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Enhancing Power System Stability through Reactive Compensation with Static VAR Compensator

Pullareddy K.[1]
Assistant Professor
EEED; Methodist College of Engineering & Technology

Amulya Tadi[2]
160721734001
BE, EEED; Methodist College of Engineering & Technology

Dhanavath Elisha[3]
160721734305
BE, EEED; Methodist College of Engineering & Technology

Gallela Kiran[4]
160721734314
BE, EEED; Methodist College of Engineering & Technology

K Jaidev[5]
160721734004
BE, EEED; Methodist College of Engineering & Technology

M Venkatesh[6]
160721734008
BE, EEED; Methodist College of Engineering & Technology

Abstract: A Static Var Compensator (SVC) is a vital component in modern electrical power systems for regulating reactive power, maintaining voltage stability, and improving power quality. The primary objective of this study is to evaluate the performance and effectiveness of SVCs in real-time reactive power compensation and voltage control, particularly in large transmission networks. By providing fast and dynamic reactive power support, SVCs help optimize power flow and reduce transmission losses, contributing to a more stable and efficient power grid. The novelty of this research lies in the use of an advanced segmented thyristor-controlled reactor (TCR) integrated with fixed capacitor (FC) systems, which allows for modular and highly adaptable reactive power compensation. This configuration improves the precision of voltage regulation, reduces harmonic distortion, and enhances the response time of the system, compared to conventional SVC setups. Additionally, this study explores the application of SVCs in power grids with high penetration of renewable energy sources, highlighting their role in managing voltage fluctuations caused by variable generation. The findings of the study demonstrate that SVCs significantly improve voltage stability and power factor correction, particularly in regions with heavy inductive loads or fluctuating renewable energy inputs. The implementation of SVCs in large transmission networks leads to a measurable reduction in power losses and increases grid resilience. Overall, the research confirms that SVCs are an indispensable tool for enhancing the reliability and efficiency of modern power systems, especially in the face of growing demand and renewable energy integration.

Keywords:- *Flexible AC Transmission System Devices, Power Systems, Power Electronics, Reactive Power, Voltage Stability.*

I. INTRODUCTION

Reactive power plays a critical role in the operation of electrical power systems, even though it does not directly contribute to the work output, like driving motors or lighting lamps. It is essential for maintaining the voltage levels necessary for active power (the real power that performs useful work) to flow through the grid. Understanding reactive power is crucial for ensuring the stability, efficiency, and reliability of power systems[1].

Reactive power is the component of alternating current (AC) power that oscillates between the source and load, rather than being consumed. It is measured in volt-amperes reactive (VAR). Unlike active power, which is measured in watts and does useful work, reactive power does not perform any real work but is essential for maintaining the voltage necessary for power transmission. It is associated with the energy stored and released by inductive (e.g., motors, transformers) and capacitive (e.g., capacitors, cables) components of the system[2].

One of the primary functions of reactive power is voltage regulation. In an electrical system, voltage levels must be maintained within specific limits to ensure the proper functioning of electrical equipment. Reactive power is key to achieving this balance. For instance, when reactive power is insufficient, voltage levels drop, potentially leading to undervoltage conditions that can harm sensitive equipment. Conversely, excess reactive power can cause overvoltage, which can also damage the system. Reactive power supports voltage at various points in the power system, enabling the effective transfer of active power from generators to consumers. Without adequate reactive power, voltage levels could fluctuate excessively, leading to system instability or even outages. Reactive power supports voltage at various points in the power system, enabling the effective transfer of active power from generators to consumers. Without

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adequate reactive power, voltage levels could fluctuate excessively, leading to system instability or even outages[3].

Reactive power is vital for system stability, especially during disturbances such as faults, sudden load changes, or the loss of a generation unit. During such events, the ability to quickly supply or absorb reactive power helps maintain system stability and prevents cascading failures that could lead to widespread blackouts. Reactive power support is especially crucial during transient conditions, where voltage levels can quickly deviate from their set points. The proper management of reactive power helps ensure that generators, transmission lines, and other components operate within safe voltage limits. This minimizes the risk of equipment damage and enhances the overall security of the power system[4].

