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Enhancing Transmission Efficiency through Series Compensation: A Case Study Perspective

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Abstract

Series compensations are implemented to reduce line reactance, improve voltage profiles, and boost power transfer capacity in long-distance transmissions. This study evaluates the effects of series compensation on load flows, voltage stability, transmission losses, and power transfer using PSS®E simulations coupled with Newton-Raphson load flow analysis. The study used a systematic placement methodology combining Voltage Sensitivity Analysis and Line Reactance Screening to identify optimal capacitor locations in the IEEE 14-bus network, specifically targeting Lines 13 - 14 and 9 - 14, both directly connected to the weakest bus. Simulation scenarios across 0% - 50% compensation levels reveal improvements of up to +1.1% in weakest-node voltage, approximately 15% - 16% increase in power transfer capacity, and measurable reductions in line losses in both lines. These outcomes highlight significant system performance gains even in lightly loaded networks. A first-level SSR frequency screening is also reported to verify that the 20% - 50% compensation range does not introduce an obvious resonance concern for the benchmark case.

Keywords

Line Losses, Line Reactance Screening, Power Transfer, Series Compensation, Voltage Sensitivity

1. Introduction

Modern high-voltage transmission networks are increasingly constrained by line reactance, voltage drop, and thermal limits that restrict power transfer capability. As loading levels increase and generation is located farther from load centres, the effective impedance of transmission corridors becomes a limiting factor in maintaining acceptable voltage profiles and system stability. Excessive reactance leads to larger voltage drops, increased angular separation between buses, and reduced transfer margins, which collectively constrain the efficient utilization of existing infrastructure. Addressing these reactance-related limitations is therefore essential for enhancing transmission efficiency and supporting reliable grid expansion [1].

One of the widely adopted solutions to address these challenges is the use of series capacitors, which are inserted into transmission lines to reduce the effective line reactance. By compensating for inductive reactance, series capacitors enhance power transfer capability and voltage regulation, reducing system losses and improving overall transmission efficiency. They also help maintain voltage stability by counteracting the effects of reactive power imbalance, which can lead to voltage collapse in stressed conditions. Furthermore, series compensation has been shown to improve transient stability by enhancing system damping and mitigating power oscillations, which is particularly beneficial for networks experiencing load fluctuations or disturbances [2].

The effectiveness of series capacitors has been demonstrated in numerous power systems worldwide. For example, in the Brazilian and Indian power grids, series compensation has been employed to enhance power transfer across long transmission corridors, allowing for efficient electricity delivery from remote generation sources to load centres [3] [4]. These applications highlight the growing importance of series compensation in modern power networks, particularly as power systems become more complex and interdependent.

This paper investigates the impact of series capacitors on load flow characteristics, voltage stability, and transmission losses in a high-voltage transmission network. The study employs a simulation-based approach using PSS®E (Power System Simulator for Engineering), a widely used power system analysis tool, to assess system performance under different compensation levels. The Newton-Raphson load flow method is used to evaluate key power system parameters, including active and reactive power distribution, voltage magnitudes, and transmission losses. By modelling a transmission network with and without series compensation, this study aims to provide a comprehensive assessment of the benefits and limitations of series capacitors in improving power system performance.

Optimal placement and sizing of series compensation (fixed series capacitors and series FACTS devices such as Thyristor-Controlled Series Capacitor (TCSC) have been extensively studied using sensitivity-based indices and optimisation techniques, with objectives such as loss minimization, congestion relief, and voltage-stability margin improvement [5]-[8]. Accordingly, this paper does not claim a previously unaddressed "critical gap"; instead, it provides a compact and reproducible IEEE 14-bus case study that demonstrates a practical two-stage screening workflow for selecting candidate corridors and moderate (20% - 50%) compensation levels using readily available steady-state tools (Newton-Raphson power flow in PSS®E).

The proposed workflow first ranks buses using Voltage Sensitivity Analysis (to identify the most reactive-power-sensitive/weak buses) and then screens transmission corridors using line reactance ranking (to identify the most impactful series-impedance reduction candidates). The quantified performance metrics (Bus-14 voltage, angle difference, losses, and transfer capability) provide an engineering interpretation of the benefits that can be expected from fixed series compensation on a small benchmark network.

