify how much positive or negative the error and its rate of change is, the input space are partitioned into more than three regions each. As described in the previous section, it is chosen to divide the positive or negative ranges of the inputs and output into 3 sub regions as small, medium, and big. In addition to the subset zero (z), there will be seven fuzzy subsets defined in the universe of e(k), Δe(k), and Δα(k). Therefore, a 7x7 decision space is obtained as table below

Table 3.3 The final 49 rule for current control

e(k)	Δe(k)						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PM	PS	PS	Z
NM	PB	PM	PM	PS	PS	Z	NS
NS	PM	PM	PS	PS	Z	NS	NS
Z	PM	PS	PS	Z	NS	NS	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	PS	Z	NS	NS	NM	NM	NB
PB	Z	NS	NS	NM	NM	NB	NB

As for FLC designed for voltage control, creating the set of rules is completely based on the theoretical knowledge of the DSTATCOM V-I characteristics. As explained in the previous section, the measured voltage input and the reference reactive current output universes are partitioned into 9 fuzzy sets. The set of rules defined for the voltage control FLC is a direct mapping between the input and output universe and it is illustrated as below

Table 3.4 Voltage control direct 9-rules mapping table

V_{meas}	NVB	NB	NM	NS	Z	PS	PM	PB	PVB
I_q^*	NVB	NB	NM	NS	Z	PS	PM	PB	PVB

3.2.6 Designing of the DSTATCOM parameters

Here the DSTATCOM parameter is designed to supply or absorb a reactive of capacity +/- 3.6MVAr by considering the existing system.

The use of high voltage (HV) power semiconductors is prevalent in converters with power levels around 1 MVA. These converters typically employ HV power semiconductors with voltage ratings of 2500 V, 3300 V, and 4500 V. To maintain a converter active power loss of 1%, the switching frequency of 3.3kV HV IGBT modules should be approximately 1 kHz. The D-STATCOM, primarily designed for reactive power handling, should have a 1% active power dissipation across its IGBT switches.

Based on this concept the active power of the DSTATCOM is calculated as

$$P=Q*0.01\% \tag{3.38}$$

P=3.6*0.01=0.036MW

Apparent power of the designed DSTATCOM is

$S = \sqrt{P^2 + Q^2} = \sqrt{0.036^2 + 3.6^2} \approx 3.6\text{MVA}$

$S_{DSTAT} = \sqrt{3} * I_D * V_L$

$I_D = \frac{3.6*10^6}{\sqrt{3}*15*10^3}$=138.6A

The secondary current of the DSTATCOM coupling transformer can be calculated using the transformer’s turn’s ratio.

$\frac{V_p}{V_s} = \frac{I_s}{I_p}, I_s = \frac{15kv*138.6}{3.3kv}$=630A

The secondary current of the coupling transformer and the line current of the medium voltage IGBT are both 630A. Because the IGBT manufacturer’s datasheet does not provide a calculated current rating, the next available rating of 800A is chosen for DSTATCOM. Based on the ABB IGBT datasheet, the 5SNA 0800N330100 3300V 800A Single IGBT is selected for the DSTATCOM design, considering its capability to operate up to 125 degree Celsius.

DC Link Capacitor Voltage

The size of the capacitor is determined by the permissible ripple component in the DC-bus voltage. To ensure proper operation, the minimum DC-bus voltage of the VSC DSTATCOM should be at least twice the peak phase-to-phase voltage of the system.

By using the secondary line-to-line voltage and the designed reactive power of the VSC DSTATCOM, we can calculate the rating of the capacitance as follows:

Assuming a modulation index of ma = 1, we can plug in the values into the formula and solve for the capacitance.

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}ma} \quad (3.39)$$

$$=\frac{2\sqrt{2}*3300}{\sqrt{3}*1}=5388.88\text{v} \approx 5400\text{v}$$

Accordingly a DC link capacitor having a rating of 5400v is selected to compensate the designed reactive power needed by the load.

Selection of DC link Capacitor

DC bus capacitor selection is made based on the following condition:

- Working Voltage: this specifies the maximum DC voltage that the capacitor can handle for a sustained period.
- Ripple current: This specifies the maximum AC current that a capacitor can handle without exceeding its internal temperature.

The D-STATCOM provides instantaneous energy support during transient conditions. Its response time is typically 200 to 350 microseconds ((Narain G. Hingorani, Laszlo Gyugyi, 2000).

When the DC voltage decreases during transient conditions, the capacitor can release energy to supply reactive power. The size of the DC capacitor in the DSTATCOM depends on how much energy it can provide during these transients. The law of energy conservation can be used to as follows:

$$Energy\ Transfer = \frac{1}{2}C_{dc}[(V_{dc}^2) - V_{dc1}^2] = 3V(I * a)t \quad (3.40)$$

Where V_{dc}^2 is a reference dc voltage

$V_{dc1}^2$is minimum voltage level of dc bus

a is overloading factor

V is phase ac voltage

I represents the phase current and t is the time it takes for the dc voltage to recover to its desired level

Let's consider minimum dc voltage (V_{dc1}) of 5380v and V_{dc} of 5400v

$V_{ph}$is 3.3KV, Because the transformer connection is in star delta V_{LL}=V_{ph}

Current (delta) is $I_D = \frac{I_{DSTATCOM}}{\sqrt{3}} = \frac{630}{\sqrt{3}} = 363.73A$

Time= input resistance * input filter capacitor

=3.125 * 112 micro farad = 350 micro seconds,

a= 1.2

$$\frac{1}{2}C_{dc}[(V_{dc}^2) - V_{dc1}^2] = 3V(I * a)t$$

$$C_{dc} = \frac{6V(I * a)t}{V_{dc}^2 - V_{dc1}^2}$$

$$C_{dc} = \frac{6 * 3300 * 363.73 * 1.2 * 350\mu s}{5400^2 - 5380^2} = 14{,}03\mu F$$

Design of AC inductor

The selection of the AC inductance (LAC) of the VSC depends on the current ripple (icr p-p), switching frequency (fs), and DC bus voltage (Vdc). AC inductance is primarily determined by these parameters and is calculated using the following formula

$$L_{AC} = \sqrt{3}\frac{m * V_{dc}}{12 * a * fs * iripple} \quad (3.41)$$

Where m is the modulation index and overloading factor.

Peak current is (I_{DP})=√2 $* II_D$=138.6*√2 =196A=IDP

I_{ripple} = I_{DP}× 20% =196A*0.2=39.2A

Consider the ripple current or icr (p -p)= 5%,

5% of I_{ripple} =39.2A*0.05=1.96A

Switching frequency (fs) = 10 kHz,

Modulation index, m= 1,

Vdc = 5400V,

Overloading factor, a=1.2,

The L_{AC} value is the required value

$$L_{AC} = \sqrt{3}\frac{1 * 5400}{12 * 1.2 * 10 * 10^3 * 1.96} = 33.1mH$$

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter discusses the Matlab result of the existing system and the proposed system. First the existing mechanically switched capacitor bank is modelled and the response of the system is analyzed. Then the proposed fuzzy logic based DSTATCOM is modelled for an equivalent reactive power compensation capacity of 3.6MVar of capacitor bank. The Simulink model discussed here is aimed to run simulations and assess the performance of the existing system and the proposed system.

