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Study of STATCOM for voltage compensation in 14-Bus IEEE grid

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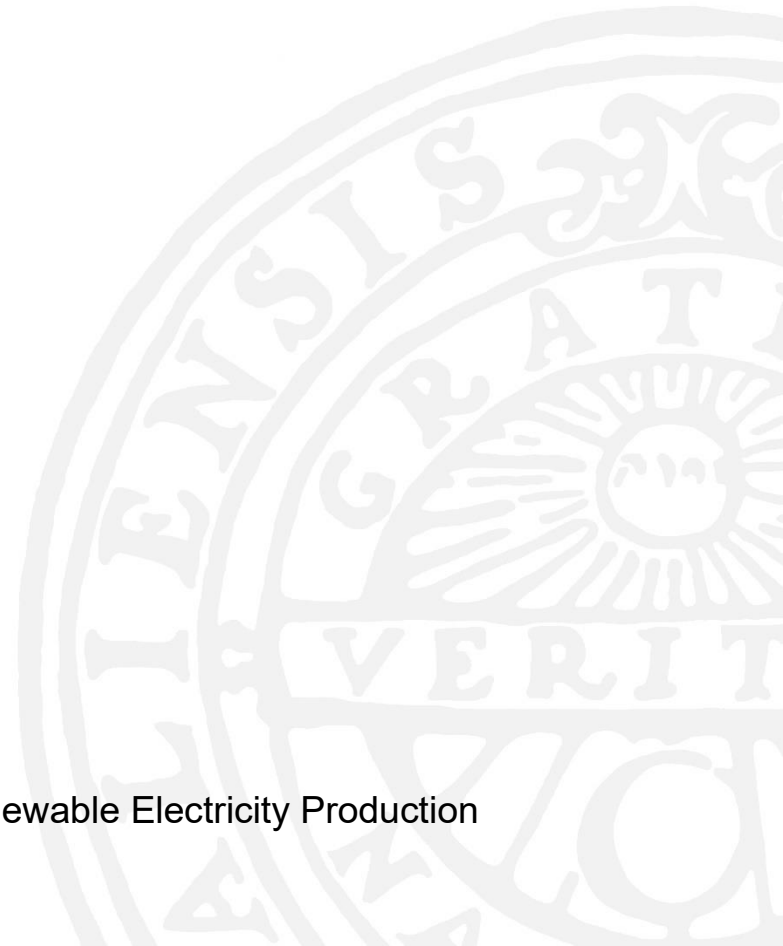

Master's Programme in Renewable Electricity Production

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Abstract

With the increasing integration of renewable energy sources and the growing demand for power quality improvement in modern power systems, the application of Static Synchronous Compensators (STATCOMs) has gained significant attention.

This master's thesis investigates the application of Multi-Level Inverter Voltage Source Converters (VSCs) in Static Synchronous Compensators (STATCOMs) for voltage stability improvement and reactive power compensation in power systems. The study focuses on the IEEE 14-Bus power system model, utilizing MATLAB/Simulink for the design, simulation, and analysis of the proposed Multi-Level Inverter-based STATCOM.

The primary objectives include assessing the advantages of Multi-Level Inverters in STATCOM applications within the complex topology of the IEEE 14-Bus system. The research aims to enhance voltage regulation, mitigate voltage sags and swells, and compensate reactive power under varying operating conditions and different type of unsymmetrical faults (line-ground, line-line, double line-ground fault).

The research outcomes contribute to the understanding of the practical implementation aspects and challenges associated with deploying Multi-Level Inverter-based STATCOMs in realistic power systems. The findings serve as a reference for power system engineers and researchers aiming to enhance the reliability and efficiency of large-scale power networks through the integration of advanced voltage control technologies.

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List of abbreviation

$DLGF$ Double-line-to-ground Fault

$IGBT$ Insulated Gate Bipolar Transistor

LLF Line-to-line Fault

MLC Multi-level Converter

MMC Modular-multi-level

PCC Point of Common Coupling

PM Power Modules

PWM Pulse Width Modulation

$SLGF$ Single-line-to -ground fault

SM Sub Modules

$STATCOM$ Static Synchronous Compensator

SVC Static Var Compensator

THD Total Harmonic Distortion

VSC Voltage Source Converter

1 Introduction

The integration of renewable energy sources and the rising demand for power quality improvement have led to increased complexity and dynamic changes in power systems. Voltage instability, characterized by voltage sags, swells, and fluctuations, poses a significant challenge to the stability and reliability of power networks. Traditional solutions such as two-level inverters exhibit limitations like higher Total Harmonic Distortion (THD) and lower power handling capabilities. There is a pressing need for advanced voltage control mechanisms to address these challenges and ensure the stable operation of modern power grids [1].

Static Synchronous Compensators (STATCOMs) have emerged as a crucial technology for mitigating voltage instability, improving power quality, and compensating reactive power. The advent of Multi-Level Inverter Voltage Source Converters (VSCs) in STATCOMs offers several advantages, including improved waveform quality, reduced THD, and enhanced power handling capabilities. This research aims to explore these benefits within the IEEE 14-Bus system, which serves as a representative model of complex power system topologies [2].

The focus of this research is on advancing control strategies to optimize the performance of Multi-Level Inverter-based STATCOMs and their application in a specific power system model—the IEEE 14-Bus system. In electrical grids, shunt compensation is often used for reactive power and voltage control. This thesis models a shunt compensation device that is increasingly used in modern grids: the Modular-Multi-level (MMC) STATCOM. The MMC-STATCOM is built using the Full-Bridge MMC block to represent a power electronics converter of 22 power modules (PM) per arm. The three MMC arms are delta-connected to an 18kV/230kV power transformer.

As power systems experience increasing complexity and dynamic changes, the need for effective voltage control mechanisms becomes paramount. Voltage instability, characterized by voltage sags, swells, and fluctuations, poses a significant challenge to the stability and reliability of power networks. STATCOMs, as flexible and fast-acting devices, offer a solution by dynamically injecting reactive power to stabilize voltage and improve power quality[3].

The choice of Multi-Level Inverter Voltage Source Converters in STATCOM applications is motivated by their inherent advantages, such as improved waveform quality, reduced Total Harmonic Distortion (THD), and enhanced power handling capabilities compared to traditional two-level invert-

ers. These attributes make Multi-Level Inverter-based STATCOMs promising candidates for addressing the evolving needs of modern power systems[4].

1.1 Aim and Goals

The primary aim of this thesis is to investigate the dynamic response of Multi-Level Inverter Voltage Source Converters in STATCOM applications, focusing on the IEEE 14-Bus power system model. Evaluate the impact of Multi-Level Inverter-based STATCOMs on voltage stability, transient response, and overall power quality in comparison to traditional STATCOM configurations. Analyze the performance of the proposed MMC-STATCOM under various operating conditions, including different types of unsymmetrical faults (line-ground, line-line, double line-ground faults). And, contribute to the understanding of the practical implementation aspects and challenges associated with deploying Multi-Level Inverter-based STATCOMs in realistic power systems.

By addressing these objectives, this research aims to enhance the reliability and efficiency of large-scale power networks through the integration of advanced voltage control technologies.

1.2 Limitations and Assumptions

The limitations and assumptions related to the use of STATCOMs for reactive power compensation and harmonic mitigation in the IEEE 14-Bus power system model, several key points can be highlighted. The control algorithms required for the effective operation of STATCOMs can be complex. They necessitate advanced knowledge and expertise for design, implementation, and maintenance. The performance of STATCOMs can be influenced by the specific conditions of the power system. Such as load characteristics and grid configuration, which may limit their effectiveness in certain scenarios while STATCOMs can mitigate harmonics. They can also introduce their harmonics into the system due to the switching actions of power electronic devices necessitating careful design and filtering. The reactive power compensation capability of a STATCOM is limited to its design specifications, and it may not be able to meet extreme reactive power demands without additional support. The operation of STATCOMs generates heat and inadequate thermal management can lead to overheating and reduced system reliability. In this study, it is assumed that the system operates under stable conditions which

may not always be the case in real-world scenarios where load dynamics can vary significantly. The analysis assumed the ideal performance of the STATCOM without accounting for real-world inefficiencies, such as losses in power electronics and control delays. It assumed that harmonics are uniformly distributed across the frequency spectrum, which can oversimplify the analysis and design of harmonic mitigation strategies.

