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College of Engineering



Electrical and Electronics Engineering

Power Quality Improvement of Grid Connected PV System Using DFACTS Devices

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M.Sc Degree in Renewable Energy Engineering

Submitted by

Saeed Salem Saeed Alhelali

ID Number: 202100226

Supervised by

Dr. Sayed Ali Abbas Al-Mosawi

Associate Professor

Department of Engineering

University of Bahrain

Co-Supervised by

Dr. Fadhel Abbas Albasri

Assistant Professor

Department of Engineering

University of Bahrain

Kingdom of Bahrain

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University of Bahrain

College of Engineering

Department of Electrical and Electronics Engineering

Defense committee's approval

The student Saeed Salem Saeed Alhelali, student ID 202100226, has defended the thesis entitled "Power Quality Improvement of Grid Connected PV System Using DFACTS Devices" and by which he partially fulfilled the requirement for the degree of Master of science on 19/02/2025.

Thesis Defense Committee

Names

Signature

Dr. S. Ali Al-Mosawi (*Supervisor*)

A blue ink signature of Dr. S. Ali Al-Mosawi, consisting of stylized initials and a surname.

Dr. Fadhel Albasri (*Co-Supervisor*)

A blue ink signature of Dr. Fadhel Albasri, featuring a cursive style with the first letters of the first and last names being prominent.

Prof. Abdulla Al-Badi (*External Examiner*)

A blue ink signature of Prof. Abdulla Al-Badi, showing a clear, somewhat blocky cursive style.

Dr. Raja Mohammed Sumsudeen (*Internal Examiner*)

A blue ink signature of Dr. Raja Mohammed Sumsudeen, characterized by large, flowing loops and a clear surname.

Academic Department's Stamp

Abstract

This thesis aims to improve the power quality of a distribution network integrated with renewable energy sources by using Distribution Flexible Alternating Current Transmission Systems (DFACTS) devices. Renewable energy sources such as PV and wind power can distort the power quality, leading to fluctuated voltage, large frequency variations, reverse power flow, and many other issues concerning the stability of the grid. Moreover, the improvement of the DFACTS devices in this thesis will focus on designing a controller that will improve the network power quality by maintaining the voltage within the prescribed range. Various models of a network embedded with DFACTS devices will be designed and simulated simultaneously to compare and show the performance of each model. The tests will cover the reaction of the DFACTS device during multiple disturbance scenarios such as voltage drop, voltage rise, renewables trip, load variation, and unbalanced faults. The designed models will incorporate various controllers, such as the PI controller, Fuzzy controller, and Negative sequence controller, to mitigate different types of network disturbances. The results will show which model has a faster response time, better transient stability, and unbalanced fault detection and mitigation, as well as stating the thesis limitations and recommendations to further improve the project for future research.

Dedication

This work is dedicated to my esteemed family, whose unwavering support and encouragement have been my greatest source of strength. To my parents, for their boundless love and sacrifices, and to my siblings, for their constant inspiration and motivation.

I also dedicate this work to my mentors and teachers, whose guidance and wisdom have profoundly shaped my academic journey. Their belief in my potential has been a driving force behind this achievement.

Lastly, I dedicate this work to all my friends and colleagues, whose camaraderie and support have made this journey memorable and fulfilling.

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List of Abbreviations

DER	Distributed Energy Resources
DFACTS	Distribution Flexible Alternating Current Transmission Systems
FLC	Fuzzy Logic Controller
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
MSC	Mechanically Switched Capacitor
MSR	Mechanically Switched Reactor
MSSR	Mechanically Switched Series Reactor
MSSC	Mechanically Switched Series Capacitor
PES	Power and Energy Society
PI	Proportional Integral
PID	Proportional – Integral – Derivative
PLL	Phase-Locked Loop
PST	Phase Shifting Transformer

PV	Photovoltaic
PWM	Pulse Width Modulation
RPF	Reverse Power Flow
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
TCR	Thyristor Controlled Reactor
TCC	Thyristor Controlled Capacitor
TSR	Thyristor Switched Reactor
TSC	Thyristor Switched Capacitor
TCSR	Thyristor Controlled Series Reactor
TCSC	Thyristor Controlled Series Capacitor
TSSR	Thyristor Switched Series Reactor
TSSC	Thyristor Switched Series Capacitor
VSC	Voltage-Sourced Converter

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Appendix A

Overhead Line Configuration Data

Underground Line Configuration Data

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Chapter 1

Introduction

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1.1 Introduction

Photovoltaics (PV) has experienced exponential growth in installations over the past decade, making it one of the fastest-growing electricity sources. However, the current distribution network faces challenges in accommodating high penetration of renewable energy from PV and Wind turbines. These challenges include power quality distortions, fluctuating voltage, frequency variations, and reverse power flow, all of which impact the grid integrity.

Effective integration of renewable energy sources into the grid necessitates careful consideration of power quality. As the adoption of renewables, such as solar PV and wind turbines, continues to grow, their intermittent nature and variable output can significantly impact grid stability. Challenges related to voltage fluctuations, harmonics, and reactive power management arise, affecting the overall reliability and efficiency of the electricity supply. Addressing these issues is essential to ensure a seamless transition toward a cleaner and more sustainable energy system.

This drawback can be resolved by integrating Distribution Flexible Alternating Current Transmission Systems (DFACTS) devices, a power electronic-based systems designed to significantly impact the power quality and system performance within the electrical grids. By adeptly managing the power flow and bus voltages, they mitigate system losses and enhance overall stability. These devices address critical challenges, including congestion management, voltage profile improvement, improving power transfer capability, and power loss reduction. Their deployment is pivotal for maintaining reliable and efficient grid operation.

1.2 Objectives and Significance

The following objectives have been outlined to focus on improving the power quality of an isolated grid-connected renewable energy system by embedding a DFACTS device.

- 1- Selecting DFACTS device that will operate in the designed network and investigate the effect of each DFACTS device on the system.
- 2- Developing control algorithms employed for the DFACTS devices switching leading to performance enhancement.
- 3- Design different controllers for the DFACTS device and improve the former model.
- 4- Maximize the efficiency of the power quality.
- 5- Improve both the controllability and reliability of the distribution network.

The study that has been made in this thesis will introduce many aspects starting from an electrical network with renewable energy sources, all the way to embedding the system with state-of-the-art DFACTS devices. It is crucial to show the importance of having such devices in a network that contains renewables like PV and wind turbine technologies as the world is headed towards replacing conventional generators with clean energy sources.

Therefore, it is a must to dive into technologies that will serve and optimize the network while the total percentage of renewable energy sources is increasing dramatically. To further enhance the efficiency of DFACTS devices, it is essential to examine and improve various components. As outlined in the objectives, this thesis primarily focuses on optimizing the controller of these devices.

1.3 Contribution

In this thesis, each test has been meticulously designed to identify and address issues within the STATCOM system, building on the extensive body of research conducted over the years. The primary contribution of this work is the development of a controller capable of mitigating electrical grid disturbances, including generation and load tripping, voltage fluctuations, and unbalanced faults. Furthermore, the controller has been enhanced to improve efficiency, demonstrating a faster response and reduced settling time during oscillations caused by these disturbances. This advancement not only resolves existing problems but also significantly enhances the overall performance and reliability of the electrical grid.

Chapter 2

Theoretical Framework and Literature Review

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The essential purpose of this thesis is to look at different DFACTS devices and controllers, gather what will improve the model, and avoid what will have a negative effect on it. Conducting research in this field will help identify the key components of the DFACTS device design. This will facilitate comparisons and aid in determining the optimal improvements for the model.

2.1 Power Quality

Power quality in electrical systems is an assessment of how effectively the voltage, frequency, and waveform of the power supply adhere to established standards. High power quality is essential for the reliable and efficient operation of electrical equipment, minimizing disruptions and potential damage.

Power quality refers to the assessment and enhancement of the electrical power supplied to ensure it meets specific standards. This involves measuring and analysing the bus voltage to maintain a consistent sinusoidal waveform at the rated voltage and frequency. Maintaining good power quality is crucial because it ensures the reliable operation of electrical equipment, minimizes disruptions, and prevents damage caused by voltage fluctuations, harmonics, and other disturbances. By focusing on power quality, we can improve the efficiency and longevity of electrical systems, ultimately leading to more stable and reliable power supply (Fuchs & Masoum, 2008). Poor power quality can result in equipment malfunctions, reduced lifespan, and increased operational costs. Ensuring high power quality involves maintaining voltage stability, frequency stability, and waveform integrity, which collectively support the smooth and efficient functioning of electrical systems (Hatziargyriou et al., 2021).

Several aspects needed to be monitored to ensure the smooth operation of electrical systems and having a better power quality. Voltage dip (or sag) is an important aspect where having a temporary reduction that lasts a few milliseconds is different than lasting for a minute as it can disrupt sensitive equipment and can cause electrical interruptions in the grid. Overvoltage caused by sudden load reduction or power system faults is another aspect that can affect power quality where the voltage exceeds normal level as it can damage electrical equipment and shorten its lifespan. On the other hand, undervoltage is another aspect where voltage drops below normal level due to overloaded transformers or undersized conductors, causing inefficient operation and potential damage to electrical devices (Reis et al., 2009).

2.2 Impact of Renewables Resources on Voltage

Over the past few decades, renewable energy has become widely known as the world is shifting toward this type of resource. This way of producing electricity is preferred because of its advantages. It has lower maintenance requirements, where solar and wind turbines have fewer moving parts compared to the conventional gas turbines. Renewables also cost less due to the low operating and maintenance costs with the elimination of fuel expenses. Environmental benefits are also provided when using renewable resources rather than conventional gas turbines (Thoubboron, 2022).

However, the large penetration of renewable energy has some disadvantages that can affect the electricity system, especially in the voltage stability of the electrical grids. Voltage stability is dependent on the balance between the electrical system capacity and the consumer load. If the energy demand, which consists of both active and reactive power, becomes higher than the current generation the voltage stability problem

will appear as it will decrease depending on the size of the problem or the difference between the demand and the capacity as the instability of the voltage can reach a certain point where the voltage drops fast and have other cascaded effects (Toma & Gavrilas, 2014).

Conventional units with high inertia have a strong capability against disturbances and can withstand abnormal instability of the system (Niu et al., 2022). Unlike the traditional large conventional power plants, renewable energy units are distributed and independently controlled like rooftops solar panels and wind farms. Their varying nature results in fluctuated power generation as it is also uncontrolled by humans and more reliant on the weather conditions or time of the day. This all leads to concerns toward the power quality which refers to maintaining the voltage and current at the rated frequency and magnitude, Achieving high power quality ensures a reliable and stable system with minimum amounts of disruptions or harmonics that can be introduced by renewable energy systems causing issues to sensitive electrical equipment (Mughees, 2020).

One of the fastest-growing electricity sources is PV, with the increasing number of installations, the consequences of these devices must be addressed. The solar irradiance obtained from the sun can be instantly changed when a cloud passes over the solar panels causing the voltage to vary. Another thing to address is the Reverse Power Flow (RPF) where the PV system generates surplus electricity leading to a change in the power flow directions which can cause voltage instability if the grid is not designed to handle it (Naidu, 2022). Wind turbines can also impact power quality in several ways such as power peaks and flicker. (Duong et al., 2014).

2.3 DFACTS Devices

To improve the power quality of the electrical grid, DFACTS devices are introduced for the stated issue. DFACTS devices are designed in a way that will enhance the power transfer controllability and capability of AC transmission networks. It will therefore optimize the system operation as it will increase the limitation of the transient stability of the system, improve voltage profiles, and reduce power losses (Singh & Pal, 2019).

Mechanical switches, the earliest DFACTS devices (Seifi et al., 2010), use parallel or series connections to control system voltage by switching capacitors or reactors to absorb or produce reactive power. The switches that are connected in parallel can be either Mechanically Switched Capacitor (MSC) or Mechanically Switched Reactor (MSR).

Series-connected mechanical switches, such as Mechanically Switched Series Capacitor (MSSC) and Mechanically Switched Series Reactor (MSSR) control reactive power and impedance to manage voltage and current. The difference between the MSR and the MSSR is that the MSR is used as a reactive power absorber while the MSSR is used to increase the impedance of the circuit and works as a current limiter (American Power, 2022). On the other hand, MSSC provides a capacitive reactance in series with the circuit to minimize the voltage drop and regulate the voltage. whereas the MSC is more specialized in enhancing the power factor by changing reactive power demand (Portal & Csanyi, 2021). Phase Shifting Transformers (PST) is another mechanically switched device used to adjust phase angles to regulate active power flow. (Zhang, 2006).

Having a constant proportion of reactive power provided by the mechanical DFACTS devices is not effective for a system, especially when

the nature of the electrical grid is transient. Therefore, embedding thyristors in DFACTS devices established a new set of types called Static Var Compensator (SVC). SVC controllers are shunt-connected thyristor controllers that consist of a controlled thyristor or switched thyristor. Controlled thyristors have firing angle control for continuous regulation, whereas switched thyristors lack this feature, operating in discrete steps and being more cost-effective. (Eremia et al., 2016b).

Thyristor Controlled Reactor (TCR) and Thyristor Controlled Capacitor (TCC) are both considered as an SVC device with a firing angle control, while Thyristor Switched Reactor (TSR) and Thyristor Switched Capacitor (TSC) are both considered as SVC devices without a firing angle control. SVC devices are part of the DFACTS devices family, that are used to regulate the voltage and reactive power in the electrical grid (Adetokun & Muriithi, 2021). Such devices also have fast-acting power compensation due to the thyristors, aiming to make the power factor of the power system close to unity. Positioning such devices near large industrial loads with significant and rapid load variations can be highly advantageous for mitigating voltage fluctuations.

Another group of devices that falls under the DFACTS devices family is the series-connected thyristor controller that consists of a controlled thyristor or switched thyristor. Like the SVC devices, the controlled thyristor is built with a firing angle control for continuous control while the switched thyristor does not have a firing angle control making it operate in discrete steps. Thyristor Controlled Series Reactor (TCSR) and Thyristor Controlled Series Capacitor (TCSC) are built with a firing angle control, while Thyristor Switched Series Reactor (TSSR) and Thyristor Switched Series Capacitor (TSSC) do not have a firing angle control (Hingorani & Gyugyi, 2000). These controllers have the same features as the series

connected mechanical switches DFACTS devices with the addition of the variable reactive power injection for the TSSC and TCSC, or variable reactive power absorption for the TSSR and TCSR, thus having automatic control of the power flow and reactive power compensation (Arora et al., 2017) making them much faster than the mechanical switches which require human interference. Thyristor Controlled Phase Shifting Transformer (TCPST) is the equivalent device of a PST with the addition of a thyristor, it consists of a combined series and parallel power transformer that regulates the power flow by adjusting the phase angle of the voltage across the device with a faster operation as compared to the PST by virtue of the thyristors (LIU et al., 2018).

The latest generation has been introduced to the DFACTS devices family with the establishment of the Insulated-Gate Bipolar Transistor (IGBT). One of the advanced DFACTS devices used in electrical power systems is the Static Synchronous Series Compensator (SSSC), a remarkable device that can improve the stability of the electrical grid, enhance voltage regulation, and provide power flow controllability. SSSC device is connected in series via a coupling transformer and comprises of Voltage Sourced Converter (VSC) which is responsible for generating the controlled voltage, and a DC Capacitor which is needed to maintain the operation of the converters (Sen, 1998).

SSSC has many applications such as controlling the real power flow linearly in the transmission system and maintaining the voltage at the consumer's end despite the load variations which will be beneficial in weak networks. SSSC devices can be used to damp wide-area low-frequency power oscillations and improve grid stability by having multiple SSSCs at different points of the system network. The main advantage of the SSSC is that it has a fast response so that it can react rapidly to changing electrical

grid conditions. SSSC can dynamically adjust the power flow by changing the line impedance, where it can emulate a controllable capacitive or inductive reactance with the help of the converters (Kazemi et al., 2009).

2.4 STATCOM

The need for an advanced DFACTS device that focuses on reactive power compensation and supports the system voltage is essential. Unlike the SSSC which targets power flow and the stability of the transmission lines, the Static Synchronous Compensator (STATCOM) is a modern shunt-connected device used to manage reactive power primarily. Despite its function, STATCOM has similar components as SSSC such as a DC capacitor, VSC, a coupling transformer, and a harmonic filter. The DC capacitor provides a constant DC voltage for the VSC ensuring a smooth conversion between DC and AC. The VSC is the most important part of the STATCOM as it converts the DC input voltage coming from the DC capacitor to an AC output voltage by using the advanced IGBTs for an efficient and fast switching. The coupling transformer acts as an inductive reactance, but its main purpose is to connect the output of the VSC to the power system. The harmonic filter maintains the electrical system quality and isolates the STATCOM from other equipment interference as well as suppressing the unwanted harmonics generated from the converters (Eremia et al., 2016a).

The term synchronous in STATCOM device indicates that it can provide both inductive (lagging) reactive power or capacitive (leading) reactive power, or in other words, absorb or generate reactive power. This process happens by adjusting STATCOM's output rapidly leading to dynamic reactive power control which will enhance the grid stability during contingency events and short circuit faults. Using a proper controller, STATCOM will automatically maintain the electrical grid

voltage at rated values and increase the power quality to strengthen the voltage stability. Moreover, the rapid response time of the STATCOM is invaluable for maintaining grid stability during changing or fluctuating conditions. Its ability to quickly adjust reactive power support helps mitigate voltage fluctuations, ensuring a more stable and reliable power supply. Additionally, by continuously managing reactive power, the STATCOM contributes to reducing system losses, enhancing overall power quality. This dynamic control not only improves the efficiency of the electrical grid but also supports the integration of renewable energy sources, which can be variable by nature. As a result, the STATCOM plays a critical role in modern power systems, ensuring both stability and efficiency in the face of ever-evolving grid demands. (Eremia et al., 2016a).

The bi-directional flow of the reactive power between the STATCOM and the system shown in Figure 1 can be clarified by the following equations (Goel et al., 2010):

$$\text{Reactive power } Q = \left(\frac{V_2}{X_L}\right)(V_1 * \cos(\delta) - V_2) \quad (1)$$

$$\text{Active Power } P = V_1 * V_2 * \sin(\delta) / X_L \quad (2)$$

where V_1 and V_2 are two sources connected through a reactance X_L :

while the phase difference between V_1 and V_2 is represented by the angle δ . If angle $\delta = 0$, then the active and reactive power equation will be as follows:

$$\text{Reactive power } Q = \left(\frac{V_2}{X_L}\right)(V_1 - V_2)$$

$$\text{Active Power } P = 0$$

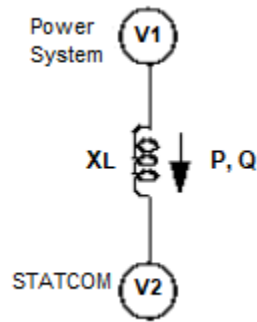


Figure 1: STATCOM and Power System Flow

The STATCOM controller now changes the output voltage dynamically to control the flow of the reactive power as described below:

If V_1 is bigger than V_2 , then reactive power will flow from V_1 to V_2 .

If V_2 is bigger than V_1 , then reactive power will flow from V_2 to V_1 .

If V_1 is equal to V_2 , then no flow of reactive power will occur.

This is done by configuring the controller of the STATCOM and adjusting it as it is required by the electrical system.

