PERFORMANCE ANALYSIS OF POWER SYSTEM DYNAMICS WITH FACTS CONTROLLERS: OPTIMAL PLACEMENT AND IMPACT OF SSSC AND STATCOM

By

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ABSTRACT

This paper explores the impact of integrating Flexible AC Transmission Systems (FACTS) controllers, specifically the Static Synchronous Series Compensator (SSSC) and the Static Synchronous Compensator (STATCOM), on power system performance. The objective of this study is to evaluate how these controllers can enhance various aspects of power system operation, including voltage regulation, power flow stability, and overall system efficiency. The methodology involves simulating power systems with and without the deployment of SSSC and STATCOM and analyzing their effects on voltage profiles, power flow characteristics, and system losses. The findings reveal that both SSSC and STATCOM significantly improve voltage stability and power flow control, leading to reduced system losses and enhanced operational efficiency. This study introduces a novel approach by comparing the performance enhancements provided by SSSC and STATCOM in different operational scenarios, offering valuable insights into their effectiveness. The results underscore the potential of FACTS technology in advancing power system stability and efficiency, making a substantial contribution to the field of power system optimization.

Keywords: FACTS Controllers, SSSC, STATCOM, Power System Optimization, Voltage Regulation, Power Flow Stability, Loss Reduction, Simulation-based Analysis.

INTRODUCTION

This paper delves into the performance analysis of modern power flow control devices, specifically the Static Synchronous Series Compensator (SSSC) and Static Synchronous Compensator (STATCOM), within power systems. Utilizing standard test cases, the study aims to evaluate the efficacy of these devices in enhancing voltage stability, minimizing power losses, and improving overall system efficiency. As power systems become increasingly complex with the integration of renewable energy sources and the need for more reliable energy distribution, the role of Flexible AC Transmission System (FACTS) devices like the SSSC and STATCOM has grown in importance. These devices are known for their ability to dynamically manage power flow and voltage levels, making them crucial for maintaining system stability and reducing transmission losses. The paper provides a detailed examination of these devices, focusing on their impact on key performance metrics such as voltage magnitude, power flow, and total system losses.

The integration of FACTS controllers, such as the Static Synchronous Series Compensator (SSSC) and Static Synchronous Compensator (STATCOM), has become a pivotal area of research in improving power system performance and stability. Recent studies highlight the significant benefits of these devices in enhancing voltage regulation, power flow stability, and overall system efficiency. For instance, (Sharma et al., 2023) provide a comprehensive review of STATCOM, focusing on its modeling, control, and optimal placement. Similarly, (Haroon et al., 2020) explore various control strategies and placement techniques for FACTS devices, emphasizing their crucial role in system stabilization. Singh and Singh (2022) further analyze the effectiveness of SSSC-based controllers in improving power system transient stability, showing notable performance enhancements. The integration of FACTS devices into AC/DC hybrid systems has also garnered attention in recent research.

1. Literature Review

Ahmed et al. (2017) and Eajal et al. (2016) discuss methodologies for power flow analysis in such systems, highlighting the advantages of FACTS devices in maintaining stability and optimizing power distribution. Zadehbagheri et al. (2023) delve into the technical and economic aspects of incorporating HVDC lines with FACTS controllers, providing a detailed examination of their combined effects on system stability. Das et al. (2019) and Patil & Karajgi (2017) review optimal placement strategies for FACTS devices. Alajrash et al. (2024) address power quality, optimal placement, and stability with renewable energy penetration. Ezeonye et al. (2024) compare the effects of series and shunt FACTS devices on voltage profiles. Chirani and Karami (2024) investigate the impact of SSSC-based fuzzy logic controllers on systems connected to wind farms. These studies collectively illustrate that the optimal application of FACTS devices can significantly enhance power system operation and reliability.

2. Modelling of Static Synchronous Series Compensator

The Static Synchronous Series Compensator (SSSC) is a series-connected Flexible AC Transmission System (FACTS) device that provides dynamic compensation for voltage and power flow control.

2.1 Operating Principle of SSSC

It is indeed one of the very FACTS devices used to control the power flow through transmission lines and also the voltage at the buses in a given power system network. It is possible to control voltage stability by regulating the voltage at a bus using a Static Synchronous Series Compensator (SSSC). This device performs its operation by injecting AC voltage in series with the transmission line, which compensates for the voltage drop. As a result, the voltage magnitude at the receiving end of the transmission line changes. The minimum allowable compensation is 20%, and the maximum compensation is 80% of the line reactance. The voltage source converters of this device are connected in series with the transmission line using a coupling transformer that injects series voltage into the line. Each Voltage Source Converter (VSC) is designed using solid-state controllers or switches and an energy storage device, such as a capacitor. The voltage injected by this device is in phase opposition (90° phase shifted) to the line current. The connection of SSSC in a transmission line with impedance (ZLine) along with-it coupling transformer is shown in Figure 1.

When the voltage injected makes the current lag behind the voltage, the total reactance offered by the transmission line increases and there is a reduction in active power flow through the transmission line. This mode of operation is called inductive mode. Whereas, when the injected voltage shifts the current to a leading position, the total reactance offered will decrease, leading to an increase in active power flow. This mode of operation is called capacitive mode. The schematic diagram of the SSSC connected between buses 'i, j' is shown in Figure 2.

2.2 Power Injection Model of SSSC

Power injection modeling is one of the most promising mathematical models for incorporating FACTS controllers

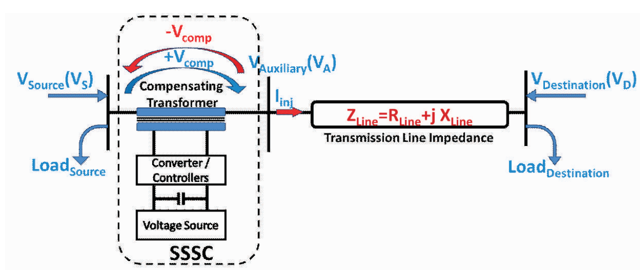

Figure 1. SSSC Connected in a Transmission Line

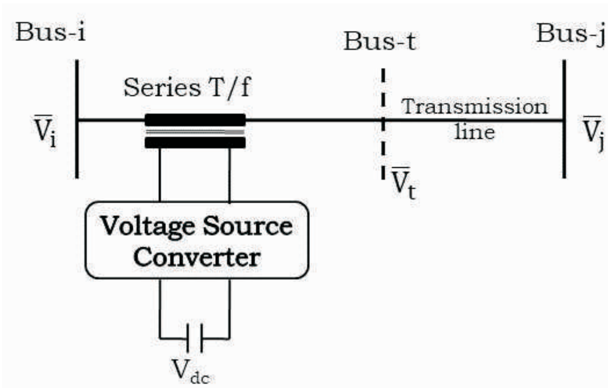

Figure 2. Schematic Representation of SSSC

into a given power system network. The SSSC is connected between two PQ buses (i and j), for which no generators or shunt capacitors are connected, and its voltages are ¯V_i and ¯V_j. Also, no transformers are connected in the device-connected transmission line. This model facilitates the incorporation procedure by simplifying it: equivalent active and reactive power is injected at the buses to which the device is connected. The controllable voltage injected by the series voltage source converter into the transmission line is ¯V_se = V_se∠ θ_se. For obtaining mathematical modeling, the coupling transformer impedance (Z_se) is considered between the sending end bus (i) and a fictitious bus (t), in series with the transmission line impedance (Z_Line) connected between the fictitious bus (t) and the receiving end bus (j). The schematic diagram of the voltage source representation of the SSSC is shown in Figure 3.

In order to obtain the power injections, the voltage source representation should be converted to current source representation using Nortons theorem. In this representation, the given voltage source in series with impedance is converter to equivalent current source "¯I_se" and in parallel with the equivalent shunt susceptance is "Bse" (where resistance/conductance of

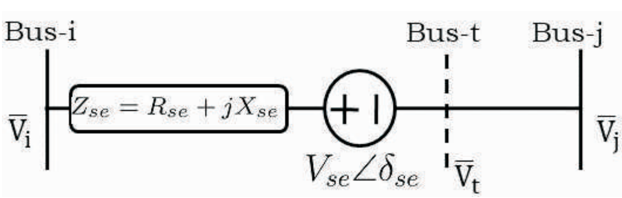

Figure 3. Voltage Source Representation of SSSC

the coupling transformer is assumed to be negligible). The current source representation of the SSSC is shown in Figure 4.

The equivalent current injected by the converter at bus- into the transmission line can be expressed as

$$\bar{I}_{se} = -jB_{se}\bar{V}_{se} \qquad (1)$$

Using this current, the complex power injected at device connected buses 'i' and 't' can be calculated as

$$\bar{S}_i^{SSSC} = P_i^{SSSC} + jQ_i^{SSSC} = \bar{V}_i(-\bar{I}_{se})^* \qquad (2)$$

Upon simplifying Eqn. (2) using Eqn. (1), we get

$$\bar{S}_i^{SSSC} = V_i < \delta_i(-jB_{se}V_{se} < -\varphi_{se}) = -jV_iV_{se}B_{se} < (\delta_i - \varphi_{se})$$
$$= -jV_iV_{se}B_{se}\cos(\delta_i - \varphi_{se}) + V_iV_{se}B_{se}\sin(\delta_i - \varphi_{se}) \qquad (3)$$

Compare Eqns (3) and (2), we get the active and reactive powers injected at bus-i can be expressed as

$$P_i^{SSSC} = V_iV_{se}B_{se}\sin(\delta_i - \varphi_{se}) \ \& \ Q_i^{SSSC} = -V_iV_{se}B_{se}\cos(\delta_i - \varphi_{se}) \qquad (4)$$

Similarly, the active and reactive powers injected at bus-t can be expressed as

$$P_t^{SSSC} = V_tV_{se}B_{se}\sin(\delta_t - \varphi_{se}) \ \& \ Q_t^{SSSC} = -V_tV_{se}B_{se}\cos(\delta_t - \varphi_{se}) \qquad (5)$$

Using these expressions, the final power injection model of SSSC is shown in Figure 5. In this model, it is necessary to balance the power injected should be balanced and made equal to zero (i.e. $Re(\bar{V}_{se}\bar{I}_{se}^*)=0$).

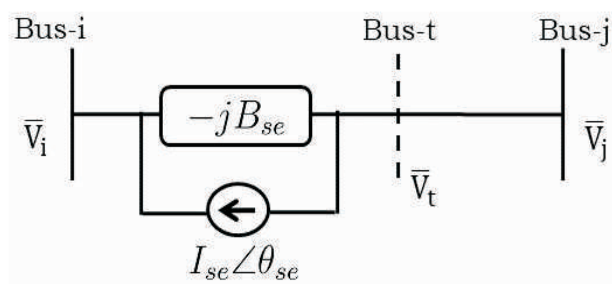

Figure 4. Current Source Representation of SSSC

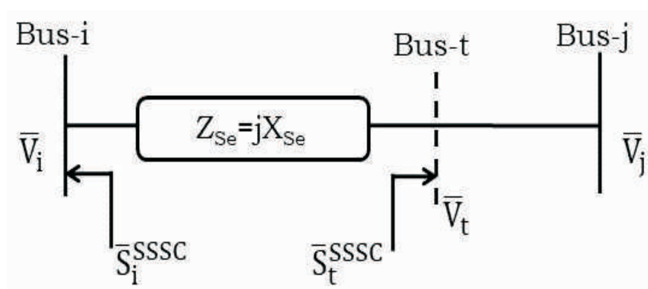

Figure 5. Final Power Injection Model of SSSC

2.3 Power Flow in the Presence of SSSC

It is necessary to evaluate the system performance in the presence of SSSC by incorporating the final power injection model into the conventional Newton Raphson load flow analysis. The power mismatches and Jacobian elements are modified in the final steady state power system network equation. This can be represented as

$$\left(\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}+\begin{bmatrix}P^{sssc}\\ Q^{sssc}\end{bmatrix}\right)=\left(\begin{bmatrix}\frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V}|V|\\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V}|V|\end{bmatrix}+\begin{bmatrix}\frac{\partial P^{sssc}}{\partial \delta} & \frac{\partial P^{sssc}}{\partial V}|V|\\ \frac{\partial Q^{sssc}}{\partial \delta} & \frac{\partial Q^{sssc}}{\partial V}|V|\end{bmatrix}\right)\begin{bmatrix}\Delta \delta\\ \frac{\Delta V}{|V|}\end{bmatrix} \quad (6)$$

Here, "ΔP, ΔQ" represents the vector of real and reactive power mismatches, "Δδ, ΔV/|V| " represents the vector of incremental changes in voltage angles and magnitudes, ∂P/∂δ, ∂Q/∂δ are the partial derivatives of active and reactive powers with respect to voltage angles, ∂P/∂V |V|, ∂Q/∂V |V| are the partial derivatives of active and reactive powers with respect to voltage magnitudes, (∂P^{SSSC})/∂δ,(∂Q^{SSSC})/∂δ are the partial derivatives of SSSC active and reactive powers with respect to voltage angles, (∂P^{SSSC})/∂V |V|,(∂Q^{SSSC})/∂V |V| are the partial derivatives of SSSC active and reactive powers with respect to voltage magnitudes.

