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VOLTAGE STABILITY ANALYSIS AND POWER OSCILLATION DAMPING USING STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)

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ABSTRACT

This paper presents an in-depth study of voltage stability improvement as well as power oscillation damping in power systems using the Static Synchronous Series Compensator (SSSC). The SSSC is a flexible FACTS (Flexible AC Transmission Systems) device capable of improving power system stability via controlling voltage as well as damping oscillations through series compensation. We explore enough of its potential in reducing voltage instability. We explore some potential in improving the damping of power oscillations, which are important to maintaining system reliability. Through a test system simulations were done to show the performance that the SSSC has in various fault scenarios and under varied load conditions. The results do indicate that the SSSC can improve on voltage stability via regulating the transmission line voltage, and suppressing oscillations in an effective manner. Additionally, that paper discusses this integration of that SSSC with a proportional-integral (PI) controller for optimizing system stability in real-time. The simulation shows a large rise in voltage stability margins and damping traits, showing the SSSC may be a key tool for power grids.

Keywords —***Voltage stability, Power oscillation damping, Static Synchronous Series Compensator (SSSC), FACTS, Power systems, Dynamic stability, Voltage profile.***

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INTRODUCTION

The increasing demand for reliable and efficient power systems necessitates the integration of advanced technologies that ensure system stability. Among the many challenges faced by modern power grids, voltage instability and power oscillations are prominent issues that can result in equipment failure or blackouts if not properly managed. To address these challenges, Flexible AC Transmission System (FACTS) devices have emerged as a viable solution. The Static Synchronous Series Compensator (SSSC) is one such FACTS device, designed to provide series compensation by injecting or absorbing reactive power, thus controlling voltage and improving system stability. Voltage stability is critical for preventing collapse during disturbances, while power oscillations, often resulting from system imbalances, must be damped to avoid system instability. This paper focuses on the use of the SSSC to address these issues in power systems. By adjusting the active power flow and regulating transmission voltages, the SSSC can play a significant role in improving voltage stability and damping low-frequency oscillations in the grid. Through simulation studies, this paper investigates the potential of SSSC to enhance power system performance, particularly under contingency scenarios like faults or load changes. The results demonstrate the efficiency of the SSSC in improving both dynamic stability and voltage profiles, thus ensuring a more robust power grid.

Principle of SSSC

A static synchronous series compensator (SSSC) is a type of flexible AC transmission system which consists of a solid-state voltage source inverter coupled with a transformer that is connected in series with a transmission line. This device can inject an almost sinusoidal voltage in series with the line. This injected voltage could be considered as an inductive or capacitive reactance, which is connected in series with the transmission line. This feature can provide controllable voltage compensation. In addition, SSSC is able to reverse the power flow by injecting a sufficiently large series reactive compensating voltage.

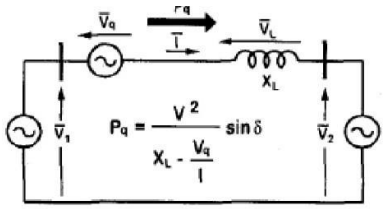


Fig (a): Principle of SSSC

The SSSC consists of a voltage source converter (VSC) connected in series with the transmission line through a transformer. The VSC, a power electronic device, converts direct current (DC) power into alternating current (AC) power, enabling the injection of the desired voltage. By controlling the magnitude and phase angle of this injected voltage, the SSSC can effectively modify the line's impedance. One of the primary functions of the SSSC is to improve power flow control. By adjusting the line impedance, the SSSC can regulate the amount of power flowing through a specific transmission line. This is particularly useful for balancing power flows between different regions of a power system or for optimizing the utilization of existing transmission infrastructure.

SYSTEM MODEL

1. Power System Model

The power system analyzed in this paper is a typical multi-machine setup based on the IEEE 14-bus test system. This system consists of synchronous generators, transmission lines, and loads. The generators are modeled using the swing equation, and the voltage at each bus is controlled by the exciter systems. The system's stability is analyzed both in steady-state and dynamic conditions. To evaluate voltage stability, the system is subjected to load variations and disturbances such as line faults or sudden load changes. The voltage stability of the system is assessed using a **Voltage Stability Margin (VSM)**, which indicates how close the system is to voltage collapse. The system's performance in handling disturbances is evaluated based on the ability of the grid to recover from transient events, with a focus on voltage profiles across the buses.