Reactive power also affects the efficiency of power transmission. Transmission lines, transformers, and other system components experience losses when transferring power, which can be exacerbated by poor reactive power management. Excess reactive power causes additional current to flow through the system, increasing losses due to resistance in conductors. By optimizing the reactive power flow, these losses can be minimized, thereby improving the overall efficiency of power delivery. Utilities often deploy reactive power compensation devices, such as capacitors and reactors, to manage the flow of reactive power. These devices help balance the reactive power in the system, reducing losses and improving voltage profiles, which ultimately enhances the efficiency of power delivery to end users[5].

The growing integration of renewable energy sources, such as wind and solar, has increased the importance of reactive power management. Unlike conventional generators, which provide both active and reactive power, renewable sources often lack inherent reactive power capabilities. For example, solar inverters and wind turbines primarily supply active power, and additional equipment is needed to manage reactive power. Proper reactive power management helps integrate these variable renewable energy sources into the grid without compromising system stability and performance[6].

A. Power Electronics Technology and Its Role in Enhancing Power Quality in Power Systems

Power electronics technology plays a crucial role in modern power systems by improving power quality, enhancing system stability, and enabling the integration of renewable energy sources. Power quality refers to the stability and reliability of the voltage, current, and frequency in the electrical system, which is vital for the efficient operation of electrical equipment and industrial processes. Power electronics devices, such as inverters, converters, and solid-state controllers, are integral in managing and conditioning power to meet stringent quality standards[7].

Power electronics technology significantly enhances power quality by mitigating common power issues such as voltage sags, swells, harmonics, flicker, and unbalanced loads. These disturbances can lead to inefficiencies, equipment malfunction, or even damage. Power electronics devices help maintain voltage stability, reduce harmonic distortion, and ensure the reliability of power delivered to consumers[8].

Power electronics devices like static synchronous compensators (STATCOMs) and dynamic voltage restorers (DVRs) are employed in power systems to regulate and stabilize voltage levels. STATCOMs, for instance, provide fast and dynamic reactive power compensation, which helps maintain steady voltage levels even during sudden load changes or faults. DVRs can inject or absorb voltage to counteract sags and swells, ensuring that sensitive loads receive consistent power[9].

Harmonics are unwanted frequency components in the power system that can distort waveforms and cause equipment overheating, increased losses, and electromagnetic interference. Power electronics devices, such as active power filters (APFs), are designed to detect and compensate for harmonic distortions by injecting compensating currents, thus maintaining a clean and stable power waveform[10].

Poor power factor, often caused by inductive loads, results in inefficient power usage and increased losses. Power electronics technologies like synchronous condensers and static VAR compensators (SVCs) improve power factor by dynamically adjusting reactive power flow, leading to more efficient energy consumption and reduced transmission losses[11].

Power electronics technology is pivotal in enhancing power quality within modern power systems. By providing advanced control over voltage, current, and frequency, power electronics devices help mitigate common power quality issues, support the integration of renewable energy, and improve the efficiency and stability of the electrical grid. As power systems continue to evolve, the role of power electronics will only grow, driving the transition towards more reliable, efficient, and sustainable power delivery[12].

B. The Role of Flexible AC Transmission System (FACTS) Devices in Enhancing Power Quality in Power Systems

Flexible AC Transmission System (FACTS) devices are a family of power electronics-based systems designed to enhance the reliability, stability, and efficiency of power systems. FACTS devices improve power quality by dynamically controlling various electrical parameters, such as voltage, impedance, and phase angle, which are crucial for maintaining optimal power flow and ensuring a stable and high-quality power supply. Their ability to provide real-time reactive power compensation, voltage regulation, and power flow control makes them vital components in modern power systems[13].

FACTS devices contribute to overall system stability by quickly responding to disturbances and adjusting power flows to prevent cascading failures. Their ability to reduce power losses by optimizing reactive power flow and balancing loads improves the overall efficiency of power transmission. This not only enhances power quality but also reduces operational costs for utilities[14].