2.4 Modifications in Power Mismatches

In order to consider the effect of SSSC in load flow solution, the power mismatches at the respective device connected buses are modified.

The active and reactive power mismatches at bus-i are modified as

$$\Delta P_i^{new}=\Delta P_i^0+P_i^{sssc}$$

$$\Delta Q_i^{new}=\Delta Q_i^0+Q_i^{sssc}$$

Similarly, at bus-t are

$$\Delta P_t^{new}=\Delta P_t^0+P_t^{sssc}$$

$$\Delta Q_t^{new}=\Delta Q_t^0+Q_t^{sssc}$$

2.5 Modifications in Jacobian Elements

In addition to power mismatches, the Jacobian elements (Partial derivatives) at the respective device connected buses needs to be modified.

Using Eqns. (4) & (5), the partial derivatives of active power with respect to voltage angle at the device connected buses are modified as

$$\frac{\partial P_p^{new}}{\partial \delta_p}=\frac{\partial P_p^0}{\partial \delta_p}+\frac{\partial P_p^{sssc}}{\partial \delta_p}=\frac{\partial P_p^0}{\partial \delta_p}-Q_p^{sssc} \qquad \forall \quad P=i,t$$

$$\frac{\partial P_p^{new}}{\partial \delta_q}=\frac{\partial P_p^0}{\partial \delta_q}+\frac{\partial P_p^{sssc}}{\partial \delta_q}=\frac{\partial P_p^0}{\partial \delta_p}+0 \quad \forall \ P=i,q=t;p=t,q=i$$

Using Eqn. (4) & (5), the partial derivatives of reactive power with respect to voltage angle at the device connected buses are modified as

$$\frac{\partial Q_p^{new}}{\partial \delta_p}=\frac{\partial Q_p^0}{\partial \delta_p}+\frac{\partial Q_p^{sssc}}{\partial \delta_p}=\frac{\partial Q_p^0}{\partial \delta_p}-P_p^{sssc} \qquad \forall \quad P=i,t$$

$$\frac{\partial Q_p^{new}}{\partial \delta_q}=\frac{\partial Q=_p^0}{\partial \delta_q}+\frac{\partial Q_p^{sssc}}{\partial \delta_q}=\frac{\partial Q_p^0}{\partial \delta_p}+0 \quad \forall \ P=i,q=t;p=t,q=i$$

Using Eqns. (4) & (5), the partial derivatives of active power with respect to voltage magnitude at the device connected buses are modified as

$$|V_p|\frac{\partial P_p^{new}}{\partial V_p}=|V_p|\frac{\partial P_p^0}{\partial V_p}+|V_p|\frac{\partial P_p^{sssc}}{\partial V_p}=|V_p|\frac{\partial P_p^0}{\partial \delta_p}+P_p^{sssc} \qquad \forall \quad P=i,t$$

$$|V_q|\frac{\partial P_p^{new}}{\partial \delta_q}=|V_q|\frac{\partial P_p^0}{\partial V_q}+|V_q|\frac{\partial P_p^{sssc}}{\partial V_q}=|V_q|\frac{\partial P_p^0}{\partial V_q}+0 \quad \forall \ P=i,q=t; \ p=t,q=i$$

Using Eqn. (4) & (5), the partial derivatives of reactive power with respect to voltage magnitude at the device connected buses are modified as

$$|V_p|\frac{\partial Q_p^{new}}{\partial V_p}=|V_p|\frac{\partial Q_p^0}{\partial V_p}+|V_p|\frac{\partial Q_p^{sssc}}{\partial V_p}=|V_p|\frac{\partial Q_p^0}{\partial \delta_p}+Q_p^{sssc} \qquad \forall \quad P=i,t$$

$$|V_q|\frac{\partial Q_p^{new}}{\partial \delta_q}=|V_q|\frac{\partial Q_p^0}{\partial V_q}+|V_q|\frac{\partial Q_p^{sssc}}{\partial V_q}=|V_q|\frac{\partial Q_p^0}{\partial V_q}+0 \quad \forall \ P=i,q=t; \ p=t,q=i$$

2.6 Overall Computational Procedure with SSSC

The following steps outline the computational procedure for applying the Newton-Raphson (NR) load flow method in the presence of a Static Synchronous Series Compensator (SSSC).

- *Data Initialization:* Gather and input the bus data, line data, and SSSC data.
- *Initial Assumptions:* Assume a flat voltage profile with all voltages set to 1.0 per unit and all angles set to 0 degrees. Set the iteration counter kkk to 0.
- *Power Mismatch Calculation:* Calculate the active and reactive power mismatches by comparing the scheduled power with the computed power at each bus.

- *Jacobian Matrix Formation:* Construct the Jacobian matrix based on the power flow equations.
- *Incorporate SSSC Effects:* Adjust the power mismatch equations and the Jacobian matrix elements for the buses connected to the SSSC to reflect the influence of the device.
- *Solve Newton-Raphson Equations:* Apply the NR method to determine the corrections for voltage magnitudes and angles.
- *Update Voltage Solution:* Use the correction vector obtained to update the voltage magnitudes and angles.
- *Iteration Update:* Increment the iteration counter kkk by 1.
- *Convergence Check:* If the maximum power mismatch is within the specified tolerance, output the results. If not, return to step 3 and repeat the process.

2.7 Optimal Location of SSSC

In order to increase the effectiveness of incorporating SSSC in a given system and to increase the performance of the system. For this, the transmission lines loading ($S_{flow,i}$) should be below its thermal limit (S^{max}_{flow}). Usually, this represents grid failures, voltage collapse conditions, etc. In order to overcome the difficulties to manage the system stability and to manage the power system disturbances due to load variations. For this, the following severity index is formulated by considering the power flows of the overloaded transmission lines under contingency conditions.

$$Severity\ Index_k = \sum_{i=1}^{N_{OL}} \left(\frac{Sflow,i}{S^{max}_{flow},i} \right)^2 \quad ; \quad K \ \forall \ N_{\text{Contingencies}} \tag{7}$$

Here, NOL is the total number of overloaded transmission lines under k^th contingency.

In this work, a Fuzzy Logic-Based Line Loading Indicator (FLLI) to identify an optimal location for installing SSSC is formulated. Table 1 shows the weight listing table for line severity indexes.

The mathematical formulation of the formulated FLLI is expressed as

S. No	Condition	Severity Index	W_{SI}
1	Low severity	Min (Severity Index$_k$)	0.25
2	Moderate severity	0.5 x Max (Severity Index$_k$)	0.50
3	High severity	0.75 x Max (Severity Index$_k$)	0.75
4	Critical severity	Max (Severity Index$_k$)	1.00

Table 1. Weight Listing Table for Line Severity Indexes

$$FLLI_k = W_{SI} \ X \sum_{i=1}^{N_{OL}} \left(\frac{Sflow,i}{S^{max}_{flow},i} \right)^2 \quad ; \quad K \ \forall \ N_{\text{Contingencies}} \tag{8}$$

After calculating the FLLI for each contingency, the line contributing the least to the highest FLLI under contingency is selected for installing an SSSC to reduce the severity of the power system. To implement this effectively and minimize the computational burden, the contingency locations are considered based on the following conditions:

- The transmission line connected with tap changing transformer is not connected.
- The transmission line connected between buses which are connected with shunt capacitors and generators is also not considered.

3. Modelling of Static Synchronous Compensator

The Static Synchronous Compensator (STATCOM) is a shunt-connected Flexible AC Transmission System (FACTS) device that provides dynamic voltage support and reactive power compensation.

3.1 Operating Principle of STATCOM

It is necessary to regulate the voltage magnitude and improving the transient stability in a given power system by installing shunt compensators. The most commonly used shunt controller is Static Synchronous Compensator (STATCOM) to control the voltage magnitude at the bus which lacks the support of reactive power. The low voltage problem in a system is due to the sudden change of power consumption by the load. To maintain voltage stability and to maximize the security, it is necessary to incorporate this device in a given power system. The connection of STATCOM with a voltage source of "VDC" at bus-i is shown in Figure 6.

This device provides accurate reactive power

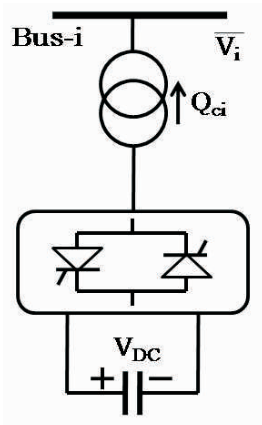

Figure 6. STATCOM Connected at Bus-i

compensation by operating the connected voltage source converter. When the device injects reactive power into the system, increasing the voltage magnitude, it is considered to be in capacitive mode of operation. Conversely, when the device absorbs reactive power from the system, decreasing the voltage magnitude, it is considered to be in inductive mode of operation.

3.2 Power Injection Model of STATCOM

This device is connected at a bus for which no generators and shunt capacitors are connected. Here, the device is connected at bus-i with voltage magnitude $\bar{V}_i$. This model facilitates the simple procure of injective active and reactive power into the system from the connected bus based on the control mode of operation. The controllable voltage injected by the shunt voltage source converter at bus-i is $\bar{V}_i = V_i \angle \theta_i$. For obtaining mathematical modeling, the coupling transformer impedance is Z_{si} is considered at bus-i. The schematic diagram of the voltage source representation of STATCOM is shown in Figure 7.

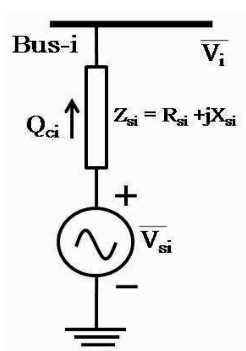

Figure 7. Voltage Source Representation of STATCOM

In order to obtain the power injections, the voltage source representation should be converted to current source representation using Nortons theorem. In this representation, the given voltage source in series with impedance is converter to equivalent current source "$\bar{I}_{si}$" and in parallel with the equivalent shunt susceptance is "B_{si}" (where resistance/conductance of the coupling transformer is assumed to be negligible). The current source representation of the STATCOM is shown in Figure 8.