As the world is heading toward cleaner energy sources, it has become very important to integrate renewable energy, such as solar and wind, into the electrical system. Despite their many advantages, these type of renewable energy sources has some disadvantages, such as fluctuating behaviour throughout the day due to the nature of renewable sources and weather dependency. This will lead to impacting several factors that are mentioned earlier like voltage quality, grid stability, and reliability. STATCOM device has a major role when integrating renewable energy sources in the system, other than voltage control and power reactive compensation. STATCOM can be used to prevent renewable energy plants from tripping when there are voltage drops and network faults in the system by maintaining the voltage above the protection tripping setpoint, thus

having the solar arrays or wind turbines in service to maintain the generation and maximize the revenue (Neeraj et al., 2019).

2.5 Controllers

Integrating an advanced DFACTS device like the STATCOM into the network offers significant advantages, particularly in regulating system voltage. However, despite its capabilities, there are instances where the STATCOM may experience severe voltage dips or prolonged oscillations, which can undermine its effectiveness. These challenges highlight the importance of incorporating a robust controller within such devices. A well-designed controller can dynamically respond to voltage fluctuations and oscillatory behaviour, ensuring that the STATCOM maintains stable operation and continues to support grid reliability. Consequently, the development and implementation of effective control strategies are crucial for enhancing the performance of STATCOMs and addressing the complexities of modern power systems. A Proportional–Integral–Derivative (PID) controller is one type of controller that can be employed in a STATCOM, as well as in various industrial control systems, to adjust multiple process variables effectively.

The PID controller comprises three parts, the first is Proportional control which regulates the output proportionally to the present error, for example, if the error is large, then the control output will be proportionally large. Nevertheless, using proportional control alone is not practical because there may be a residual error after applying the proportional control. Hence comes Integral control, the second part of the PID controller which is responsible for the past values of the error. It eliminates the error that the proportional control cannot remove by integrating the past error over time. Moreover, the output value may overshoot and generate oscillations that can cause a problem for the system. The third part of the

PID controller is Derivative control which accounts for the rate of change of the error, resulting in future behaviour anticipation to reduce the overshoot (Johnson, 2005).

Having these three parts together forms a PID controller which can be represented by the following equation (Ang et al., 2005):

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de}{dt} \quad (3)$$

Where:

$u(t)$ = PID control variable

K_p = Proportional gain

K_i = Integral gain

K_d = Derivative gain

$e(t)$ = error value

de/dt = rate of change in error value with respect to time

PID controllers can be found in various applications due to their effectiveness in variable adjustment, the reason why industrial process plants deal with pressure, flow, and temperature, as these parameters can be very critical for operating the machinery, as well as stabilizing the parameters to a certain range of operation (Xu & Ding, 2016). PID controllers are also widely used in motion control systems for regulating motor speed, acceleration, and position. Moreover, it has also become common in the power electronics industry, as the controller in a STATCOM is one of the main components. PID controller adjusts STATCOM parameters to optimize power transfer and minimize losses, and with fine-tuning, it can maximize transmission efficiency and capability.

The PID controller in a STATCOM provides other advantages such as it ensures that the electrical system operates within its rated ranges by stabilizing the voltage. Dampened the oscillations to improve the stability of a system integrated with renewable energy sources and enhance the overall power quality (Chethan & Kuppan, 2024).

Another controller that can be used in a STATCOM is the Fuzzy logic controller (FLC), which provides flexible and intuitive solutions to overcome complex control scenarios. It has been used in many areas such as machine control and artificial intelligence as it can be very useful for decision making and rule-based systems. FLC can play a critical role in production processes for manufacturing and industrial purposes by having robust control and settings. In addition, it is applied in automotive systems like subway control systems to regulate acceleration and train movement ensuring the safety of the passengers and the train efficiency. Robotics, automation, and traffic control are other applications that can benefit from using FLC (Kovacic & Bogdan, 2017).

FLC components shown in Figure 2 comprises of four main parts, Fuzzifier, Fuzzy Rule Base, Fuzzy inference engine, and Defuzzifier. The Fuzzifier is the first stage of the FLC that converts crisp input values into fuzzy linguistic terms. To simplify the way that fuzzification works, crisp set defines an input to be either zero or one, and Fuzzy set defines the value to be between zero and one, such as 80% zero and 20% one, based on the fuzzy membership functions which represent the degree of truth in a fuzzy set. The second component is the Fuzzy Rule Base which contains a set of if-then rules that express the relationships between the input values and the output value. For example, if the temperature is hot, then adjust the air conditioner power. The next component is the Fuzzy Inference Engine which combines the rules from the Fuzzy Rule Base to make a decision, so

the Fuzzy Inference Engine will give a Fuzzy set output based on the input and the rules that have been set. The final component of the FLC is the Defuzzifier which converts the Fuzzy set output back to a crisp output (Foulloy et al., 1994).

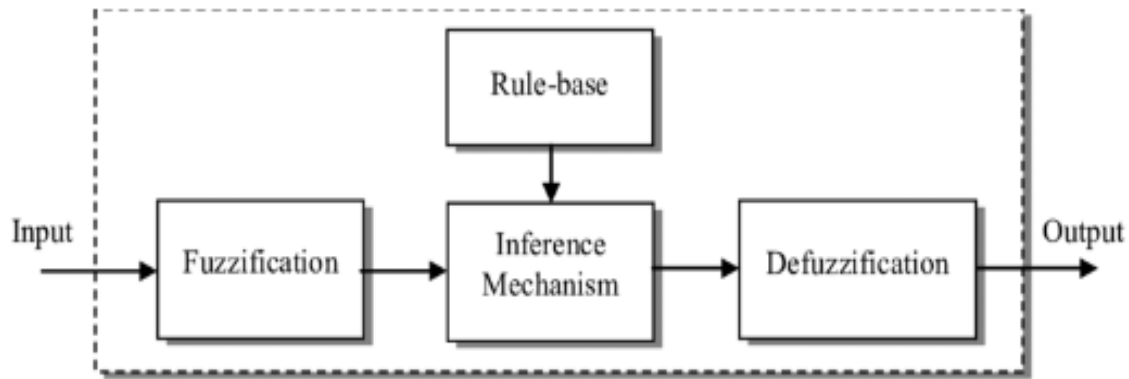


Figure 2: Fuzzy Controller Components Diagram

STATCOM operation is often controlled by the conventional PID controller. However, replacing the PID controller with FLC can add more benefits to the STATCOM operation. First, it can provide adaptability and robustness ensuring an efficient and fast-acting controller for handling variable load. This will also enhance voltage control, especially during dynamic conditions as it will refine the power quality. However, the most important feature of the FLC is that it combines human intuitive control and precise mathematical models by using a knowledge rule-based system (Rajan & Ebenezer, 2022).

STATCOM can restore the system to its normal condition after any dynamic or abnormal disturbances. However, an electrical disturbance may occur in the form of an unbalanced or asymmetrical fault. This type of fault requires a controller that can manage to balance the voltage in the healthy phases. The negative sequence controller uses a technique that can detect and eliminate the negative sequence component during the asymmetrical fault. It is essential to have a negative sequence controller because of the

issues that can be caused by asymmetrical faults such as reverse rotation, heating, and torque pulsations on generators and motors due to the reverse rotation of the magnetic field caused by the negative sequence component (Guiping Yi & Renjie Hu, 2013).

When imbedding a negative sequence controller in STATCOM, it will offer many benefits such as stabilizing the electrical grid where the STATCOM will mitigate voltage fluctuations and prevent severe voltage drops in transmission lines by compensating for negative sequence current. In addition, the combination of a STATCOM and a negative sequence control will provide a fast response time towards the negative sequence currents to further improve grid stability and minimize losses (Yu et al., 2021).

Chapter 3

Methods and Procedures

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3.1 Methods

This section will present the selected test feeder case from the Institute of Electrical and Electronics Engineers (IEEE) Power and Energy Society (PES) and the renewable energy sources integrated into the system. The engineering tool used for testing and simulating the former system is MATLAB/Simulink.

This section is structured into two primary parts. The first part details the IEEE PES test feeder utilized throughout the procedure and data collection. The second part outlines the renewable energy sources integrated into the system, their locations within the selected IEEE PES test feeder, and the total capacity of both active and reactive power generated by these renewable sources.

3.1.1 IEEE PES Test Feeder

The main purpose of using IEEE PES test feeders is to help programmers or developers check the accuracy of their system by having common parameters and data. The circuit model that has been selected for this thesis is IEEE 13-node test feeder which can be shown in Figure 1. This model is considered to be small as it is used to examine different features that are added to the distribution system (Schneider, 2017). The model is highly loaded considering that the model is short compared to other test feeders. It also has a combination of both underground and overhead cables, shunt inductors, and capacitors.

The model in Figure 3 is a 60Hz electrical system that operates at 4.16kV, and has 13 busbars though the model that has been used. It does not include the regulating transformer between nodes 650 and 632. Thus, the number of busbars was reduced to 12. The reason for excluding the regulating transformer is to observe the operation of the DFACTS devices

that will be applied later without the influence of voltage variation by changing the taps in the regulator transformer. The system has 10 loads, 2 capacitors, a breaker between nodes 671 and 692, and a 4160/480V transformer between nodes 633 and 634. Moreover, the total active power in the system is 3518.74kW while the total reactive power is 1540.14kVar. The detailed system data is given in Appendix A.

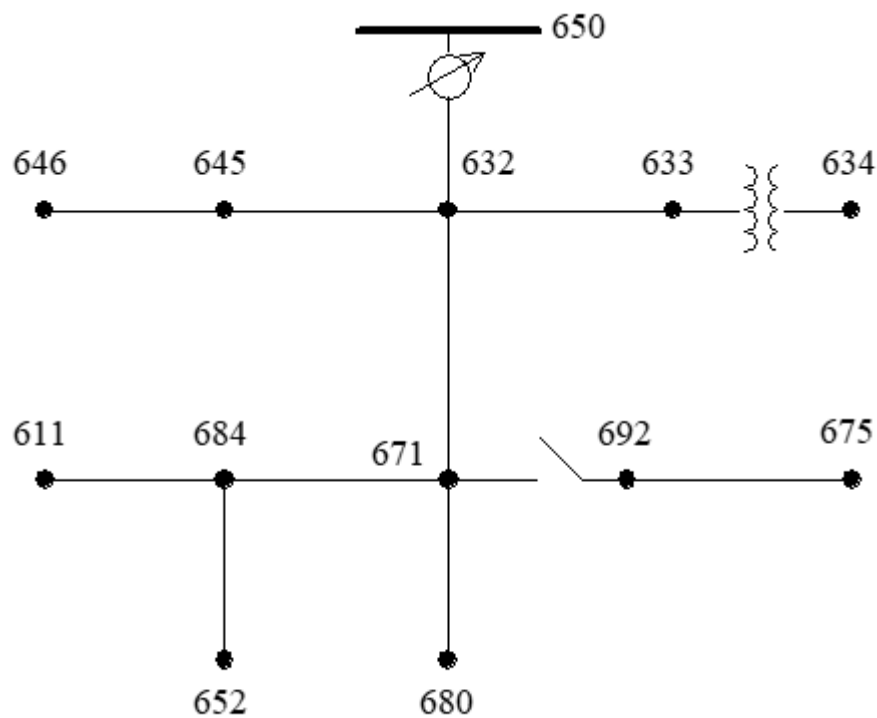


Figure 3: IEEE 13 Node Test Feeder

3.1.2 Renewable Energy Sources

After setting up the test feeder, Distributed Energy Resources (DER) can be interconnected to the electrical system. There are two DERs (LeSage, 2023) that have been connected in the system, a PV array, and a wind turbine, both are connected between nodes 692 and 675, two separate breakers that can be used to trip the renewable generations individually.

The PV array models a grid-connected solar array as seen in Figure 4 by using the Three-Phase Dynamic Load block in Simulink. The PV array generates 600kW of power supplying approximately 17% of the total load in the distribution system. It is useful for phasor load flow simulations as it has no inverters that will require to run the simulation on continuous type. The tests in this thesis focus on the changes in magnitude and the phases of currents and voltages when we have different cases such as voltage overshoots, dips, or circuit trips. Therefore, the lack of inverters in the selected PV array is ideal for running the simulation in phasor type. Additionally, the input to this block is the required power output of the PV array, so it does not depend on irradiance or temperature. However, a sinusoidal curve can be set as the input to the block to represent a daily generation of a PV array if required.

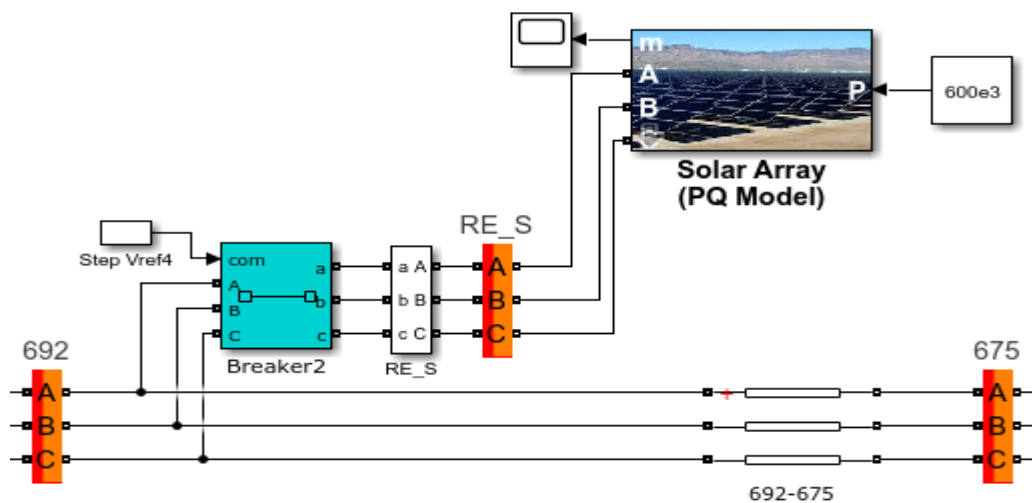


Figure 4: PV Array Model

The wind turbine that has been used as shown in Figure 5, serves as an active and reactive power source depending on the wind power curve which can be defined by the dimensions of the wind turbine, simple cubic power curve, and look-up vector from a wind turbine data sheet. The minimum operating wind speed is at 5m/s and the maximum operating

wind speed at 25m/s. The nominal wind speed is at 15m/s at which it will generate maximum power rated at 1.5MW which represents around 42.6% of the total demand in the distribution system, and it also supplies 1.125MVar of reactive power. Both the PV array and wind Turbine are kept generating their maximum power of 600kW and 1.5MW respectively during the simulation.

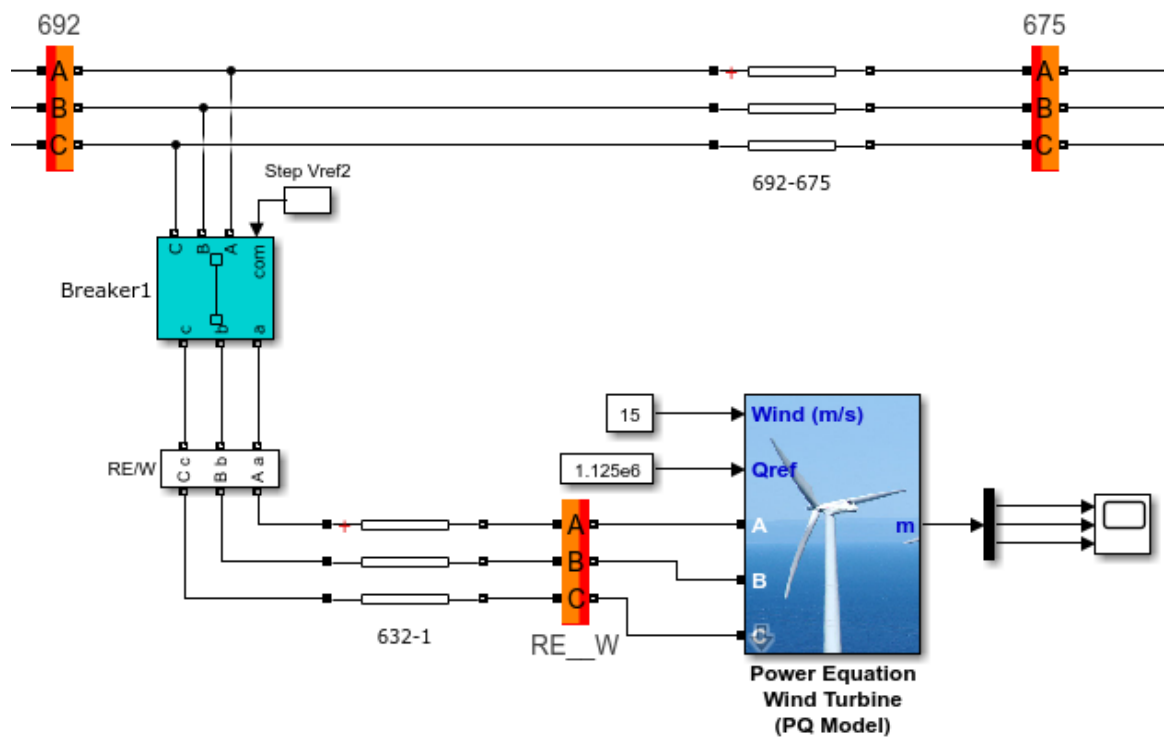


Figure 5: Wind Turbine Model

3.2 Procedures

After setting up the test system, this part of the chapter will show the different designs that have been implemented in order to observe the effects of such designs and STATCOM controllers separately.

3.2.1 STATCOM Control System

There will be three different STATCOM controllers that will be connected to the system individually between nodes 692 and 675 as can be seen in Figure 6. In addition, a fourth design will not have a STATCOM device to notice the effect and compare it with the rest of the designs.