2 Literature review

The deployment of STATCOM in power systems has garnered considerable attention due to their effectiveness in mitigating voltage instability and enhancing power quality. This section reviews the existing literature on the use of MMC-STATCOM applications.

2.1 Multi-Level Inverters in Power Systems

Multi-Level Inverters have been widely investigated as a solution to improve the quality of voltage waveform and increase the power handling capabilities of converters. The ability of Multi-Level Inverters to synthesize stepped voltage waveform allows for reduced harmonic content and enhanced performance in power systems. Various modulation techniques, including Sinusoidal Pulse Width Modulation (SPWM) and Selective Harmonic Elimination (SHE), have been employed to optimize the operation of Multi-Level Inverters [5]. Multi-Level Inverters (MLIs) have emerged as a crucial technology for enhancing power quality and efficiency in modern power systems. This literature review explores recent research (2019-2024) on MLIs, highlighting their applications, advantages, and technological advancements. Multi-Level Inverters are power electronic devices designed to synthesize a stepped voltage waveform from multiple voltage levels, significantly reducing harmonic distortion and improving power quality. They are widely used in renewable energy systems, distributed generation, and high-power applications.

This research [2] provide a comprehensive review of modular multilevel converters, discussing submodule topologies and modulation techniques. They highlight the benefits of MLIs in reducing Total Harmonic Distortion (THD) and improving voltage waveform quality.

Here [6] examines the role of MLIs in power electronics, particularly in mitigating power quality issues in electrical networks. The study emphasizes the advantages of MLIs over traditional two-level inverters in handling high-power applications.

In [7] compares various multilevel inverter topologies and highlights the suitability of three-phase eleven-level inverters for distributed generation systems. The research focuses on the efficiency and performance improvements brought by MLIs in distributed power systems.

In [8] investigates the performance of a five-level reduced switch count Bridge Multi-Level Inverter, emphasizing its application in renewable energy

systems. The study demonstrates the inverter's effectiveness in improving power quality and reducing switching losses.

This report [9] introduces a capacitor-based topology for cross-square-switched T-type MLIs, showcasing new advancements in MLI design. The research highlights the potential of this topology to enhance the reliability and efficiency of power conversion systems.

For applications this [10] reviews the application of MLIs in photovoltaic (PV) systems, detailing their ability to handle fluctuating power inputs from solar panels. The paper discusses various MLI topologies and their impact on the performance of PV systems.

This article [11]explores sustainable design approaches for MLIs in grid-integrated renewable power systems. The research focuses on optimizing inverter performance to meet the demands of modern renewable energy applications . Recent advancements in MLI technology focus on improving efficiency, reducing costs, and enhancing control strategies. This [12] reviews high-power applications of MLIs, discussing techniques to overcome the limitations of traditional inverters. The paper emphasizes the role of MLIs in enhancing the performance of high-power systems and ensuring stable operation under varying load conditions.

The reviewed literature highlights the significant advancements and applications of Multi-Level Inverters in power systems over the past five years. MLIs have proven to be essential in enhancing power quality, integrating renewable energy sources, and improving the overall efficiency and stability of modern power systems. Future research should focus on addressing the remaining challenges and further optimizing MLI technologies to meet the evolving demands of the power industry.

2.2 Challenges and Future Directions

While MLIs offer numerous benefits, several challenges need to be addressed to fully realize their potential.Here [13] discuss control algorithms for DSTATCOMs to compensate for negative and zero sequence voltage unbalance in consumer-generated power systems. The study highlights the importance of advanced control strategies in optimizing the performance of MLIs . In [14] investigate the stability of phase-locked loops in STATCOMs with different grid R/L ratios, emphasizing the need for robust control mechanisms to ensure stable operation of MLIs in various power system configurations . This [4] provide a comprehensive review of CHB MLI based PV inverters,

discussing the feasibility of integrating MLIs with STATCOMs for improved performance in renewable energy systems . This [5] offer a state-of-the-art review of reactive power compensation technologies, including MLIs. The paper underscores the advantages of MLIs in providing dynamic reactive power support and enhancing voltage stability .And here [13] compare various FACTS controllers, highlighting the role of MLIs in improving the efficiency and reliability of power systems .While this [15] analyze the transient stability of the IEEE 14-bus power system using MLIs, demonstrating their effectiveness in maintaining system stability under fault conditions .And [1] discuss reactive power control in modified IEEE 14-bus systems using MLIs, emphasizing the importance of advanced control strategies in optimizing the performance of power systems .

2.3 Case Studies on IEEE 14-Bus Power System

The IEEE 14-Bus power system model has been widely adopted as a testbed for evaluating the performance of various power system components and control strategies. Researchers have conducted numerous case studies to assess the impact of different STATCOM configurations on voltage stability, transient response, and overall power quality. However, there is a gap in the literature concerning the specific application of MMC-STATCOM in the IEEE 14-Bus system.

2.4 Power Quality and Voltage Stability

Power quality and voltage stability in power systems are critical aspects of power system operation, directly impacting the reliability and efficiency of electrical networks. This literature review provides an overview of the existing research on power quality and voltage stability, focusing on the challenges, methodologies, and solutions employed to enhance these key parameters. Power quality refers to the degree to which the voltage, current, and frequency of the electrical supply meet the requirements of the connected electrical equipment. Issues such as voltage sags, swells, harmonics, and transients can degrade power quality, leading to equipment malfunction, increased losses, and operational inefficiencies. Numerous studies have investigated the sources of power quality disturbances and proposed various mitigation techniques [13]. Voltage stability is the ability of a power system to maintain acceptable voltages at all buses under normal operating condi-

tions and after being subjected to disturbances. Voltage instability can lead to cascading failures, voltage collapse, and blackouts. Researchers have extensively studied voltage stability indicators, assessment methodologies, and control strategies to prevent voltage instability in power systems [4].

2.4.1 Power Quality Disturbances

Voltage sags, caused by short circuits or sudden load changes, are a common power quality disturbance. Mitigation techniques include the use of custom power devices like Dynamic Voltage Restorers (DVRs) and the application of advanced control algorithms. Harmonic distortion, originating from nonlinear loads, has been addressed through the use of filters, active power filters, and the adoption of improved converter technologies [14].

2.4.2 Voltage Stability Assessment

Voltage stability assessment involves analyzing the system's response to disturbances and identifying critical points where instability may occur. Methods such as continuation power flow analysis, modal analysis, and time-domain simulations have been employed for voltage stability assessment. Early detection of voltage instability allows for the implementation of preventive control measures [16].

2.4.3 Mitigation Strategies

Mitigation strategies for both power quality and voltage stability issues often involve the use of Flexible AC Transmission Systems (FACTS) devices and advanced control techniques. STATCOMs for example, play a crucial role in enhancing power system stability by providing fast and accurate reactive power compensation [17].

2.4.4 Integration of Renewable Energy Sources

The increasing integration of renewable energy sources introduces additional challenges to power quality and voltage stability. Inverter-based renewable energy sources, such as photovoltaic systems and wind turbines, can contribute to voltage fluctuations and harmonics. Researchers are exploring smart grid technologies, energy storage systems, and improved control strategies to mitigate these challenges [13].

2.5 Reactive Power Compensation Techniques

Reactive power compensation is a critical aspect of power system operation, aimed at maintaining power factor, voltage stability, and overall system efficiency. This comprehensive review explores various reactive power compensation techniques, encompassing both traditional and advanced methods, with a focus on their application in modern power systems [18].

2.5.1 Traditional Reactive Power Compensation

Synchronous condensers have long been employed for reactive power compensation. These rotating machines, decoupled from the mechanical load, generate or absorb reactive power as needed. While effective, they have limitations in terms of size, cost, and response time [19]. **Fixed capacitor banks** are simple and cost-effective solutions for reactive power compensation. They provide capacitive reactive power to counteract inductive loads. However, their drawback lies in their inability to adapt to varying system conditions [19]. **Tap-changing transformers** adjust the voltage ratio to control reactive power flow. While effective, they are relatively slow in response and may introduce transient disturbances [19].