The equivalent current injected by the converter at bus-i can be expressed as

$$\bar{I}_{si} = -jB_{si}\bar{V}_{si} \quad (9)$$

Using this current, the complex power injected at device connected bus 'i' can be calculated as

$$\bar{S}_i^{STATCOM} = P_i^{STATCOM} + jQ_i^{STATCOM} = \bar{V}_i(-\bar{I}_{si})^* \quad (10)$$

Upon simplifying Eqn. (9) using Eqn. (10), we get

$$\bar{S}_i^{STATCOM} = V_i < \delta_i(-jB_{si}V_{si} < -\varphi_{si}) = -jV_iV_{si}B_{si} < (\delta_i - \varphi_{si})$$
$$= -jV_iV_{si}B_{si}\cos(\delta_i - \varphi_{si}) + V_iV_{si}B_{si}\sin(\delta_i - \varphi_{si}) \quad (11)$$

Compare Eqns (11) and (10), we get the active and reactive powers injected at bus-i can be expressed as

$$P_i^{STATCOM} = V_iV_{si}B_{si}\sin(\delta_i - \varphi_{si}) \;\&\; Q_i^{STATCOM} = -V_iV_{si}B_{si}\cos(\delta_i - \varphi_{si}) \quad (12)$$

Using these expressions, the final power injection model of STATCOM is shown in Figure 9. In this model, it is necessary to balance the power injected should be balanced and made equal to zero (i.e. $Re(\bar{V}_{si}\bar{I}_{si}^*) = 0$).

3.3 Power Flow in the Presence of STATCOM

It is necessary to evaluate the system performance in the presence of STATCOM by incorporating the final power injection model into the conventional Newton Raphson load flow analysis. The power mismatches and Jacobian

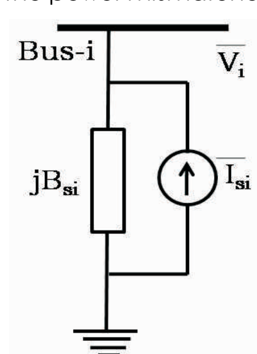

Figure 8. Current Source Representation of STATCOM

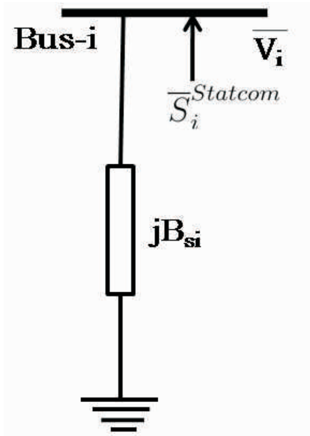

Figure 9. Final Power Injection Model of STATCOM

elements are modified in the final steady state power system network equation. This can be represented as

$$\left(\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}+\begin{bmatrix}P^{\text{STATCOM}}\\ Q^{\text{STATCOM}}\end{bmatrix}\right)=\left(\begin{bmatrix}\frac{\partial P}{\partial\delta} & \frac{\partial P}{\partial V}|V|\\ \frac{\partial Q}{\partial\delta} & \frac{\partial Q}{\partial V}|V|\end{bmatrix}+\begin{bmatrix}\frac{\partial P^{\text{STATCOM}}}{\partial\delta} & \frac{\partial P^{\text{STATCOM}}}{\partial V}|V|\\ \frac{\partial Q^{\text{STATCOM}}}{\partial\delta} & \frac{\partial Q^{\text{STATCOM}}}{\partial V}|V|\end{bmatrix}\right)\begin{bmatrix}\Delta\delta\\ \frac{\Delta V}{|V|}\end{bmatrix} \quad (13)$$

Here, "ΔP, ΔQ" represents the vector of real and reactive power mismatches, "$\Delta\delta$,$\Delta V/|V|$ " represents the vector of incremental changes in voltage angles and magnitudes, $\partial P/\partial\delta$, $\partial Q/\partial\delta$ are the partial derivatives of active and reactive powers with respect to voltage angles, $\partial P/\partial V\,|V|$, $\partial Q/\partial V\,|V|$ are the partial derivatives of active and reactive powers with respect to voltage magnitudes, $(\partial P^{STATCOM})/\partial\delta$,$(\partial Q^{STATCOM})/\partial\delta$ are the partial derivatives of STATCOM active and reactive powers with respect to voltage angles, $(\partial P^{STATCOM})/\partial V\,|V|$,$(\partial Q^{STATCOM})/\partial V\,|V|$ are the partial derivatives of STATCOM active and reactive powers with respect to voltage magnitudes.

3.4 Modifications in Power Mismatches

In order to consider the effect of STATCOM in load flow solution, the power mismatches at the respective device connected buses are modified.

The active and reactive power mismatches at bus-i are modified as

$$\Delta P_i^{new}=\Delta P_i^0+P_i^{\text{STATCOM}}$$

$$\Delta Q_i^{new}=\Delta Q_i^0+Q_i^{\text{STATCOM}}$$

3.5 Modifications in Jacobian Elements

In addition to power mismatches, the Jacobian elements (Partial derivatives) at the respective device connected buses needs to be modified.

Using Eqn. (12), the partial derivatives of active power with respect to voltage angle at the device connected bus is modified as

$$\frac{\partial P_p^{new}}{\partial\delta_p}=\frac{\partial P_p^0}{\partial\delta_p}+\frac{\partial P_p^{\text{STATCOM}}}{\partial\delta_p}=\frac{\partial P_p^0}{\partial\delta_p}-Q_p^{\text{STATCOM}} \qquad \forall \quad P=i$$

Using Eqn. (12), the partial derivatives of reactive power with respect to voltage angle at the device connected bus is modified as

$$\frac{\partial Q_p^{new}}{\partial\delta_p}=\frac{\partial Q_p^0}{\partial\delta_p}+\frac{\partial Q_p^{\text{STATCOM}}}{\partial\delta_p}=\frac{\partial Q_p^0}{\partial\delta_p}-P_p^{\text{STATCOM}} \qquad \forall \quad P=i$$

Using Eqn. (12), the partial derivatives of active power with respect to voltage magnitude at the device connected bus is modified as

$$|V_p|\frac{\partial P_p^{new}}{\partial V_p}=|V_p|\frac{\partial P_p^0}{\partial V_p}+|V_p|\frac{\partial P_p^{\text{STATCOM}}}{\partial V_p}=|V_p|\frac{\partial P_p^0}{\partial\delta_p}+P_p^{\text{STATCOM}} \qquad \forall \quad P=i$$

Using Eqn. (12), the partial derivatives of reactive power with respect to voltage magnitude at the device connected bus is modified as

$$|V_p|\frac{\partial Q_p^{new}}{\partial V_p}=|V_p|\frac{\partial Q_p^0}{\partial V_p}+|V_p|\frac{\partial Q_p^{\text{STATCOM}}}{\partial V_p}=|V_p|\frac{\partial Q_p^0}{\partial\delta_p}+Q_p^{\text{STATCOM}} \qquad \forall \quad P=i$$

3.6 Overall Computational Procedure with STATCOM

The following steps outline the computational procedure for applying the Newton-Raphson (NR) load flow method in the presence of a Static Synchronous Compensator (STATCOM).

- *Data Initialization:* Gather and input the bus data, line data, and STATCOM data.
- *Initial Assumptions:* Assume a flat voltage profile with all voltages set to 1.0 per unit and all angles set to 0 degrees. Set the iteration counter kkk to 0.
- *Power Mismatch Calculation:* Calculate the active and reactive power mismatches by comparing the scheduled power with the computed power at each bus.
- *Jacobian Matrix Formation:* Construct the Jacobian matrix based on the power flow equations.
- *Incorporate STATCOM Effects:* Adjust the power mismatch equations and the Jacobian matrix

elements for the buses connected to the STATCOM to reflect the influence of the device.

- *Solve Newton-Raphson Equations:* Apply the NR method to determine the corrections for voltage magnitudes and angles.
- *Update Voltage Solution:* Use the correction vector obtained to update the voltage magnitudes and angles.
- *Iteration Update:* Increment the iteration counter kkk by 1.

3.7 Optimal Location of STATCOM

In order to increase the effectiveness of incorporating STATCOM in a given system and to increase the performance of the system. For this, the bus voltage (V_i) should be nearer to nominal voltage (V_i^{nom}). For this, the following severity index is formulated by considering the voltage magnitudes of the violated buses under contingency conditions.

$$Severity\ Index_k = \sum_{i=1}^{N_{VB}} \left(\frac{V_i - V_i^{nom}}{V_i^{nom}} \right)^2 \quad ; \quad K \ \forall \ N_{\text{Contingencies}} \tag{14}$$

Here, NVB is the total number of voltage violated buses under k^{th} contingency.

In this work, a Fuzzy Logic-Based Voltage Violated bus indicator (FVVI) to identify an optimal location for installing STATCOM is formulated. Table 2 shows the weight listing table for bus voltage violation indexes.

The mathematical formulation of the formulated FVVI is expressed as

$$FVVI_k = W_{SI}\ X \sum_{i=1}^{N_{VB}} \left(\frac{V_i - V_i^{nom}}{V_i^{nom}} \right)^2 \quad ; \quad K \ \forall \ N_{\text{Contingencies}} \tag{15}$$

After calculating FVVI for every contingency, the bus which is contributing less for the highest FVVI under contingency is considered for installing STATCOM in order to decrease the severity of the power system. For effective implementation and to minimize the computational burden on the system, the contingency locations are considered with the following conditions.

- The buses connected line having connection with tap changing transformer are not connected.
- The buses which are connected

S. No	Condition	Severity Index	W_{SI}
1	Low severity	Min (Severity $Index_k$)	0.25
2	Moderate severity	0.5 x Max (Severity $Index_k$)	0.50
3	High severity	0.75 x Max (Severity $Index_k$)	0.75
4	Critical severity	Max (Severity $Index_k$)	1.00

Table 2. Weight Listing Table for Bus Voltage Violation Indexes

4. Implementation Methodology

To analyze the impact of both Static Synchronous Series Compensator (SSSC) and Static Synchronous Compensator (STATCOM) in an AC-DC load flow analysis (ADahane & Sharma, 2024), a comprehensive methodology needs to be followed.

4.1 Step 1: Data Acquisition

Bus Data : Gather information about all buses, including voltage magnitudes, phase angles, active and reactive power loads, and generation capacities.

Line Data : Collect data on transmission lines, such as impedance, admittance, line charging, and thermal limits.

SSSC and STATCOM Data : Obtain parameters specific to SSSC and STATCOM, including their locations, voltage limits, and control settings.

DC System Data : Acquire data on the DC system, such as converter ratings, DC voltages, and DC power flows.

4.2 Step 2: Initialization

Initial Conditions : Assume initial voltage profiles (flat start) with all voltage magnitudes set to 1.0 per unit and phase angles to 0 degrees.

Set initial DC voltages and power flows.

Set the iteration counter k=0k = 0k=0.

Initial Power Flow Solution : Perform an initial AC load flow analysis without considering the SSSC and STATCOM to establish a baseline solution.

4.3 Step 3: Incorporate SSSC and STATCOM Models

SSSC Modeling

Series Voltage Injection

Model the SSSC as a controllable voltage source in series with the transmission line, injecting a voltage VSSSC with controllable magnitude and phase angle.

Power Injection Model (PIM) : Derive the equivalent power injections at the SSSC-connected buses and modify the power flow equations accordingly.

STATCOM Modeling

Shunt Reactive Power Injection

Model the STATCOM as a controllable reactive power source at the bus to which it is connected.

Reactive Power Control : Adjust the bus reactive power injection to reflect the STATCOM's contribution.

4.4 Step 4: Incorporate AC-DC Load Flow Interaction

DC Converter Modeling : Model the AC-DC converters, including their operating characteristics and interaction with the AC system.

AC-DC Power Flow Equations : Integrate the DC power flow equations with the AC load flow equations, ensuring proper coupling between AC and DC systems.

4.5 Step 5: Iterative Solution Using Newton-Raphson Method

Power Mismatch Calculation : Compute the active and reactive power mismatches for all buses, including the effects of SSSC, STATCOM, and AC-DC interactions.

Jacobian Matrix Formation : Construct the Jacobian matrix based on the combined AC-DC power flow equations.

Modify Jacobian for SSSC and STATCOM : Update the Jacobian matrix to reflect the power injections and voltage corrections due to SSSC and STATCOM.

Solve Linearized Equations : Solve the linearized power flow equations to find the voltage magnitude and angle corrections for the AC system, as well as the DC voltage and power corrections.