2. SSSC Model

The SSSC is modeled as a voltage-source converter that injects a controllable voltage in series with the transmission line. By adjusting the magnitude and phase of the injected voltage, the SSSC can influence both the active power flow and the voltage profile at various buses. This ability to regulate power flow is particularly

useful for mitigating voltage instability and damping oscillations. The SSSC's response is controlled by a Proportional-Integral (PI) controller that adjusts its output voltage based on real-time system measurements. The controller's tuning parameters are optimized to enhance system stability. The SSSC can be strategically placed at critical locations in the network to maximize its effect on voltage stability and damping performance.

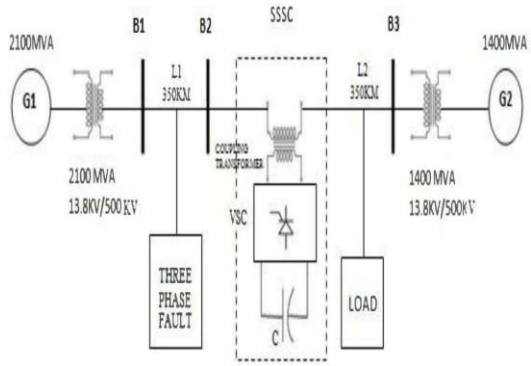


Fig (b): Block Diagram

METHODOLOGY

1. Simulation Setup

The simulation is performed using MATLAB/Simulink, where the dynamic equations governing the IEEE 14-bus system are implemented. Each generator, load, and transmission line is modelled, and the system is subjected to different operating conditions, including both normal and fault scenarios. The SSSC is added to the network, and its parameters are adjusted using a PI controller to optimize voltage stability and damping performance. The simulation includes various fault conditions such as three-phase faults, and load variations to evaluate the system's robustness with and without the SSSC. The performance of the system is assessed by monitoring the voltage profiles at key buses, the frequency of oscillations, and the system's ability to return to steady-state after disturbances.

2. Control Strategy

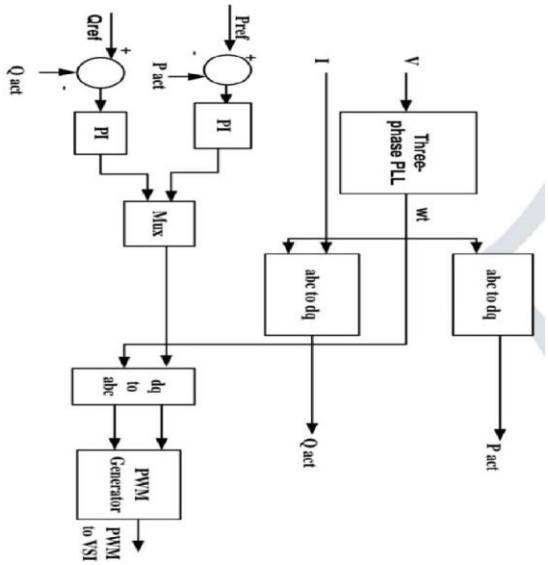


Fig (c): Control Strategy

A PI controller is implemented to manage the SSSC's voltage injection. The controller adjusts the injected voltage in real-time to minimize voltage deviations and to dampen oscillations. The proportional and integral gains of the PI controller are optimized using an iterative approach to achieve desired performance. This control strategy aims to enhance both transient and steady-state stability by reducing the system's susceptibility to voltage collapse and minimizing the amplitude of low-frequency oscillations. The optimization process includes setting the controller parameters based on system performance metrics such as the damping ratio and voltage stability margin.

The **Static Synchronous Series Compensator (SSSC)** is a type of Flexible AC Transmission System (FACTS) device used to enhance the performance and stability of power systems. The SSSC is a voltage-sourced converter (VSC)-based device that is connected in series with the transmission line to control the flow of power. The main function of the SSSC is to inject a controllable voltage in series with the transmission line to regulate the power flow and improve the system's stability.

Control Strategy of SSSC:

The control strategy of the SSSC is focused on controlling the voltage injected into the transmission line to achieve specific operational goals, such as controlling power flow, improving voltage profile, and enhancing system stability. The following are key aspects of the control strategy:

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1. **Voltage Source Converter (VSC) Control:**

The SSSC uses a Voltage Source Converter (VSC) to inject a voltage into the transmission line. The converter is controlled to produce a voltage that can vary in both magnitude and phase, depending on the requirements.