2.5.2 Advanced Reactive Power Compensation

Static Var Compensators SVCs utilize thyristor-controlled reactors and capacitors to provide rapid and precise reactive power compensation. They are capable of dynamic response and are often employed for voltage control and stability enhancement [20]. **Static Synchronous Compensators** STATCOMs, based on VSCs, offer fast and precise reactive power compensation. They can regulate voltage and provide dynamic support during transient events. Multi-Level Inverter-based STATCOMs further enhance the performance, reducing harmonics and improving overall power quality [18]. **Unified Power Flow Controller** UPFC is a versatile device capable of simultaneous control of active and reactive power flows. It consists of a combination of series and shunt compensators, providing comprehensive control over power system parameters [20]. **Smart Inverter Control for Distributed Generation** With the increasing integration of distributed generation, smart inverter control strategies have gained prominence for reactive power compensation. Inverters in photovoltaic systems and wind turbines

can contribute to grid stability by providing reactive power support. Advanced control algorithms, such as droop control and virtual impedance, enable precise and coordinated compensation.

Reactive power compensation techniques have evolved significantly, driven by advances in power electronics and the changing landscape of power systems. Future research should focus on the integration of these techniques into smart grids, the development of adaptive control strategies, and the optimization of hybrid solutions combining multiple compensators for enhanced overall performance. This review provides a comprehensive understanding of the diverse approaches to reactive power compensation, setting the stage for further advancements in the field [2].

2.6 Role of STATCOMs in Grid Compensation

The evolving landscape of power systems, characterized by increased renewable energy integration and changing load profiles, demands advanced solutions for maintaining grid stability and power quality. This comprehensive overview delves into the crucial role of STATCOMs in grid compensation, emphasizing their capabilities, applications, and contributions to enhancing system performance.Reactive power can be produced or absorbed by the STATCOM. The phase reactance facilitates the transfer of reactive power. A voltage that is in phase with the grid voltage is produced by the converter. The STATCOM absorbs reactive power by acting as an inductor when the converter voltage's amplitude is less than the grid voltage. The STATCOM functions as a capacitor and produces reactive power when the converter voltage's amplitude is greater than the bus voltage [21].

2.6.1 Basics of STATCOM

A STATCOM is a power electronics-based device employing VSCs to provide fast and dynamic reactive power compensation. It operates by injecting or absorbing reactive power into the grid, effectively regulating voltage levels and improving overall power system stability [14]. **Voltage Control and Stability** one of the primary functions of a STATCOM is voltage control. By dynamically adjusting the reactive power output, STATCOMs can regulate bus voltages and mitigate voltage fluctuations. This capability is particularly crucial in modern grids with varying loads and intermittent renewable energy sources [17]. **Reactive Power Compensation** STATCOMs play a vital

role in compensating reactive power, balancing the inductive and capacitive elements in the grid. This compensation helps in maintaining power factor close to unity, reducing line losses, and ensuring efficient power transfer across the transmission network. **Grid Support during Transients** during sudden load changes or disturbances, STATCOMs exhibit rapid response capabilities. They can provide immediate reactive power support, dampen voltage fluctuations, and contribute to grid resilience by minimizing the impact of transient events [21]. **Mitigation of Voltage Sags and Swells** voltage sags and swells, often associated with network faults or rapid changes in load, can adversely affect sensitive equipment. STATCOMs act as effective solutions for mitigating these disturbances, ensuring a stable and reliable power supply to critical loads [5]. **Harmonic Mitigation** in addition to reactive power compensation, STATCOMs contribute to harmonic mitigation by regulating the voltage waveform. Their ability to generate high-quality, low-harmonic voltage waveforms helps in reducing (THD) and maintaining power quality within acceptable limits [22]. **Integration with Renewable Energy Sources** as renewable energy sources like solar and wind become integral parts of the grid, STATCOMs facilitate their seamless integration. They assist in managing the intermittency of renewable generation, providing grid support and ensuring a smooth transition to a cleaner and more sustainable energy mix. **Dynamic Stability Enhancement** STATCOMs enhance the dynamic stability of the grid by improving the system's response to disturbances. Their rapid and accurate control of reactive power supports the grid's ability to withstand and recover from unforeseen events, thereby preventing cascading failures. **Smart Grid Applications** in the context of smart grids, STATCOMs contribute to the development of adaptive and self-healing systems. Their incorporation into intelligent grid management enhances the overall reliability and resilience of the power network.

The role of STATCOM in grid compensation is multifaceted, encompassing voltage control, reactive power compensation, transient response, and support for renewable energy integration. As power systems continue to evolve, the deployment of STATCOMs becomes increasingly pivotal in ensuring a stable, efficient, and high-quality electrical grid. This overview provides a comprehensive understanding of the diverse contributions of STATCOMs to grid compensation, emphasizing their significance in the context of modern power systems[5].

2.7 Multilevel Converter

MMC is a type of power electronics converter that has gained significant attention in high-voltage, high-power applications such as HVDC transmission systems and medium-voltage motor drives. The modular structure of MMC allows it to achieve high voltage levels with reduced stress on the power semiconductors [1]. Here's a brief review of some MMC topologies Figure 1:

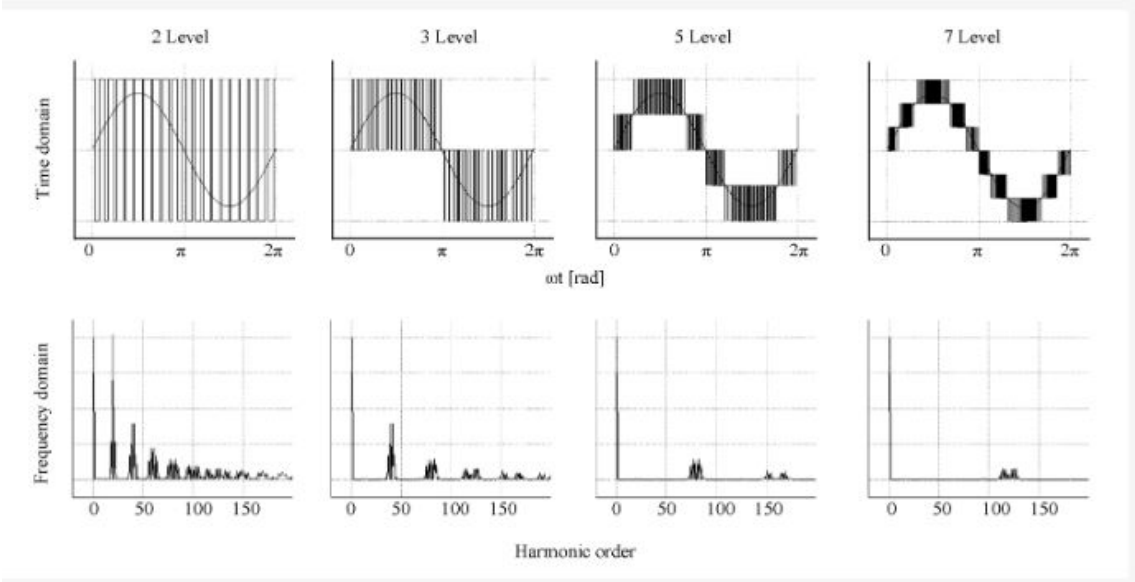

Figure 1: Influence of the voltage levels that an MLC can produce on the harmonic spectrum [2].

2.7.1 Half-Bridge MMC

In a half-bridge MMC, each arm of the converter consists of half-bridge submodules connected in series. It is commonly used in medium-voltage applications and offers advantages such as modularity, scalability, and reduced voltage stress on individual semiconductors. The half-bridge structure simplifies the control scheme and is well-suited for applications like motor drives [14].

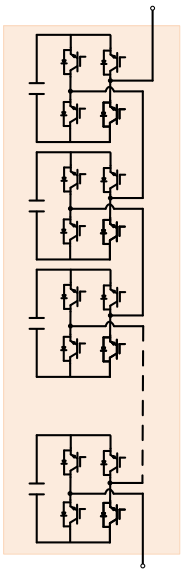

Figure 2: Cascaded H-Bridge MMC[21]

2.7.2 Full-Bridge MMC

The full-bridge MMC employs full-bridge sub-modules, allowing for higher voltage levels and increased power capability compared to the Half-Bridge MMC. The full-bridge configuration enhances the converter's ability to handle higher voltages and power levels, making it suitable for applications such as HVDC transmission systems [14].

2.7.3 Cascaded H-Bridge MMC

- The Cascaded H-Bridge MMC topology is an extension of the MMC concept where each arm of the converter comprises multiple H-bridge sub-modules connected in series Figure 2. This topology provides enhanced voltage levels and is suitable for applications requiring very high voltage levels, such as ultra-high-voltage DC transmission [21].