Update Solution : Use the correction vectors to update the voltage magnitudes, phase angles, and DC voltages/power flows.

Iteration Update : Increment the iteration counter $k=k+1k = k+1k=k+1$.

Convergence Check : Check if the maximum power mismatch is below the specified tolerance. If not, return to Step 5. Otherwise, proceed to the next step.

4.6 Step 6: Output Results

Final Solution : Output the final bus voltages, phase angles, power flows in the AC system, and DC voltages and power flows.

Performance Analysis : Analyze the impact of SSSC and STATCOM on voltage profiles, reactive power distribution, and overall system stability.

5. Results and Analysis

In order to analyze the impact of power electronic based converters on the power system performance in terms of voltage magnitude at buses, power flow through the transmission lines and total power losses in a given system. To do this, in this work SSSC and STATCOM FACTS controllers are considered. By following the detailed modeling presented for these controllers, these devices are incorporated in the given system. The entire work is divided into two cases explained as follows:

- *Case-1:* Identifying optimal location for these devices in a given system. For this, the procedure explained in sections 2 and 3 are implemented.
- *Case-2:* Analyzing the impact of these FACTS controller effect on load flow and line flow results when compared to base case condition.

5.1 IEEE-14 Bus System

For this system, the possible installation locations for SSSC and STATCOM are identified and shown in Table 3. From this table, it is noted that the contingency line-9, connected between buses 4 and 9, has the highest FLLI value. The line contributing the least to this highest value is line-7, connected between buses 4 and 5, which is considered for installing the SSSC. Similarly, the FVVI value is high for the contingency line-8, connected between buses 4 and 7. At this contingency, the bus contributing the least to the highest FVVI is bus-5. Hence, it is considered for installing the STATCOM. Further analysis is performed by installing these FACTS controllers at these locations.

After this, the optimal location for the HVDC link is determined by placing the HVDC link at each possible device installation location one at a time and evaluating the total power losses. The results are shown in Table 4.

Location No	Contingency			FLLI value	FVVI value
	Line no	From bus	To bus		
1	7	4	5	290.38	7.384
2	8	4	7	227.11	9.728
3	9	4	9	312.27	8.839
4	15	7	9	293.23	9.334
5	16	9	10	301.28	9.102
6	17	9	14	287.58	8.495
7	18	10	11	295.39	9.002
8	19	12	13	288.57	8.467
9	20	13	14	290.54	7.574

Table 3. Calculated FLLI and FVVI Values of IEEE-14 Bus System

From this table, it is identified that the line-19, which connects buses 12 and 13, has the highest power losses. By installing the HVDC link on this line and varying the converter control parameters, it is possible to reduce the power losses. Further analysis is conducted by installing the HVDC link on this line.

In order to study the impact of installing SSSC in line-7 (4-5) and STATCOM at bus-5 along with HVDC link in line-19 (12-13). Variation of voltage magnitude by varying the device control parameters with SSSC and STATCOM for the following cases are shown in Figures 10 and 11.

- *For SSSC*: Varying Vse from 0 p.u. to 0.1 p.u. in steps of 0.025 p.u & θse from 00 to 3600 in steps of 450.
- *For STATCOM:* Varying Vsi from 0 p.u. to 0.1 p.u. in steps of 0.025 p.u & θsi from 00 to 3600 in steps of 450.

It is identified that significant voltage magnitude variations can be achieved by varying device control parameters. Voltage magnitude variations are notably high at the device-connected buses (4 and 5 with SSSC, and 5 with STATCOM). It has been proven that system performance can be controlled by adjusting the device control parameters.

Location No	HVDC link installed line			TPL (kW)
	No	From bus	To bus	
1	7	4	5	12.6331
2	8	4	7	13.8800
3	9	4	9	12.8231
4	15	7	9	10.2209
5	16	9	10	10.1136
6	17	9	14	13.1554
7	18	10	11	13.1296
8	19	12	13	15.8310
9	20	13	14	13.9861

Table 4. TPL Values in Different Possible Locations of IEEE-14 Bus System

Table 5 shows the impact of varying control parameters on voltage magnitudes using both the Static Synchronous Series Compensator (SSSC) and the Static Synchronous Compensator (STATCOM). The voltage magnitudes (Vmin, Vmax) show slight variations across the buses when SSSC and STATCOM are applied, with STATCOM generally resulting in a more stable voltage profile. For instance, at Bus 4, the voltage difference (Vdiff) with SSSC is significantly higher at 0.078 p.u., compared to 0.03 p.u. with STATCOM, indicating better voltage stability with STATCOM. Similarly, Bus 5 shows a greater voltage difference with SSSC at 0.064 p.u., compared to 0.047 p.u. with STATCOM. The convergence of voltage angles (θ), particularly with STATCOM, demonstrates improved control over reactive power, enhancing overall power quality. These observations suggest that STATCOM provides more effective voltage regulation and stability across the system, particularly in scenarios involving significant reactive power variations.

Variation of power flow by varying the device control parameters with SSSC and STATCOM for the previously given cases are shown in Figures 12 and 13. From these figures, it is identified that significant power flow variations can be obtained by varying device control parameters. Power flow variations are very high in Line 7 with SSSC, and

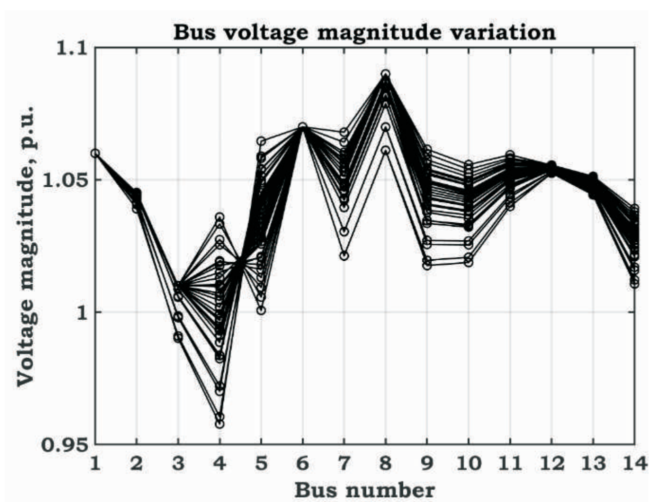

Figure 10. Variation of Voltage Magnitude by Varying SSSC Control Parameters of IEEE-14 Bus System

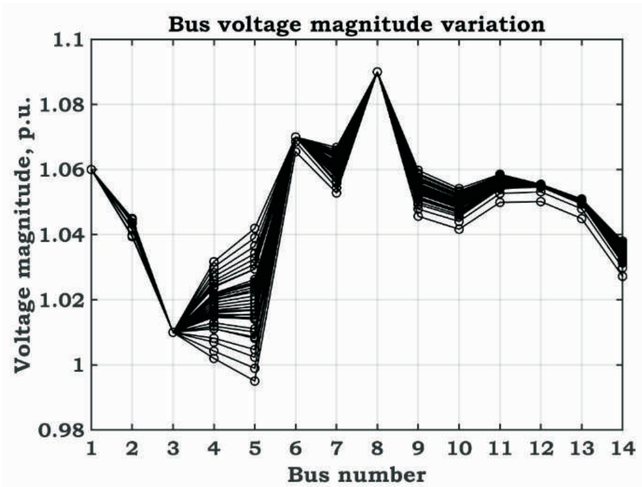

Figure 11. Variation of Voltage Magnitude by Varying STATCOM Control Parameters of IEEE-14 Bus System

in Lines 7 and 4 with STATCOM. It has been proven that the system performance can be controlled by varying the device control parameters.

Table 6 shows that the power flow differences (Sdiff) indicate significant changes in MVA levels across several lines. For example, Line 1 shows a notable power flow difference of 31.819 MVA with SSSC, while STATCOM results in a higher difference of 68.522 MVA, illustrating the more dynamic control offered by STATCOM. Lines 2, 5, and 7 also show considerable differences, with STATCOM consistently yielding higher power flow differences, indicating its superior ability to handle power variations across the network. However, some lines, such as Line 9 and Line 19, exhibit minimal differences in power flow between SSSC and STATCOM, suggesting that for certain lines, the impact of these compensators might be less pronounced. Overall, STATCOM appears to provide more robust control over power flows, particularly in lines with higher initial flows, highlighting its effectiveness in enhancing the stability and reliability of the power system.

Variation in power loss by varying the device control parameters with SSSC and STATCOM for the previously given cases are shown in Figures 14 and 15. From these figures, it is evident that significant power loss variations can be obtained by varying device control parameters.

Table 7 shows the Total Power Losses (TPL) when using the

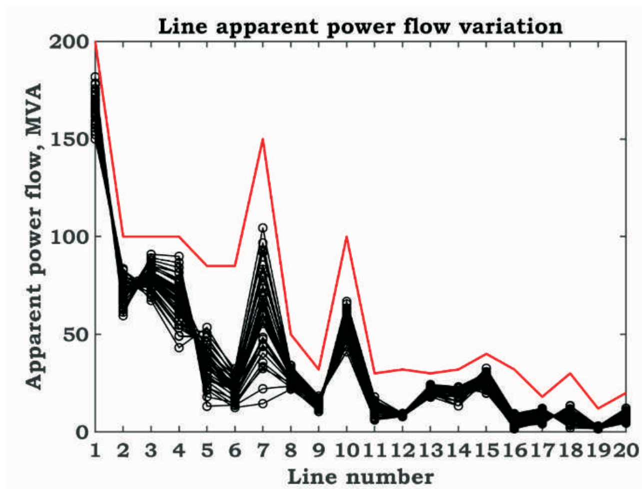

Figure 12. Variation of Power Flow by Varying SSSC Control Parameters of IEEE-14 Bus System

	With SSSC							With STATCOM						
Bus No	V_{min} (p.u.)	Vse (p.u.)	θse (deg)	V_{max} (p.u.)	Vse (p.u.)	θse (deg)	V_{diff} (p.u.)	V_{min} (p.u.)	Vsi (p.u.)	θsi (deg)	V_{max} (p.u.)	Vsi (p.u.)	θsi (deg)	V_{diff} (p.u.)
1	1.06	0	0	1.06	0	0	0	1.06	0	0	1.06	0	0	0
2	1.039	0.1	270	1.045	0.075	0	0.006	1.039	0.1	225	1.045	0	0	0.006
3	0.99	0.1	225	1.01	0	0	0.02	1.01	0	0	1.01	0	0	0
4	0.958	0.1	225	1.036	0.1	45	0.078	1.002	0.1	180	1.032	0.1	0	0.03
5	1.001	0.1	45	1.065	0.1	225	0.064	0.995	0.1	180	1.042	0.1	0	0.047
6	1.07	0	0	1.07	0	0	0	1.065	0.1	180	1.07	0	0	0.005
7	1.021	0.1	270	1.068	0.1	90	0.047	1.053	0.1	180	1.067	0.1	0	0.014
8	1.061	0.1	270	1.09	0	0	0.029	1.09	0	0	1.09	0	0	0
9	1.018	0.1	270	1.062	0.1	90	0.044	1.046	0.1	180	1.06	0.1	0	0.014
10	1.019	0.1	270	1.056	0.1	90	0.037	1.042	0.1	180	1.054	0.1	0	0.012
11	1.04	0.1	270	1.059	0.1	90	0.019	1.05	0.1	180	1.059	0.1	0	0.009
12	1.053	0.1	225	1.056	0.1	45	0.003	1.05	0.1	180	1.055	0.1	0	0.005
13	1.044	0.1	270	1.051	0.1	90	0.007	1.045	0.1	180	1.051	0.1	0	0.006
14	1.011	0.1	270	1.039	0.1	90	0.028	1.027	0.1	180	1.038	0.1	0	0.011

Table 5. Voltage Magnitudes with SSSC and STATCOM by Varying Control Parameters of IEEE-14 Bus System

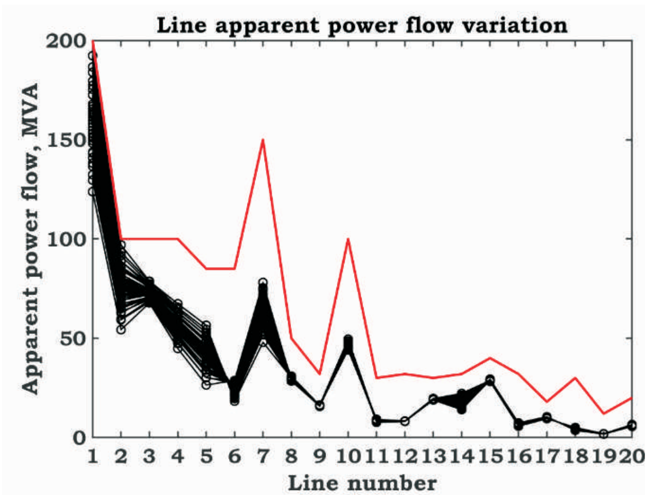

Figure 13. Variation of Power Flow by Varying STATCOM Control Parameters of IEEE-14 Bus System

Static Synchronous Series Compensator (SSSC) and the Static Synchronous Compensator (STATCOM) under varying control parameters. The Power Loss Differences (TPLdiff) between the minimum and maximum values reveal the impact of these devices on system efficiency.