4.2 Simulink Model of the Mechanically Switched Capacitor Bank

A mechanically switched capacitor bank is modelled by considering the configuration of the existing system. The capacitor bank is connected to a bus bar of 15KV, which has a total of five (5) outgoing feeders. The feeders are supplied from a 50MVA transformer.

The system is expected to operate at a power factor of 0.95, resulting in a total load of 47.5MW and a reactive load of 15.6MVAr. Distribution loads are known to have a dynamic reactive power demand, which causes deterioration in power factor.

At low power factors, the substation is required to provide more reactive power than expected. This extra reactive power demand can put the stress on the national grid.

To overcome these conditions, the substation operators are expected to switch the shunt connected capacitor bank in and out, based on the load’s reactive power demand. This approach is aims to maintain the desired power factor and reduce the stress of the national grid.

While switching in and out the capacitor bank can help to manage the excessive reactive power demand of the load, it introduces its own challenges. The process of switching the capacitor bank can create transient effects, which can lead to power quality issues.

In this thesis, the focus is to analyze the transient effects caused by the switching of the capacitor bank. A circuit breaker is used to switch the capacitor bank in and out at specific time intervals.

The analysis examines the power quality issues that arise due to these transient effects. Factors such as voltage fluctuations, current spikes and potential harmonic distortions are studied to understand the impact of the switching transients on the overall power system.

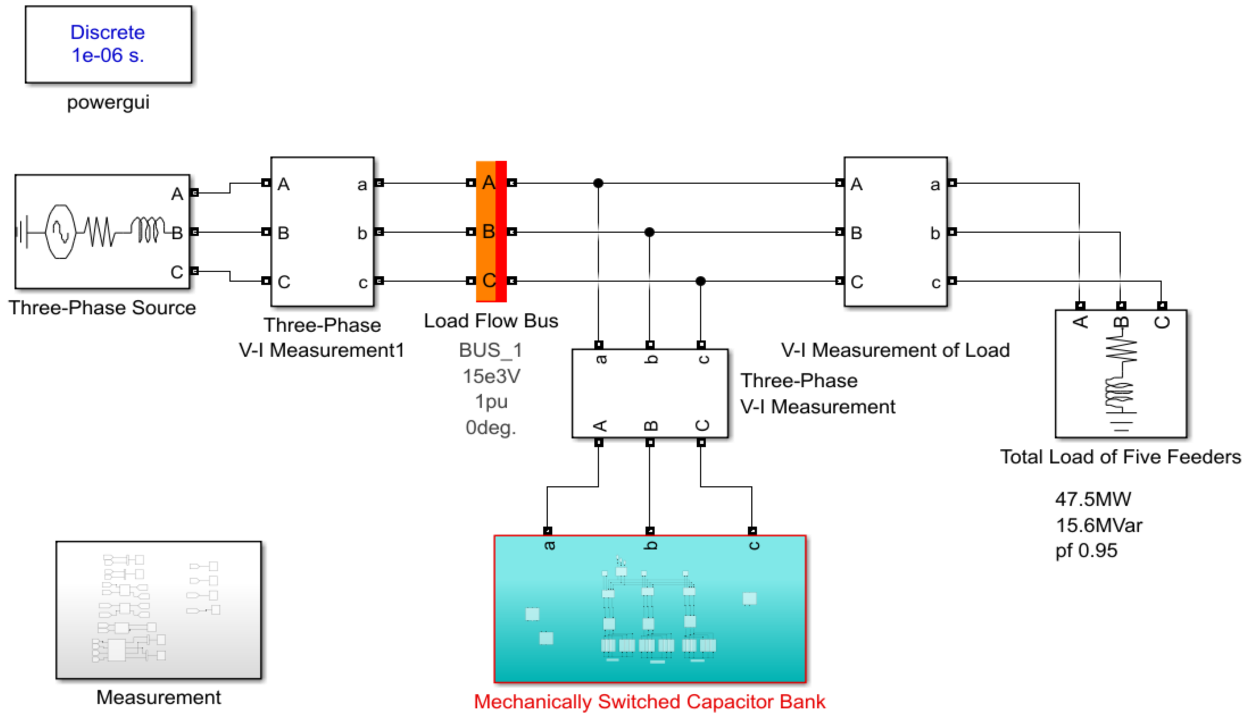

Figure 4.1 Matlab Simulink Model of the existing system

Here the capacitor bank is modelled by taking the parameters of the installed system.

The parameters are

Table 4.1 Parameters of the system

	Value
Voltage(phase to phase)	15KV
230/15 KV Transformer rating	50MVA
Capacitor Bank Rating	3.6 MVar
Series reactor of capacitor bank	500µH
Capacitance value	8.48µF
In(Capacitor bank)	26.9A
Frequency	50Hz

The configuration of the capacitor bank is double star ungrounded system. It has three stages of operation in which each of them have a capacity of 1.2MVar and making a total capacity of 3.6MVar. Its operation is back to back mechanism which is aimed at reducing high amount of transient on the system.