2.7.4 Hybrid MMC

- Hybrid MMC topologies combine features of different MMC configurations to achieve specific objectives. For example, a combination of Half-Bridge

MMC and Full-Bridge MMC elements can be used to optimize the trade-off between complexity, voltage capability, and ease of control.

These MMC topologies offer flexibility and scalability, making them well-suited for a variety of applications. The choice of a particular MMC topology depends on factors such as voltage requirements, power levels, and the specific control strategy needed for the application at hand. Ongoing research continues to refine MMC topologies and explore new configurations to address emerging challenges in power electronics and grid integration Figure 3.

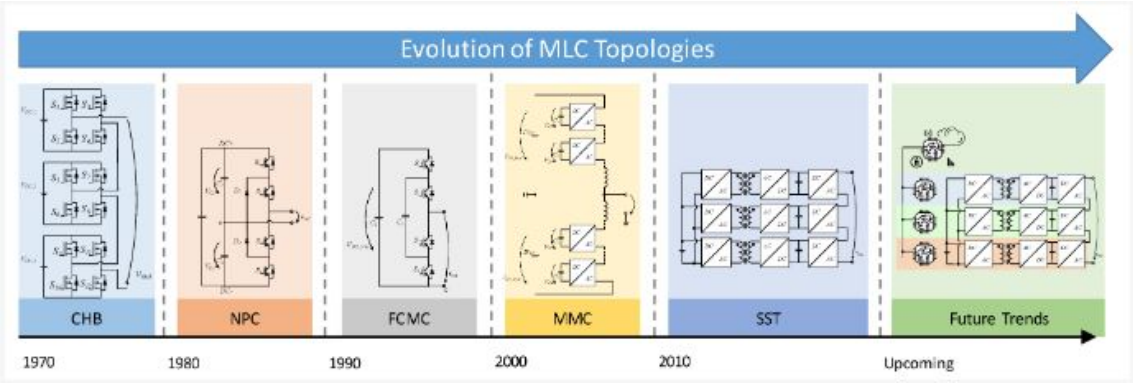

Figure 3: Evolution and emergence of new MLC topologies [2].

2.7.5 PWM Techniques Applied on MLC

Pulse Width Modulation (PWM) is a widely used control strategy in power electronics, including the control of Modular Multilevel Converters (MMCs). PWM is employed to synthesize desired voltage waveforms by modulating the width of the pulses in the converter's output voltage [2].

- Basic Operation of MMC

In an MMC, the converter is made up of multiple sub-modules connected in series. Each sub-module typically consists of several power electronic switches (such as IGBTs) arranged in a certain topology (e.g., half-bridge or full-bridge). The sub-modules are connected in a staircase fashion to form the converter arms [23].

- Voltage Synthesis with PWM

PWM is applied to control the voltage output of each sub-module. By adjusting the width of the pulses, the average voltage across each sub-module can be modulated to create a sinusoidal waveform or any other desired waveform. This modulation helps in achieving the desired output voltage and controlling the flow of power [23].

- Carrier-Based PWM

Carrier-Based PWM is a commonly used technique for MMCs. In this method, a high-frequency triangular carrier waveform is compared with a reference waveform (usually a sinusoidal waveform) to generate the PWM signals. The width of the pulses is adjusted based on the instantaneous values of the carrier and reference waveforms. This results in a series of pulses that, when filtered, produce the desired output voltage [23].

- Phase-Shifted PWM

Phase-Shifted PWM is another technique used in MMCs. In this method, multiple carriers are generated with a phase shift between them. Each carrier is compared with the reference waveform to generate PWM signals for different sub-modules. This technique is known for reducing harmonic content in the output voltage and improving the overall performance of the converter [23].

- Selective Harmonic Elimination (SHE) PWM

SHE PWM is a more advanced technique that aims to eliminate specific harmonics from the output voltage. By carefully selecting the modulation indices, certain harmonics can be canceled out, leading to a lower (THD) in the output voltage waveform [23].

- Over-modulation

In certain cases, over-modulation techniques are employed to extend the output voltage range beyond the linear modulation range. This allows the MMC to generate higher voltage levels than what would be achievable with linear modulation alone [23].

- Common-Mode Voltage Control

In MMCs, it is essential to control the common-mode voltage to ensure the reliability of the converter. PWM techniques are applied to minimize common-mode voltage, which can otherwise lead to issues such as increased stress on the insulation and bearings of connected equipment [23].

- Fault Ride-Through Capability

Advanced PWM control strategies are implemented to enhance the fault ride-through capability of MMCs. This involves modifying the PWM patterns during grid faults to maintain grid stability and ride through the disturbances [23].

The application of PWM in MMCs is a complex process that involves careful consideration of modulation strategies, carrier frequencies, and control objectives. Researchers continue to explore novel PWM techniques and control strategies to improve the performance, efficiency, and reliability of MMCs in various power system applications.

2.8 STATCOM operation and control

The operation and control of STATCOM involve several key aspects to ensure effective voltage regulation and reactive power compensation in power systems.

The operation principle of the STATCOM utilizing MMC That consists of an MMC with cascaded IGBT H-bridges and isolated capacitors . Each converter branch has only two terminals, and the switching states of a module include "Off" states, "Plus" states contributing to a positive voltage, and "Minus" states contributing to a negative voltage as seen in Figure 4.

The converter control strategy ensures that only one module is switched at a time, and there is no direct change from the Plus state to the Minus state and vice versa during regular operation . This approach limits voltage steps in the converter voltage to the capacitor voltage of a single module, reducing insulation stresses and electromagnetic interference .

Despite using a low switching frequency, the STATCOM device achieves a fine approximation of the desired output voltage, such as a sinusoidal voltage, by utilizing multiple modules and levels . The high frequency content due to voltage steps is removed by a noise filter, and the reduced switching frequency

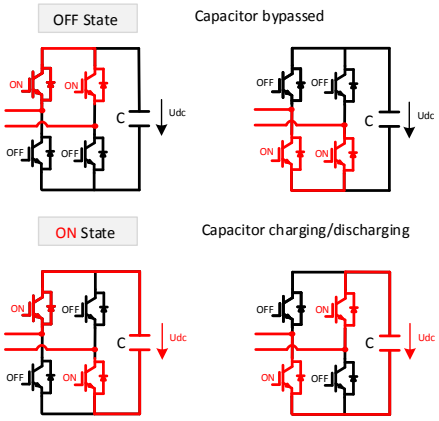

Figure 4: The operation principle of the STATCOM [21]

minimizes overall switching losses . The MMC STATCOM device operates based on a sophisticated control strategy, MMC topology, and protective features to provide efficient reactive power compensation, voltage regulation, and grid support in power systems. Its advanced design and capabilities make it a valuable asset for enhancing system performance and reliability in diverse applications[21].

2.9 Discussion of various control strategies for STATCOMs

Various control strategies can be employed for STATCOMs to effectively regulate voltage and reactive power in power systems [1]. Some common control strategies include:

2.10 Voltage Control

STATCOMs can be controlled to regulate the voltage at the point of connection by adjusting the output voltage magnitude and phase angle. This is crucial for maintaining voltage stability and preventing voltage collapse in power systems [24].

$$V_{ref} - V_{meas} = 0 \tag{1}$$

where V_{ref} is the reference voltage and V_{meas} is the measured voltage at the point of connection.

2.11 Reactive Power Control

Control strategies can focus on maintaining the desired level of reactive power flow in the system by adjusting the output of the STATCOM. By dynamically controlling reactive power, STATCOMs help in balancing the load and improving the voltage profile across the network [25].

$$Q_{ref} - Q_{meas} = 0 \tag{2}$$

where Q_{ref} is the reference reactive power and Q_{meas} is the measured reactive power.

2.12 Current Control

By controlling the output current of the STATCOM, it can inject or absorb reactive power as needed to stabilize the system. Current control strategies ensure that the STATCOM responds quickly to transient disturbances, helping to maintain the overall stability of the power grid during fault conditions [26].

$$I_{ref} - I_{meas} = 0 \tag{3}$$

where I_{ref} is the reference current and I_{meas} is the measured current.

2.13 Frequency Control

Some control strategies involve monitoring and controlling the frequency of the system to ensure stability and proper operation. Although STATCOMs are primarily used for voltage and reactive power control, they can also support frequency regulation by adjusting the reactive power flow to maintain the system frequency within acceptable limits [27].

$$f_{ref} - f_{meas} = 0 \tag{4}$$

where f_{ref} is the reference frequency and f_{meas} is the measured frequency.