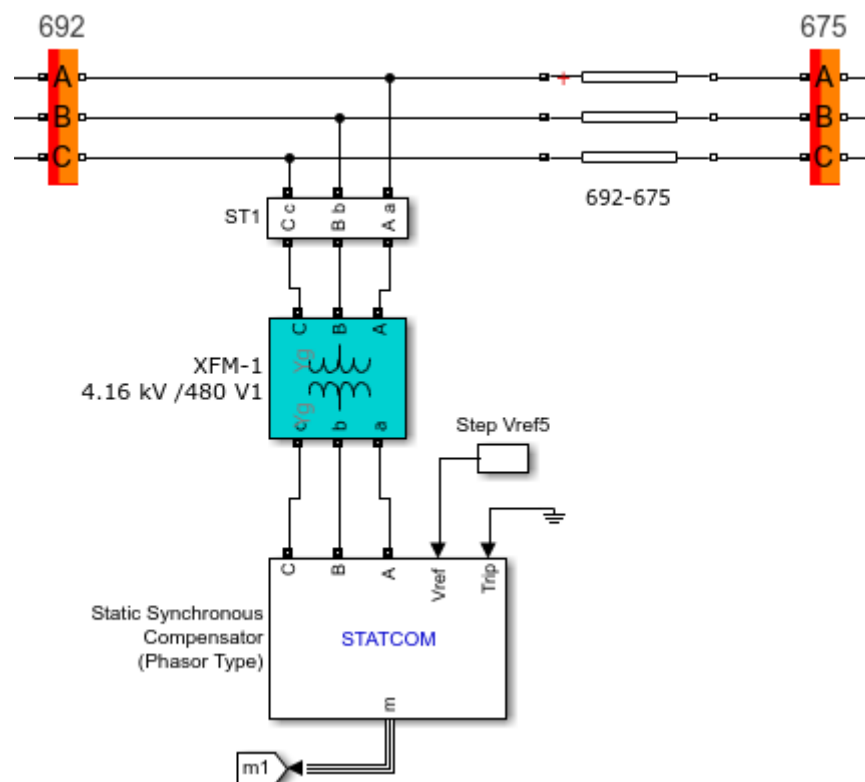


Figure 6: STATCOM Model

The converter rating of the STATCOM (Phasor Type) block in Figure 6 is rated at 6MVA with a DC link nominal voltage of 560V which has an equivalent capacitance of 114.8mF. It has a VSC that varies the reactive power using IGBT that operates by using the Pulse Width Modulation (PWM) method. A single-line diagram of a STATCOM and its control

system block diagram is shown in Figure 7. However, the VSC and PWM modulator parameters remain unchanged and are configured using the default settings provided by Matlab/Simulink in the procedure

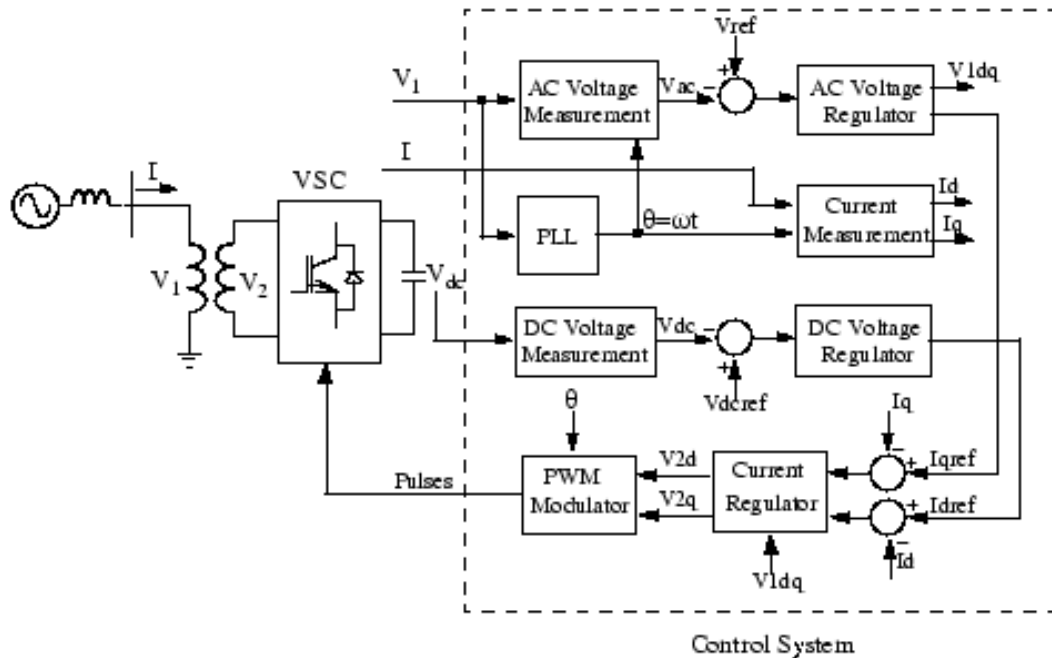


Figure 7: STATCOM Control System

There are four main parts in the control system of the STATCOM:

1- Phase-Locked Loop (PLL) which synchronizes on the positive-sequence component of the three-phase primary voltage and current across node 692 which are V_1 and I respectively in Figure 7. The PLL outputs angle θ that will be used to determine the quadrature-axis and direct-axis components of the AC three-phase currents and voltages are shown in Figure 7 as I_d , I_q , V_d , and V_q . Having a three-phase system represented as phases a, b, and c, the positive-sequence components V_1 and I can be calculated using the following equations:

$$V_1 = 1/3(V_a + kV_b + k^2 * V_c) \quad (4)$$

$$I = 1/3(I_a + kI_b + k^2 * I_c) \quad (5)$$

Where $k = \exp(j * 2 * \pi / 3)$

V_1 can be transferred from the cartesian form to the polar form to get the angle θ .

2- Measurement systems consist of DC Voltage Measurement which will compute the DC voltage V_{dc} , AC Voltage Measurement, and Current Measurement which will compute the q and d components of the AC three-phase currents and voltages. The magnitude of V_1 can be used to get V_d and V_q by transferring the magnitude back to the cartesian form so that the real component is equal to V_d while the imaginary component is equal to V_q . The same procedure is used to obtain I_d and I_q by transferring the polar form to the cartesian form after subtracting the resultant angle by θ .

3- Outer regulation loop that consists of a DC Voltage Regulator and an AC Voltage Regulator. The DC Voltage Regulator outputs the reference current I_{dref} which is current in phase with the voltage that controls the active power flow, while the AC Voltage Regulator outputs the reference current I_{qref} which is in quadrature with voltage that controls the reactive power flow. Both I_{dref} and I_{qref} will be used as input for the inner current regulation loop. Both I_{qref} and I_{dref} are outputs of two separate PI controllers with a reference AC voltage (equal to system voltage) and DC voltage (equal to converters DC link) respectively that are used as a setpoint to calculate the error that will be the input of the PI controller. The K_p and K_i gains in the V_{ac} and V_{dc} regulators are shown in Figure 8.

Static Synchronous Compensator (Phasor Type) (mask)

Implement phasor model of three-phase static synchronous compensator (STATCOM).

Power Controller

Mode:

Voltage regulation

Reference voltage Vref (pu): 1.00 ☒ External

Maximum rate of change of reference voltage (pu/s): 10

Droop (pu): 0.03

Vac Regulator gains [Kp, Ki]: [5, 1000]

Vdc Regulator gains [Kp, Ki]: [0.1e-3, 20e-3]

Figure 8: STATCOM Controller Parameters

4- The inner current regulation loop, shown in the diagram as the Current Regulator controls the phase and magnitude of the voltage generated by the PWM converter (V_{2q} and V_{2d}) using the reference currents I_{qref} and I_{dref} that are generated from the AC Voltage Regulator and DC Voltage Regulator respectively. The following sections will present the different controllers that have been implemented in the inner current regulation loop.

3.2.2 STATCOM – PI Controller

The first controller used is the Proportional Integral (PI) controller. The input of the Inner current regulation loop are I_{qref} and I_{dref} , these values are subtracted by I_q and I_d respectively, to obtain the error values, which will serve as inputs of the PI controller shown in Figure 9 where K_p

$= 0.3$ and $K_i = 10$. In addition, a limiter has been added to the controller to limit the output current.

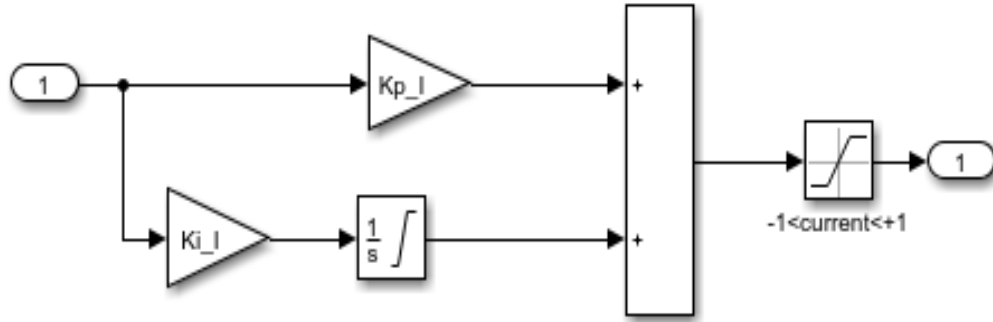


Figure 9: Current Regulator PI Controller

The PI controller output V_{dref} and V_{qref} will be subtracted from V_d and V_q respectively to get V_{2d} and V_{2q} which will be used along with angle θ for the PWM converter.

3.2.3 STATCOM – Fuzzy Logic Controller

The next controller used is the Fuzzy Logic Controller. The current regulator Fuzzy Logic Controller in Figure 10 will have the same input values as the PI controller. Therefore, the input of the fuzzy controller will be the error value obtained by subtracting I_q and I_d from I_{qref} and I_{dref} respectively.

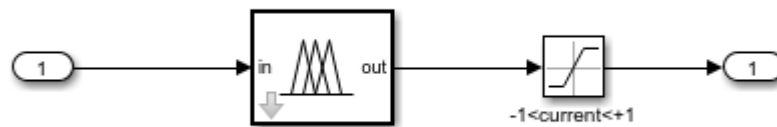


Figure 10: Current Regulator Fuzzy Logic Controller

The input range of the Fuzzy Logic Controller ranges from -8 to 8, while the output ranges from -20 to 20. There are 9 fuzzy sets for the inputs and for the outputs as illustrated in Figures 11 and 12.

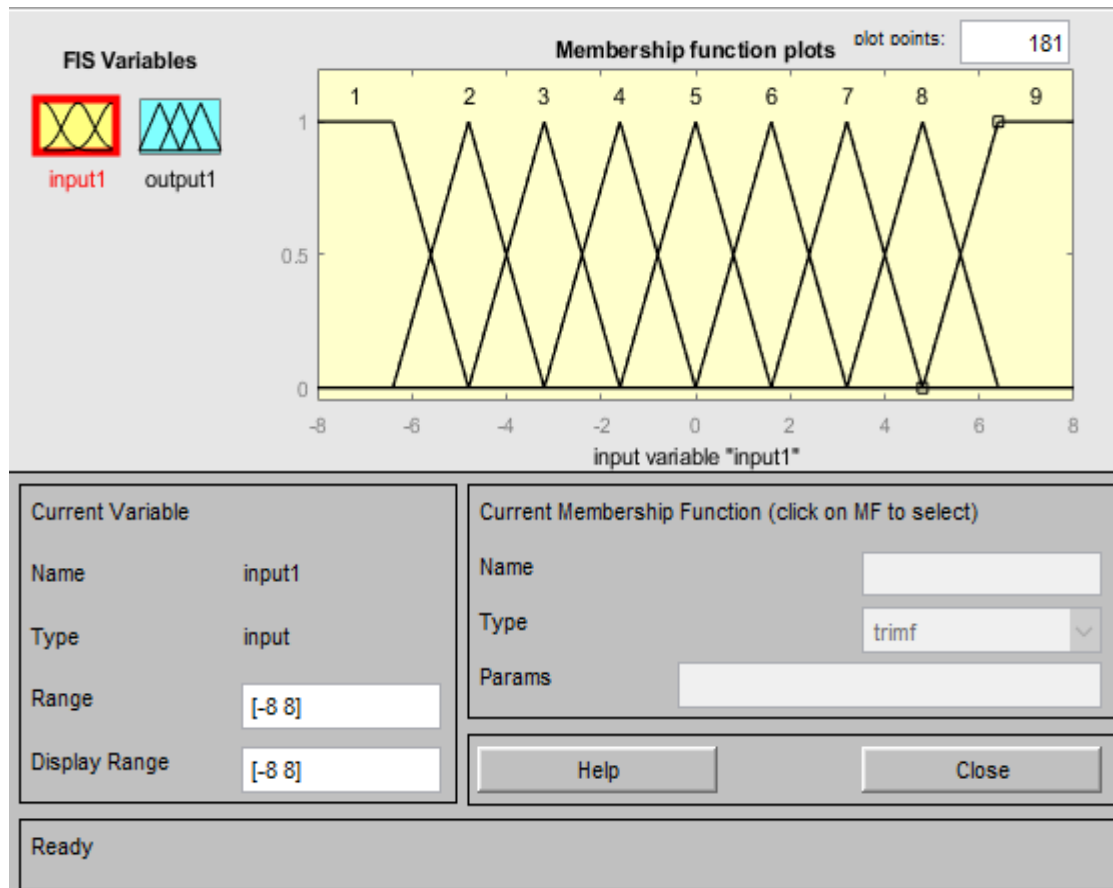


Figure 11: Fuzzy Logic Controller Input sets

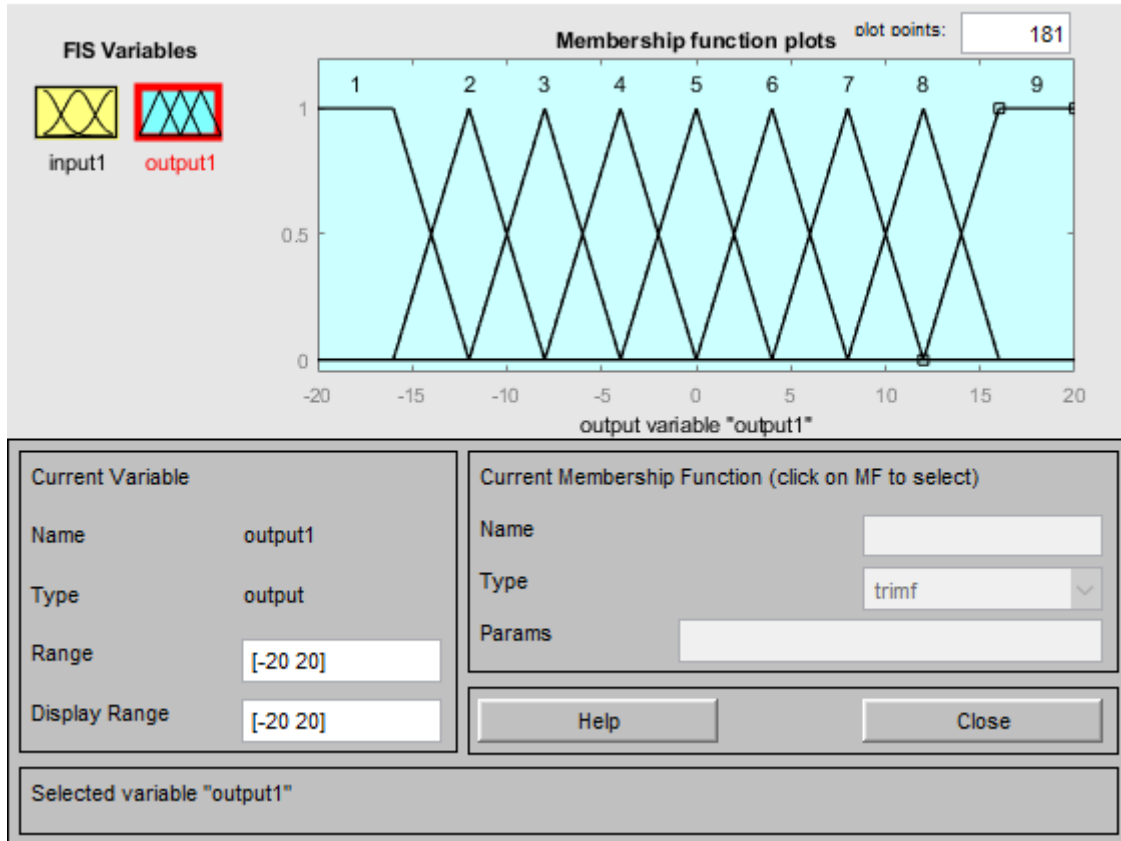


Figure 12: Fuzzy Logic Controller Output sets

The first and last sets of the membership function plots for the input and output of the Fuzzy Logic Controller are trapezoidal membership functions while the remaining sets are triangular membership functions. The rules of the Fuzzy Logic Controller are straightforward, if the input falls within the first set of membership function, then the output will correspondingly fall within the first set of membership function. And if the input falls within the second set of membership function, then the output will correspondingly fall in the second set of membership, and so on. The rules of the Fuzzy Logic Controllers are shown in Figure 13.

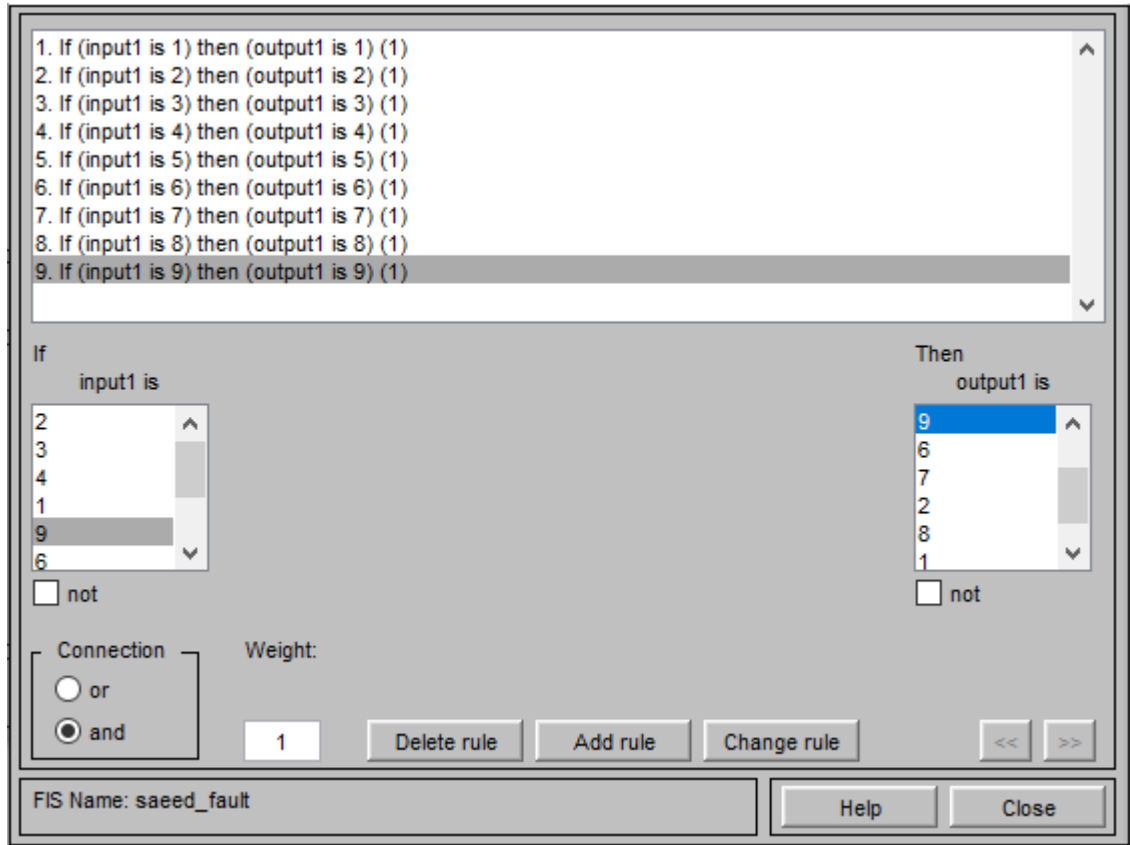


Figure 13: Fuzzy Logic Controllers Rules

3.2.4 STATCOM – Negative Sequence Controller

The final controller will use a PI controller or a Fuzzy Logic Controller in addition to a negative sequence controller that will be triggered or operated when an unbalanced fault condition is detected in the system.

Having a three-phase system represented as phases a, b, and c, the negative sequence V_2 and I_2 can be calculated using the following equations:

$$V_2 = 1/3(V_a + kV_c + k^2 * V_b) \quad (6)$$

$$I_2 = 1/3(I_a + kI_c + k^2 * I_b) \quad (7)$$

Where $k = \exp(j * 2 * \pi / 3)$

The negative sequence controller is designed to obtain the negative sequence voltage and current in case of unsymmetrical faults:

- 1- Single line-to-ground fault.
- 2- Line-to-line fault.
- 3- Double Line-to-ground fault.