With the SSSC, the total power losses range from a minimum of 13.447 MW at a Voltage Source (Vse) of 0.05 p.u. and an angle (θse) of 90 degrees to a maximum of 40.019 MW at a Vse of 0.1 p.u. and an angle of 270 degrees. This significant difference highlights the sensitivity of power losses to the control settings of the SSSC. In contrast, when using the STATCOM, the power losses are lower, ranging from a minimum of 9.383 MW at a voltage source (Vsi) of 0.1 p.u. and an angle (θsi) of 90 degrees to a maximum of 18.741 MW at a Vsi of 0.1 p.u. and an angle of 270 degrees. This narrower range indicates that the STATCOM provides a more stable and efficient control over power losses compared to the SSSC.

The load flow results shown in Table 8 highlight the performance under three different configurations, the AC-DC load flow with an HVDC link, the system equipped with a Static Synchronous Series Compensator (SSSC), and the system utilizing a Static Synchronous Compensator (STATCOM) device at the lowest power loss condition.

At Bus 5, where the STATCOM is connected, the system exhibits a voltage magnitude of 1.025 p.u. with a voltage angle of -6.208 degrees. This configuration offers a relatively stable voltage profile, as evidenced by the less negative voltage angle, which indicates reduced reactive power demand. The STATCOM's ability to provide rapid voltage support and reactive power compensation

	With SSSC							With STATCOM							
Line No	S_{min} (MVA)	Vse (p.u.)	θse (deg)	S_{max} (MVA)	Vse (p.u.)	θse (deg)	S_{diff} (MVA)	S_{min} (MVA)	Vsi (p.u.)	θsi (deg)	S_{max} (MVA)	Vsi (p.u.)	θsi (deg)	S_{diff} (MVA)	MVA limit
1	150.016	0.1	135	181.835	0.1	315	31.819	123.818	0.1	90	192.339	0.1	270	68.522	200
2	59.607	0.1	315	83.632	0.1	135	24.025	54.316	0.1	90	96.997	0.1	270	42.681	100
3	67.363	0.1	135	90.962	0.1	315	23.599	67.781	0.1	90	78.761	0.1	270	10.98	100
4	43.179	0.1	135	89.923	0.1	315	46.744	44.85	0.1	90	67.387	0.1	270	22.537	100
5	13.146	0.1	315	53.536	0.1	135	40.39	26.466	0.1	90	56.547	0.1	270	30.081	85
6	12.47	0.1	360	32.37	0.1	180	19.9	18.363	0.1	270	28.72	0.1	90	10.356	85
7	14.527	0.1	0	104.481	0.1	180	89.954	47.991	0.1	270	78.071	0.1	90	30.08	150
8	21.891	0.1	0	34.171	0.1	180	12.28	28.434	0.1	45	30.943	0.1	225	2.509	50
9	10.447	0.1	315	18.404	0.1	135	7.957	15.693	0.1	135	16.404	0.1	315	0.711	32
10	41.021	0.1	135	66.789	0.1	270	25.768	44.126	0.1	225	49.515	0.1	45	5.388	100
11	6.172	0.1	90	17.908	0.1	270	11.736	7.66	0.1	0	9.147	0.1	135	1.487	30
12	7.867	0.1	135	9.511	0.1	270	1.644	8.101	0.1	360	8.315	0.1	135	0.214	32
13	17.782	0.1	135	24.28	0.1	270	6.498	18.892	0.1	0	19.66	0.1	135	0.768	30
14	13.353	0.1	90	23.142	0.05	315	9.789	14.043	0.1	0	22.22	0.1	180	8.177	32
15	19.774	0.1	315	32.599	0.1	135	12.825	28.249	0.1	135	29.4	0.1	315	1.151	40
16	1.589	0.075	270	9.392	0.1	135	7.803	5.704	0.1	135	7.374	0.1	0	1.67	32
17	4.15	0.1	270	12.073	0.1	135	7.923	9.491	0.1	135	10.437	0.1	0	0.946	18
18	2.185	0.1	90	13.505	0.1	315	11.32	3.628	0.1	315	5.044	0.1	135	1.417	30
19	1.535	0.1	90	3.074	0.1	270	1.539	1.698	0.1	0	1.926	0.075	180	0.227	12
20	4.544	0.1	135	12.123	0.1	315	7.579	5.584	0.1	315	6.503	0.1	135	0.919	20

Table 6. Power Flows with SSSC and STATCOM by Varying Control Parameters of IEEE-14 Bus System

			With SSSC							With STATCOM			
TPL_{min} (MW)	Vse (p.u.)	θse (deg)	TPL_{max} (MW)	Vse (p.u.)	θse (deg)	TPL_{diff} (MW)	TPL_{min} (MW)	Vsi (p.u.)	θsi (deg)	TPL_{max} (MW)	Vsi (p.u.)	θsi (deg)	TPL_{diff} (MW)
13.44669	0.05	90	40.01907	0.1	270	26.572	9.383	0.1	90	18.741	0.1	270	9.358

Table.7 Power Losses with SSSC and STATCOM by Varying Control Parameters of IEEE-14 Bus System

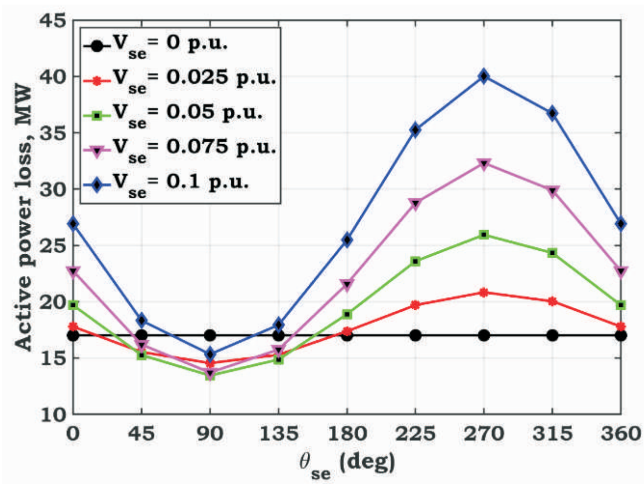

Figure 14. Variation of Power Loss by Varying SSSC Control Parameters of IEEE-14 Bus System

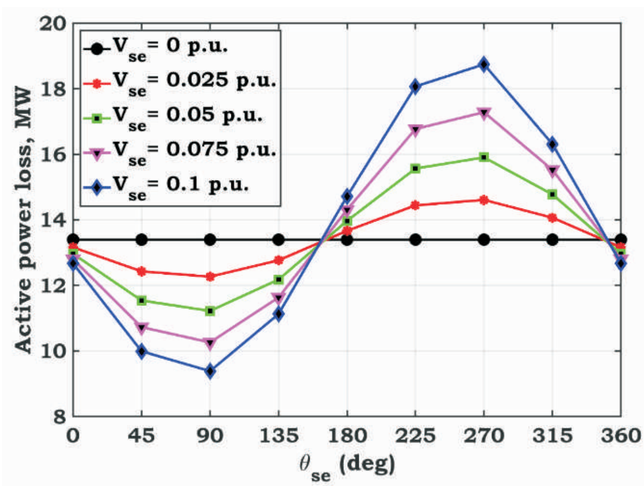

Figure 15. Variation of Power Loss by Varying STATCOM Control Parameters of IEEE-14 Bus System

is particularly beneficial, resulting in better voltage regulation and enhanced system stability. In comparison, the system with the SSSC at Line 7 shows a voltage magnitude of 1.06 p.u. and a voltage angle of -13.469 degrees. Although the voltage magnitude is maintained close to the desired level, the more negative angle suggests higher reactive power demand and potential instability. The SSSC primarily functions by injecting a series voltage in phase with the line current, thereby influencing the power flow. However, its effectiveness in stabilizing the voltage profile appears less than that of the STATCOM, as indicated by the steeper voltage angle.

Finally, the HVDC link in the AC-DC load flow configuration at Line 19 results in a voltage magnitude of 1.056 p.u. with a voltage angle of -14.965 degrees. While the HVDC link maintains a high voltage magnitude, the significantly negative voltage angle points to potential challenges in managing reactive power and ensuring system stability. The HVDC link's role in enabling long-distance power transmission with reduced losses is clear, yet it requires careful reactive power management to prevent voltage instability. Variation of voltage magnitude with HVDC link, SSSC, and STATCOM is shown in Figure 16.

The line flow results shown in Table 9 provide a detailed comparison of power flows and apparent power flows across various transmission lines under three configurations, AC-DC load flow with an HVDC link, a system with a Static Synchronous Series Compensator (SSSC), and a system using a Static Synchronous

	AC-DC [12]		SSSC		STATCOM	
Bus No	VM, p.u	VA, deg	VM, p.u	VA, deg	VM, p.u	VA, deg
1	1.06	0	1.06	0	1.06	0
2	1.045	-4.963	1.045	-5.009	1.045	-3.867
3	1.01	-12.665	1.01	-12.819	1.01	-10.989
4	1.023	-10.352	1.018	-10.468	1.022	-8.091
5	1.028	-8.874	1.021	-8.703	1.025	-6.208
6	1.07	-14.258	1.07	-14.237	1.07	-11.741
7	1.063	-13.385	1.06	-13.469	1.062	-11.06
8	1.09	-13.385	1.09	-13.469	1.09	-11.06
9	1.056	-14.965	1.054	-15.027	1.055	-12.606
10	1.051	-15.125	1.049	-15.172	1.05	-12.738
11	1.057	-14.823	1.056	-14.836	1.057	-12.372
12	1.057	-15.143	1.055	-15.099	1.055	-12.606
13	1.054	-15.301	1.05	-15.183	1.05	-12.697
14	1.036	-16.07	1.034	-16.097	1.035	-13.647

Table 8. Load Flow Results Obtained with SSSC and STATCOM of IEEE-14 Bus System

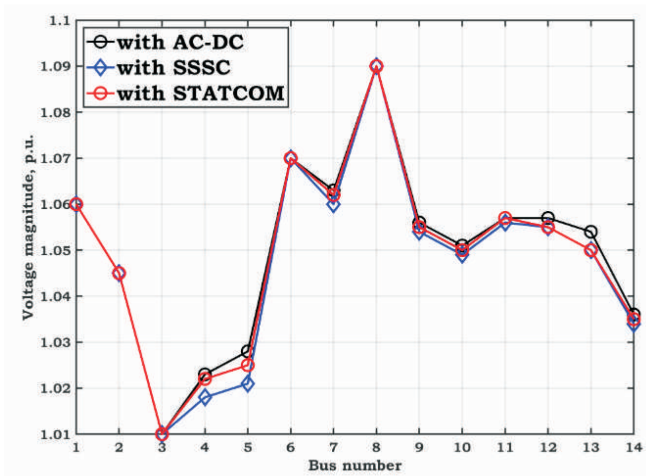

Figure 16. Variation of Voltage Magnitude with HVDC Link, SSSC and STATCOM of IEEE-14 Bus System

Compensator (STATCOM) device under the lowest power loss condition. For instance, in Line 1-2, the AC-DC configuration achieves a power flow of 156.302 MW and an apparent power flow of 157.611 MVA. The SSSC configuration slightly enhances this power flow to 157.695 MW, demonstrating its effectiveness in improving power transfer. Conversely, the STATCOM configuration significantly reduces the power flow to 123.216 MW, indicating its robust capability in managing reactive power and enhancing system stability. Additionally, Line 4-5 shows that while the AC-DC and SSSC configurations maintain similar power flows (around -61.754 MW and -58.816 MW), the STATCOM configuration increases power flow to -76.355 MW, further highlighting its superior performance in reactive power compensation.