2.14 Power Factor Control

STATCOMs can be used to improve power factor by adjusting the reactive power output to align with the active power demand. This is essential for efficient power delivery and reducing losses in the system. By maintaining a high power factor, STATCOMs help in optimizing the utilization of electrical infrastructure [28].

$$PF = \frac{P}{\sqrt{P^2 + Q^2}} \tag{5}$$

where PF is the power factor, P is the active power, and Q is the reactive power.

2.15 Voltage Stability Control

Control strategies can focus on enhancing voltage stability by dynamically adjusting the reactive power output to maintain voltage levels within acceptable limits. This is particularly important in scenarios with high load demand or during contingencies when the risk of voltage instability is higher [29].

$$\Delta V = V_{ref} - V_{meas} \tag{6}$$

where ΔV is the voltage deviation.

2.16 Adaptive Control

Adaptive control strategies can be implemented to adjust the STATCOM operation based on changing system conditions and load demands. This approach allows the STATCOM to provide optimal performance under varying conditions, ensuring continuous voltage support and reactive power compensation [30].

$$u(t) = K \cdot e(t) \tag{7}$$

where $u(t)$ is the control input, K is the adaptive gain, and $e(t)$ is the error signal.

2.17 Hierarchical Control

Hierarchical control structures can be used to coordinate the operation of multiple STATCOMs in a network to achieve optimal system performance.

This type of control enables centralized and decentralized decision-making, ensuring that the overall network operates efficiently and reliably [31].

$$\min \sum_{i=1}^{N} (Q_{i,ref} - Q_{i,meas})^2 \tag{8}$$

where N is the number of STATCOMs, $Q_{i,ref}$ is the reference reactive power for the i-th STATCOM, and $Q_{i,meas}$ is the measured reactive power for the i-th STATCOM. These control strategies play a crucial role in ensuring the effective operation of STATCOMs in power systems, providing voltage support, reactive power compensation, and overall system stability. The implementation of these strategies enhances the resilience of power systems against disturbances and improves the quality and reliability of power supply.

3 Method and Modeling

The method used in the research for improving the transient stability of the IEEE 14 Bus System with STATCOM involved simulation and analysis using MATLAB/Simulink software. Analyzed the transient behavior of the standard IEEE 14 bus system to assess the impact of different type of faults and the effectiveness of STATCOM in voltage regulation .

The modeling approach included simulating different scenarios such as single Line-ground fault, Line-line fault, and double line-ground at bus 4 in the IEEE 14 Bus System. By introducing faults and observing the voltage variations, the researchers demonstrated the need for a compensating device like STATCOM to maintain system stability as in Figure 5.

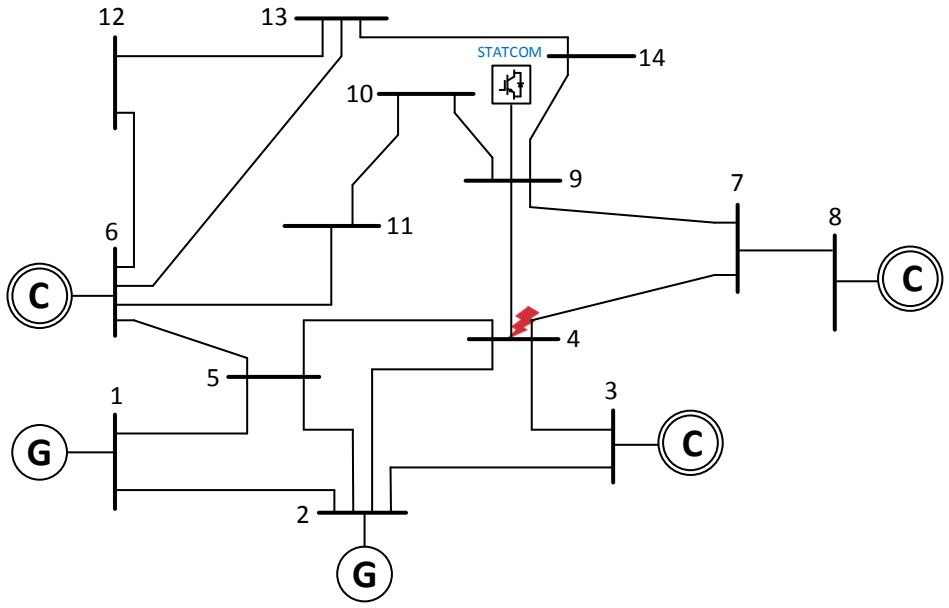

Figure 5: IEEE-14 bus System with MMC STATCOM under study.

Through simulation studies using MATLAB/Simulink, the performance of the system is evaluated with and without STATCOM, showcasing the effectiveness of the FACTS device in improving voltage profile and system stability under varying load conditions.

3.1 Detailed description of the 14-bus IEEE grid

The use of STATCOM improves the transient performance of the IEEE 14 Bus System by providing reactive power support and voltage regulation.

STATCOM works as a voltage source converter and can help in regulating voltage levels in the system . By dynamically injecting reactive power into the system, STATCOM can stabilize voltage fluctuations, improve system voltage profile, and enhance system stability during both heavy and light load conditions [22].

The IEEE 14-bus test system is a widely used benchmark system in power systems research for testing and validating various power system analysis and optimization techniques. As seen in Table 1. The IEEE 14-bus system consists of 14 buses interconnected by transmission lines and transformers. It includes 5 generator buses, 11 load buses, and 3 transformers. The system has different types of buses, including generator buses, load buses, and slack bus. Generator buses supply real power, load buses consume power, and the slack bus maintains system balance. There are 5 generators in the system that supply real power. Some generators may also act as reactive power sources (synchronous condensers). The system has 11 loads that represent the consumer demand for electrical power. There are 3 transformers in the system that step up or step down the voltage levels between buses. The system has a total real load of 332 MW and a reactive load of 88 MVAr. Voltage and Frequency: The bus voltage is typically 230 kV, and the system operates at a frequency of 60 Hz. The system includes information about the resistances, reactances, and susceptances of the transmission lines and transformers [32]. In this study the STATCOM was connected in Bus9 as illustrated in Figure 5 with 50 MVA capacity.

Table 1: IEEE 14-Bus Test System Details

Category	Details
Buses	• **Total Buses:** 14 • **Generator Buses:** 5 (Buses 1, 2, 3, 6, 8) • **Load Buses:** 11 • **Slack Bus:** 1 (Bus 1)
Generators	• **Total Generators:** 5 • **Locations:** Buses 1, 2, 3, 6, 8
Loads	• **Total Loads:** 11 • **Total Real Load:** 332 MW • **Total Reactive Load:** 88 MVAr
Transformers	• **Total Transformers:** 3
Parameters	• **Bus Voltage:** 230 kV • **System Frequency:** 60 Hz

3.2 Control Modeling

The following are the primary subsystems that make up the STATCOM control system: By executing an abc-dq transformation in the synchronous reference given by a three-phase PLL synchronized on the primary voltages,

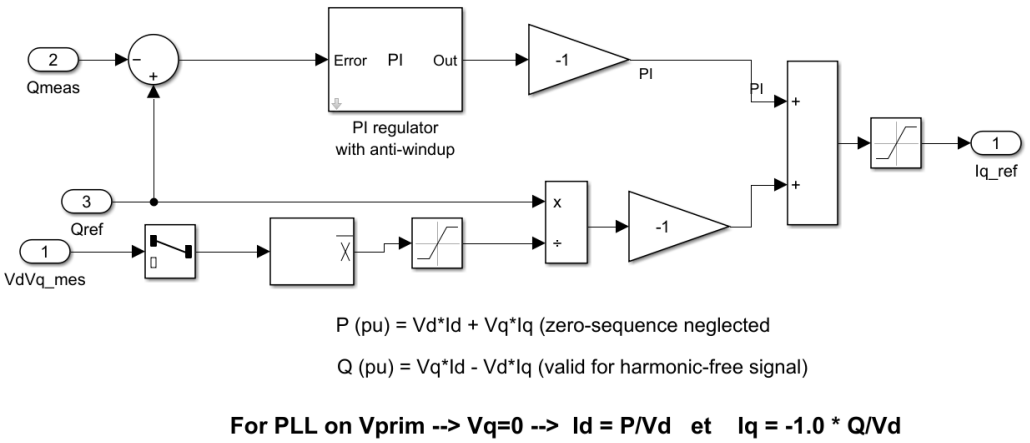

Figure 6: Reactive power regulator

measurements calculate the d-axis and q-axis components of the primary voltages and currents. The Reactive Power Regulator calculates the necessary reactive current reference value ($I_{q,ref}$) in order to regulate the reactive power generated or absorbed by the STATCOM. The DC Voltage Regulator keeps all capacitor PM average values within the designated reference value ($V_{nom,PM} = 1600V$). The regulator calculates the necessary active current reference value ($I_{q,ref}$) in order to do this duty, which involves controlling the active power generated or absorbed by the STATCOM. Measured current values (I_d/I_q) must equal for the converter output voltage signals (V_d,V_q) to be generated by the current regulator. Figure 6 shows the reactive power regulator used in MATLAB/Simulink to give ($I_{q,ref}$).