The results of the study are expected to provide valuable insights into how series capacitors can be optimally deployed to enhance transmission efficiency and stability. Understanding the impact of compensation levels and placement strategies will assist power system planners and operators in making informed decisions regarding grid expansion and reinforcement. As power systems continue to evolve with increasing penetration of renewable energy sources and growing demand, the role of series capacitors in ensuring efficient and stable transmission networks will become even more significant. The findings of this study will contribute to the ongoing efforts to optimize power system performance through advanced compensation techniques and strategic infrastructure investments.

2. Load Flows and Series Compensation

2.1. Load Flow Analysis and Computational Methods

Load flow analysis plays a crucial role in power system studies by determining the steady-state voltages, power flows, and losses in a transmission network under specific loading conditions. It is a nonlinear problem requiring iterative numerical solutions, with various methods developed to enhance computational efficiency and accuracy [1]. The three most widely used methods for load flow studies are the Gauss-Seidel (GS) method, Newton-Raphson (NR) method, and Fast Decoupled Load Flow (FDLF) method, each with distinct advantages and limitations [1] [9] [10]. For brevity and to keep the focus on the application of series compensation, the standard textbook derivations of the Gauss-Seidel and Fast Decoupled methods are omitted here; **Table 1** retains only a high-level comparison. The remainder of this study uses the Newton-Raphson (NR) power-flow solution as implemented in PSS®E.

Table 1. Comparative analysis of load flow methods [1].

Method	Convergence Speed	Computational Complexity	Accuracy	Memory Requirement	Suitability
Gauss-Seidel	Slow	Low	Moderate	Low	Small systems
Newton-Raphson	Fast	High	High	High	Large systems
Fast Decoupled Load Flow	Very Fast	Medium	Moderate	Medium	High-voltage systems

2.1.1. Newton-Raphson Formulation

The Newton-Raphson (NR) method is based on the Taylor series expansion and uses the Jacobian matrix to solve the nonlinear load flow equations. The power flow equations are given by [10]:

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos\left(\theta_{ij} - \delta_i + \delta_j\right) \quad (1)$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin\left(\theta_{ij} - \delta_i + \delta_j\right) \quad (2)$$

where:

P_i, Q_i is the real and reactive power at bus i

$|V_i|, |V_j|$ is the voltage magnitudes at buses i and j

δ_i, δ_j is the voltage angles at bus i and j

θ_{ij} is the angle of the admittance Y_{ij}

The Newton-Raphson method linearizes these equations around the current operating point using the first-order Taylor series expansion, resulting in a system of linear equations:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = J \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad (3)$$

where:

ΔP, ΔQ is the mismatches between the specified and calculated power.

$\Delta\delta$, $\Delta|V|$ is the corrections to voltage angles and magnitudes.

J : is the jacobian matrix consisting of partial derivatives of P and Q with respect to δ and $|V|$.

The state variables are updated iteratively as:

$$\begin{bmatrix} \delta^{k+1} \\ |V|^{k+1} \end{bmatrix} = \begin{bmatrix} \delta^{k} \\ |V|^{k} \end{bmatrix} J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (4)$$

The iterative process continues until the mismatches ΔP and ΔQ fall below a predefined tolerance, indicating that power balance has been achieved at all buses.

2.1.2. Comparative Analysis of Load Flow Methods

Among the classical power-flow methods, NR is selected for this work because it is robust for ill-conditioned cases and converges rapidly for transmission networks as shown in Table 1 [1]. GS and FDLF are referenced for completeness but are not used for the compensation studies reported in Section 4.

2.2. Series Capacitors in Power Systems

Series capacitors are widely employed in transmission systems to enhance power transfer capability, improve voltage stability, and mitigate line losses by reducing the effective series reactance of a transmission line. This results in increased system efficiency and better voltage regulation over long-distance transmission. However, series compensation also introduces challenges such as subsynchronous resonance (SSR), which requires proper mitigation strategies in power system planning and operation [1] [9].

2.2.1. Impact on Line Reactance and Power Transfer

The reactance of a transmission line with series compensation can be represented as:

$$X_{eff} = X_L - X_C = X_L \times \left(1 - \frac{X_C}{X_L}\right) = X_L \times \left(1 - \text{Compensation Level}\right) \tag{5}$$

where:

X_{eff} is the effective reactance of the line with series compensation.

X_L is the original inductive reactance of the transmission line.

X_C is the capacitive reactance introduced by the series capacitor.

$\frac{X_C}{X_L}$ is the series compensation level.