Power losses (Ploss) within the system also vary significantly across the configurations. The AC-DC configuration results in power losses of 13.30265 MW, which slightly increase to 13.44669 MW under the SSSC configuration. However, the STATCOM configuration stands out with a substantial reduction in power losses to 9.38334 MW. This marked decrease underscores the STATCOM's efficiency in minimizing energy dissipation. Overall, while the SSSC offers moderate improvements in power flow management compared to the AC-DC configuration, the STATCOM proves to be the most effective in reducing power losses and stabilizing power flows across the network. The STATCOM's ability to manage reactive power more effectively not only enhances system stability but also leads to significant energy savings, making it a vital component in modern power systems. Variation of power flows with HVDC link, SSSC, and STATCOM is shown in Figure 17.

5.2 IEEE-30 Bus System

For this system, the procedures followed to identify all possible installation locations for SSSC and STATCOM are

	AC-DC [12]		SSSC		STATCOM	
Line no	Pflow, MW	Sflow, MVA	Pflow, MW	Sflow, MVA	Pflow, MW	Sflow, MVA
1-2	156.302	157.611	157.695	159.035	123.216	123.818
1-5	76.001	76.001	74.891	74.97	54.205	54.316
2-3	72.865	72.954	73.846	73.929	67.655	67.781
2-4	55.996	56.214	57.398	57.432	44.829	44.85
2-5	41.475	41.658	40.408	40.418	26.399	26.466
3-4	-23.635	23.635	-22.716	22.937	-28.533	28.72
4-5	-61.754	62.238	-58.816	60.795	-76.355	78.071
4-7	28.144	29.169	27.614	29.108	27.484	28.635
4-9	16.13	16.141	15.809	15.809	15.746	15.753
5-6	43.946	46.98	44.835	46.693	45.027	47.556
6-11	7.286	8.086	7.797	8.722	7.926	8.659
6-12	7.652	7.838	7.854	8.255	7.859	8.242
6-13	17.808	18.26	17.984	19.448	18.043	19.421
7-8	0	16.241	0	17.813	0	16.753
7-9	28.144	28.99	27.614	28.48	27.484	28.397
9-10	5.294	6.802	4.793	6.173	4.664	6.351
9-14	9.48	10.125	9.129	9.743	9.066	9.782
10-11	-3.72	4.035	-4.218	4.642	-4.348	4.606
12-13	1.486	1.486	1.681	1.856	1.686	1.838
13-14	5.597	6.265	5.94	6.253	6.004	6.235
Ploss, MW	13.30265		13.44669		9.38334	
Iterations	5		7		6	

Table 9. Line Flow Results Obtained with SSSC and STATCOM of IEEE-14 Bus System

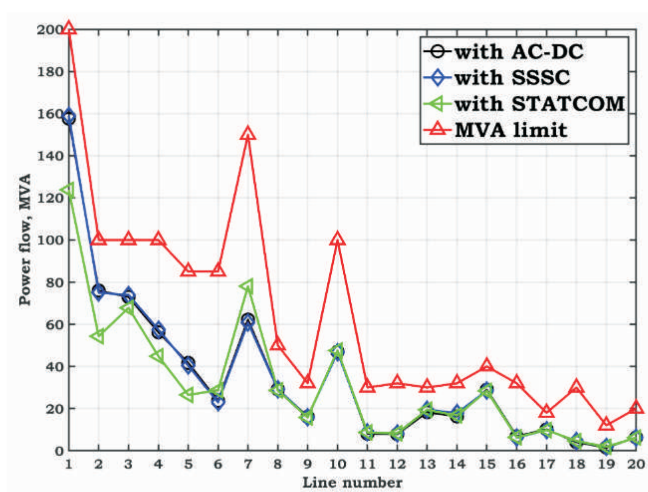

Figure 17. Variation of Power Flows with HVDC Link, SSSC and STATCOM of IEEE-14 Bus System

tabulated in Table 10. From this table, it is noted that the contingency line-30, connected between buses 15 and 23, has the highest FLLI value. The line contributing least to this highest value is line-7, connected between buses 4 and 6, which is considered for installing the SSSC. Similarly, the FVVI value is high for the contingency line-24, connected between buses 19 and 20. At this contingency, the bus contributing least to the highest FVVI is bus-3; therefore, it is considered for installing the STATCOM. Further analysis is performed by installing these FACTS controllers at these locations.

After this, the optimal location for the HVDC link is obtained by placing the HVDC link at all possible device installation locations one at a time, and the total power losses are evaluated. The results are shown in Table 11. From this table, it is identified that line 24, connected between buses 19 and 20, has the highest power losses. By installing the HVDC link in this line and varying the converter control parameters, it is possible to decrease the power losses in this line. Further analysis is performed by installing the HVDC link in this line.

Location No	Contingency			FLLI value	FVVI value
	Line no	From bus	To bus		
1	20	14	15	260.4	9.591
2	22	15	18	237.7	9.523
3	30	15	23	298.9	10.7
4	21	16	17	296.4	5.253
5	23	18	19	221.1	7.614
6	24	19	20	137.9	12.42
7	29	21	22	168.7	8.909
8	34	25	26	103.7	9.146
9	39	29	30	6.706	6.169

Table 10. Calculated FLLI and FVVI Values of IEEE-30 Bus System

Location No	HVDC link installed line			TPL (kW)
	No	From bus	To bus	
1	20	14	15	5.142
2	22	15	18	5.818
3	30	15	23	5.542
4	21	16	17	2.477
5	23	18	19	9.221
6	24	19	20	9.724
7	29	21	22	9.399
8	34	25	26	10.5
9	39	29	30	4.59

Table 11. TPL Values in Different Possible Locations of IEEE-14 Bus System

In order to study the impact of installing SSSC in line-7 (4-6) and STATCOM at bus-3 along with HVDC link in line-19 (12-13). Variation of voltage magnitude by varying the device control parameters with SSSC and STATCOM for the following cases are shown in Table 12.

- *For SSSC:* Varying Vse from 0 p.u. to 0.1 p.u. in steps of 0.025 p.u & θse from 00 to 3600 in steps of 450.
- *For STATCOM:* Varying Vsi from 0 p.u. to 0.1 p.u. in steps of 0.025 p.u & θsi from 00 to 3600 in steps of 450.

It is identified that significant voltage magnitude variations can be obtained by varying device control parameters. Voltage magnitude variations are very high at device-connected buses (4 & 5 with SSSC, 5 with STATCOM). It has been proven that the system performance can be controlled by varying the device control parameters.

Table 12 shows the voltage magnitudes at each bus when equipped with a Static Synchronous Series Compensator (SSSC) and a Static Synchronous Compensator (STATCOM). The table reveals the effects of varying control parameters, including voltage magnitude (Vmin and Vmax), series injected voltage (Vse for SSSC and Vsi for STATCOM), and phase angle (θse and θsi) on the voltage profiles across different buses. For example, Bus 2 under the SSSC configuration maintains a voltage magnitude between 1.045 p.u. (Vmin) and 1.045 p.u. (Vmax) with Vse set to 0 p.u. and θse at 0 degrees. However, the STATCOM configuration results in a broader voltage range, from 1.034 p.u. to 1.16 p.u., with Vsi varying between 0.075 p.u. and 0.1 p.u., and a phase angle shift of 225 degrees. This increased flexibility in voltage control reflects the STATCOM's enhanced capability to manage voltage stability under different load conditions.

Furthermore, the difference in voltage magnitudes (Vdiff) between the minimum and maximum values across buses provides insight into the overall voltage stability. For instance, Bus 3 shows a more significant voltage variation under STATCOM, with Vdiff reaching 0.366 p.u., compared to 0.055 p.u. under SSSC, highlighting the STATCOM's superior voltage regulation capabilities. Similarly, Buses 26, 29, and 30 exhibit more substantial voltage variations with STATCOM, indicating a broader control range, which is essential for maintaining system reliability, particularly in stressed operating conditions. The STATCOM configuration generally provides better voltage support across the network, leading to more stable and efficient operation, especially in high-demand scenarios where voltage fluctuations could otherwise compromise system performance. These findings emphasize the STATCOM's advantages in dynamic voltage control and its critical role in enhancing the stability and efficiency of power systems.

The data shown in Table 13 illustrate the impact of integrating Static Synchronous Series Compensator (SSSC) and Static Synchronous Compensator (STATCOM) devices, highlighting how varying control parameters influence these effects. For each transmission line, the table details the minimum and maximum power flows (in MVA), as well as the corresponding voltage magnitude (Vse for SSSC, Vsi for STATCOM) and phase angle (θse for SSSC, θsi for STATCOM) adjustments. The results indicate that both SSSC and STATCOM significantly enhance the power handling capabilities of the lines, with STATCOM generally providing more substantial increases. For instance, on Line 1, the integration of SSSC increases the maximum power flow from 175.166 MVA to 197.338 MVA, while STATCOM further boosts it to 344.554 MVA, showcasing a remarkable improvement in the line's capacity. However, the effectiveness of these devices is closely tied to the control parameters, particularly the phase angle adjustments. For example, in Line 6, altering the phase angle from 90° to 270° with STATCOM results in a significant rise in power flow, underscoring the importance of optimal control settings. Despite these improvements, the use of STATCOM also brings the lines