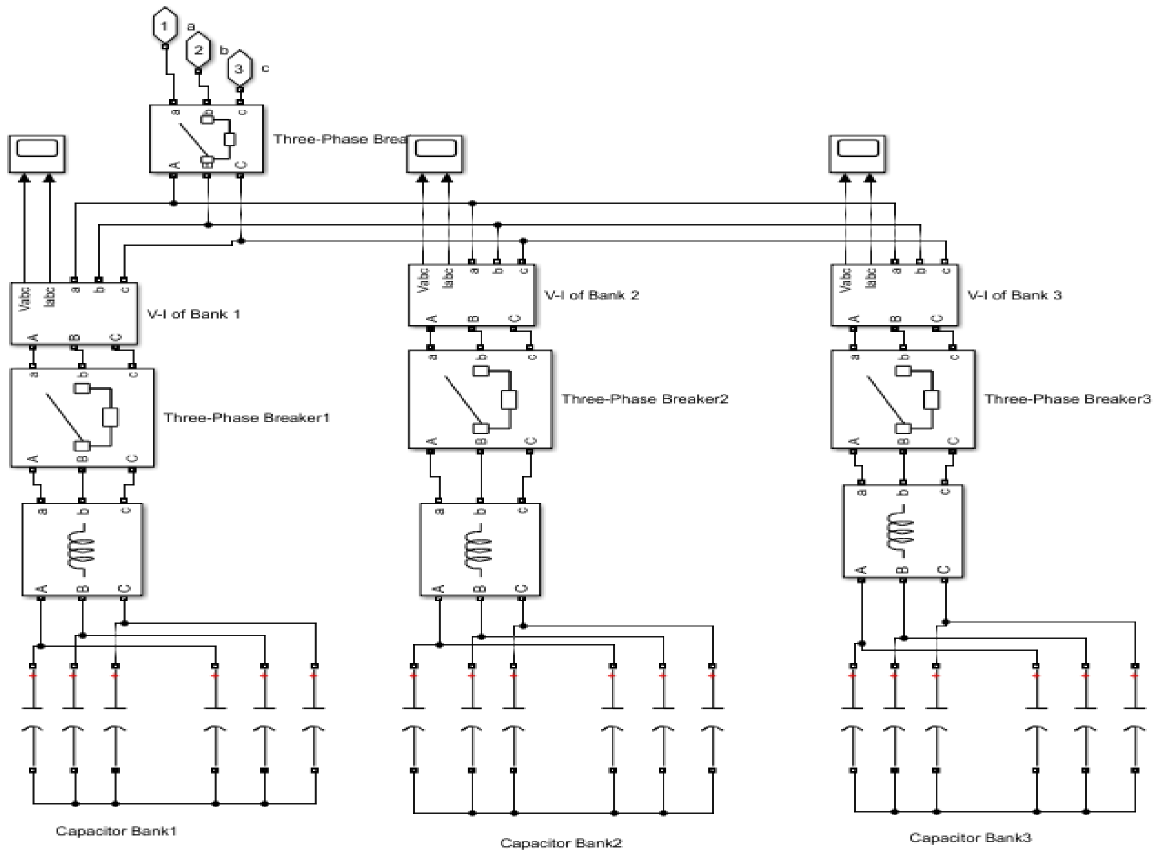

Figure 4.2 Matlab Model of the double star ungrounded capacitor bank

As the figure depicts the capacitor bank has three stages and here the analysis is done on how the transient looks like while switching into the system.

To illustrate the capacitor switching transient, first see the switching of one stage of the bank which will provide a reactive power of 1.2MVar. The capacitor is switched in at 0.08s.

4.2.1 Response of Transient at the capacitor bank

Let's see the transient at the point of PCC. Initially, the first stage of the three stage is switched in and its transient is analyzed. Then a back to back switching is done in a difference of 0.04 sec starting form 0.08 sec from start of simulation.

Figure 4.3 and 4.4 illustrates the voltage and current transient while switching in the first stage of the bank which supplies a reactive power of 1.2MVAr.

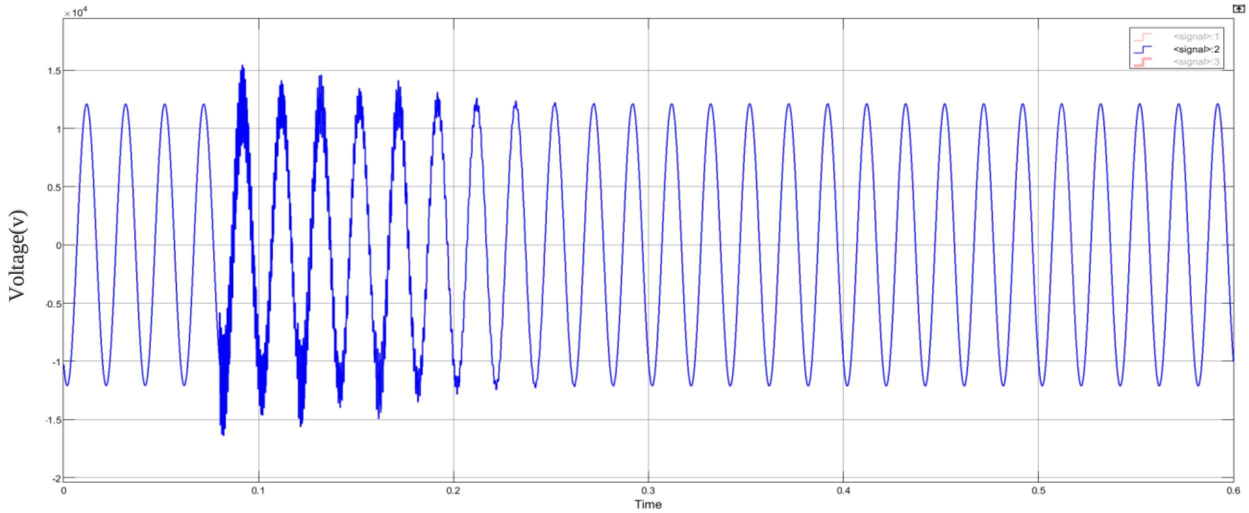

Figure 4.3 Capacitor Bank side Voltage transient of phase B

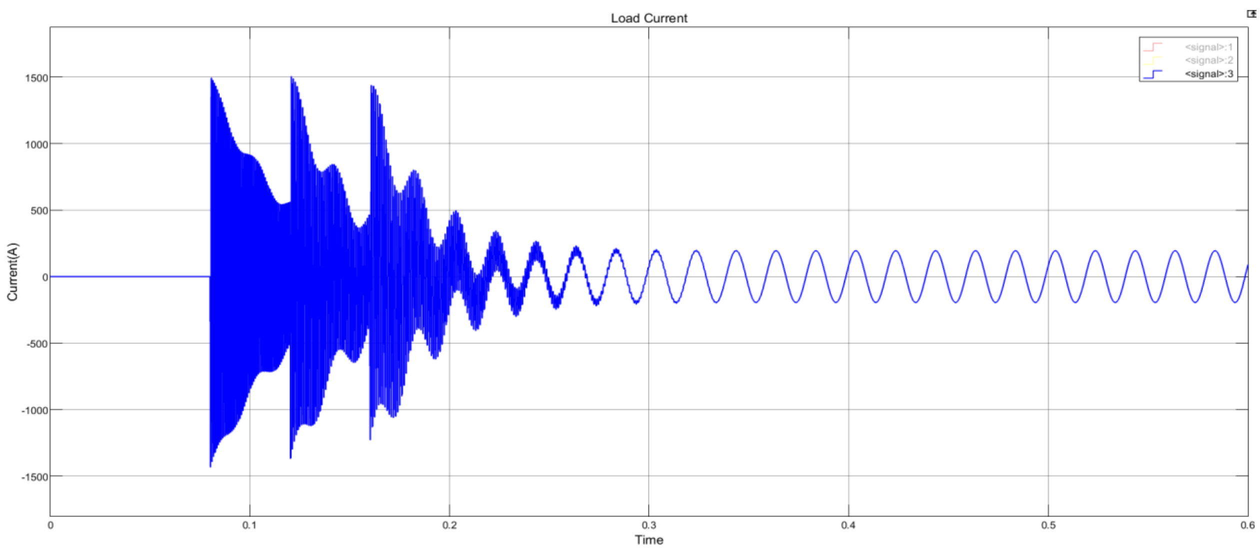

Figure 4.4 Capacitor Bank side current transient of phase C

4.2.2 Response of Transient at the load

Now let's see the transient from load side.

Here also the transient simulated by both switching in a single bank only and then a back to back switching in a difference of 0.04sec.