3.2.1 Current control

One common control strategy used in STATCOMs is current control, where the converter output currents are controlled to achieve the desired system performance. The current control equations in a STATCOM typically involve regulating the output currents to maintain the desired reactive power injection or absorption.

Here are the basic current control equations used in a STATCOM: Current Regulator (with feedforward):

$$L_{tot} = Lx_{fo} + L_{conv} \tag{9}$$

$$R_{tot} = Rx_{fo} + R_{conv} \tag{10}$$

$$V_{d,mes} + I_d R - I_q L + \frac{dI_d}{dt} L = V_{d,conv} \tag{11}$$

$$V_{q,mes} + I_d L + I_q R + \frac{dI_q}{dt} = V_{q,conv} \tag{12}$$

For $L_{tot} >> R_{tot}$:

$$(V_{d,prim} - V_{d,conv}) \ = +I_q L_{tot} \tag{13}$$

$$(V_{q,prim} - V_{q,conv}) \ = -I_d L_{tot} \tag{14}$$

If I_d positive: the converter generates active power= Active Power P positive. If I_q negative: The converter generates reactive power ("Capacitive mode") = Reactive Power Q positive.

Reference Current Generation: The control system generates reference currents (I_{ref}) based on the desired reactive power output and the measured system parameters (such as voltage and current). The reference currents represent the desired output of the converter to achieve the required reactive power compensation.

Current Error Calculation: The control system compares the reference currents with the actual output currents I_{out} of the converter to calculate the current error (I_{error}). The current error represents the deviation between the desired and actual currents and is used to adjust the converter output.

Controller Design: A controller (such as a PI controller) is used to calculate the control signals that adjust the converter output currents to minimize the current error. The controller output is typically the modulation index or duty cycle of the converter switches.

Current Control Loop: The control signals from the controller are applied to the converter to regulate the output currents and achieve the desired reactive power injection or absorption. The control loop continuously adjusts the converter output to maintain the system performance.

Feedback and Monitoring: The control system continuously monitors the system parameters, such as voltage, current, and power factor, to ensure that the STATCOM operates within the desired operating limits. Feedback from the system is used to adjust the control signals and maintain the system stability.

By implementing these current control equations in the control system of a STATCOM, the device can effectively regulate the reactive power output

and provide voltage support to the power system, improving system stability and power quality.

3.2.2 Reactive power control

Reactive power control in a STATCOM is closely related to voltage regulation. By injecting or absorbing reactive power, the STATCOM can help maintain voltage levels within acceptable limits, especially during transient conditions or disturbances in the grid.

$$P(pu) = V_d I_d + V_q I_q \tag{15}$$

(zero-sequence neglected)

$$Q(pu) = V_q I_d - V_d I_q \tag{16}$$

(valid for harmonic-free signal). For PLL on V_{prim} has V_q=0 and I_d = P/V_d. Furthermore I_q = -1.0 Q/V_d

4 Modeling of MMC STATCOM

Figure 7 depicts an MMC STATCOM's arrangement. connected to capacitor converters as SM(Sub Modules), Each phase leg consists of a phase reactor and cascaded SM. The cascaded SM consists of a number of individually switched, series-connected, full bridges referred full-bridge converters. The dc capacitor voltage per module and the line voltage rating determine how many SMs are in a phase arm. The three-phase arms are connected to Bus9, which is thought of as the point of common coupling (PCC), via their filters with an impedance of R_f+jωL_f on the transmission lines.

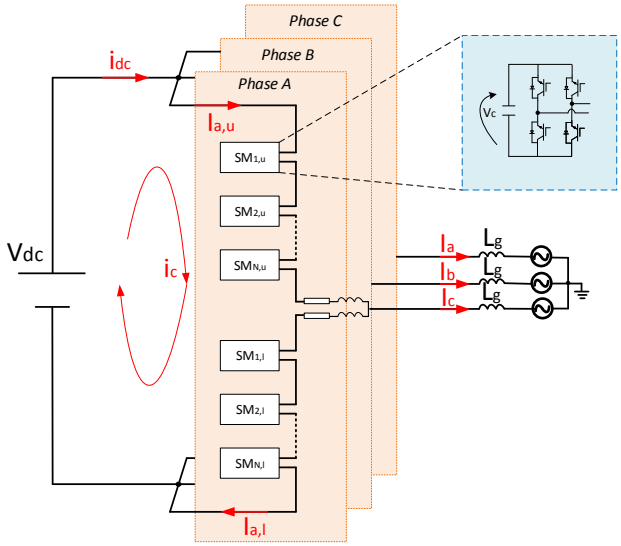

Figure 7: Topology of the MMC-STATCOM

5 Results

The results presented using MATLAB/Simulink demonstrate the effectiveness of the proposed MMC STATCOM in improving transient stability in the grid, particularly during unsymmetrical faults or disturbances. During the simulation different references of reactive power were applied to the system along a single-line-to-ground, line-to-line, and double-line-ground fault. The simulation time was 1 second with step size 1e-6 and the solver in MATLAB/Simulink was ode23tb.

Figure 8 shows the STATCOM supply 0 Mvar in the beginning of the simulation. From 0.1 seconds to 0.3 seconds, Q_{ref} value is changed to -30 Mvar (inductive var) resulting in a drop of voltage Figure 8 (a) and an increase of current Figure 8 (b) in the primary side. Furthermore, the same behaviour could be seen in the secondary side of the STATCOM Figure 8 (c) and (d).

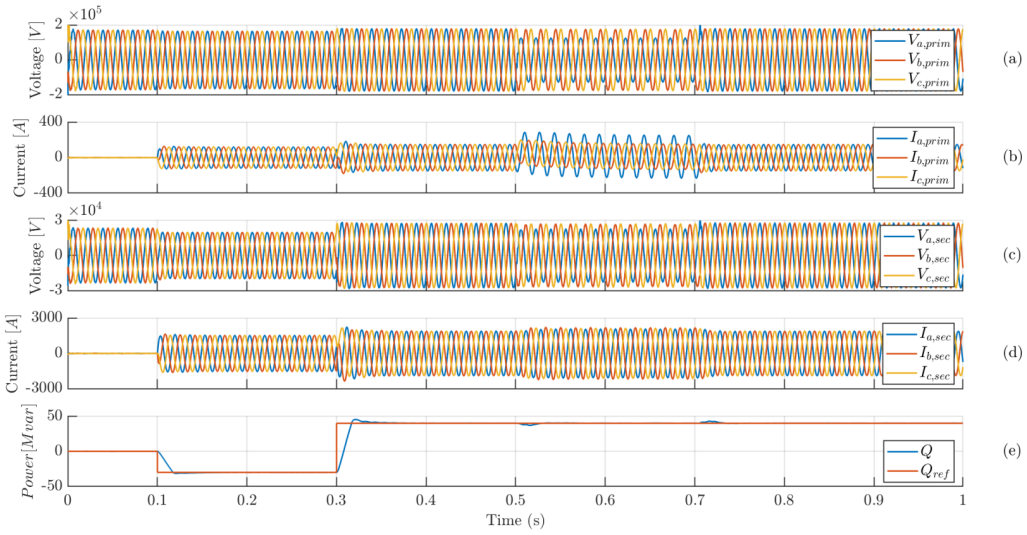

Figure 8: Waveforms of the system when under a SLGF (a) voltage and (b) current at primary side of STATCOM, (c) voltage and (d) current at secondary side of STATCOM and (e) reactive power.