However, a positive sequence voltage and current should be used during symmetrical faults:

- 1- Three-phase short circuit fault.
- 2- Three-phase-to-ground fault.

Therefore, the negative sequence controller is designed to find out whether it is a symmetrical fault and continues with the positive sequence components or an unsymmetrical fault and switches to the negative sequence components.

By measuring the voltages on each phase (V_a , V_b , and V_c), the controller can decide if there is a fault and the type of that fault by using logical comparisons with counter and IF condition functions as shown in Figure 14.

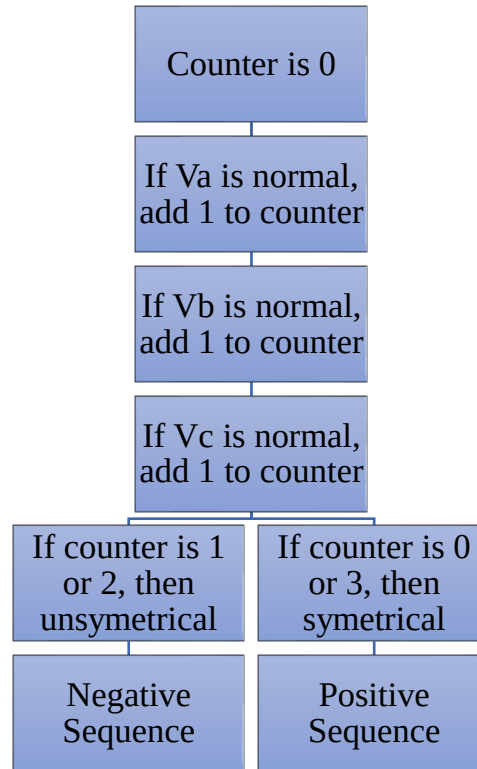


Figure 14: Negative Sequence Controller Function

If the counter is 3, it means that the voltage on each phase is normal, and no fault has occurred. Therefore, the PLL derives the positive sequence components for the controller. On the other hand, if the counter is 0, it means that there is a fault on each phase and the voltage is below its intended value, meaning that there is either a three-phase short circuit fault or a three-phase-to-ground fault. Both cases are considered as a balanced or a symmetrical fault, thus the PLL will also derive the positive sequence components for the controller.

Now if the counter is 1, which means that there are two phases that have an abnormal voltage and only one phase is healthy and normal, it will either be a double line-to-ground fault or a line-to-line fault. In this case, the fault is unbalanced so the PLL will derive the negative sequence components for the controller. Finally, if the counter is 2, then it means that there will be one faulted phase and two phases that are not faulty, meaning that a single line-to-ground fault occurred in this case. Knowing that the

single line-to-ground fault is an unsymmetrical fault, the PLL will also derive the negative sequence for the controller.

Chapter 4

Results and Discussions

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4.1 Results

In this section, multiple tests and scenarios will be applied to four different systems, a system with no STATCOM, a system with a STATCOM that has a PI controller, a system with a modified STATCOM that has a PI controller and a negative sequence controller, and a system with a modified STATCOM that has a Fuzzy controller and a negative sequence controller. The results will be illustrated to show and compare the performance of these systems in the proposed IEEE 13-node test feeder.

4.1.1 Initial Conditions

The following initial conditions have been set before running the simulation for all the tests to ensure accurate outcomes and fair comparisons between the different systems.

- The initial source voltage is set to 1.04 p.u where 1 per unit phase voltage is 2401.78V (phase-to-phase voltage = 4160V) and a system frequency of 60Hz.

- The total system active power load is 3518.74kW while the reactive power load is 1540.14kVar.

- The data collected for the results is measured at Bus 692.

- The faults are applied at Bus 671 for a duration of 4 cycles of power frequency (4/60 seconds).

- STATCOM's converter rating (6MVA), converter impedance, DC link nominal voltage, DC link total equivalent capacitance, as well as controller droop characteristics are not changed throughout the entire simulation.

4.1.2 Test No. 1: Voltage Drop

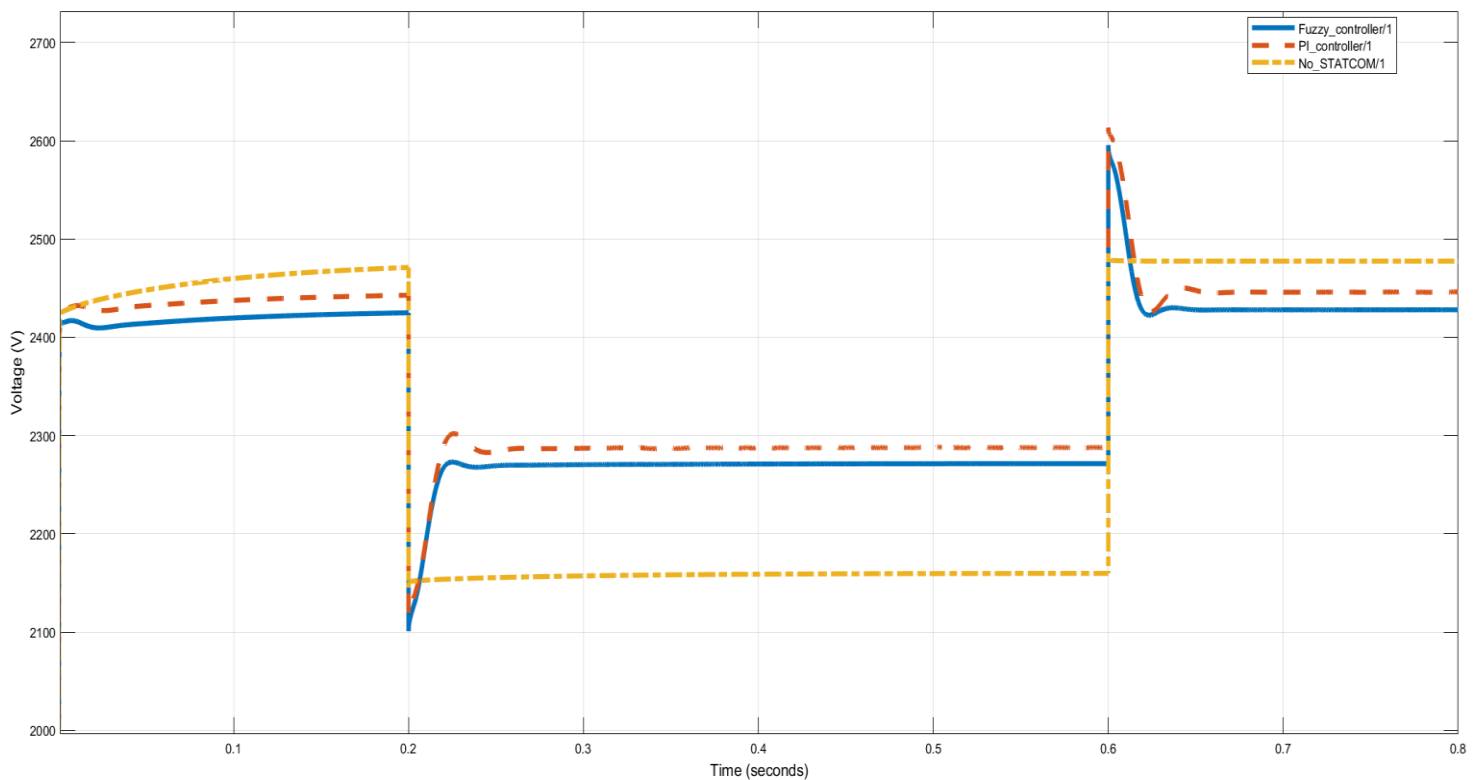


Figure 15: 0.9p.u Source Voltage Drop Condition

The first test that has been made is a voltage drop test. The source voltage located at Bus 632 shown in Figure 1 has been programmed to drop down to 0.9p.u. The graph in Figure 15 shows the simulated voltage for three different systems against time.

The yellow dotted line in Figure 15 represents a system with no STATCOM. Before the voltage dip, the phase voltage was 2477V which is around 1.03p.u at Bus 692. After the voltage drop occurred at 0.2 seconds, the voltage dropped at Bus 692 down to 2160V or approximately 0.89p.u. The disturbance finishes at 0.6 seconds and the voltage recovers to its normal condition value at 2477V.

The orange dashed line in Figure 15 represents a system with a STATCOM that has a PI controller. Before the voltage dip, the phase to line voltage was 2446V which is around 1.02p.u at Bus 692. After the voltage drop occurred at 0.2 seconds, the voltage dropped at Bus 692 down to

2287V or approximately 0.95p.u. The disturbance finishes at 0.6 seconds and the voltage recovers to its normal condition value at 2446V.

The blue solid line in Figure 15 represents a system with a STATCOM that has a Fuzzy controller. Before the voltage dip, the phase voltage was 2428V which is around 1.01p.u at Bus 692. After the voltage drop occurred at 0.2 seconds, the voltage dropped at Bus 692 down to 2271V or approximately 0.95p.u. The disturbance finishes at 0.6 seconds and the voltage recovers to its normal condition value at 2428V.

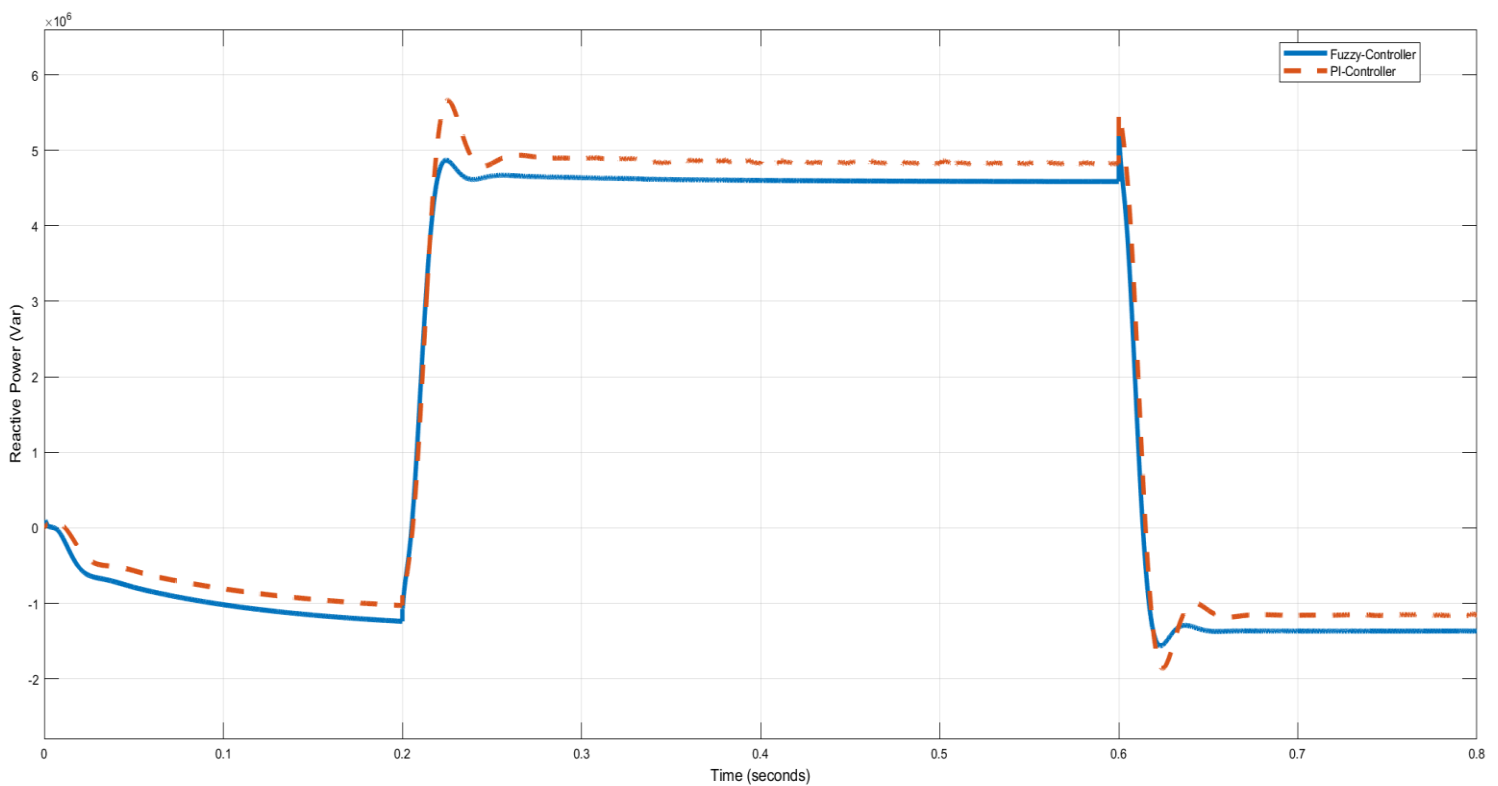


Figure 16: STATCOM Contribution During Voltage Drop Condition

Figure 16 shows the reactive power of the STATCOM with different controllers. It can be seen that both cases generated reactive power at the time of the voltage drop at 0.2 seconds. The STATCOM with PI controller has generated around 4.8MVar across the 3-phases, while controller STATCOM with Fuzzy controller has generated a total of 4.6MVar

approximately across the 3-phases. However, during the time of the disturbance at 0.2 seconds and the end of the voltage drop at 0.6 seconds, it can be noticed that there are differences in the response of the STATCOMs where the Fuzzy controller has better transient performance and smaller overshoots as compared to the STATCOM with PI controller where the orange dashed line represents the STATCOM with PI controller and the blue solid line represents the STATCOM with Fuzzy controller.

4.1.3 Test No. 2: Voltage Rise

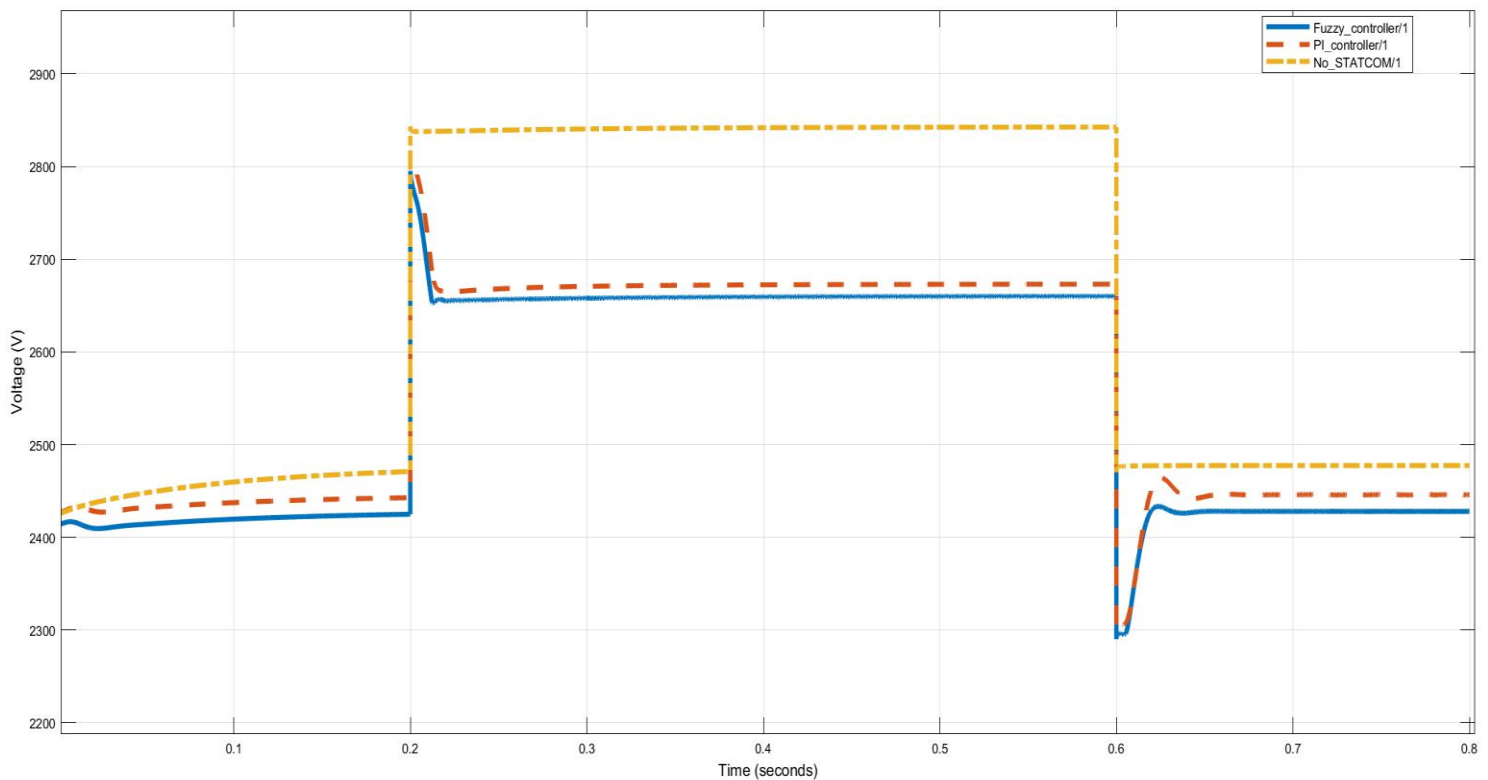


Figure 17: 1.2p.u Source Voltage Raise

The second test that has been made is a voltage rise test. The source voltage located at Bus 632 shown in Figure 1 has been programmed to increase up to 1.2p.u. The graph in Figure 17 shows the simulated voltage for three different scenarios against time.

The yellow dotted line in Figure 17 represents a system with no STATCOM. Before the voltage increment, the phase voltage was 2477V

which is around 1.03p.u at Bus 692. After the voltage rise occurred at 0.2 seconds, the voltage increased at Bus 692 up to 2842V or approximately 1.18p.u. The disturbance finishes at 0.6 seconds and the voltage recovers to its normal condition value at 2477V.

The orange dashed line in Figure 17 represents a system with a STATCOM that has a PI controller. Before the voltage rise, the phase voltage was 2446V which is around 1.02p.u at Bus 692. After the voltage increment occurred at 0.2 seconds, the voltage increased at Bus 692 up to 2673V or approximately 1.11p.u. The disturbance finishes at 0.6 seconds and the voltage recovers to its normal condition value at 2446V.

The blue solid line in Figure 17 represents a system with a STATCOM that has a Fuzzy controller. Before the voltage rise, the phase voltage was 2428V which is around 1.01p.u at Bus 692. After the voltage increment occurred at 0.2 seconds, the voltage increased at Bus 692 up to 2659V or approximately 1.10p.u. The disturbance finishes at 0.6 seconds and the voltage recovers to its normal condition value at 2428V.