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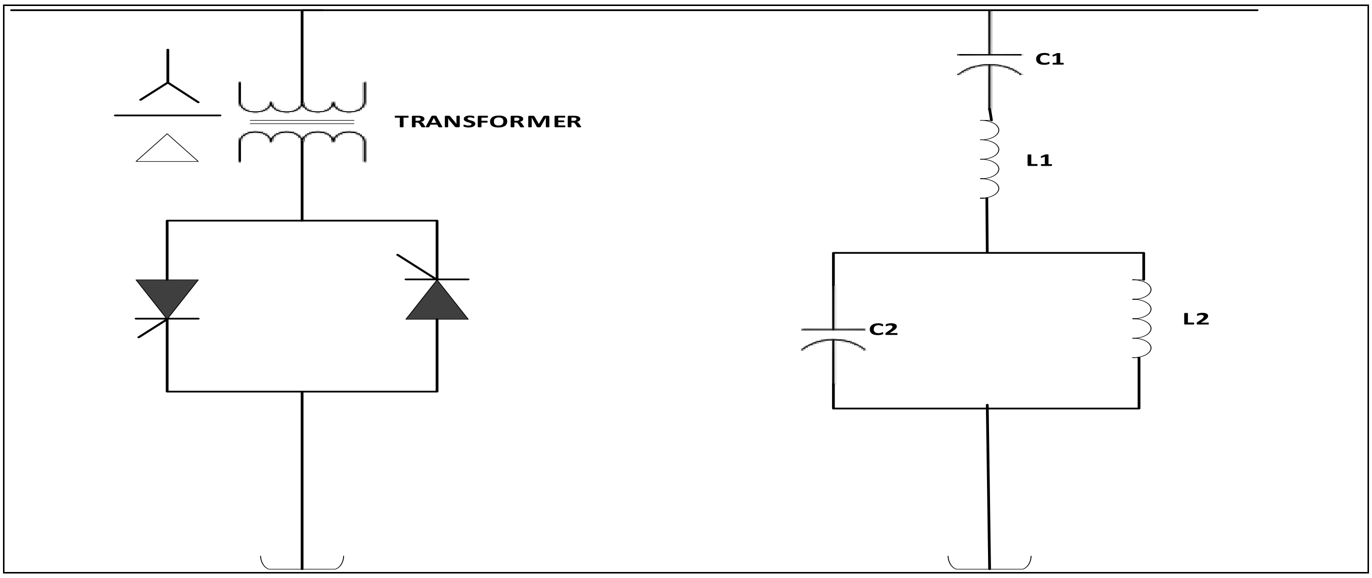

Fig 1: Schematic Diagram of FACTS Device

The increasing penetration of renewable energy sources, such as wind and solar, presents challenges related to power quality due to their intermittent nature. FACTS devices help mitigate these issues by providing grid support services, such as voltage regulation, reactive power compensation, and harmonics filtering[15].

Voltage flicker, caused by rapid changes in load, can lead to noticeable fluctuations in lighting and other sensitive equipment. FACTS devices such as SVCs can respond rapidly to these variations, compensating for the reactive power swings that cause flicker. This makes them highly effective in industrial environments where large, rapidly changing loads are common[16].

FACTS devices are indispensable tools for enhancing power quality in modern power systems. By providing dynamic control over voltage, reactive power, and power flow, these devices help maintain stable and reliable electricity supply, mitigate harmonic distortions, and support the integration of renewable energy sources. As power grids become more complex and the demand for high-quality power increases, the role of FACTS devices will continue to expand, driving improvements in power system performance and resilience[17].

II. PROPOSED FACTS DEVICE

Static Var Compensator device is a shunt active device.

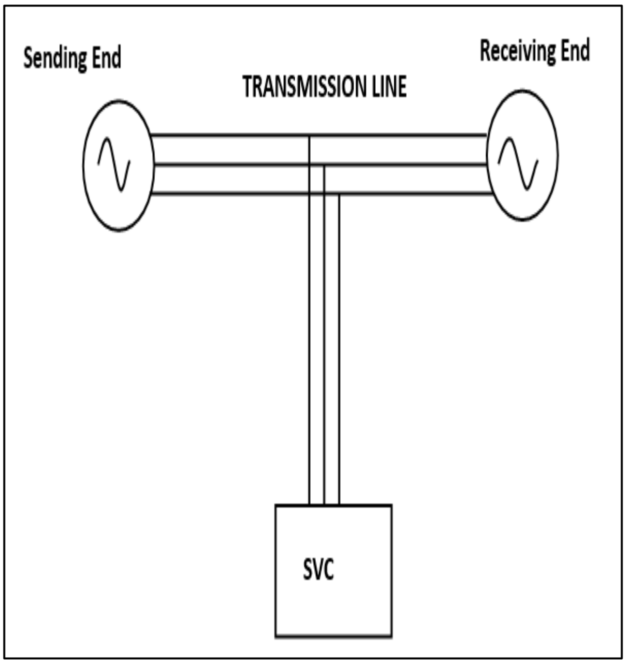

Fig 2: Block Diagram of Proposed FACTS Device

A. Construction

A **Static Var Compensator (SVC)** is a device used in power systems to provide fast-acting reactive power compensation. It helps maintain the voltage levels within desired limits by injecting or absorbing reactive power. SVCs are a part of Flexible AC Transmission Systems (FACTS) and are widely used in power transmission to improve system stability and power factor.