	With SSSC							With STATCOM						
Bus No	V_{min} (p.u.)	Vse (p.u.)	θse (deg)	V_{max} (p.u.)	Vse (p.u.)	θse (deg)	V_{diff} (p.u.)	V_{min} (p.u.)	Vsi (p.u.)	θsi (deg)	V_{max} (p.u.)	Vsi (p.u.)	θsi (deg)	V_{diff} (p.u.)
1	1.06	0	0	1.06	0	0	0	1.06	0	0	1.06	0	0	0
2	1.045	0	0	1.045	0	0	0	1.034	0.075	225	1.16	0.1	225	0.127
3	1.001	0.1	180	1.056	0.1	0	0.055	0.89	0.075	180	1.255	0.1	225	0.366
4	0.988	0.1	180	1.055	0.1	0	0.067	0.939	0.075	180	1.234	0.1	225	0.295
5	1.01	0	0	1.01	0	0	0	1.01	0	0	1.218	0.1	225	0.208
6	1.005	0.1	0	1.026	0.1	180	0.021	0.97	0.075	180	1.229	0.1	225	0.26
7	0.999	0.1	0	1.012	0.1	180	0.012	0.978	0.075	180	1.219	0.1	225	0.241
8	1.01	0	0	1.01	0	0	0	0.978	0.075	180	1.236	0.1	225	0.258
9	1.023	0.1	0	1.03	0.1	180	0.007	1.001	0.075	180	1.259	0.1	225	0.258
10	1.009	0.1	45	1.015	0.1	225	0.006	0.984	0.075	180	1.246	0.1	225	0.263
11	1.082	0	0	1.082	0	0	0	1.082	0	0	1.333	0.1	225	0.251
12	1.02	0.1	180	1.037	0.1	0	0.017	0.998	0.075	180	1.269	0.1	225	0.271
13	1.071	0	0	1.071	0	0	0	1.071	0	0	1.328	0.1	225	0.257
14	1.006	0.1	180	1.02	0.1	360	0.014	0.982	0.075	180	1.256	0.1	225	0.274
15	1.002	0.1	180	1.013	0.1	360	0.011	0.977	0.075	180	1.251	0.1	225	0.274
16	1.01	0.1	180	1.018	0.1	360	0.008	0.984	0.075	180	1.254	0.1	225	0.27
17	1.005	0.1	90	1.009	0.1	270	0.004	0.978	0.075	180	1.245	0.1	225	0.267
18	0.994	0.1	135	1	0.1	315	0.007	0.966	0.075	180	1.24	0.1	225	0.274
19	0.991	0.1	135	0.996	0.1	315	0.005	0.963	0.075	180	1.236	0.1	225	0.273
20	0.995	0.1	90	0.999	0.1	270	0.004	0.968	0.075	180	1.238	0.1	225	0.271
21	0.997	0.1	45	1.003	0.1	225	0.006	0.971	0.075	180	1.238	0.1	225	0.267
22	0.998	0.1	45	1.004	0.1	225	0.006	0.971	0.075	180	1.238	0.1	225	0.267
23	0.994	0.1	135	1	0.1	315	0.006	0.966	0.075	180	1.24	0.1	225	0.275
24	0.99	0.1	45	0.994	0.1	270	0.004	0.96	0.075	180	1.233	0.1	225	0.273
25	0.99	0.1	45	0.998	0.1	225	0.008	0.957	0.075	180	1.231	0.1	225	0.274
26	0.971	0.1	45	0.98	0.1	225	0.008	0.938	0.075	180	1.218	0.1	225	0.28
27	0.998	0.1	0	1.009	0.1	180	0.011	0.965	0.075	180	1.237	0.1	225	0.272
28	1.002	0.1	360	1.018	0.1	180	0.015	0.968	0.075	180	1.229	0.1	225	0.261
29	0.977	0.1	0	0.989	0.1	180	0.012	0.944	0.075	180	1.222	0.1	225	0.278
30	0.966	0.1	0	0.978	0.1	180	0.012	0.931	0.075	180	1.213	0.1	225	0.282

Table 12. Voltage Magnitudes with SSSC and STATCOM by Varying Control Parameters of IEEE-30 Bus System

closer to their MVA limits more rapidly, as seen in Line 2, where the power flow nearly doubles compared to SSSC, approaching the system's 130 MVA limit. This suggests that while STATCOM offers more aggressive power flow enhancement, it requires careful management to prevent overloading. Additionally, the differential impact (Sdiff) between the devices highlights their complementary nature: STATCOM tends to deliver higher power flow improvements, whereas SSSC provides more precise control, making it advantageous in scenarios where fine adjustments are necessary. Ultimately, the choice between SSSC and STATCOM should be based on the specific needs of the power system, balancing the desire for increased power flow with the risk of overloading and the need for nuanced control.

Variation of power loss by varying the device control parameters with SSSC and STATCOM for the previously given cases are shown in Figures 18 and 19. From these figures it is identified that, the significant power loss variations can be obtained by varying device control parameters.

	With SSSC							With STATCOM							
Line No	S_{min} (MVA)	Vse (p.u.)	θse (deg)	S_{max} (MVA)	Vse (p.u.)	θse (deg)	S_{diff} (MVA)	S_{min} (MVA)	Vsi (p.u.)	θsi (deg)	S_{max} (MVA)	Vsi (p.u.)	θsi (deg)	S_{diff} (MVA)	MVA limit
1	175.166	0.1	225	197.338	0.1	45	22.172	26.639	0.1	90	344.554	0.1	270	317.915	130
2	67.707	0.1	90	87.321	0.1	270	19.614	6.521	0.05	90	236.407	0.1	270	229.886	130
3	23.047	0.1	90	51.186	0.1	270	28.138	9.325	0.05	90	117.04	0.1	270	107.715	65
4	63.293	0.1	90	82.512	0.1	270	19.219	8.227	0.05	270	265.2	0.1	45	256.973	130
5	80.031	0.1	225	95.239	0.1	45	15.208	58.15	0.1	90	106.806	0.1	270	48.656	130
6	55.9	0.1	270	89.051	0.1	90	33.151	9.459	0.1	90	115.628	0.1	270	106.169	90
7	25.145	0.1	90	85.326	0.1	225	60.181	12.504	0.1	270	163.25	0.1	45	150.747	90
8	5.181	0.1	90	19.639	0.1	270	14.458	4.359	0.075	270	39.948	0.1	90	35.589	70
9	25.921	0.1	45	40.454	0.1	225	14.533	16.239	0.1	270	64.673	0.1	45	48.434	130
10	29.484	0.025	45	42.152	0.1	180	12.668	29.804	0.025	270	48.058	0.1	315	18.254	65
11	24.147	0.1	90	32.61	0.1	270	8.463	26.689	0.1	45	40.617	0.1	180	13.927	65
12	12.863	0.1	90	17.628	0.1	270	4.765	15.11	0.1	45	20.144	0.1	180	5.034	32
13	25.795	0.1	180	29.071	0.1	0	3.276	8.205	0.1	0	46.03	0.1	180	37.825	65
14	25.102	0.1	45	32.707	0.1	225	7.604	28.087	0.1	45	35.633	0.1	180	7.546	65
15	40.083	0.1	270	57.198	0.1	90	17.114	39.163	0.1	270	55.472	0.1	180	16.308	65
16	25.433	0.1	0	37.207	0.1	180	11.774	0.888	0.1	0	55.918	0.1	180	55.03	65
17	7.721	0.1	225	9.457	0.1	45	1.736	7.751	0.1	270	8.609	0.1	180	0.858	32
18	17.188	0.1	225	24.204	0.1	45	7.015	17.138	0.1	270	20.33	0.1	90	3.193	32
19	6.105	0.1	225	13.535	0.1	45	7.43	6.292	0.1	270	9.43	0.1	90	3.138	32
20	1.233	0.1	225	2.922	0.1	45	1.689	1.382	0.1	270	2.086	0.1	225	0.705	16
21	2.111	0.1	225	9.568	0.1	90	7.456	2.629	0.1	270	5.748	0.1	225	3.119	16
22	5.297	0.1	225	9.371	0.1	45	4.074	5.23	0.1	270	7.131	0.1	90	1.901	16
23	1.928	0.1	225	5.968	0.1	90	4.041	2.01	0.1	270	3.734	0.1	225	1.724	16
24	4.594	0.1	45	8.171	0.1	225	3.577	6.071	0.1	225	8.311	0.1	270	2.24	32
25	6.904	0.1	45	10.693	0.1	225	3.79	8.163	0.1	225	10.817	0.1	270	2.654	32
26	3.782	0.1	0	8.695	0.1	225	4.912	4.842	0.1	225	8.672	0.1	270	3.83	32
27	17.409	0.1	45	18.271	0.1	225	0.862	16.317	0.1	225	18.857	0.1	180	2.54	32
28	8.061	0.1	45	8.627	0.1	225	0.567	7.636	0.1	225	8.948	0.1	180	1.312	32
29	2.799	0.1	225	3.581	0.1	45	0.782	2.523	0.075	180	3.734	0.1	360	1.211	32
30	4.348	0.1	225	8.628	0.1	45	4.28	4.586	0.1	360	6.391	0.1	225	1.806	16
31	4.412	0.1	45	5.881	0.1	225	1.468	4.606	0.1	45	6.325	0.1	180	1.719	16
32	0.809	0.1	225	5.074	0.1	45	4.265	0.974	0.1	0	3.262	0.1	225	2.288	16
33	0.17	0.075	45	2.885	0.1	270	2.715	1.516	0.1	135	3.377	0.1	360	1.861	16
34	4.265	0.1	225	4.267	0.1	45	0.001	3.905	0.1	225	4.322	0.1	180	0.418	16
35	4.063	0.1	45	6.677	0.1	225	2.615	4.758	0.1	225	7.626	0.1	360	2.869	16
36	18.035	0.1	45	20.941	0.1	225	2.905	17.763	0.1	225	21.79	0.1	360	4.027	65
37	6.416	0.1	180	6.421	0.1	360	0.005	5.986	0.1	225	6.835	0.1	180	0.849	16
38	7.291	0.1	180	7.297	0.1	360	0.006	6.843	0.1	225	7.832	0.1	180	0.99	16
39	3.754	0.1	180	3.756	0.1	360	0.001	3.588	0.1	225	4.097	0.1	180	0.509	16
40	0.461	0.075	315	5.887	0.1	180	5.426	0.496	0.025	135	7.33	0.075	315	6.834	32
41	17.508	0.1	45	21.093	0.1	180	3.585	17.438	0.1	225	22.617	0.1	0	5.179	32

Table 13. Power Flows with SSSC and STATCOM by Varying Control Parameters of IEEE-30 Bus System

Table 14 shows the Total Power Losses (TPL) when using Static Synchronous Series Compensator (SSSC) and Static Synchronous Compensator (STATCOM) under varying control parameters. The power loss differences (TPLdiff) between minimum and maximum values reveal the impact of these devices on system efficiency.

When the SSSC is deployed, the system experiences a minimum power loss of 17.483 MW with a voltage magnitude of 0.075 p.u. and a phase angle of 225°. The maximum power loss rises to 19.630 MW when the voltage magnitude is increased to 0.1 p.u. and the phase angle is adjusted to 45°. The differential (TPLdiff) between the minimum and maximum power losses with the SSSC is 2.147 MW, indicating a relatively moderate increase in power losses as the control parameters are varied.

In contrast, the STATCOM integration shows a significantly wider range of power loss variation. The minimum power loss with STATCOM is notably lower at 11.036 MW, achieved with a voltage magnitude of 0.05 p.u. and a phase angle of 90°. However, the maximum power loss escalates dramatically to 63.946 MW when the voltage magnitude is 0.1 p.u. and the phase angle is 270°. This results in a substantial differential of 52.910 MW between the minimum and maximum power losses, which is considerably higher than that observed with the SSSC.

This analysis underscores the significant impact that control parameter settings have on the power losses in the system. While both SSSC and STATCOM devices can be tuned to minimize losses, STATCOM's sensitivity to control settings is much more pronounced, leading to a much larger variation in losses. The lower TPLmin with STATCOM suggests that, with optimal settings, it is more effective at reducing losses compared to SSSC. However, the potential for much higher losses (TPLmax) with STATCOM also indicates that improper tuning could lead to inefficient operation, making careful calibration of the control parameters essential when using STATCOM. Conversely, the SSSC exhibits a more stable performance with less drastic changes in power losses across different control settings, which might be advantageous in systems where predictability and stability are prioritized.