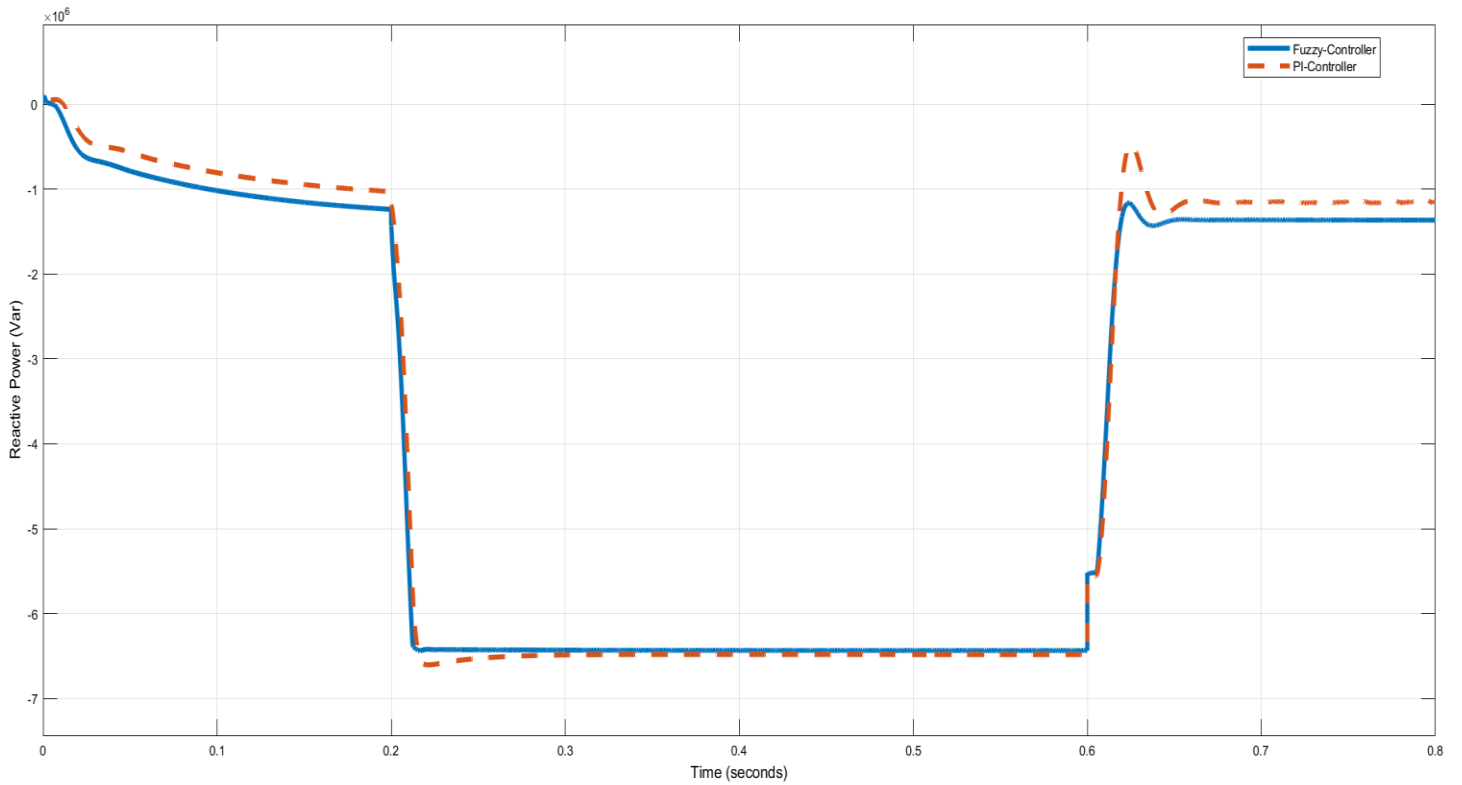


Figure 18: STATCOM Contribution During Voltage Rise Condition

Figure 18 shows the contribution of the STATCOM with the reactive power under different controllers. It can be seen that both controllers absorbed reactive power at the time of the voltage drop at 0.2 seconds. The STATCOM with PI controller and the STATCOM with Fuzzy controller have both absorbed around 6.4MVar across the 3-phases. However, during the time of disturbance at 0.2 seconds and the end of the voltage drop at 0.6 seconds, it can be noticed that there are differences in the reaction of the STATCOMs. The Fuzzy controller has better transient performance and smaller overshoots as compared to the PI controller where the orange dashed line represents the STATCOM with PI controller and the blue solid line represents the STATCOM with Fuzzy controller.

4.1.4 Test No. 3: Renewables Trip

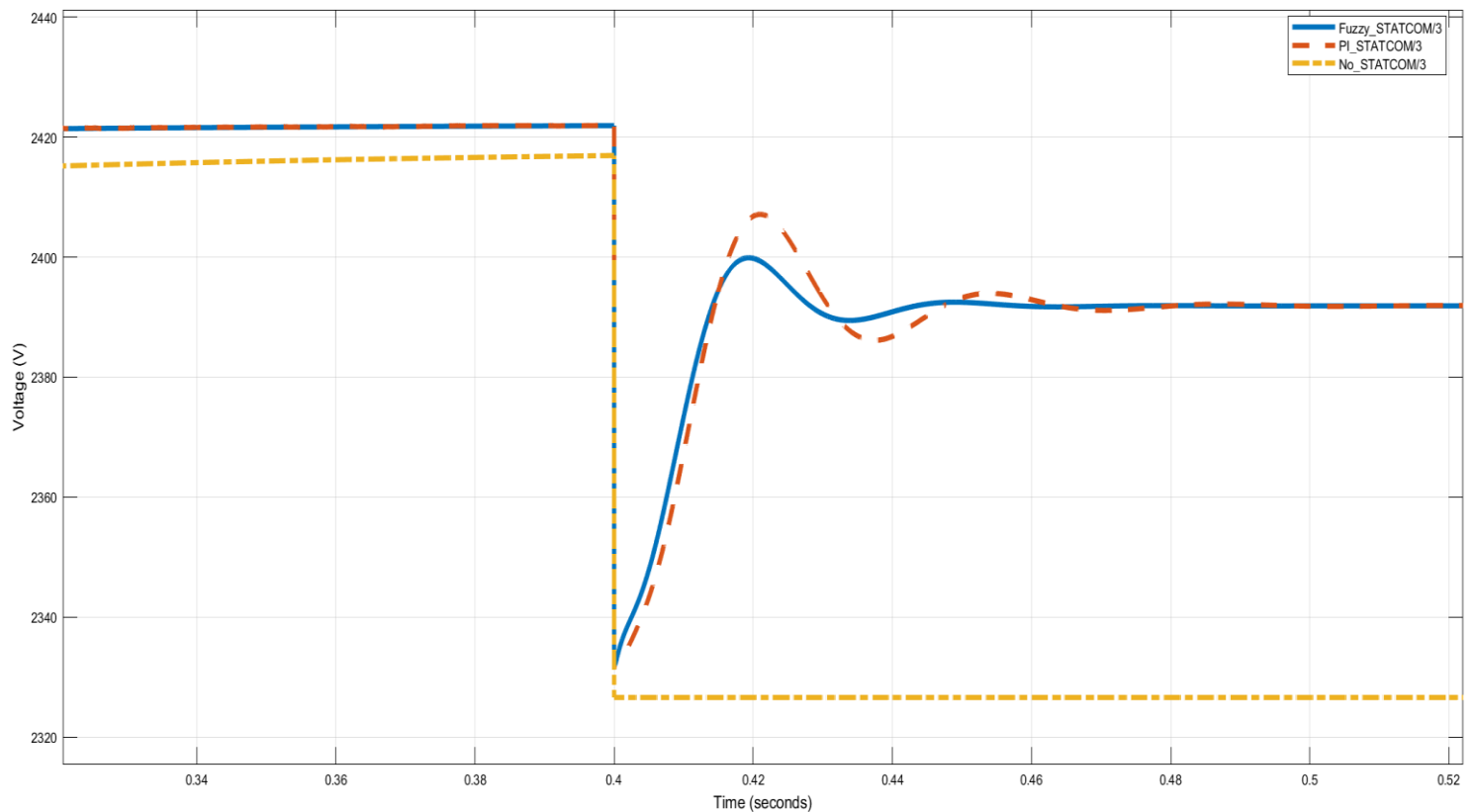


Figure 19: Renewables Trip Voltage Disturbance Condition

The third test that has been simulated is a renewables trip test in which the PV array and the wind turbine at Bus 692 are programmed to trip at 0.4 seconds. Figure 19 shows the simulated voltage for the three different cases against time.

The yellow dotted line in Figure 19 represents a system with no STATCOM. Before the voltage increment, the phase voltage was 2417V which is around 1.01p.u at Bus 692. After the renewables trip occurred at 0.4 seconds, the voltage dropped at Bus 692 down to 2327V or approximately 0.96p.u.

The orange dashed line in Figure 19 represents a system with a STATCOM that has a PI controller. Before the renewables trip, the phase

voltage was 2421V which is around 1.01p.u at Bus 692. After the renewables trip occurred at 0.4 seconds, the voltage decreased at Bus 692 down to 2391V or approximately 1.00p.u.

The blue solid line in Figure 19 represents a system with a STATCOM that has a Fuzzy controller. Before the renewables trip, the phase voltage was 2422V which is around 1.01p.u at Bus 692. After the renewables trip occurred at 0.4 seconds, the voltage dropped at Bus 692 down to 2392V or approximately 1.00p.u.

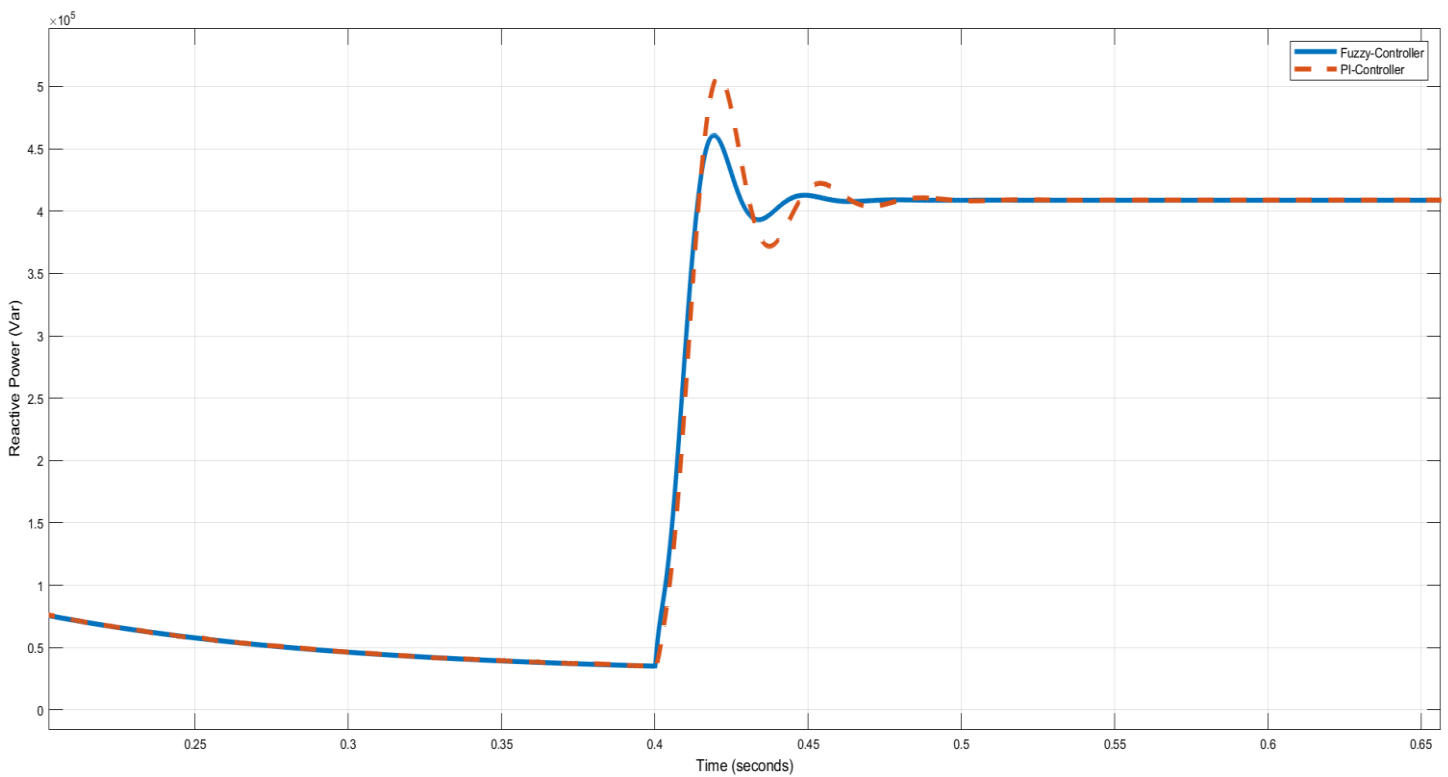


Figure 20: STATCOM Contribution After Renewables Trip Condition

Figure 20 shows the contribution of the STATCOM with the reactive power under different controllers. It can be seen that both controllers generated reactive power at the time of the renewables trip at 0.4 seconds. The STATCOM with PI controller and the STATCOM with Fuzzy controller both absorbed around 1.2MVar across the 3-phases. However, After the renewables trip occurred at 0.4 seconds, it can be noticed that there are differences in the reaction of the STATCOMs where the Fuzzy

controller has better transient performance and smaller overshoots as compared to the PI controller where the orange dashed line represents the STATCOM with PI controller and the blue solid line represents the STATCOM with Fuzzy controller.

4.1.5 Test No. 4: Load Variation

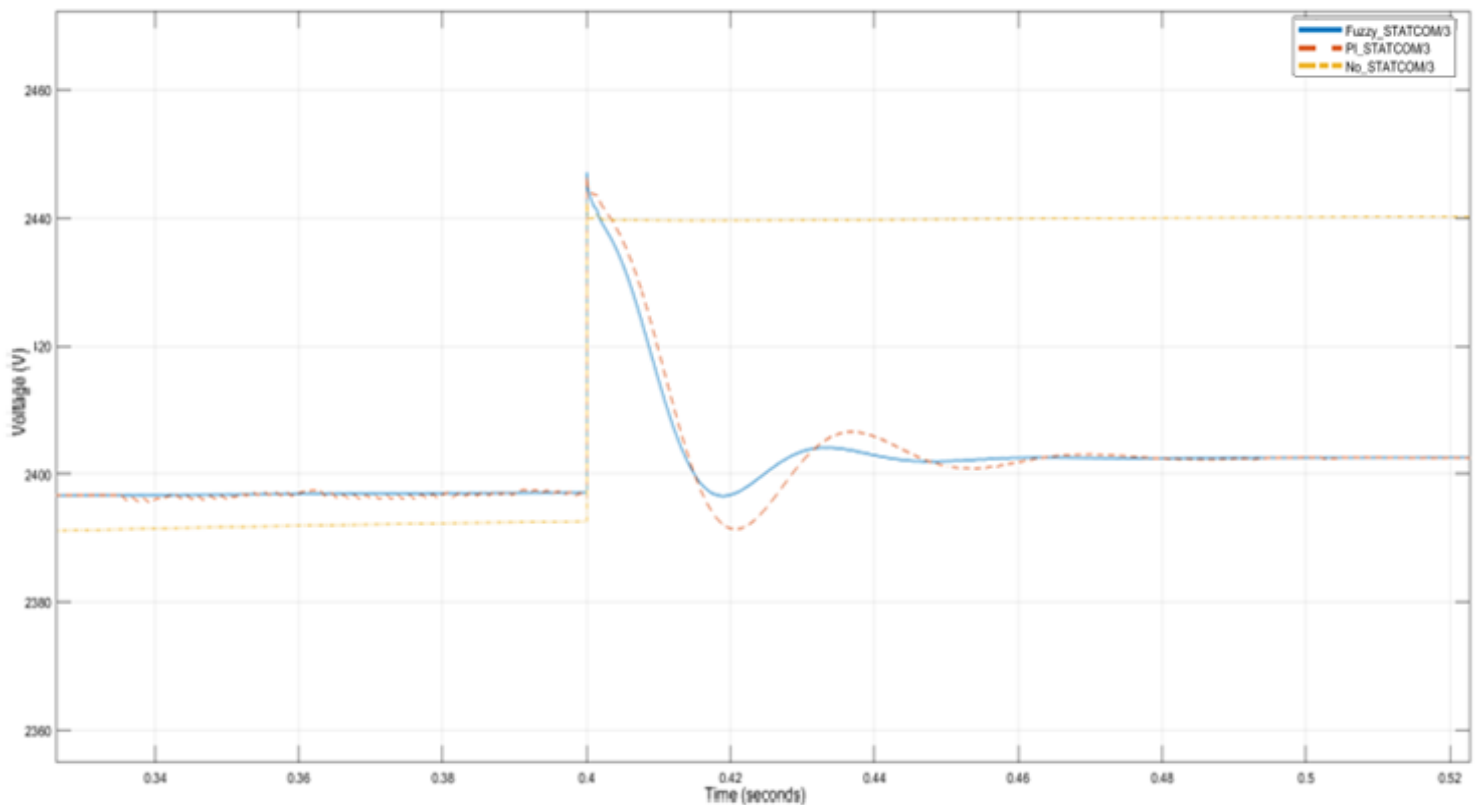


Figure 21: 843kW Load Variation Condition

The fourth test that has been made is a Load variation test. The load on Bus 675 shown in Figure 1 has been programmed to trip at 0.4 seconds. The total loss of supply on Bus 675 is 843kW which represents 23.96% of the total system load. The graph in Figure 21 shows the simulated voltage for three different systems against time.

The yellow dotted line in Figure 21 represents a system with no STATCOM. Before the load variation, the phase voltage was 2393V which is around 1.00p.u at Bus 692. After the load variation occurred at 0.4

seconds, the voltage increased at Bus 692 up to 2440V or approximately 1.02p.u.

The orange dashed line in Figure 21 represents a system with a STATCOM that has a PI controller. Before the load variation, the phase voltage was 2397V which is around 1.00p.u at Bus 692. After the voltage increment occurred at 0.4 seconds, the voltage increased at Bus 692 up to 2403V or approximately 1.00p.u.

The blue solid line in Figure 21 represents a system with a STATCOM that has a Fuzzy controller. Before the load variation, the phase voltage was 2397V which is around 1.00p.u at Bus 692. After the voltage increment occurred at 0.4 seconds, the voltage increased at Bus 692 up to 2402V or approximately 1.00p.u.