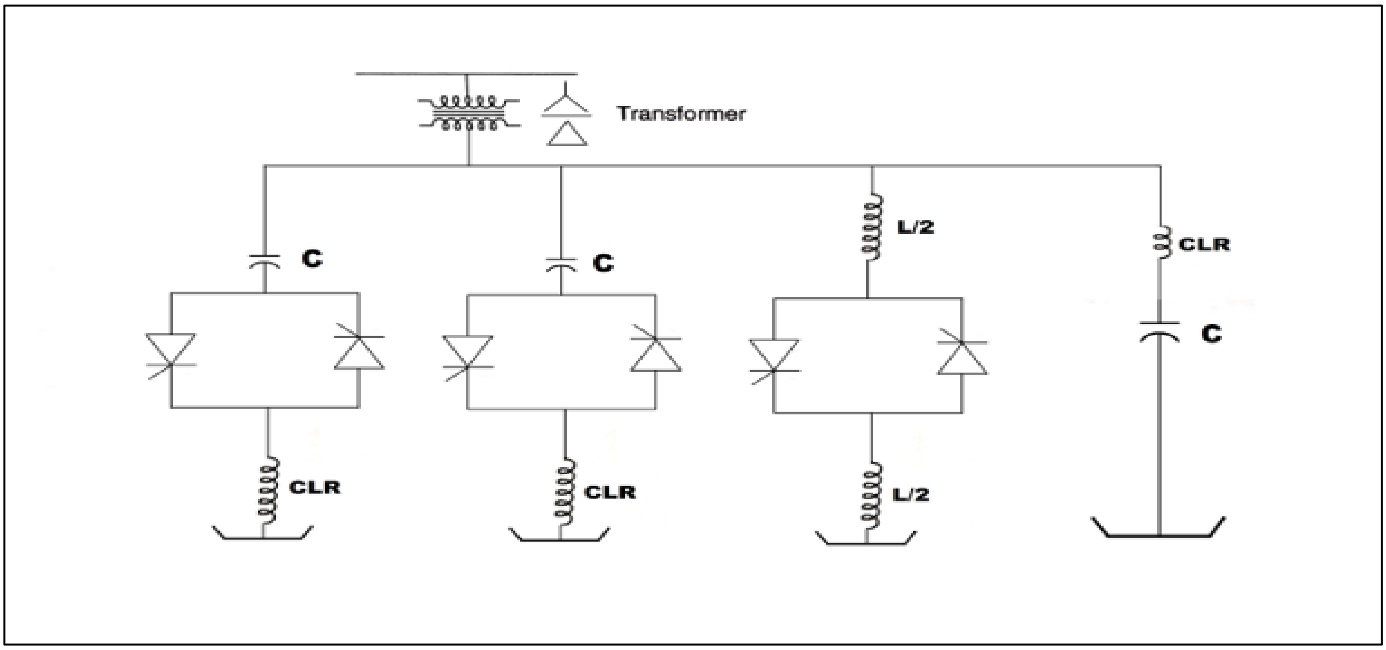

Fig 3: Schematic Diagram SVC

➢ *An SVC Typically Consists of the Following Key Components:*

- **Thyristor Controlled Reactor (TCR)**: A reactor (inductor) whose inductance is controlled by thyristors. The firing angle of the thyristors is adjusted to control the amount of reactive power absorbed by the reactor.
- **Thyristor Switched Capacitor (TSC)**: Capacitors are switched on or off by thyristors to inject reactive power into the system. TSCs are designed to provide capacitive reactive power in steps.
- **Filters**: SVC systems often include filters to mitigate the harmonic distortion produced by the switching of the thyristors. These filters help ensure that the system operates within acceptable harmonic levels.

B. Working Principle of SVC

The SVC operates by adjusting the firing angle of thyristors in the TCR and TSC components to control the amount of reactive power injected into or absorbed from the system.