The injected voltage is in series with the transmission line, which can affect the line's impedance, thus controlling the power flow.

2. **Power Flow Control:**

By adjusting the amplitude and phase angle of the injected voltage, the SSSC can regulate the active power (P) and reactive power (Q) flowing through the transmission line.

If the injected voltage is in phase with the transmission line current, the SSSC provides reactive power compensation (shunt-like behavior), whereas if it is out of phase, it can control the active power flow (series-like behavior).

3. **Reactive Power Compensation:**

The SSSC can be used to provide or absorb reactive power, which helps in voltage regulation along the transmission line.

This reactive power compensation allows the system to maintain voltage stability, especially during periods of high demand or system disturbances.

4. **Dynamic Control:**

The control system of the SSSC typically operates with a real-time dynamic control mechanism, using feedback from the system's parameters (such as current, voltage, and power flow).

This feedback is used to adjust the output of the VSC to keep the transmission system stable and ensure that the voltage injected by the SSSC aligns with the desired values for system operation.

5. **Decoupled Control of Active and Reactive Power:**

The control of active and reactive power can be decoupled, allowing for independent regulation of the real and reactive components of the power flow.

6. **Modeling and Optimization:**

Advanced modeling and optimization techniques, such as state-space modeling or optimization-based control, may be used to achieve optimal control of the SSSC.

For example, control algorithms can be designed to minimize transmission line losses, prevent overloading of transmission lines, and improve the overall efficiency of the power system.

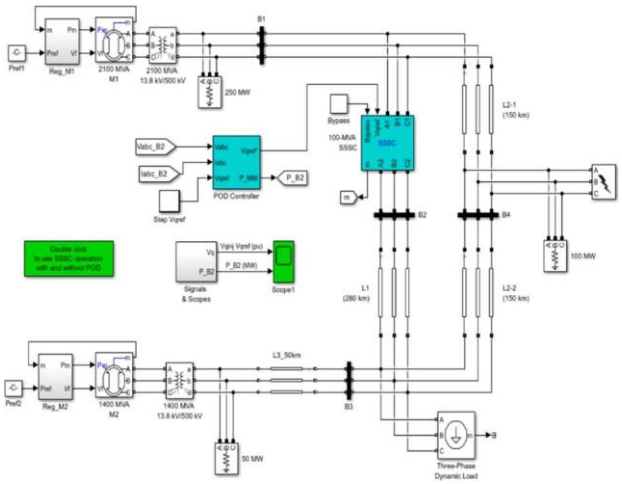


Fig (d): Simulation Circuit

RESULTS AND DISCUSSION

1. Voltage Stability Improvement

The introduction of the SSSC significantly enhances voltage stability in the simulated power system. In normal operating conditions, the voltage profiles across all buses remain within acceptable limits, even when load conditions fluctuate. Under fault scenarios, the SSSC helps to restore voltage levels to stable values more quickly compared to a system without the device. The Voltage Stability Margin (VSM) of the system increases substantially with the inclusion of the SSSC, indicating that the system is further from the voltage collapse point. These improvements suggest that the SSSC can play a vital role in maintaining voltage stability, especially in networks prone to large load variations or external disturbances.