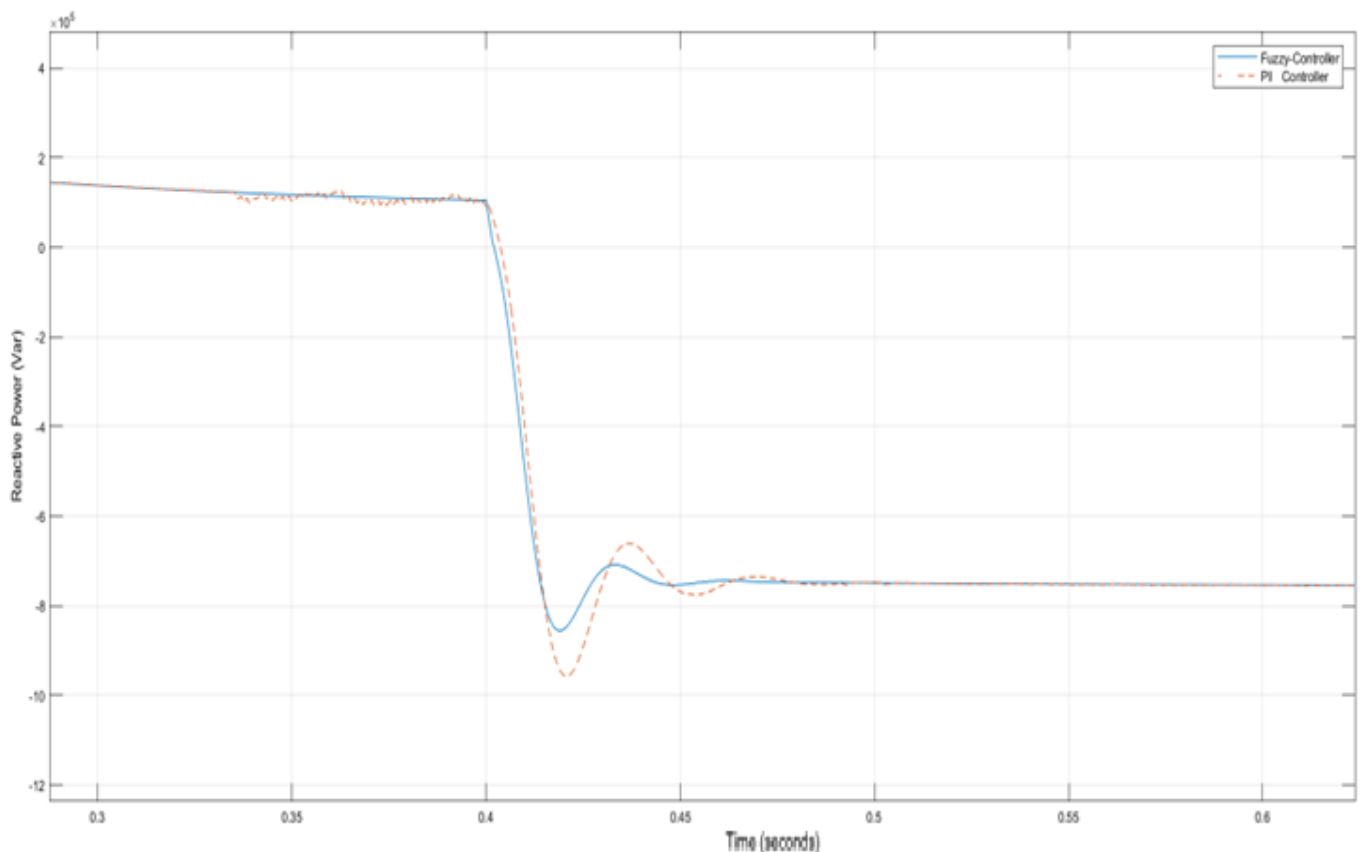


Figure 22: STATCOM Contribution After Load Variation Condition

Figure 22 shows the contribution of the STATCOM with the reactive power under different controllers. It can be seen that both controllers absorbed reactive power at the time of the renewables trip at 0.4 seconds. The STATCOM with PI controller and the STATCOM with Fuzzy controller have both absorbed around 751kVar across the 3-phases. However, After the load variation occurred at 0.4 seconds, it can be noticed that there are differences in the reaction of the STATCOMs where the Fuzzy controller has better transient performance and smaller overshoots as compared to the PI controller where the orange dashed line represents the STATCOM with PI controller and the blue solid line represents the STATCOM with Fuzzy controller.

4.1.6 Test No. 5: Single Phase to Ground Fault

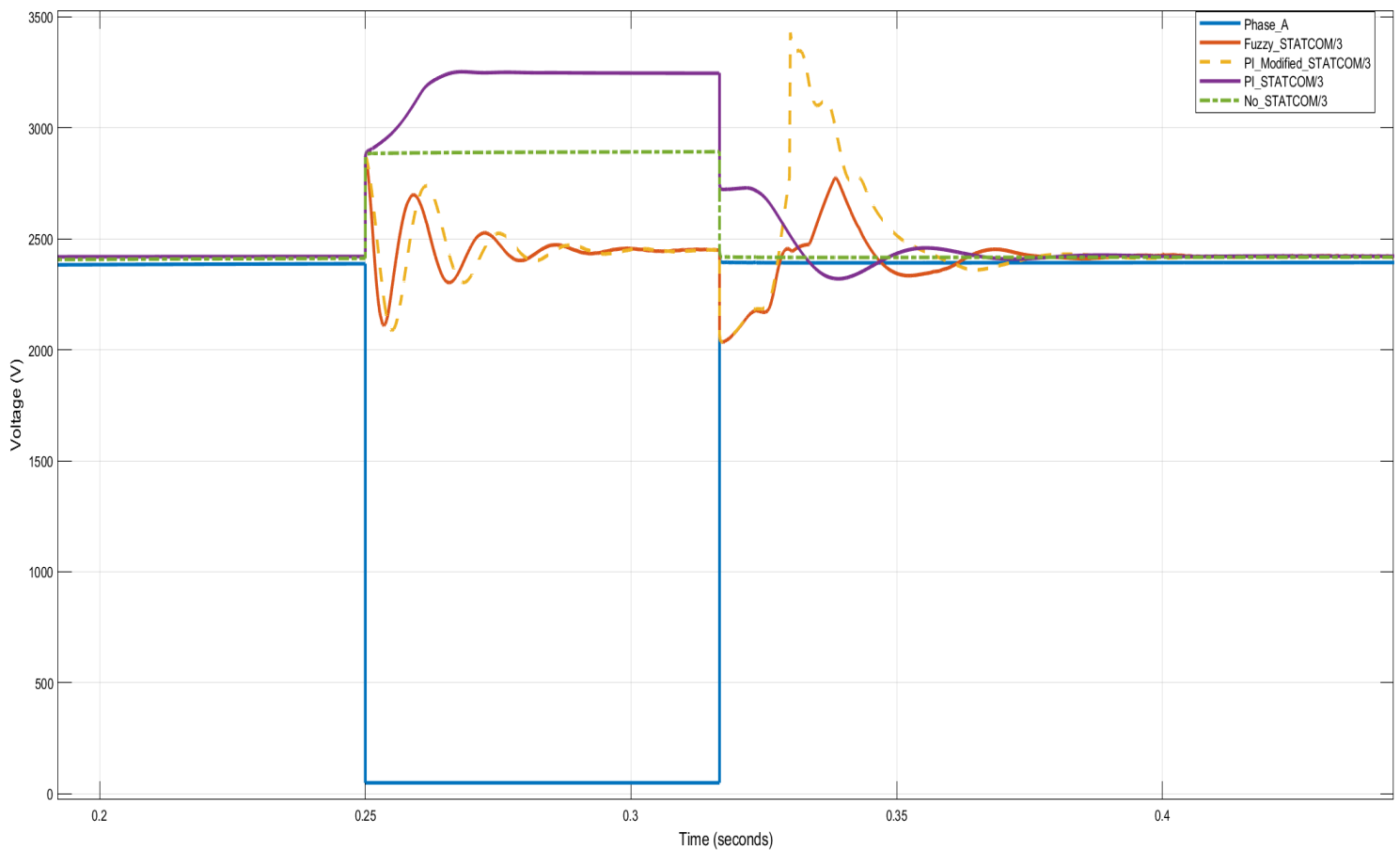


Figure 23: Single Phase to Ground Fault Condition

The Fifth test that has been simulated is a single phase to ground fault test. The short circuit applied at Bus 671 in Figure 1 where phase A is the faulted phase. The fault has been programmed to start at 0.25 seconds and last for 4 cycles of the power frequency (60Hz), which means that the fault will be cleared at 0.31 seconds. The graph in Figure 23 shows the simulated voltage for four different test cases against time.

The blue solid line in Figure 23 represents phase A voltage for all the test cases during AG fault condition. It can be noticed that before the fault, the voltage of phase A was 2387V or 0.99p.u. However, during the fault which started at 0.25 seconds, phase A voltage dropped severely to approximately 0V. After the fault has been cleared at 0.31 seconds, the voltage has been restored back to 2387V.

The green dotted line in Figure 23 represents the healthy phases, B and C, for a system with no STATCOM. Before the fault, the phase voltage was 2373V which is around 0.98p.u at Bus 692. After the fault occurred at 0.25 seconds, the voltage increased at Bus 692 up to 2844V or approximately 1.18p.u. The fault is cleared at 0.31 seconds and the voltage recovers to its normal condition value.

The purple solid line in Figure 23 represents the healthy phases, B and C, for a system with a STATCOM that has a PI controller. Before the fault, the phase voltage was 2382V (0.99p.u) at Bus 692. After the fault occurred at 0.25 seconds, the voltage increased at Bus 692 up to 3180V (1.32p.u.). The fault is cleared at 0.31 seconds and the voltage recovers to its normal condition value.

The yellow dashed line in Figure 23 represents the healthy phases, B and C, for a system with a modified STATCOM that has a PI controller and a negative sequence controller. Before the fault, the phase voltage was

2382V (0.99p.u.) at Bus 692. After the fault occurred at 0.25 seconds, the voltage slightly increased at Bus 692 up to 2440V (1.01p.u.). The fault is cleared at 0.31 seconds and the voltage recovers to its normal condition value.

The orange solid line in Figure 23 represents the healthy phases, B and C, for a system with a modified STATCOM that has a Fuzzy controller and a negative sequence controller. Before the fault, the phase voltage was 2382V (0.99p.u.) at Bus 692. After the fault occurred at 0.25 seconds, the voltage slightly increased at Bus 692 up to 2440V (1.01p.u.). The fault is cleared at 0.31 seconds and the voltage recovers to its normal condition value.

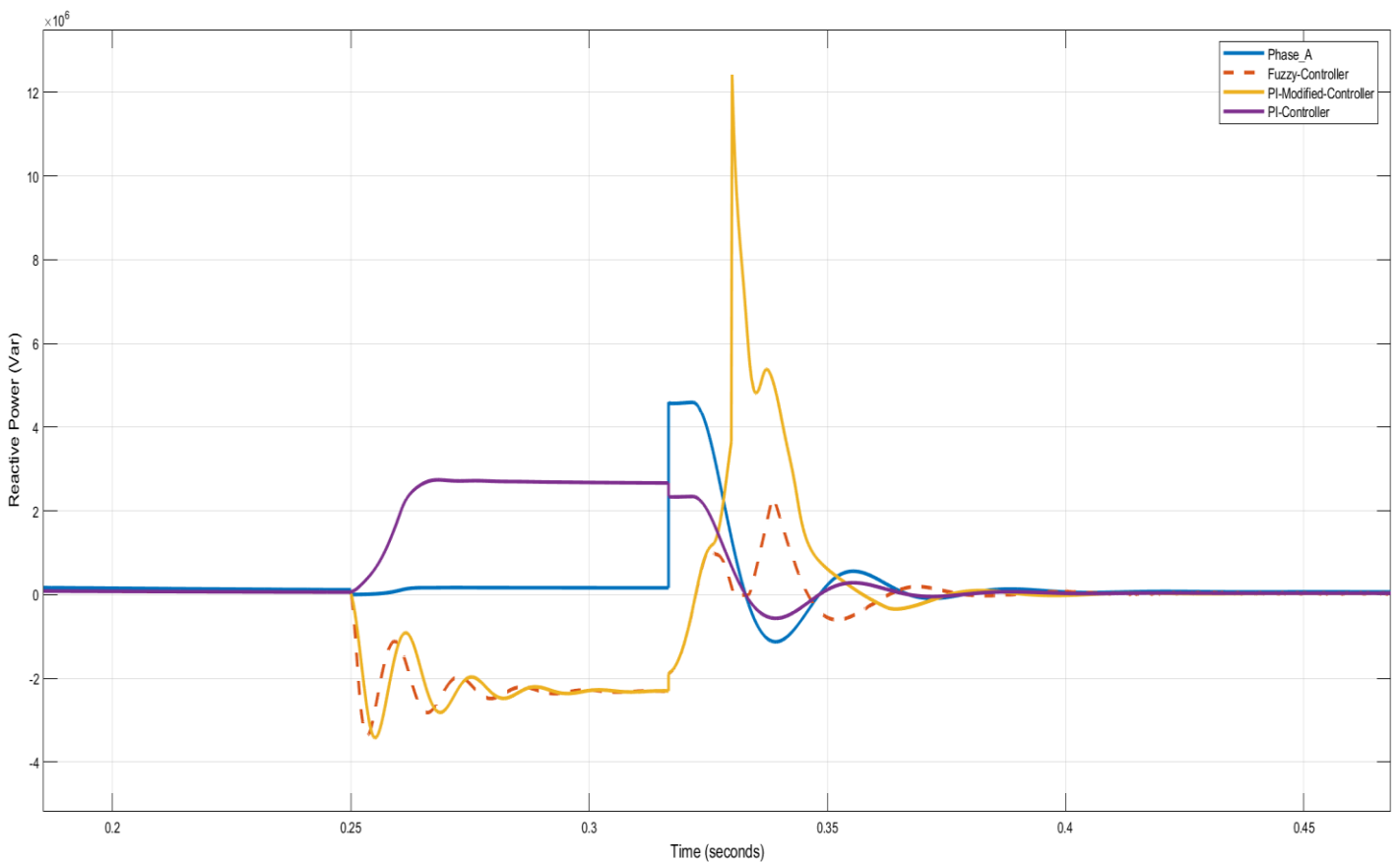


Figure 24: STATCOM Contribution After Single Phase to Ground Fault Condition

Figure 24 shows the contribution of the STATCOM with the reactive power from different controllers. The blue solid line represents phase A for

all the test cases as it is shorted to ground. It can be seen that there is no contribution by the faulted phase as it is equal to 0MVar.

The purple solid line represents the healthy phases, B and C, for a system with a STATCOM that has a PI controller. During the time of the fault after 0.25 seconds, the STATCOM generated 5.34MVar in total for the healthy phases until the end of the fault at 0.31 seconds.

The yellow solid line represents the modified STATCOM with PI controller and the orange dashed line represents the modified STATCOM with Fuzzy controller. It can be noted that both of these cases are integrated with a negative sequence controller. Both controllers absorbed reactive power at the time of the single phase to ground fault at 0.25 seconds. The modified STATCOM with PI controller and the modified STATCOM with Fuzzy controller have both absorbed around 4.7MVar across the two healthy phases (B and C). However, After the fault is cleared at 0.31 seconds, it can be noticed that there are differences in the reaction of the STATCOMs where the modified Fuzzy controller has better transient performance and smaller overshoots as compared to the modified PI controller.

4.1.7 Test No. 6: Double Phase to Ground Fault

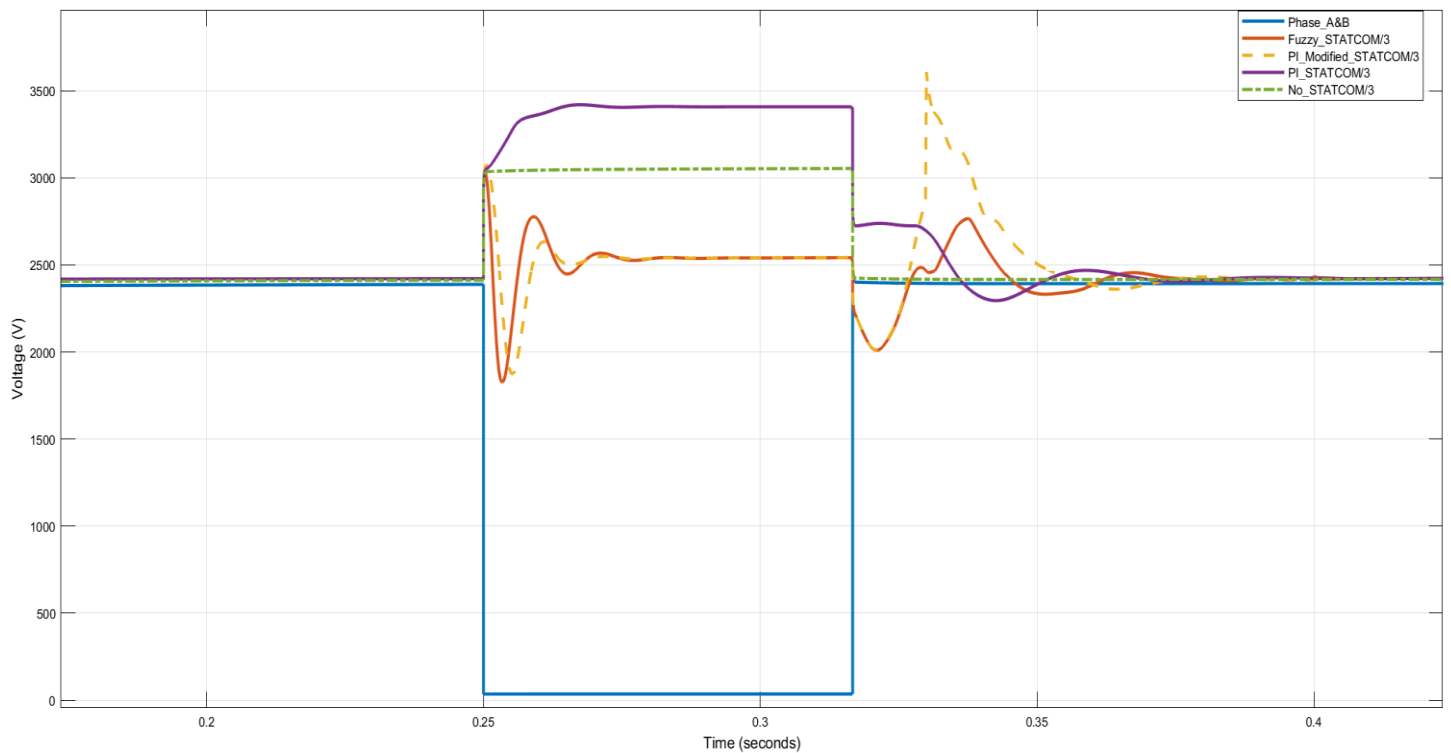


Figure 25: Double Phase to Ground Fault Condition

Test number 6 is a double phase to ground fault test. The short circuit is applied at Bus 671 shown in Figure 1 where phases A and B will be the faulted phases. The fault has been programmed to start at 0.25 seconds and clear after 4 cycles at 0.31 seconds. The graph in Figure 25 shows the simulated voltage for four different test cases against time.

The blue solid line in Figure 25 represents phases A and B for all the test cases during short circuit condition. It can be noticed that before the fault, the voltage of phases A and B is 2392V (0.99p.u.), but during the fault which started at 0.25 seconds, phases A and B voltages dropped severely to approximately 0V. After the fault has been cleared at 0.31 seconds, the voltage has been restored back to 2392V.

The green dotted line in Figure 25 represents the healthy phase C for a system with no STATCOM. Before the fault, the phase voltage was 2417V (1.01p.u.) at Bus 692. After the fault occurred at 0.25 seconds, the

voltage increased at Bus 692 up to 3052V (1.27p.u.). The fault is cleared at 0.31 seconds and the voltage recovers to its normal condition value at 2417V.

The purple solid line in Figure 25 represents the healthy phase C for a system with a STATCOM that has a PI controller. Before the fault, the phase voltage was 2428V (1.01p.u.) at Bus 692. After the fault occurred at 0.25 seconds, the voltage increased at Bus 692 up to 3407V (1.42p.u.). The fault is cleared at 0.31 seconds and the voltage recovers to its normal condition value.

The yellow dashed line in Figure 25 represents the healthy phase C for a system with a modified STATCOM that has a PI controller and a negative sequence controller. Before the fault, the phase voltage was 2413V (1.00p.u.) at Bus 692. After the fault occurred at 0.25 seconds, the voltage slightly increased at Bus 692 up to 2540V (1.05p.u.) The fault is cleared at 0.31 seconds and the voltage recovers to its normal condition value.