From 0.3 seconds to 0.5 seconds, the set-point changes from -30 Mvar to 40 Mvar (capacitive var). The STATCOM control system reacts to modify the inverter output voltage to follow the new Q_{ref}. This change caused a swell in the voltage Figure 8 (a) and an increase of current Figure 8 (b)

on the primary side. Furthermore, the same behavior could be seen in the secondary side of the STATCOM Figure 8 (c) and (d). From 0.5 seconds to 0.7 seconds, a single line-ground fault is applied at bus 4 forcing the STATCOM to compensate the system under this disturbance. As seen in Figure 8(a) when applying the fault in phase A the voltage drops in phase A but does not go to zero because the fault impedance is not zero. Due to the small fault impedance the current in phase A increases Figure 8(b). However, due to the transformer configuration (Y-Δ) the secondary side has a different behavior as can be seen in Figure 8 (c) and (d). In Figure 8 (e) can be seen that even during the SLGF the STATCOM still supplies the desired reactive power.

Other scenario when applying line to line fault between B and C phases From 0.5 seconds to 0.7 seconds, a LLF is applied at bus 4 forcing the STATCOM to react under this disturbance. As seen in Figure 9(a) when applying the fault in phase B and C the voltage drops and also became almost aliened but does not go to zero because the fault impedance is not zero. Due to the small fault impedance the current in phase B and C increases and became opposite to each others(180 degree)Figure 9(b). However, due to the transformer configuration (Y-Δ) the secondary side has a different behavior as can be seen in Figure 9 (c) and (d). In Figure 9 (e) can be seen that even during the LLF the STATCOM still supplies the desired reactive power.

But when the fault happened between the same phases with the ground there were slight difference in the voltage and current wave forms as seen in Figure 10 when the grid's bus 4 has a double Line-ground failure. As seen from the wave forms that phase A was healthy in voltage but the current affected by the fault. At the same time STATCOM response was rapid and it was obvious that the supplied reactive power was affected slightly at the start of the fault but at 0.53 seconds return to supply the same reactive power required by the system despite that the fault was still exist. And at the moment of fault clearing 0.7 seconds the STATCOM reactive power went a little higher than the reference for 0.03 seconds and return to be aliened with the reference value.

For load flow of the system with and without STATCOM. Figure 11 shows load flow of the grid without using of STATCOM. It is clear that the volatge level in most of the buses is less than the standard voltage regulation 0.95pu for example at load bus 9 the voltage was 0.889pu. After adding STATCOM to the grid the voltage levels have been enhanced for most of the load buses as Figure 12 as seen in load bus 9 it became 0.969pu.

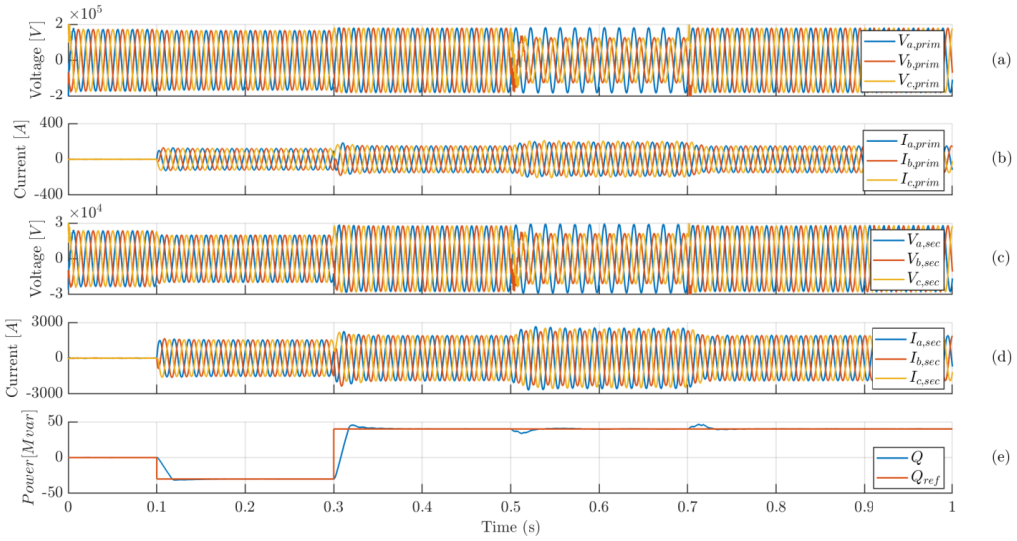

Figure 9: Waveforms of the system when under a LLF (a) voltage and (b) current at primary side of STATCOM, (c) voltage and (d) current at secondary side of STATCOM and (e) reactive power

In conclusion, the results highlights the significance of the proposed MMC STATCOM in enhancing transient stability in power grid, showcasing its effectiveness in improving system performance and reliability during grid disturbances.

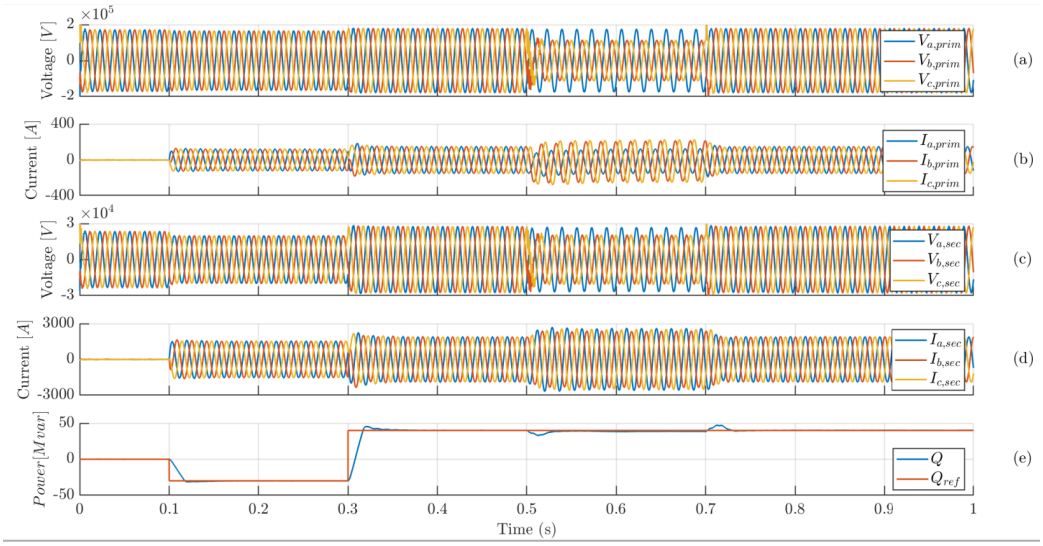

Figure 10: Waveforms of the system when under a DLGF (a) voltage and (b) current at primary side of STATCOM, (c) voltage and (d) current at secondary side of STATCOM and (e) reactive power.

6 Discussion

The results of the MATLAB/Simulink simulations validate the thesis objective, showcasing the proposed MMC STATCOM's efficacy in enhancing transient stability and reactive power control in the power grid. The system's performance under various fault conditions, such as SLGF, LLF, and DLGF, demonstrated the STATCOM's rapid response and stability, ensuring minimal disruption and maintaining power quality. The integration of the MMC STATCOM proved to be beneficial in improving voltage levels across the grid, particularly in scenarios with significant voltage drops. These improvements highlight the potential of MMC STATCOM in modern power systems, making it a crucial component for maintaining grid reliability and stability in the face of disturbances. In summary, the proposed MMC STATCOM not only enhances transient stability but also provides robust voltage support, making it a valuable asset for power system operators aiming to ensure uninterrupted and high-quality power delivery.

7 Conclusions

For future work in the field of transient stability improvement of power systems using STATCOM in the IEEE 14-bus system, several areas of research and development can be explored:

Advanced Control Strategies: Investigate and develop advanced control strategies for STATCOM to enhance its performance in mitigating voltage fluctuations and improving system stability under various operating conditions.

Integration of Energy Storage: Explore the integration of energy storage systems with STATCOM to provide additional support for transient stability enhancement and grid resilience.

Dynamic Modeling and Simulation: Develop more detailed and dynamic models of the IEEE 14-bus system to capture complex system dynamics and interactions for a more accurate assessment of transient stability improvement with STATCOM.