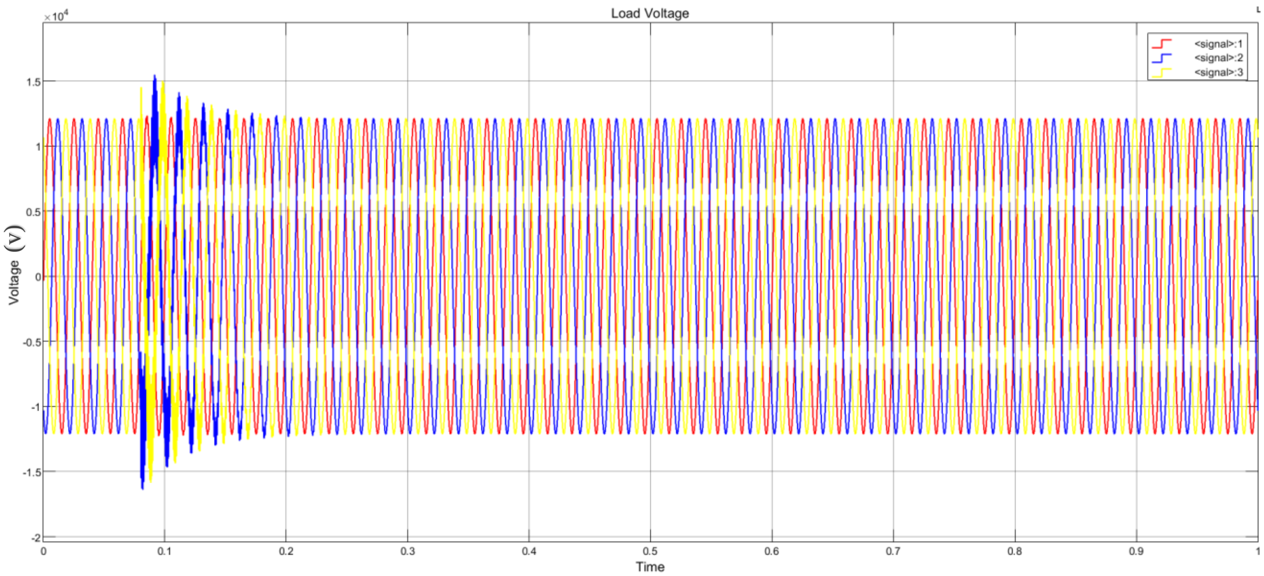

Figure 4.5 Transient Response of Three Phase Load Voltage

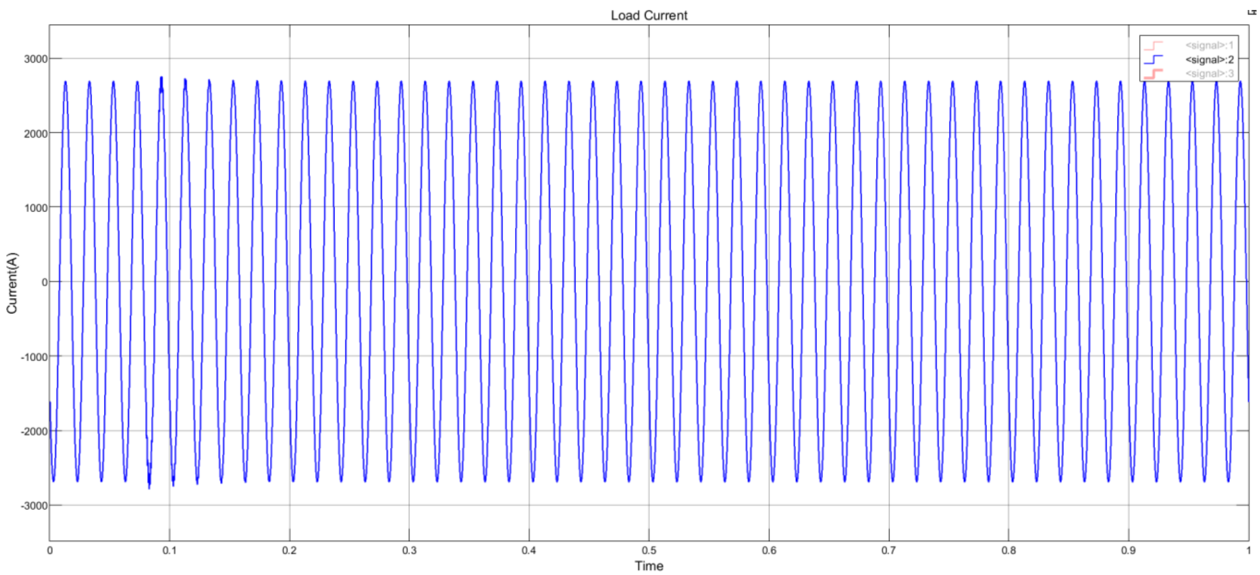

Figure 4.6 Transient response of load current of phase B

The figure 4.5 and 4.6 illustrates the transient that has happened on the load. Here only the first stage of the bank is switched with a capacity of injecting a reactive power of 1.2MVAr.