The orange solid line in Figure 25 represents the healthy phase C for a system with a modified STATCOM that has a Fuzzy controller and a negative sequence controller. Before the fault, the phase to line voltage was 2426V (1.01p.u.) at Bus 692. After the fault occurred at 0.25 seconds, the voltage slightly increased at Bus 692 up to 2540V (1.05p.u.) The fault is cleared at 0.31 seconds and the voltage recovers to its normal condition value.

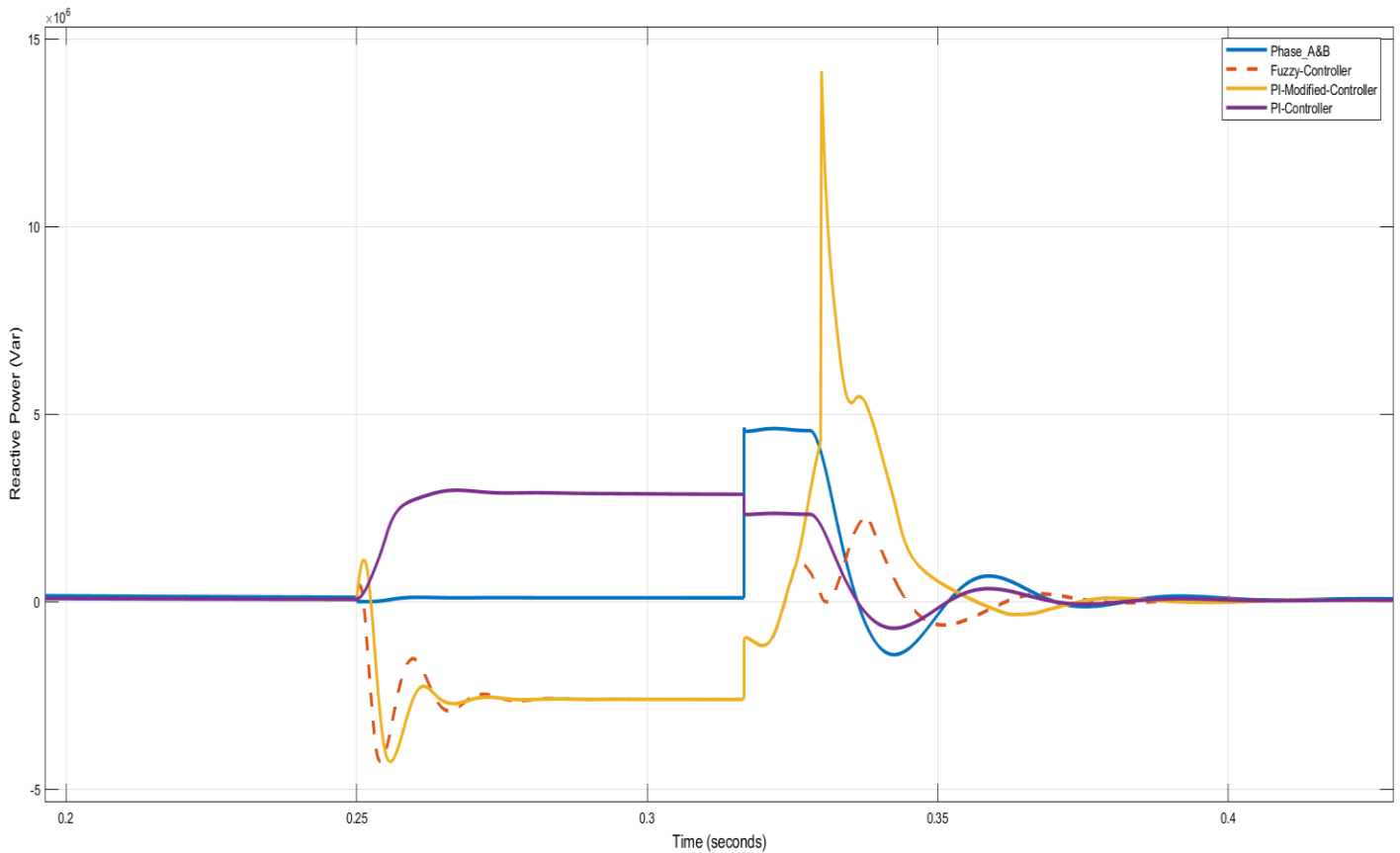


Figure 26: STATCOM Contribution After Double Phase to Ground Fault Condition

Figure 26 shows the contribution of the STATCOM with the reactive power from different controllers. The blue solid line represents phases A and B for all the test cases for ABG fault condition. It can be seen that there is no contribution in the faulted phase as it is equal to 0MVar.

The purple solid line represents the healthy phase C for a system with a STATCOM that has a PI controller. During the time of the fault after 0.25

seconds, the STATCOM generated 2.87MVar for the healthy phase until the end of the fault at 0.31 seconds.

The yellow solid line represents the modified STATCOM with PI controller and the orange dashed line represents the modified STATCOM with Fuzzy controller both of which are integrated with a negative sequence controller. Both of the modified STATCOM absorbed reactive power at the time of the single phase to ground fault at 0.25 seconds. The modified PI controller and the modified Fuzzy controller have both absorbed around 2.61MVar across the healthy phase C. However, After the fault has cleared at 0.31 seconds, it can be noticed that there are differences in the reaction of the STATCOMs where the modified Fuzzy controller has better transient performance and smaller overshoots as compared to the modified PI controller.

4.1.8 Test No. 7: Phase to Phase Fault

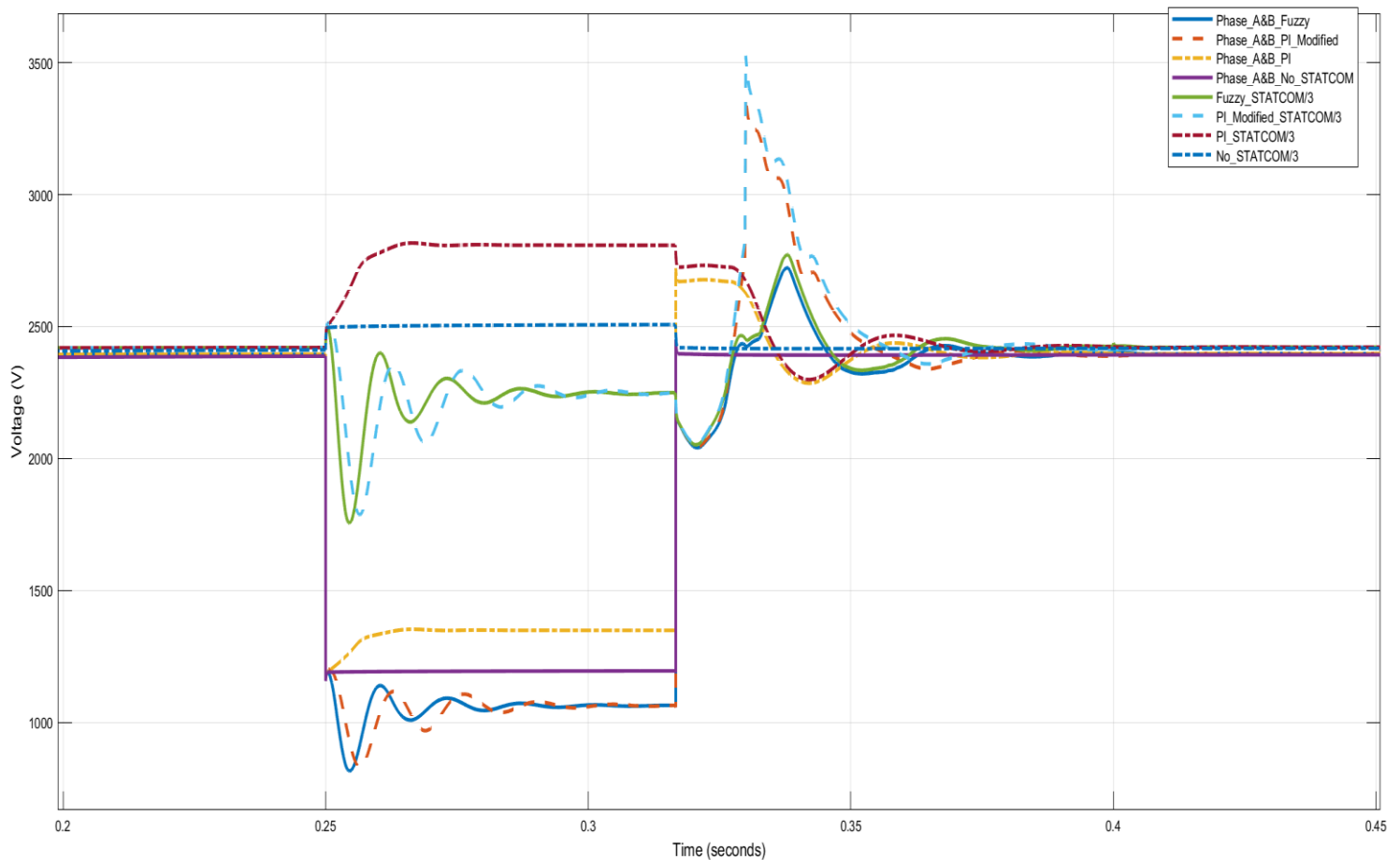


Figure 27: Phase to Phase Fault Condition

Test number 7 is a phase-to-phase fault test. The short circuit is applied at Bus 671 shown in Figure 1 where phases A and B will be the faulted phases. The fault has been programmed to start at 0.25 seconds and clear after 4 cycles at 0.31 seconds. The graph in Figure 27 shows the simulated voltage for the faulted phases and the healthy phase for four different test cases against time.

The purple solid line in Figure 27 represents phases A and B for a system with no STATCOM. It can be noticed that before the fault, the voltage of phases A and B was 2387V (0.99p.u.), but during the fault which started at 0.25 seconds, phases A and B voltage dropped severely to approximately 1195V (0.49p.u.). After the fault has been cleared at 0.31 seconds, the voltage has been restored back to 2387V.

The yellow dotted line in Figure 27 represents phases A and B for a system with a STATCOM that has a PI controller. It can be noticed that before the fault, the voltage of phases A and B is 2395V (1.00p.u.), but during the fault which started at 0.25 seconds, phases A and B voltage dropped severely to approximately 1349V (0.56p.u.). After the fault has been cleared at 0.31 seconds, the voltage recovers to its normal condition value.

The orange dashed line in Figure 27 represents phases A and B for a system with a modified STATCOM that has a PI controller and a negative sequence controller. It can be noticed that before the fault, the voltage of phases A and B is 2395V (1.00p.u.), but during the fault which started at 0.25 seconds, phases A and B voltage dropped severely to approximately 1063V (0.44p.u.). After the fault has been cleared at 0.31 seconds, the voltage recovers to its normal condition value.

The blue solid line in Figure 27 represents phases A and B for a system with a modified STATCOM that has a Fuzzy controller and a negative sequence controller. It can be noticed that before the fault, the voltage of phases A and B is 2395V (1.00p.u.), but during the fault which started at 0.25 seconds, phases A and B voltage dropped severely to approximately 1065V (0.44p.u.). After the fault has been cleared at 0.31 seconds, the voltage recovers to its normal condition value.

The blue dotted line in Figure 27 represents the healthy phase C for a system with no STATCOM. Before the fault, the phase voltage was 2411V (1.00p.u.) at Bus 692. After the fault occurred at 0.25 seconds, the voltage increased at Bus 692 up to 2507V (1.04p.u.). The fault is cleared at 0.31 seconds and the voltage recovers to its normal condition value.

The red dotted line in Figure 27 represents the healthy phase C for a system with a STATCOM that has a PI controller. Before the fault, the phase voltage was 2420V (1.01p.u.) at Bus 692. After the fault occurred at 0.25 seconds, the voltage increased at Bus 692 up to 2808V (1.17p.u.). The fault is cleared at 0.31 seconds and the voltage recovers to its normal condition value.

The blue dashed line in Figure 27 represents the healthy phase C for a system with a modified STATCOM that has a PI controller and a negative sequence controller. Before the fault, the phase voltage was 2420V (1.01p.u.) at Bus 692. After the fault occurred at 0.25 seconds, the voltage decreased at Bus 692 down to 2245V (0.93p.u.). The fault is cleared at 0.31 seconds and the voltage recovers to its normal condition value.

The green solid line in Figure 27 represents the healthy phase C for a system with a modified STATCOM that has a Fuzzy controller and a negative sequence controller. Before the fault, the phase voltage was 2420V (1.01p.u.) at Bus 692. After the fault occurred at 0.25 seconds, the voltage decreased at Bus 692 down to 2249V (0.94p.u.). The fault is cleared at 0.31 seconds and the voltage recovers to its normal condition value.

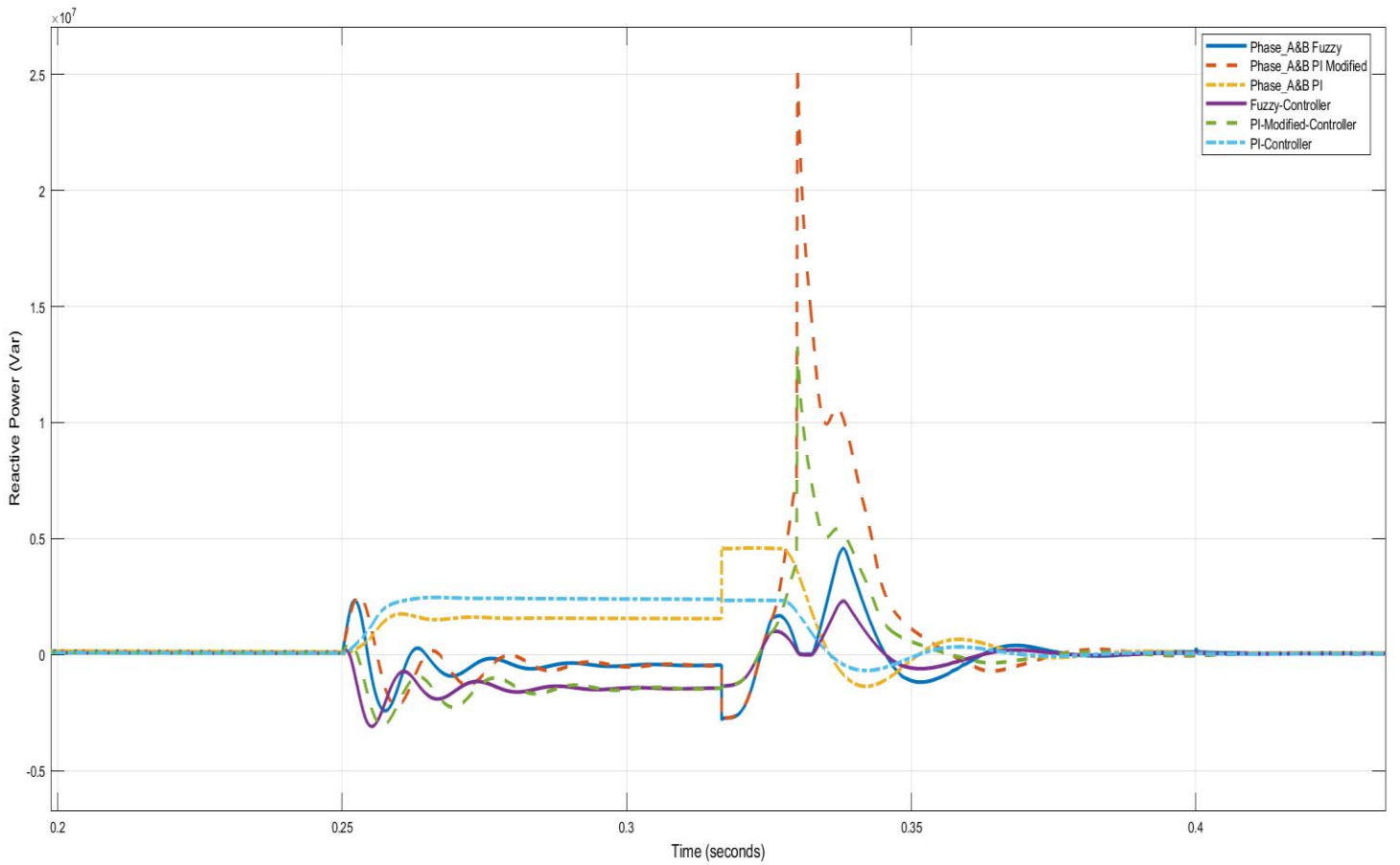


Figure 28: STATCOM Contribution Phase to Phase Fault Condition

Figure 28 shows the contribution of the STATCOM with the reactive power from different controllers for the faulted phases (A and B) and the healthy phase (C). The yellow dotted line represents phases A and B for a system with a STATCOM that has a PI controller. During the time of the fault after 0.25 seconds, the STATCOM generated 1.55MVar for the faulted phases A and B in total until the end of the fault at 0.31 seconds.

The orange dashed line represents phases A and B for a modified PI controller STATCOM and the blue solid line represents phases A and B for a modified Fuzzy controller STATCOM, both of which are integrated with a negative sequence controller. Both of the modified STATCOM absorbed reactive power at the time of the phase-to-phase fault at 0.25 seconds. The modified PI controller STATCOM and the modified Fuzzy controller

STATCOM have both absorbed around 0.47MVar in total across the faulted phases A and B.

The blue dotted line represents the healthy phase C for a system with a STATCOM that has a PI controller. During the time of the fault after 0.25 seconds, the STATCOM generated 2.39MVar for the healthy phase until the end of the fault at 0.31 seconds.

The green dashed line represents phase C for a modified STATCOM with PI controller and the purple solid line represents phase C for a modified STATCOM with Fuzzy controller, which are integrated with a negative sequence controller. Both systems absorbed reactive power at the time of the single phase to ground fault at 0.25 seconds. The modified STATCOM with PI controller and the modified STATCOM with Fuzzy controller have both absorbed around 1.45MVar across the healthy phase C. However, After the fault has cleared at 0.31 seconds, it can be noticed that there are differences in the response of the STATCOMs where the modified Fuzzy controller has better transient performance and smaller overshoots as compared to the modified PI controller.

4.2 Discussion

This section will discuss the results that have been shown earlier, by comparing and stating the reasons for the different performances. The discussion part will be divided into three parts, and end with the recommendation part for future research.

4.2.1 Test 1 and 2 (Voltage Drop and Rise)

The results of Tests 1 and 2 show the response of the STATCOM at Bus 632 during voltage disturbance. The STATCOM worked as intended in the first test where it injected reactive power during voltage drop disturbance as seen in Figure 16 to increase the voltage as shown in Figure 15. Moreover, the STATCOM in the second test absorbed reactive power during the voltage rise disturbance as seen in Figure 18 to decrease the voltage as shown in Figure 17. The results for both tests are also compared with a system that does not have a STATCOM to show the impact of having a system that contains a STATCOM device.

However, there are two types of STATCOMs that have been implemented during these two tests, one with a PI controller and one with a Fuzzy controller. It can be observed that the Fuzzy controller has faster settling time, and smaller overshoots as compared to the PI controller STATCOM. The obtained results is in agreement with the results of previous study conducted by (Augustine et al., 2016) in which the fuzzy controller performed better than the PI controller in controlling the voltage.