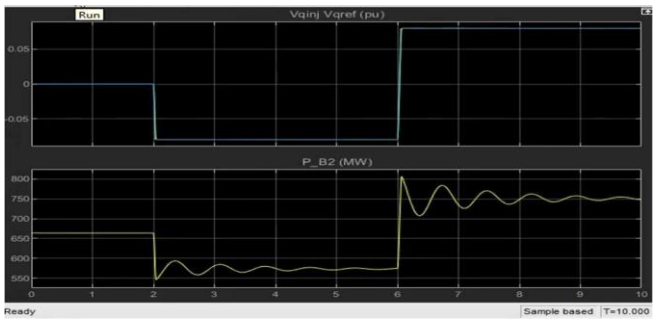


Fig (e): Output

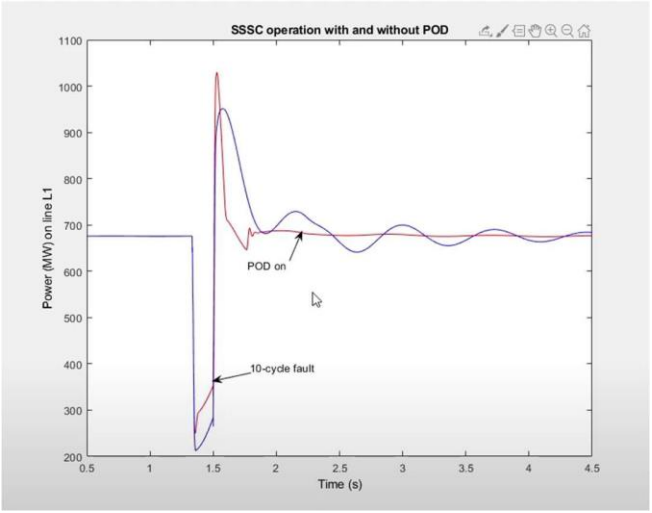


Fig (f): SSSC Operation with and without POD

2. Power Oscillation Damping

Power oscillations, which are typically caused by disturbances such as sudden faults or changes in generation, are effectively mitigated by the SSSC. The damping performance is assessed by analyzing the decay rate and frequency of oscillations following a disturbance. The results show a significant reduction in oscillation amplitude and a faster settling time in the system with the SSSC compared to systems without it. The damping ratio, which quantifies the effectiveness of the oscillation suppression, improves notably. This demonstrates that the SSSC is highly effective in enhancing the dynamic performance of the power system and ensuring that oscillations are quickly attenuated, preventing potential system instability.

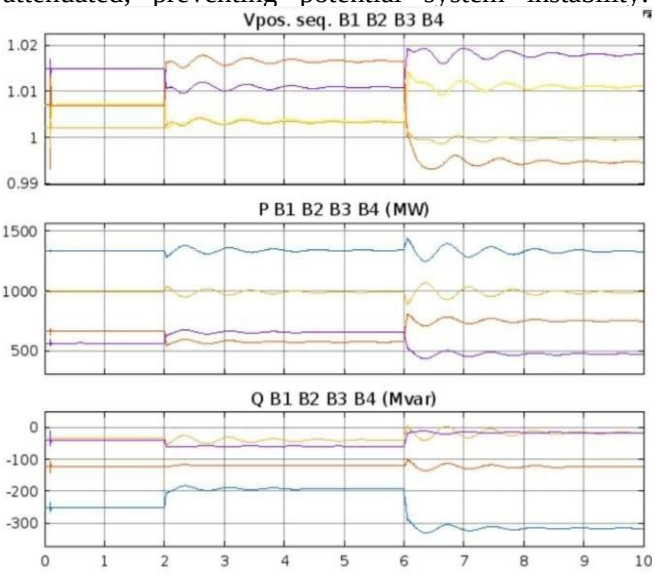


Fig (g): VPQ Waveforms

4.3. Comparative Analysis

A comparative analysis between the SSSC and other FACTS devices, such as the SVC and TCSC, reveals that while each device offers distinct benefits, the SSSC provides superior control over power flow and voltage stability in the studied scenario. The SSSC's ability to regulate both active power and voltage through series compensation makes it especially effective in systems with significant oscillatory behavior. In contrast, devices like SVC and TCSC offer limited damping capabilities and are primarily used for reactive power compensation. This comparative performance underscores the SSSC's versatility in enhancing both voltage stability and damping.

5. Conclusion

Bus no.	Voltage (kV)- R.M.S.	Current (Amp)- R.M.S.	Active power (MW)	Reactive power (MVAR)
1	446.89	848.53	920	680
2	446.89	410.12	400	400
3	431.33	397.4	251	450
4	410.12	1195	1160	910

Fig (h): With SSSC

Bus no.	Voltage (kV)- R.M.S.	Current (Amp)- R.M.S.	Active power (MW)	Reactive power (MVAR)
1	438.4	848.53	848	734
2	438.4	415.7	400	371
3	427	388.9	257	425
4	405.1	1195	1120	932

Fig (i): Without SSSC

This study demonstrates the significant advantages of using the Static Synchronous Series Compensator (SSSC) for improving voltage stability and damping power oscillations in power systems. The results from simulations on the IEEE 14-bus system confirm that the SSSC effectively enhances system stability by regulating voltage profiles and mitigating oscillations. The optimization of control strategies, such as the

implementation of a PI controller, further improves the overall performance. As the power grid continues to evolve, the SSSC can provide a valuable tool for ensuring reliability and stability, particularly in grids facing challenges from increased demand and the integration of renewable energy sources. Future research can explore the integration of multiple FACTS devices and advanced control algorithms to further enhance system performance and stability.

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