- **Reactive Power Injection**: When the system voltage falls below the desired level (indicating a lagging power factor), the SVC injects reactive power by switching in the capacitors (TSCs). This helps boost the voltage.
- **Reactive Power Absorption**: When the system voltage rises above the desired level (indicating a leading power factor), the SVC absorbs reactive power by controlling the thyristor firing angle in the TCR, which increases the current through the inductors and decreases the voltage.
- **Continuous Voltage Regulation**: The SVC continuously monitors the system voltage through its control system. Depending on the voltage levels, the SVC either injects or absorbs reactive power to maintain the voltage within the desired range. It can rapidly respond to changes in system conditions, making it ideal for dynamic compensation.

C. Advantages

- **Fast and Dynamic Voltage Regulation**: SVCs provide rapid and continuous control of reactive power, which allows for real-time voltage regulation and helps stabilize power system voltage during transient disturbances.
- **Improved Power Factor**: By dynamically injecting or absorbing reactive power, SVCs help improve the power factor of the electrical network, reducing the overall reactive power flow and enhancing the efficiency of power transmission.
- **Reduced Transmission Losses**: Improved power factor and voltage regulation help reduce the reactive power flowing through transmission lines, thereby reducing power losses in the system and improving energy efficiency.
- **Enhanced System Stability**: SVCs contribute to the overall stability of the power grid by mitigating voltage fluctuations and dampening system oscillations, thus improving both transient and steady-state stability.
- **Increased Transmission Capacity**: By maintaining proper voltage levels and reducing reactive power flow, SVCs can increase the transmission capacity of existing power lines without the need for major infrastructure upgrades.
- **Enhanced System Reliability**: By providing fast and reliable reactive power compensation, SVCs improve the overall reliability and security of power supply systems.

D. Applications

- **Transmission and Distribution Systems**: SVCs are commonly used in high-voltage transmission networks to provide voltage support, improve system stability, and enhance the power-carrying capacity of transmission lines.

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- **Renewable Energy Integration**: SVCs are crucial in integrating renewable energy sources like wind and solar into the grid. These energy sources often cause voltage fluctuations due to their intermittent nature, and SVCs help stabilize the grid by providing reactive power compensation.
- **Industrial Applications**: In industries with large fluctuating loads (e.g., steel plants, rolling mills, arc furnaces, etc.), SVCs help stabilize voltage levels, improve power factor, and ensure efficient operation of the equipment.
- **Railway Electrification**: SVCs are used in railway electrification systems to stabilize the voltage and provide reactive power compensation, ensuring smooth and efficient operation of electric trains.
- **Mining and Oil & Gas Industries**: In heavy-duty industries like mining and oil & gas, SVCs are used to maintain power quality, reduce voltage drops, and stabilize large loads, improving operational reliability.
- **Flicker Mitigation**: SVCs help mitigate flicker issues caused by rapid voltage changes in power systems, particularly in industrial applications with varying loads, like arc furnaces.