With SSSC							With STATCOM						
TPL_{min} (MW)	Vse (p.u.)	θse (deg)	TPL_{max} (MW)	Vse (p.u.)	θse (deg)	TPL_{diff} (MW)	TPL_{min} (MW)	Vsi (p.u.)	θsi (deg)	TPL_{max} (MW)	Vsi (p.u.)	θsi (deg)	TPL_{diff} (MW)
17.48298	0.075	225	19.63044	0.1	45	2.1474	11.03575	0.05	90	63.94562	0.1	270	52.9098

Table 14. Power Losses with SSSC and STATCOM by Varying Control Parameters of IEEE-30 Bus System

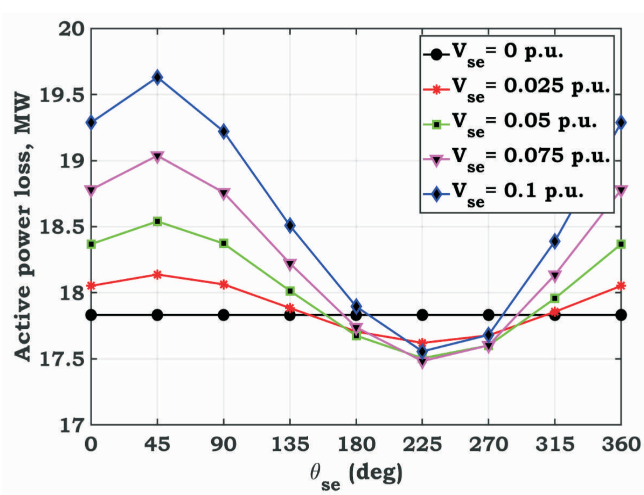

Figure 18. Variation of Power Loss by Varying SSSC Control Parameters of IEEE-30 Bus System

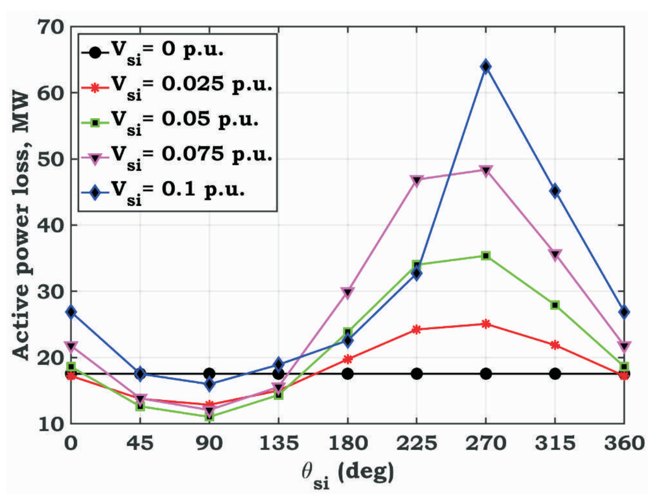

Figure 19. Variation of Power Loss by varying STATCOM Control Parameters of IEEE-30 Bus System

The load flow results shown in Table 15 highlight the performance under three different configurations: the AC-DC load flow with an HVDC link, the system equipped with a Static Synchronous Series Compensator (SSSC), and the system utilizing a Static Synchronous Compensator (STATCOM) device at the lowest power loss condition. At Bus 1, which serves as the reference or slack bus, the voltage magnitude remains constant at 1.06 p.u., with a voltage angle of 0° in all three scenarios, highlighting its role in maintaining system stability. However, as we move to Bus 2 and beyond, noticeable differences emerge. For example, at Bus 2, while the voltage magnitude remains stable at 1.045 p.u., the voltage angle varies slightly between the AC-DC method (-5.527°), the SSSC (-5.462°), and more significantly with the STATCOM (-2.912°). This pattern continues across the other buses, where the STATCOM generally exhibits a more substantial impact on reducing voltage angle deviations, especially when compared to the AC-DC and SSSC scenarios. The overall results indicate that while the SSSC provides some improvement in voltage angle correction, the STATCOM offers a more pronounced stabilization effect across the bus system, reflecting its efficacy in enhancing the voltage profile and mitigating angular discrepancies within the network.

	AC-DC [12]		SSSC		STATCOM	
Bus No	VM, p.u	VA, deg	VM, p.u	VA, deg	VM, p.u	VA, deg
1	1.06	0	1.06	0	1.06	0
2	1.045	-5.527	1.045	-5.462	1.045	-2.912
3	1.021	-7.986	1.016	-7.931	1.052	-0.552
4	1.012	-9.64	1.006	-9.577	1.033	-3.627
5	1.01	-14.375	1.01	-14.172	1.01	-10.343
6	1.011	-11.368	1.021	-11.264	1.02	-6.045
7	1.003	-13.13	1.009	-12.981	1.008	-8.327
8	1.01	-12.111	1.01	-11.841	1.01	-6.623
9	1.051	-14.387	1.029	-14.573	1.03	-9.177
10	1.045	-15.966	1.015	-16.305	1.017	-10.812
11	1.082	-14.387	1.082	-14.573	1.082	-9.177
12	1.058	-15.253	1.024	-15.684	1.032	-9.94
13	1.071	-15.253	1.071	-15.684	1.071	-9.94
14	1.043	-16.139	1.009	-16.605	1.017	-10.888
15	1.038	-16.23	1.005	-16.686	1.012	-10.994
16	1.045	-15.827	1.013	-16.241	1.018	-10.594
17	1.04	-16.131	1.009	-16.507	1.012	-10.965
18	1.029	-16.831	0.996	-17.292	1.001	-11.662
19	1.026	-16.997	0.994	-17.447	0.998	-11.858
20	1.03	-16.796	0.998	-17.222	1.002	-11.657
21	1.033	-16.411	1.002	-16.774	1.005	-11.275
22	1.034	-16.398	1.003	-16.759	1.005	-11.258
23	1.029	-16.618	0.996	-17.047	1.001	-11.428
24	1.025	-16.792	0.993	-17.16	0.996	-11.644
25	1.027	-16.431	0.997	-16.663	0.998	-11.242
26	1.009	-16.843	0.979	-17.1	0.98	-11.678
27	1.037	-15.948	1.008	-16.08	1.008	-10.719
28	1.008	-12.016	1.014	-11.862	1.014	-6.63
29	1.017	-17.145	0.988	-17.349	0.988	-11.987
30	1.006	-18.003	0.976	-18.26	0.977	-12.897

Table 15. Load Flow Results Obtained with SSSC and STATCOM of IEEE-30 Bus System

Table 16 shows an in-depth analysis of line flow results within the IEEE-30 bus system under three different configurations, the traditional AC-DC method, and systems incorporating a Static Synchronous Series Compensator (SSSC) and a Static Synchronous Compensator (STATCOM). The table lists the active power flow (Pflow, MW) and apparent power flow (Sflow, MVA) for each line, offering insights into how these compensators influence power distribution across the network.

The results show that both SSSC and STATCOM have a significant impact on power flow, particularly in reducing overall system losses. For instance, the total power losses (Ploss) for the AC-DC method are recorded at 17.599 MW, which is slightly reduced to 17.483 MW with the SSSC. However, the STATCOM configuration leads to a more substantial reduction in power losses, bringing the total down to 11.036 MW. This reduction in losses highlights the effectiveness of the STATCOM in optimizing power flow and improving system efficiency.

Line-specific results also reveal interesting patterns. For example, Line 1 (between buses 1 and 2) shows a marked reduction in both Pflow and Sflow when moving from the AC-DC method to the STATCOM configuration. The Pflow drops from 177.932 MW (AC-DC) to 97.116 MW (STATCOM), indicating a significant shift in power distribution and potential load balancing benefits offered by the STATCOM. Similar trends are observed across other lines, such as Line 4 (between buses 3 and 4), where the Pflow with STATCOM is 154.899 MW, compared to 77.868 MW with the AC-DC method and 77.612 MW with SSSC, illustrating STATCOM's capability to handle higher power flows more effectively. Additionally, the number of iterations required for convergence varies slightly between the methods, with the AC-DC method requiring

5 iterations, while both SSSC and STATCOM configurations require 7 iterations. This suggests that while STATCOM and SSSC enhance power flow and reduce losses, they also introduce additional complexity that requires more computational effort to achieve convergence.

Conclusion

In this paper, a comprehensive analysis of power flow and loss optimization using advanced compensation devices, such as the Static Synchronous Series Compensator (SSSC) and the Static Synchronous Compensator (STATCOM), was conducted on both IEEE-14 and IEEE-30 bus systems. The study compared traditional AC-DC power flow methods with configurations incorporating SSSC and STATCOM, revealing significant improvements in system performance. For the IEEE-14 bus system, both compensators effectively reduced power losses and enhanced voltage profiles, demonstrating their potential for improving load flow and system stability.

	AC-DC [12]		SSSC		STATCOM	
Line no	Pflow, MW	Sflow, MVA	Pflow, MW	Sflow, MVA	Pflow, MW	Sflow, MVA
1 (1-2)	177.932	179.789	175.896	177.707	97.116	97.258
2 (1-3)	83.067	83.239	82.816	83.237	6.497	6.521
3 (2-4)	45.715	45.905	46.628	47.268	9.093	9.325
4 (3-4)	77.868	77.922	77.612	77.612	154.899	154.918
5 (2-5)	83.059	83.104	81.817	81.866	70.302	70.41
6 (2-6)	61.959	61.966	60.379	60.542	34.409	34.47
7 (4-6)	70.216	71.901	74.723	76.459	108.395	108.43
8 (5-7)	-14.134	18.005	-15.288	16.583	-26.051	28.341
9 (6-7)	37.458	37.543	38.603	38.663	49.861	49.876
10 (6-8)	29.676	30.475	29.749	34.335	29.634	33.989
11 (6-9)	27.5	28.624	28.673	30.656	27.162	29.515
12 (6-10)	15.712	15.715	15.706	16.633	14.884	16.035
13 (9-11)	0	15.701	0	26.371	0	25.868
14 (9-10)	27.5	28.182	28.673	31.729	27.162	29.909
15 (4-12)	43.888	46.163	42.133	43.488	45.084	45.212
16 (12-13)	0	10.119	0	34.486	0	28.781
17 (12-14)	7.807	8.158	7.591	7.93	7.944	8.301
18 (12-15)	17.724	18.921	16.942	18.035	18.216	19.467
19 (12-16)	7.157	7.891	6.4	6.985	7.724	8.502
20 (14-15)	1.534	1.652	1.317	1.423	1.664	1.784
21 (16-17)	3.604	3.871	2.856	2.996	4.16	4.464
22 (15-18)	6.004	6.264	5.588	5.791	6.331	6.608
23 (18-19)	2.765	2.88	2.352	2.415	3.086	3.214
24 (19-20)	-6.74	7.225	-7.152	7.702	-6.421	6.896
25 (10-20)	9.038	9.698	9.467	10.205	8.717	9.365
26 (10-17)	5.422	7.015	6.171	7.918	4.869	6.465
27 (10-21)	15.515	18.089	15.508	18.163	15.339	17.945
28 (10-22)	7.438	8.512	7.433	8.556	7.322	8.415
29 (21-22)	-2.089	2.98	-2.103	2.893	-2.27	3.105
30 (15-23)	4.837	5.457	4.262	4.84	5.107	5.752
31 (22-24)	5.3	5.634	5.277	5.695	5.001	5.358
32 (23-24)	1.609	1.829	1.039	1.223	1.874	2.116
33 (24-25)	-1.83	1.858	-2.423	2.445	-1.863	1.915
34 (25-26)	3.544	4.261	3.547	4.265	3.546	4.265
35 (25-27)	-5.38	5.759	-5.981	6.327	-5.417	5.753
36 (28-27)	18.688	18.768	19.317	20.57	18.744	19.952
37 (27-29)	6.187	6.406	6.194	6.417	6.194	6.417
38 (27-30)	7.088	7.278	7.097	7.292	7.097	7.291
39 (29-30)	3.703	3.752	3.705	3.755	3.705	3.755
40 (8-28)	-0.433	0.989	-0.389	3.999	-0.501	3.985
41 (6-28)	19.183	19.202	19.777	20.549	19.313	20.028
Ploss, MW	17.59943		17.48298		11.03575	
Iterations	5		7		7	

Table 16. Line Flow Results Obtained with SSSC and STATCOM of IEEE-30 Bus System

The analysis of the IEEE-30 bus system further underscored these benefits, with STATCOM showing a more pronounced impact on reducing total power losses from 17.599 MW in the AC-DC method to 11.036 MW, compared to a smaller reduction with SSSC. Additionally, STATCOM effectively managed higher power flows across critical lines, such as Line 4, where the power flow increased significantly, highlighting its ability to handle increased loads while maintaining system stability. These findings underscore the critical role of SSSC and STATCOM in enhancing power system efficiency, particularly in large, complex networks like the IEEE-30 bus system, by optimizing power distribution, reducing losses, and improving overall system reliability.

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