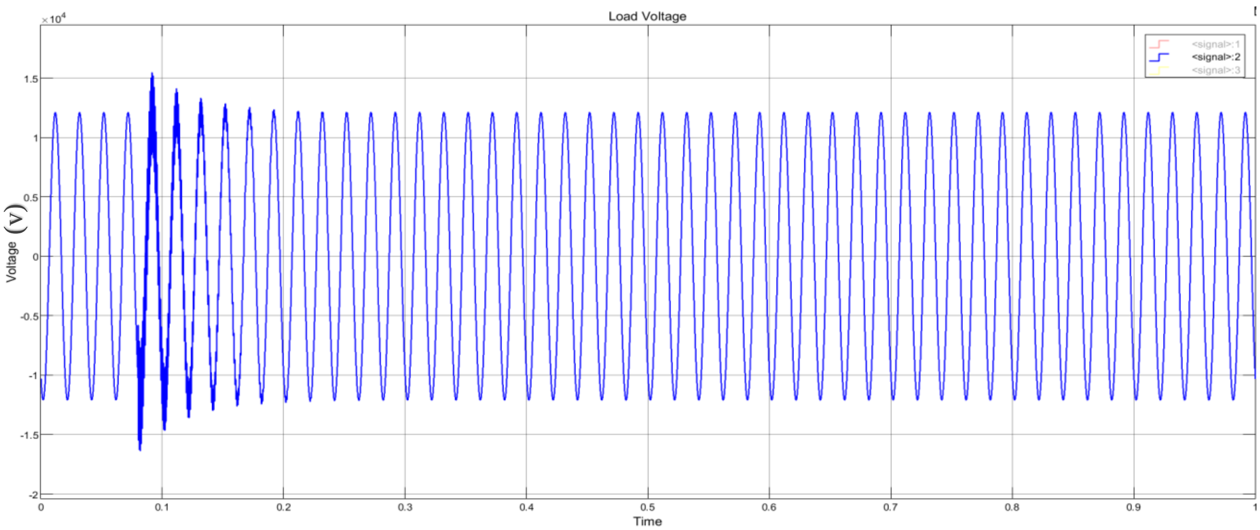

Figure 4.7 Load Voltage of Phase B

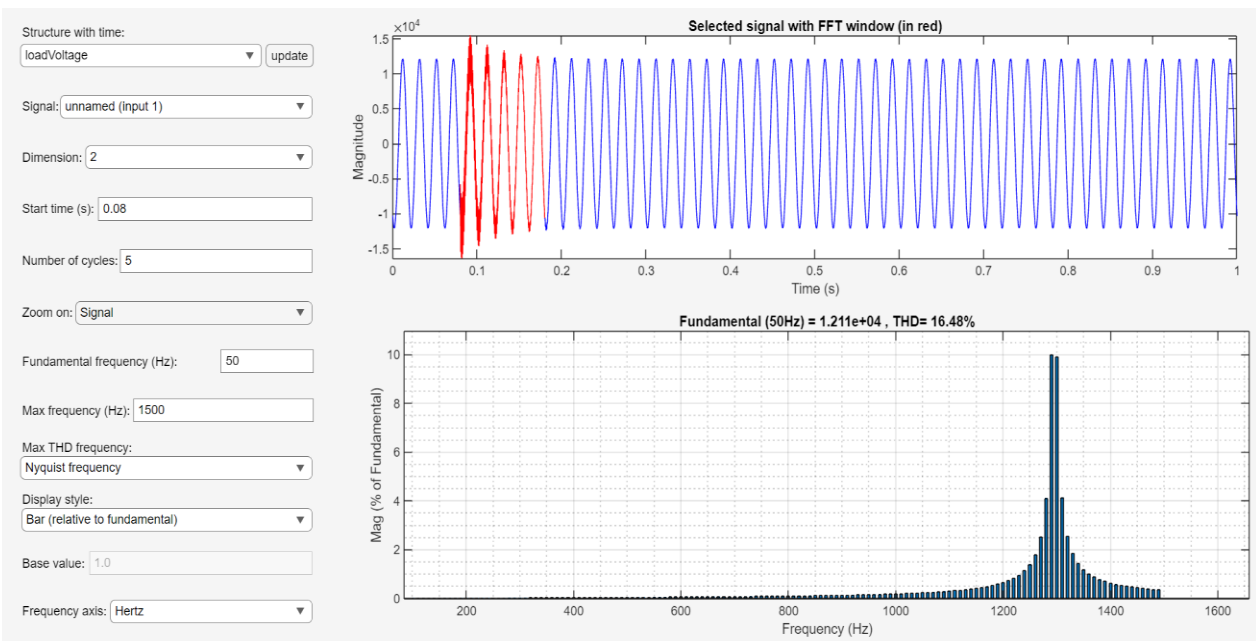

Figure 4.8 THD of load voltage during single bank switching

As we can see from the waveform of voltage and its FFT analysis, it has experienced a transient leading to a THD of 16.48%. This amount of THD is not acceptable as it will cause a power quality issue.

Next a back to back switching is done. Figure 4.9 and and figure 4.10 shows the voltage transient and its consequent THD. During this time the capacitor bank has capacity of supplying a total reactive power of 3.6MVAr from the three stages. But as we can understand form the voltage waveform FFT analysis, this condition has created a THD of 17.03 on phase B.

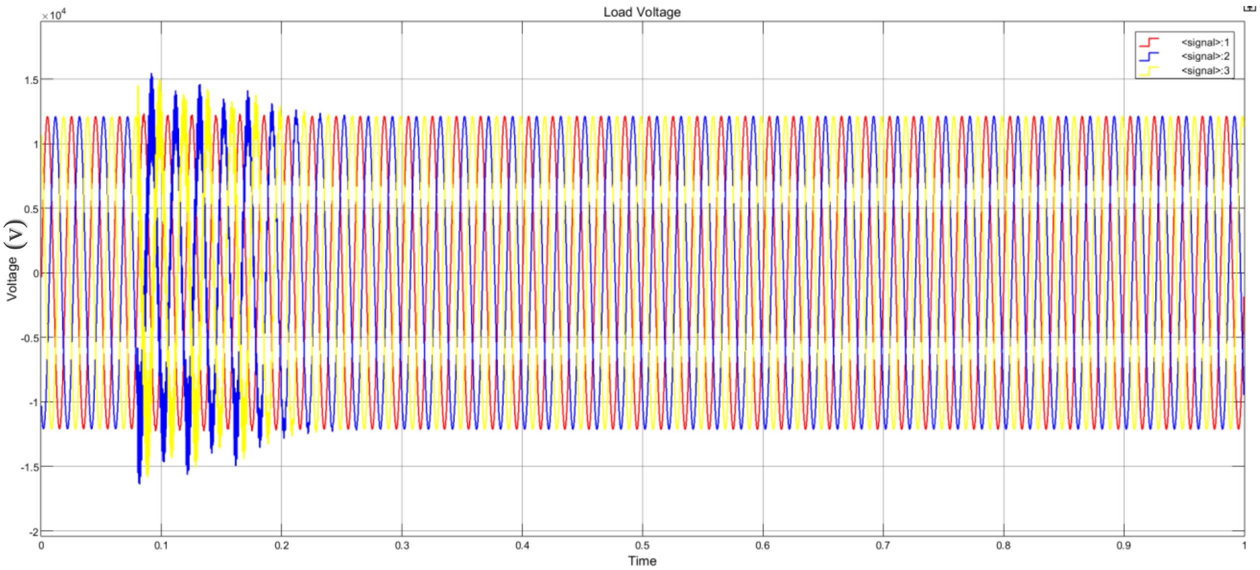

Figure 4.9 Three phase load voltage transient during back to back switching of capacitor bank

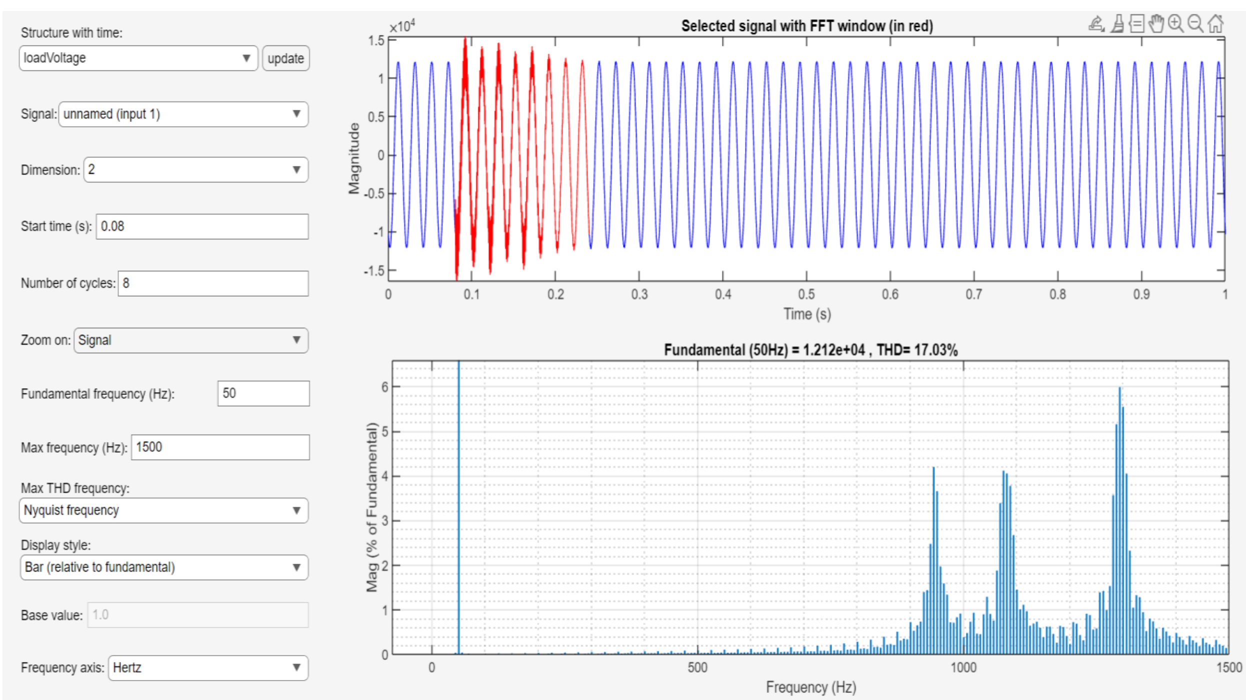

Figure 4.10 THD of load voltage during back to back energizing of the capacitor bank

The result shows a mechanically switched capacitor bank is only feasible at switching in and out at necessary time of the day. But it is understandable that the load demand is varying throughout the day needs a compensating device that can handle easy switching in and out. So in this paper a fuzzy based DSTATCOM is studied and the result of the simulation is presented as follows.