III. RESULTS

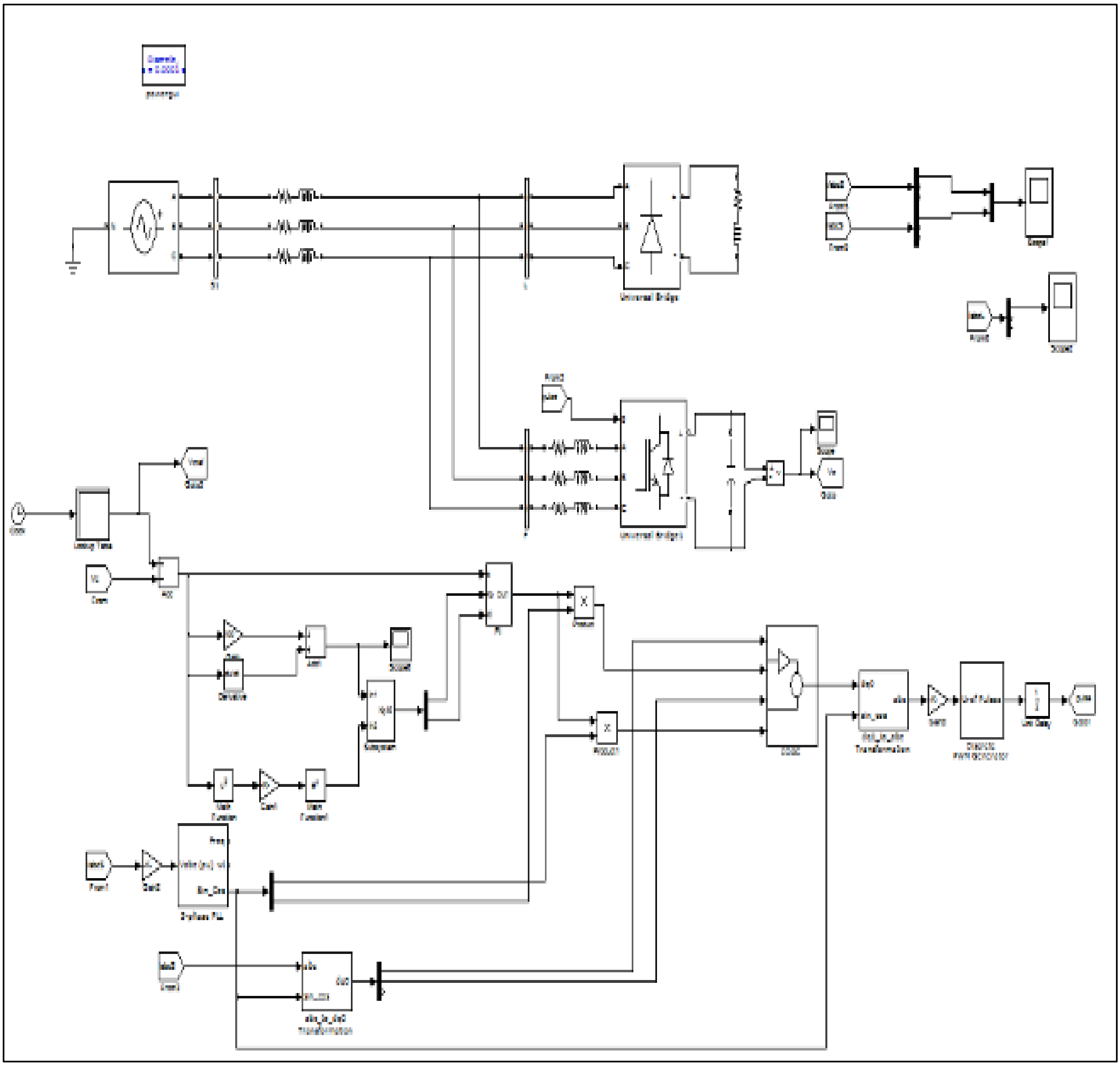

Fig 4: Simulation Diagram of Proposed Topology

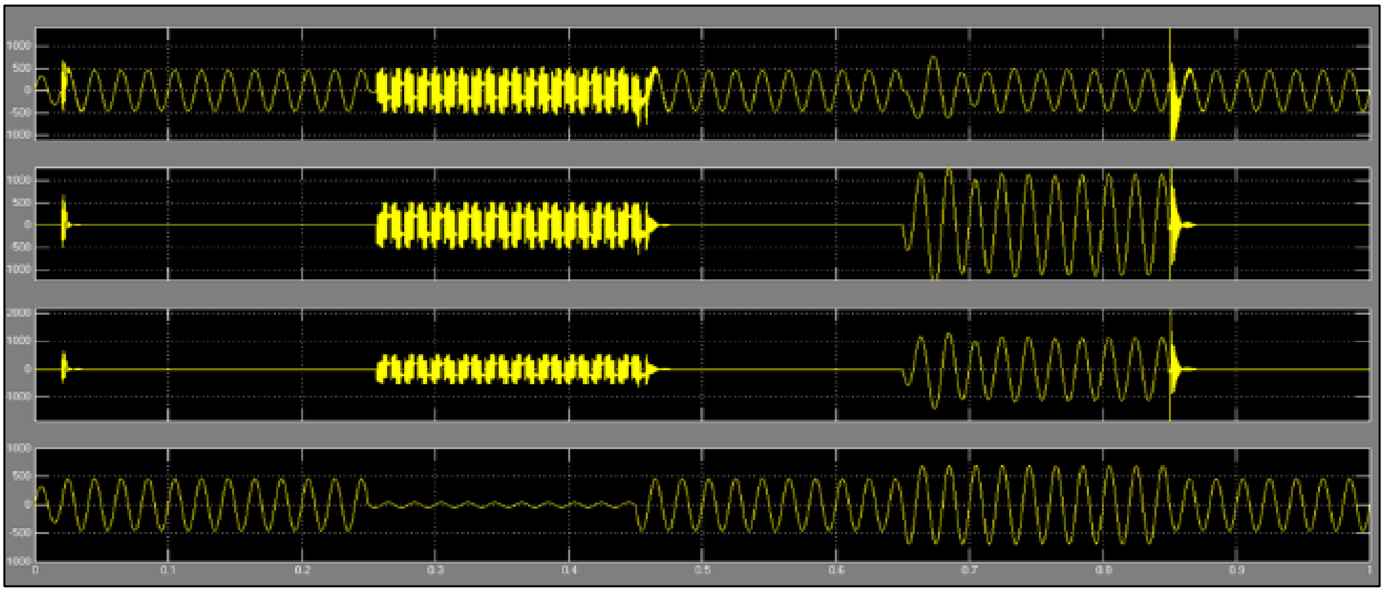

Fig 5: Simulation Results

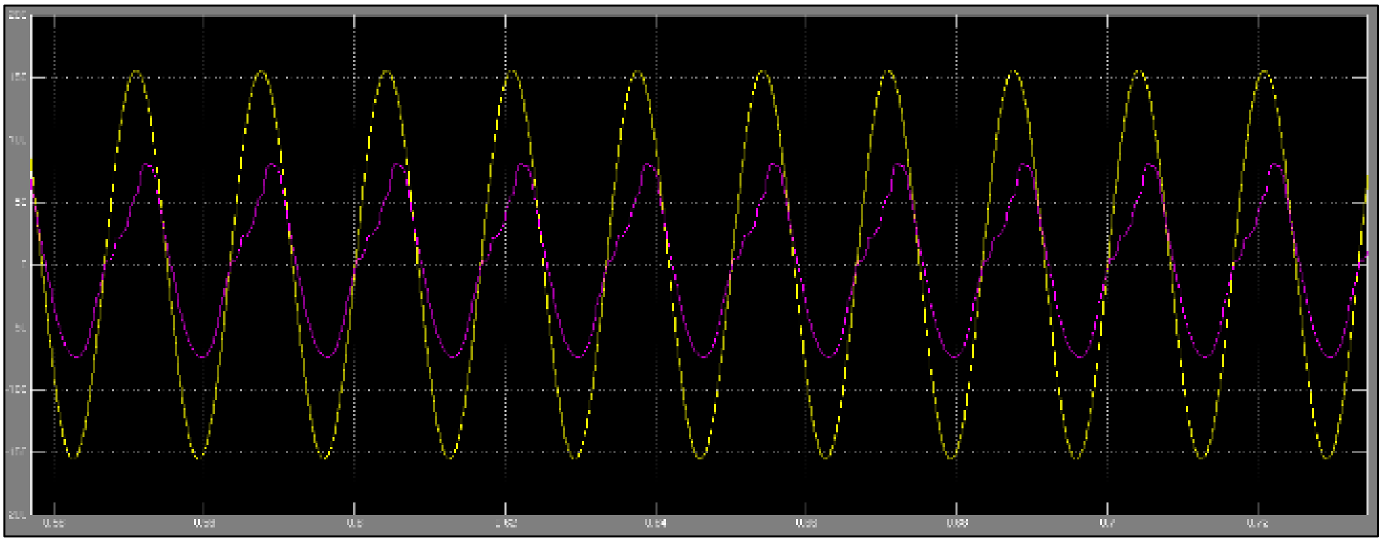

Fig 6: Simulation Results

IV. CONCLUSION

The **Static Var Compensator (SVC)** plays a vital role in modern power systems by providing fast-acting, dynamic reactive power compensation. It is a key component of Flexible AC Transmission Systems (FACTS), helping to maintain voltage stability, improve power quality, and increase the transmission capacity of existing power lines. SVCs are particularly valuable in environments where voltage fluctuations, load variations, and power factor issues affect system performance. The modular and scalable design of SVCs makes them adaptable to a wide range of applications, from high-voltage transmission networks to industrial operations with fluctuating loads. They are also critical in integrating renewable energy sources like wind and solar, which inherently cause voltage instability due to their intermittent nature. SVCs help smooth out these fluctuations, ensuring consistent power delivery to the grid.

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