The reason for having a similar outcome to the previous study of (Augustine et al., 2016) is that the Fuzzy logic STATCOM adapts better to the dynamic systems and sudden network changes like voltage drop and voltage rise that have been simulated in tests 1 and 2. This adaptive nature serves the STATCOM in terms of recovery time offering adaptability and

robustness, unlike the STATCOM with PI controller which takes longer settling time after such complex and dynamic network disturbances.

4.2.2 Test 3 and 4 (Renewables and Load Variation)

The results of Test 3 show the reaction of the STATCOM at Bus 632 for the condition of tripping the renewables generation. Figure 19 illustrates the sudden loss of renewable generation which leads to a significant drop in voltage. This occurs because renewables inject reactive power into the electrical system. When they trip, the reactive power they provided is lost, causing a substantial voltage drop. In case the system has a STATCOM, the voltage will increase due to the injection of reactive power from the STATCOM as can be depicted from Figure 20. Stabilizing the voltage can also prevent disconnection from other wind or solar farms as it will maintain the voltage at a relatively constant value to avoid triggering protective equipment and leading to cascade tripping. This result is also observed in another previous study that simulated the impact of the STATCOM on the terminal voltage of renewable energy sources during voltage drop (Karoui et al., 2016) where the voltage dropped below 0.8p.u. in a system without STATCOM while the voltage was higher than 0.9p.u. in a system with STATCOM.

Test 4 shows that the STATCOM can deal with load variation which is common in electrical grids because of the changing behavior of consumer demands. Figure 21 shows how the voltage increases when there is a sudden drop in demand caused by a trip on Bus 675. The STATCOM absorbed the surplus reactive power as seen in Figure 22 to maintain voltage regulation during the disturbance. The reason why STATCOM is a valuable device for the electrical system is because of its ability to respond rapidly to load variations as seen in the fourth test. Both tests 3 and 4 were also conducted with two types of STATCOM controllers, Fuzzy logic

controller and PI controller, and showed the same reaction that happened in the first two tests.

4.2.3 Test 5, 6, and 7 (Unbalanced Faults)

The Unbalanced Faults tests have been made to study the performance of the STATCOM when these types of faults occur. Figure 23 illustrates the result of test 5 which is a single phase to ground fault. Phase A has been shorted to ground resulting in full voltage collapse down to 0V. However, the voltage of the remaining phases will naturally increase due to the imbalance currents flowing in the phases as seen in Figure 23 in the case of having a system with no STATCOM.

Conversely, having a STATCOM with PI controller only revealed an inadequate outcome as the voltage has increased in the healthy phases even more as compared with the case without a STATCOM in the system. The voltage reached up to 1.32p.u in the case of a system having a STATCOM with PI controller, whereas the voltage increased up to 1.18p.u in the case of a system with no STATCOM. The issue arises because the STATCOM injects reactive power instead of absorbing it (as shown in Figure 24). This model only considers positive sequence currents, which decrease during an unbalanced fault. Consequently, the STATCOM incorrectly perceives a low voltage, even though the voltage in the healthy phases is actually high, exacerbating the problem. To overcome this problem, either switch off the STATCOM during the fault or improve the STATCOM controller by embedding a negative sequence controller.

The results of the modified STATCOM, including the Fuzzy STATCOM which is presented in Figure 23, clearly illustrate the STATCOM's response during a single-phase-to-ground fault. In this scenario, the STATCOM operates in negative sequence mode to effectively mitigate the negative sequence components generated by the fault. By

absorbing reactive power in the healthy phases, the STATCOM helps to reduce voltage fluctuations, thereby maintaining balanced operation and preventing overvoltage conditions. This reactive power management is crucial for enhancing system stability during disturbances and underscores the effectiveness of the modified STATCOM in improving the overall resilience of the electrical network. This matches the result of a different case of single phase to ground fault (Hochgraf & Lasseter, 1998) with the effect of a STATCOM, which shows that the percent of unbalance goes from 17.7% in the case of not having a STATCOM down to 9.3% when having a STATCOM.

Test 6 shows how the STATCOM will react when a double phase to ground fault occurs. Similar to test 5, the unmodified STATCOM severely increased the voltage in the remaining healthy phase to 1.42p.u, while the modified STATCOMs that have a negative sequence controller, both PI controller STATCOM and Fuzzy controller STATCOM, decreased the voltage in the healthy phase to 1.05p.u.

Test 7 was the final conducted test showing a different outcome as compared with the previous two tests. Figure 27 shows the results of test 7 for a phase-to-phase condition. The STATCOM with PI controller reacted to this fault by increasing the voltage in the healthy phase up to 1.17p.u, whereas the voltage decreased to approximately 0.93p.u. for the case with the modified STATCOMs, both PI and Fuzzy controllers. However, the best result obtained is when there is no STATCOM in the system, where the healthy phase voltage slightly increased up to 1.04p.u making it the closest result to the rated voltage as compared with the rest of the models.

It can be concluded from the results of test 7 that it is better not to use any type of STATCOM used in this test to stabilize the voltage of the remaining healthy phase and keep the voltage within the rated limits. The

reason why the modified STATCOM did not overcome the rest of the models as seen in the previous tests is that the model can only operate either a positive sequence controller or a negative sequence controller. Although all unbalanced faults will have negative sequence currents, a phase-to-phase fault will not affect the healthy phase voltage and will have minimal impact on it as seen in Figure 27 in the case of not having a STATCOM. The nature of having a phase-to-phase fault acts in a unique way as compared with other unbalanced faults where the fault contribution of the faulty phases will cancel out as they will have equal and opposite voltages relative to the ground, leaving the healthy phase unchanged (Myatt, 2014). Therefore, employing a STATCOM with a negative sequence controller is not advisable, as it will reduce the voltage of the healthy phase. Similarly, using an unmodified PI STATCOM with a positive sequence controller is also not recommended, as it will increase the voltage of the healthy phase in the presence of an unbalanced fault.

Chapter 5

Conclusion and Recommendations

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5.1 Summary

The various systems developed in this research demonstrate significant improvements in STATCOM performance through a focus on controller optimization. The final system, which integrates a STATCOM with both a Fuzzy controller and a negative sequence controller, effectively addresses numerous challenges encountered in the electrical grid. These challenges include voltage drops, voltage rises, renewable energy trips, load trips, phase-to-ground faults, and double phase-to-ground faults. This advanced configuration not only mitigates these issues but also enhances the overall stability and reliability of the electrical grid.

5.2 Recommendations

The results of all the tests that have been done can be related to the former studies that have been addressed in the discussion section. However, the different models did not handle the final test very well, and one of the solutions that can be recommended to overcome a phase-to-phase fault disturbance is to introduce a zero-sequence controller in the models. Being the only component that can differentiate between phase-to-phase fault and the other unbalanced fault conditions that involve the ground, zero sequence can be utilized to identify the type of unbalanced fault that occurred, hence dealing with the fault more properly. During a phase-to-phase fault, the zero sequence current of each faulty phase will cancel out each other as they will be equal in magnitude but in opposite directions, thus canceling each other out, making it the reason why the zero sequence components are not present as can be illustrated by the following equation of the zero-sequence component.

$$V_0 = 1/3(V_a + V_b + V_c) \quad (8)$$

$$I_0 = (I_a + I_b + I_c) \quad (9)$$

Where V_0 and I_0 are the zero sequence components of the voltage and current respectively.

By using a zero-sequence controller, a phase-to-phase fault can be detected, with other modifications in the controller like individual phase control, STATCOM can be optimized to adjust the phase angle and magnitude of its voltage for the healthy phase only in case a capacitive or inductive reactive power is needed to regulate the voltage.

5.3 Future Work

For future research to maintain the current research efforts, it can be suggested to use different controllers to be compared with the PI, Fuzzy, and negative sequence controllers. A zero-sequence controller and individual phase control are some of the suggestions that have already been brought up. A neural network fuzzy controller is one of the advanced controllers that have the capability of learning and adaption combined with a human-like reasoning style, making the STATCOM an intelligent control system, as it will enhance damping speed and improve control and stability (Li & Xiangjie, 2009).

Another controller worth considering for future research is the predictive adaptive controller, which is highly effective in enhancing STATCOM performance. Its ability to predict future system behaviour allows it to make more informed adjustments in real time, improving the dynamic response and stability of the system. By anticipating fluctuations and proactively managing reactive power, this controller can provide better voltage regulation, which is critical for maintaining system balance. Furthermore, its adaptability to changing conditions makes it ideal for optimizing overall power grid management, offering a promising avenue

for improving the reliability and efficiency of modern electrical networks (Akbari & Kadivar, 2017).

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Appendices

Appendix A

Overhead Line Configuration Data:

Config	Phasing	Phase	Neutral	Spacing
		ACSR	ACSR	ID
601	B A C N	556,500 26/7	4/0 6/1	500
602	C A B N	4/0 6/1	4/0 6/1	500
603	C B N	1/0	1/0	505
604	A C N	1/0	1/0	505
605	C N	1/0	1/0	510

Data 1

Underground Line Configuration Data:

Config.	Phasing	Cable	Neutral	Space ID
606	A B C N	250,000 AA, CN	None	515
607	A N	1/0 AA, TS	1/0 Cu	520

Data 2

Line Segment Data:

Node A	Node B	Length(ft.)	Config.
632	645	500	603
632	633	500	602
633	634	0	XFM-1
645	646	300	603
650	632	2000	601
684	652	800	607
632	671	2000	601
671	684	300	604
671	680	1000	601
671	692	0	Switch
684	611	300	605
692	675	500	606

Data 3

Transformer Data:

	kVA	kV-high	kV-low	R - %	X - %
Substation:	5,000	115 - D	4.16 Gr. Y	1	8
XFM -1	500	4.16 – Gr.W	0.48 – Gr.W	1.1	2

Data 4

Capacitor Data:

Node	Ph-A	Ph-B	Ph-C
	kVAr	kVAr	kVAr
675	200	200	200
611			100
Total	200	200	300

Data 5

Spot Load Data:

Node	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
	Model	kW	kVAr	kW	kVAr	kW	kVAr
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
	TOTAL	1158	606	973	627	1135	753

Data 6

Distributed Load Data:

Node A	Node B	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
		Model	kW	kVAr	kW	kVAr	kW	kVAr
632	671	Y-PQ	17	10	66	38	117	68

Data 7

Appendix B

Simulation Tests Results Data:

Initial source voltage is set to 1.04 p.u. System Load = 3518.74kW / 1540.14kvar

(V_{phase-line}) at Bus 692 1 p.u. = 2401.78V	Without STATCOM	PI STATCOM	Fuzzy STATCOM
Vrms at normal condition	2477	2446	2428
Vrms p.u. normal condition	1.03	1.02	1.1
Vrms at abnormal condition	2160	2287	2271
Vrms p.u. abnormal condition	0.89	0.95	0.95

Table 1: 0.9 p.u. source voltage drop

(V_{phase-line}) at Bus 675 1 p.u. = 2401.78V	Without STATCOM	PI STATCOM	Fuzzy STATCOM
Vrms at normal condition	2477	2446	2428
Vrms p.u. normal condition	1.03	1.02	1.1
Vrms at abnormal condition	2842	2673	2673
Vrms p.u. abnormal condition	1.18	1.11	1.10

Table 2: 1.2 p.u. source voltage rise

(V_{phase-line}) at Bus 675 1 p.u. = 2401.78V	Without STATCOM	PI STATCOM	Fuzzy STATCOM
Vrms at normal condition	2417	2421	2422
Vrms p.u. normal condition	1.01	1.01	1.01
Vrms at abnormal condition	2327	2391	2392
Vrms p.u. abnormal condition	0.96	1.00	1.00

Table 3: Renewables trip (wind generator lagging 0.8 p.u.)

(V_{phase-line}) at Bus 675 1 p.u. = 2401.78V	Without STATCOM	PI STATCOM	Fuzzy STATCOM
Vrms at normal condition	2417	2421	2422
Vrms p.u. normal condition	1.01	1.01	1.01
Vrms at abnormal condition	2500	2424	2424
Vrms p.u. abnormal condition	1.041	1.009	1.009

Table 4: 843kW (23.96%) Load variation (Bus 675)

(V_{phase-line}) at Bus 675 1 p.u. = 2401.78V	Without STATCOM	STATCOM	Modified STATCOM
Vrms at normal condition	2417	2421	2422
Vrms p.u. normal condition	1.01	1.01	1.01
Vrms at abnormal condition	2892	3248	2445
Vrms p.u. abnormal condition	1.204	1.352	1.018

Table 5: Single Phase to Ground Fault

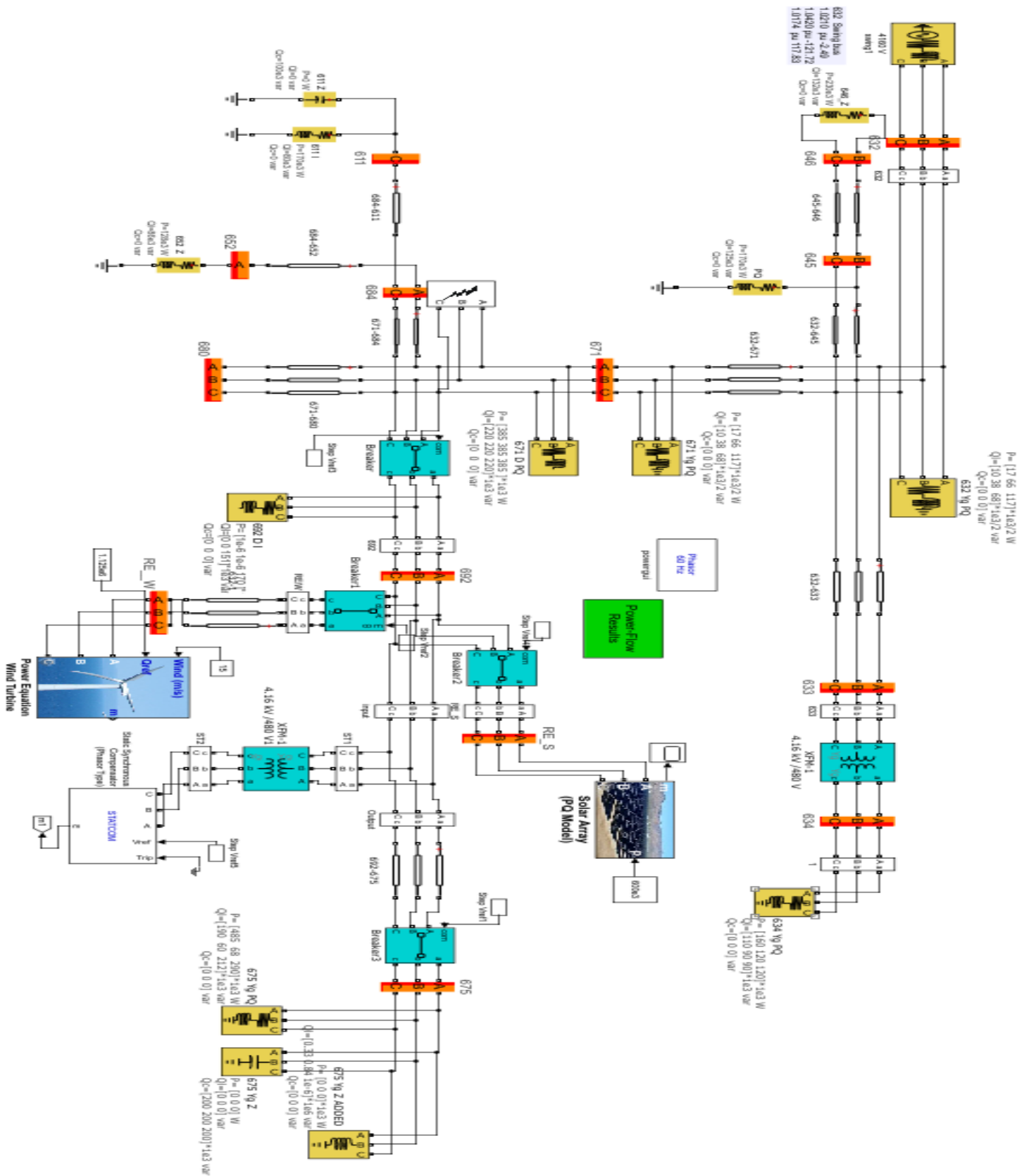
(V_{phase-line}) at Bus 675 1 p.u. = 2401.78V	Without STATCOM	STATCOM	Modified STATCOM
Vrms at normal condition	2417	2421	2422
Vrms p.u. normal condition	1.01	1.01	1.01
Vrms at abnormal condition	3052	3409	2539
Vrms p.u. abnormal condition	1.271	1.419	1.057

Table 6: double Phase to Ground Fault

(V_{phase-line}) at Bus 675 1 p.u. = 2401.78V	Without STATCOM	STATCOM	Modified STATCOM
Vrms at normal condition	2417	2421	2422
Vrms p.u. normal condition	1.01	1.01	1.01
Vrms at abnormal condition	2507	2809	2242
Vrms p.u. abnormal condition	1.044	1.170	0.933

Table 7: Phase to Phase Fault

Thesis Test Feeder Network



الملخص

تهدف هذه الأطروحة إلى تحسين أجهزة أنظمة نقل التيار البديلة المرنة للتوزيع التي سيتم استخدامها في شبكة توزيع متكاملة مع مصادر الطاقة المتجددة التي يمكن أن تقلل من جودة الطاقة، مما يؤدي إلى تقلب الجهد، وتغيرات كبيرة في التردد، وتدفق الطاقة العكسي، والعديد من قضايا أخرى تتعلق باستقرار الشبكة. علاوة على ذلك، فإن تحسين أجهزة أنظمة نقل التيار البديلة المرنة للتوزيع في هذه الأطروحة سوف يركز على تصميم وحدة تحكم من شأنها زيادة كفاءة كل من إمكانية التحكم وموثوقية الشبكة من خلال الحفاظ على الجهد ضمن النطاق المحدد مما يؤدي إلى زيادة جودة الطاقة. سيتم تصميم نماذج متعددة ومحاكاتها في وقت واحد لمقارنة وإظهار التأثيرات المختلفة لكل نموذج. ستغطي الاختبارات تفاعل جهاز أجهزة أنظمة نقل التيار البديلة المرنة للتوزيع أثناء سيناريوهات الاضطراب المتعددة مثل انخفاض الجهد وارتفاع الجهد وانقطاع مصادر الطاقة المتجددة وتغير الأحمال والأعطال غير المتوازنة. ستحتوي هذه الأنواع من النماذج التي تم تصميمها على وحدات تحكم مختلفة للتغلب على اضطرابات الشبكة. ستظهر النتائج النموذج الذي يتمتع بوقت رد فعل واستقرار أسرع، واكتشاف الأخطاء غير المتوازنة وتخفيفها، بالإضافة إلى تحديد قيود الأطروحة وتوصياتها لمواصلة تحسين المشروع للبحث المستقبلي.

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كلية الهندسة



تحسين جودة الطاقة للنظام الكهروضوئي المتصل بالشبكة باستخدام أجهزة المعوض المتزامن الثابت

أطروحة مقدمة كجزء من متطلبات الحصول على درجة الماجستير في هندسة الطاقة المتجددة

إعداد

سعيد سالم سعيد الهلالي

رقم الهوية: ٢٠٢١٠٠٢٢٦

إشراف

د. سيد علي عباس الموسوي

أستاذ مشارك

قسم الهندسة

جامعة البحرين

مشرف مشارك

د. فاضل عباس البصري

أستاذ مساعد

قسم الهندسة

جامعة البحرين

مملكة البحرين

فبراير ٢٠٢٥