4.3 FLC Based DSTATCOM

This section illustrates how fuzzy logic based controller is applied to the system in regulating voltage due to inductive nature of the distribution load.

The substation 15KV side is designed using Simscape library of Matlab Simulink.

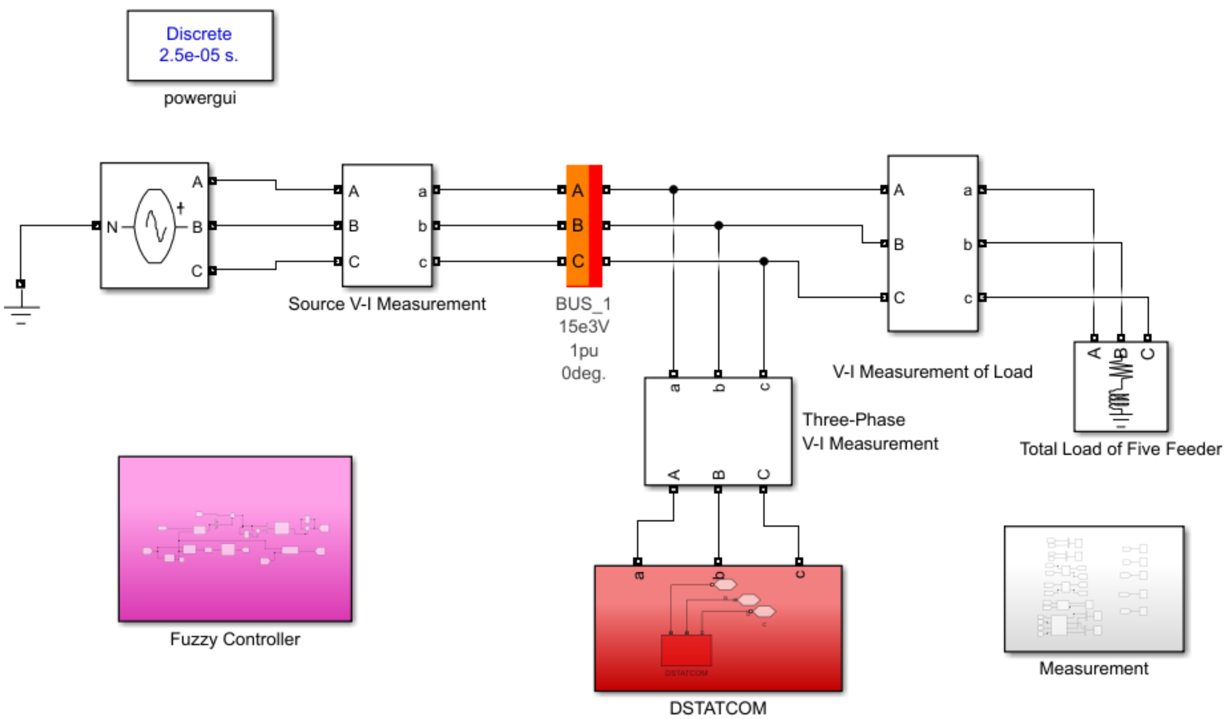

Figure 4.11 Matlab Simulink of fuzzy logic based DSATCOM

4.3.1 Forward Clarke and Park Transformation Block

The Clarke transform converts three phase voltages or currents from abc frame (time domain) to the αβ frame (stationary).The park transform then converts these αβ components to the dq frame (rotating).

Here the model is used to convert the source voltage Vabc and Shunt Reactive Current Iabc into their rotating dq frame.

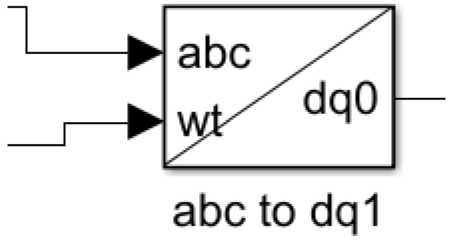

Figure 4.12 Clarke and Park transformation block

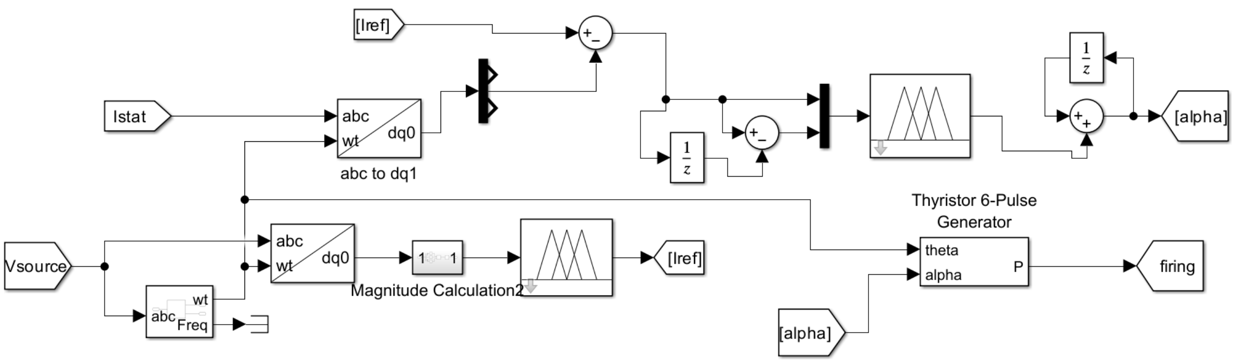

Figure 4.13 Overall Fuzzy logic controller of the DSTATCOM

4.3.2 Simulation Result of FLC Based DSTATCOM

To highlight the dynamic characteristics of the DSTATCOM (Distribution Static Synchronous Compensator), we conduct a simulation where the amplitude of the source voltage is varied over time. Initially, the source voltage is set at 1 per unit (pu). At T = 0.1 seconds, this voltage amplitude is reduced to 0.955 pu. Subsequently, at T = 0.2 seconds, the voltage amplitude is increased to 1.045 pu, and finally, it returns to its original value of 1 pu at T = 0.3 seconds.

The DSTATCOM plays a crucial role in maintaining voltage stability within the system. When it is connected, it actively responds to the variations in source voltage by either absorbing or supplying reactive power. This capability allows the DSTATCOM to regulate the voltage levels, ensuring that the system remains stable despite the fluctuations in source voltage amplitude.