Robustness Analysis: Perform robustness analysis to evaluate the effectiveness of STATCOM in improving transient stability under uncertainties, parameter variations, and contingencies in the power system.

Smart Grid Integration: Study the integration of STATCOM and other smart grid technologies such as demand response, distributed generation, and grid automation for comprehensive transient stability enhancement in modern power systems.

By focusing on these future research directions, advancements can be made in enhancing the transient stability of power systems using STATCOM, leading to more reliable, resilient, and efficient operation of electrical grids.

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8 Appendix

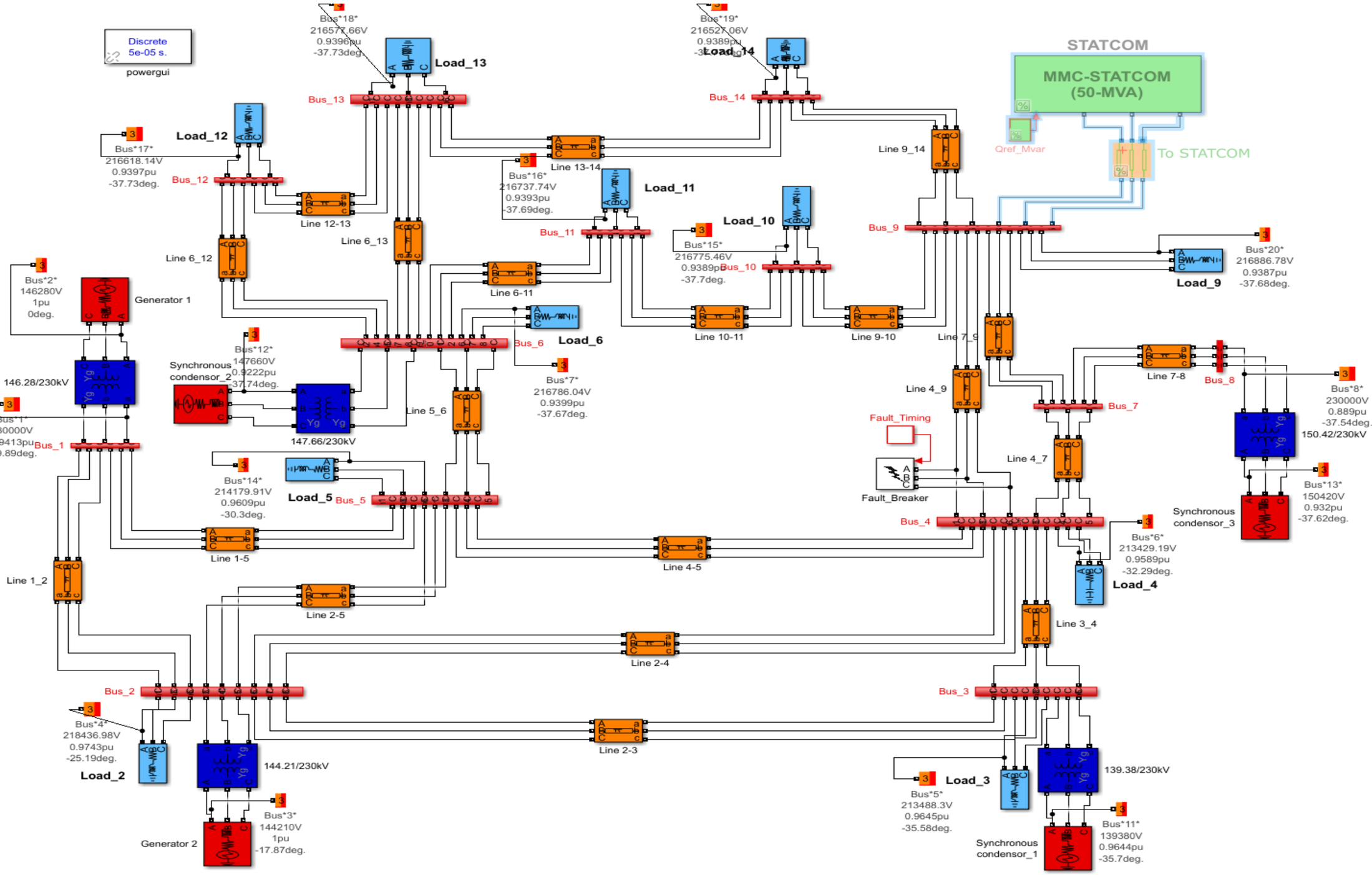

Figure 11 Load flow of the grid without STATCOM

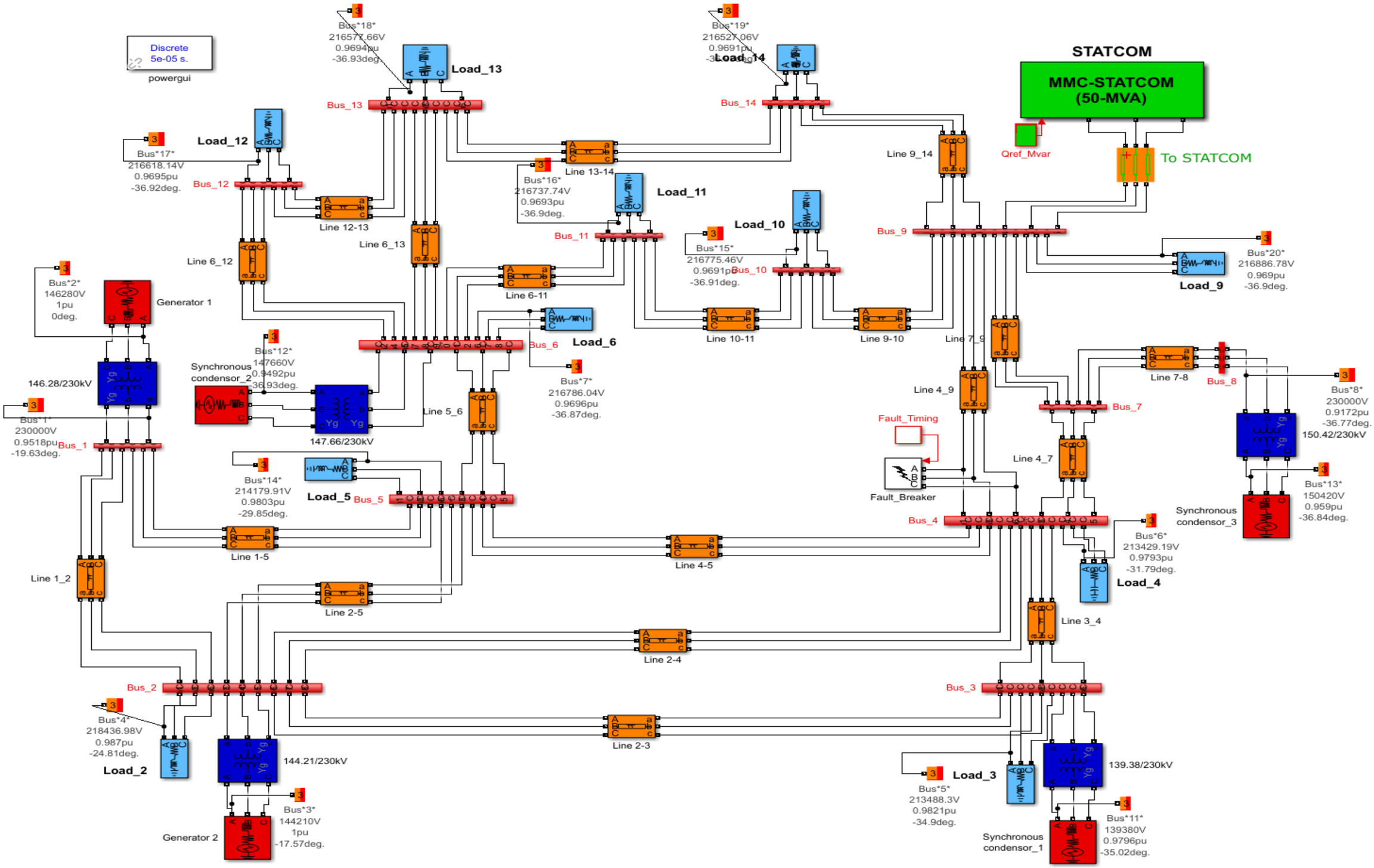

Figure 12 Load flow of the grid with STATCOM