Figures 4.14 and 4.15 provide a visual representation of how the fuzzy logic controller (FLC) processes these voltage variations. The FLC maps the differences in source voltage to a quadrature reference current in real-time, without any time delay, based on a set of predefined rules. This immediate response is essential for effective voltage regulation.

For example, at T = 0.1 seconds, when the line voltage experiences drop below 0.98 pu, then FLC generates an equivalent reference reactive current output of approximately 0.92 pu. This output is determined by the established rules within the FLC, which are designed to optimize the DSTATCOM's performance under varying conditions. Thus, the DSTATCOM effectively contributes to the overall stability and reliability of the power system by dynamically adjusting its reactive power output in response to changes in source voltage.

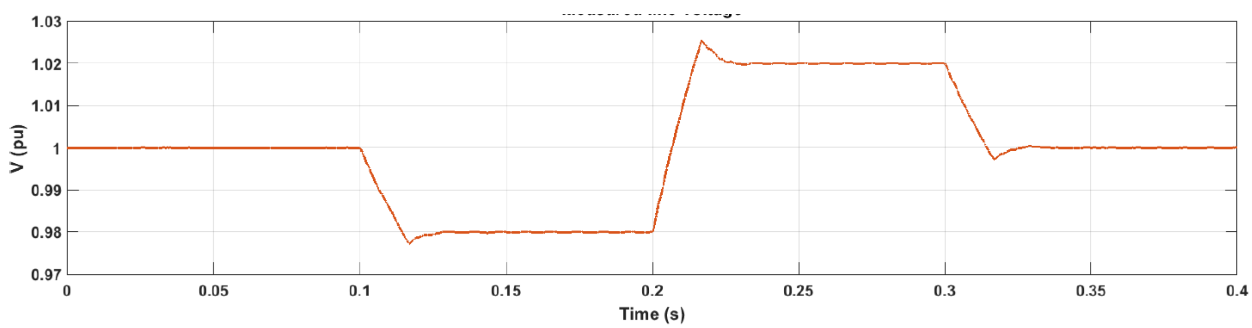

Figure 4.14 Measured Line voltage in pu

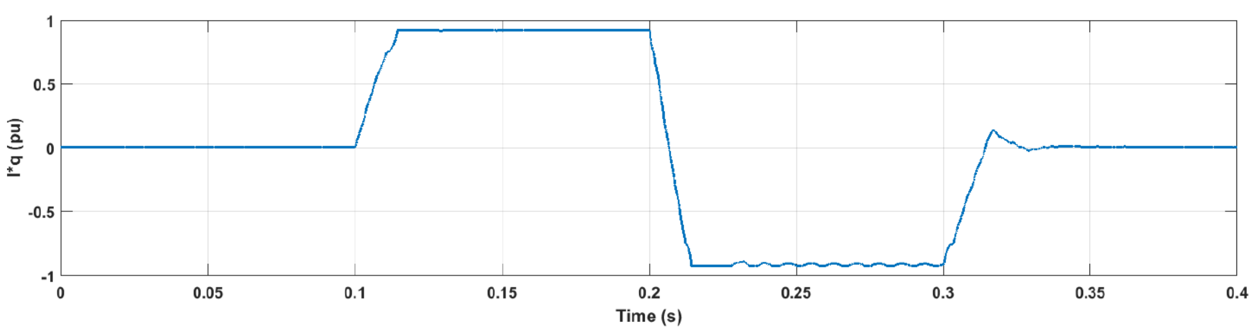

Figure 4.15 Reference reactive current

To demonstrate the effectiveness of the reactive current control utilizing a fuzzy logic controller (FLC), figure 4.16 presents a simultaneous plot of both the reference reactive current and the actual reactive current.

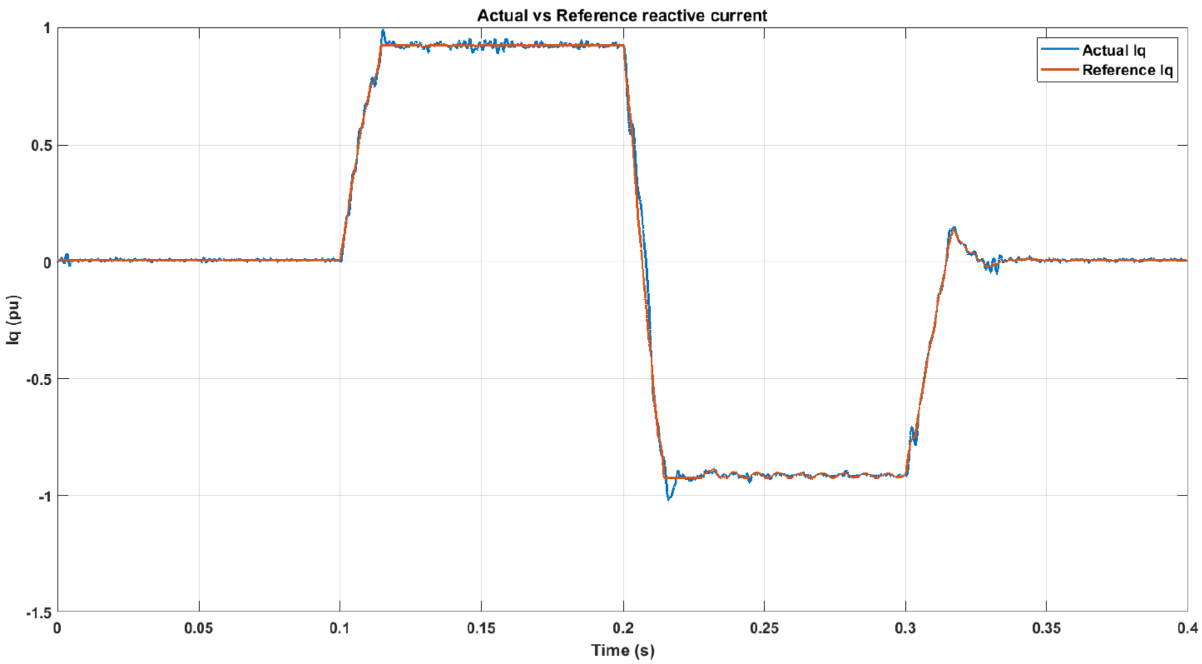

Figure 4.16 Reactive current of actual and reactive current of reference in FLC based DSTATCOM

The results clearly show that the FLC, which employs a carefully designed set of membership functions along with a precisely calibrated rule base, excels in tracking the desired reference reactive current. This performance indicates that the controller is not only responsive but also achieves a high degree of accuracy, effectively minimizing any deviations between the actual and reference values.

Such consistent performance highlights the FLC's capability to adapt to variations in system voltage, allowing it to maintain effectiveness across different operating conditions. This adaptability is crucial for applications that demand precise reactive power management, as it ensures the stability and efficiency of power systems.

By accurately following the reference reactive current, the FLC contributes significantly to enhancing power quality, reducing the risk of voltage instability, and optimizing the overall performance of the electrical network. Its robust design and responsiveness make it an invaluable asset in modern power distribution systems, particularly in environments characterized by fluctuating loads and renewable energy integration.

Conclusion and Recommendation

Conclusion

In conclusion, the FLC based DSTATCOM represents a sophisticated solution for managing voltage stability and enhancing power quality in electrical distribution systems. Its dynamic response to variations in source voltage allows it to effectively absorb or supply reactive power in real-time, which is crucial for maintaining system reliability.

In contrast, mechanically switched capacitors (MSCs) are often employed in power systems to provide reactive power support, particularly during peak load conditions. The simulation indicates MSCs imposes a voltage THD of 16.48% and 17.03% while switching a single bank and all the three stages of the bank respectively. Even though MSCs can be effective in boosting voltage levels, they have significant limitations:

Transient Power Quality Issues: MSCs are typically switched in and out based on predefined load conditions. This mechanical switching can lead to transient disturbances in the system, such as voltage spikes or sags, which may adversely affect sensitive equipment. The abrupt changes caused by mechanical switching can introduce flicker and other power quality issues that are less prevalent with the continuous operation of a DSTATCOM.

Response Time: The FLC based DSTATCOM's rapid response capability allows it to address voltage fluctuations almost instantaneously. In contrast, MSCs can have delays associated with their mechanical operation, which may not adequately respond to fast-changing load conditions or transient events. This slower response can result in prolonged periods of voltage instability, affecting overall power quality.

Operational Flexibility: The FLC based DSTATCOM offers greater operational flexibility compared to MSCs. It can provide reactive power support across a wide range of operating conditions, which is particularly advantageous in systems with variable loads or intermittent renewable energy sources. MSCs, however, are generally limited to specific operational regimes, making them less adaptable to fluctuating power demands.

FLC based DSTATCOM is seen having a good compensation capability maintaining an acceptable source voltage of 0.955 pu to 1.045 pu. Their ability to maintain voltage stability without introducing transient issues positions them as a more effective solution compared to mechanically switched capacitors, making them essential for modern electrical distribution networks

Recommendation

Based on the thesis work, switching in and out a mechanically switched capacitor bank throughout the whole day based on reactive power demand raises a power quality problem due to transient. Rather a power electronic based DSTATCOM is seen more effective in meeting the reactive power demand of the load. Due to that EEP is recommended to use this proposed system as they can maintain the system parameter with in an acceptable limit. The FLC is also seen as a good controller in generating the reference quadrature reactive current

To make the controller more advanced, it’s better to include an artificial neural network (ANN) so it can learn and update the weights of each rule to bring out the best output from fuzzy inference system.

References

A. L. de Oliveira, A. L. Pereira. (2010). Introduction of the Mechanically Switched Capacitors (MSCs) application on PowerTransmission Systems. Transmission and Distribution Conference and Exposition. Latin America:: IEEE/PES.

Amirnaser.Y, Reza Iravani. (2010). *VOLTAGE-SOURCED CONVERTERSINPOWER SYSTEMS: Modeling, Control, and Applications.* New Jersey: Wiley.

Amoozegar.D. (2016). DSTATCOM modelling for voltage stability with fuzzy logic PI current. 129–135.

Andreas.B, Raphael.C, Damien.J. (2017). *Reduction of Technical and Non-Technical Losses in Distribution Networks.* International Conference on Electricity Distribution.

Arati, Dr. G.. Jayaramaiah. (2022). Design of FLC based Control Strategy for DSTATCOM for Power Quality. *International Research Journal of Engineering and Technology (IRJET)*, Volume: 09.

Bjarne R. Andersen, Stig L. . (2020). *Flexible AC Transmission Systems FACTS.* Switzerland: Springer.

C.S. Sai , K.Harinath, P.Suresh Babu. (2014). Power Quality Enhancement in Distribution Systems Using D-STATCOM with Fuzzy Controller. *International Journal of Engineering Research and Development*, PP. 24-29.

Desta, M. (2019). Voltage and Reactive Power Control for Power loss Minimization of Distribution Networks Case Study- (Sebeta I Substation Outgoing Feeder).

E.Brown, R. (n.d.). Electrical Power Distribution Reliability. In R. E.Brown. Newyork: Marcel Dekker, Inc.

Emer.B, Marylu L. (2020). Optimization of Type-2 Fuzzy Logic Controller Design Using the GSO and FA Algorithms. *International Journal of Fuzzy Systems*.

G.Gupta, W.Fritz, M.T.E . (2017). A Comprehensive Review of DSTATCOM: Control and Compensation. *International Journal of Applied Engineering Research ISSN 0973- 4562*, Volume 12, pp. 3387-3393.

Garima S, Pankaj.K , Sudhir .K. (2018). A Comparative Strategy Using PI & Fuzzy Controller for Optimization of Power Quality Control. *Indonesian Journal of Electrical Engineering and Informatics (IJEEI),* pp. 118~124.

Grebe T.E. (1996). Application of Distribution System Capacitor Banks and their Impact on Power Quality. *IEEE Transactions on Industry Applications,*, p.714-719.

Jinho Jung, Hong.H, David .S. (2019). FUZZIFICATION: Anti-Fuzzing Techniques. *Georgia Institute of Technology*.

Kalyan K. and Mey Ling . (2009). *Introduction to FACTS Controllers: Theory, Modelling, Applications.* Wiley.

Mr. Amit , Mr. Vinayak K U. (2021). Design and Simulation of DSTATCOM using Fuzzy Logic Controller. *International Research Journal of Engineering and Technology (IRJET)*, Volume: 08.

Nan, Q. (2018). *Voltage Control in the Future Power Transmission Systems.* Cham, Switzerland: Springer International Publishing.

Narain G. Hingorani, Laszlo Gyugyi. (2000). *Understanding FACTS: Concepts and Technology of Flexible AC Transmission System* . Newyork: Institute of Electrical and Electronics Engineers, Inc.

Naser Mahdavi , Ali Jafari , Nicu Bizon, Frede Blaabjerg. (2017). *Reactive Power Control in AC Power Systems: Fundamentals and Current Issues.* Switzerland: Springer.

Prerna.J, R. J. (2021). FUZZY LOGIC CONTROLLER BASED D-STATCOM FOR POWER QUALITY SOLUTION IN DISTRIBUTED GENERATED SYSTEM. *International Journal of Technical Research & Science*, Volume VI Issue VII.

R. C. , D. O. Lacerda. (2010). Mechanically Switched Capacitor with Damping Network (MSCDN). *Engineering Aspects of Application, Design and Protection. Transmission and Distribution Conference and Exposition.* Latin America: IEEE/PES.

R. Mohan, Rajiv K. (2002). *Thyristor-Based FACTS Controllers For Electrical Transmission Systems.* USA: IEEE Press, Willey.

T. Varadharaj, S. Krishna.K. (2014). Fuzzy Logic based DSTATCOM for Voltage Regulation and Harmonic Reduction. *International Journal of Advanced Research in Electrical and Electronics Engineering*, Volume: 2 Issue: 1.

Tomohiro.T and Michio.S. (1985). Fuzzy Identification of Systems and Its Applications to Modeling and Control. IEEE.

Xiao-Ping , Christian Rehtanz, Bikash Pal. (n.d.). *Flexible AC Transmission Systems: Modelling and Control.* Newyork: Springer.

APPENDIX

The existing mechanically switched capacitor bank