The capacitive reactance X_C is given by:

$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f} \tag{6}$$

where:

ω is the angular frequency of the system,

f is the system frequency (typically 50 or 60 Hz).

By reducing the effective reactance, X_{eff}, the line impedance is lowered, allowing more active power to be transmitted over the same line for a given voltage and phase angle difference. This improves both system efficiency and stability margins, especially in long-distance transmission scenarios. The maximum active power that can be transmitted over the line, given by the power transfer equation, is increased [9]:

$$P = \frac{V_S V_R}{X_{eff}} \sin\delta \tag{7}$$

where:

P is the transmitted active power.

V_S, V_R is the sending and receiving end voltages.

δ is the phase angle difference between the sending and receiving ends.

A lower effective reactance allows for greater power flow for the same voltage levels and phase angle difference, improving system performance [1] [9].

2.2.2. Voltage Profile Improvement

Series capacitors help maintain voltage levels by compensating for the voltage drops across transmission lines. The voltage drop across an uncompensated line is given by:

$$\Delta V = I X_L \tag{8}$$

where:

ΔV is the voltage drop,

I is the line current,

X_L is the inductive reactance of the line.

When a series capacitor is introduced, the effective voltage drop becomes:

$$\Delta V_{comp} = I\left(X_L - X_C\right) \tag{9}$$

Since X_C partially offsets X_L, the net voltage drop is reduced, resulting in improved voltage profiles, especially over long-distance transmission lines [2].

2.2.3. Reduction of Line Losses

The power loss in a transmission line is primarily caused by the resistive and reactive components of its impedance. The reactive power loss in an uncompensated line is given by:

$$Q_{loss} = I^2 X_L \tag{10}$$

where:

Q_{loss} is the reactive power loss,

With the introduction of series compensation, the reactive power loss becomes:

$$Q_{loss,comp} = I^2 \left(X_L - X_C \right) \tag{11}$$

where:

$Q_{loss,comp}$ is the reduced reactive power loss.

2.2.4. Sub-Synchronous Resonance (SSR) and Considerations

Despite their numerous benefits, series capacitors can introduce a phenomenon known as subsynchronous resonance (SSR), a potentially harmful interaction between electrical resonance in the power system and the mechanical torsional modes of turbine-generator shafts. This interaction can lead to sustained oscillations and possible mechanical failure.

The electrical resonant frequency introduced by the capacitor-inductor combination is given by [9]:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{12}$$

where:

f_r is the resonance frequency

L is the line inductance,

C is the capacitance of the series capacitor,

If f_r it coincides with one of the natural torsional frequencies of the turbine shaft system, dangerous oscillations may be excited, resulting in mechanical stress, fatigue, and even shaft failure.

In this paper, the SSR theory is applied as a first-level screening step by calculating the electrical resonance frequency associated with each proposed compensation level (20% - 50%). The resulting subsynchronous frequencies are reported and discussed in Section 4 to confirm that the selected compensation range does not introduce an obvious resonance concern for the benchmark test case.

3. Methodology

3.1. Load Flow Model

Load flow analysis is used to determine the steady-state operating conditions of a power system by solving a set of nonlinear algebraic equations. The key objectives are to calculate the bus voltages, phase angles, active power (P), and reactive power (Q) flows throughout the network. The load flow problem is solved using the Newton-Raphson method, which is favoured for its quadratic convergence and robustness in large-scale systems. The method involves forming and updating the Jacobian matrix and iteratively refining voltage magnitudes and phase angles until the power mismatches at all buses fall below a predefined convergence threshold.

When a series capacitor is applied to a candidate line, the compensated branch reactance is updated ($X' = X(1-k)$) and the network admittance model (Ybus) is rebuilt prior to solving the power flow. As described in Section 2.1.1, the Newton–Raphson Jacobian is then constructed from the updated conductance/susceptance matrices, ensuring that the compensation effect is fully reflected in the iterative solution.

3.2. Series Capacitor Modelling and Placement

Series capacitors are introduced into transmission lines to reduce the effective reactance, thereby enhancing power transfer capability and improving voltage stability. The impact of series compensation is modelled by modifying the line reactance as in Equation (9). Voltage sensitivity analysis and line reactance screening diagnostic techniques are employed to identify the most effective location for series capacitor installation within the IEEE 14 Bus network.

3.2.1. Voltage Sensitivity Analysis

The Voltage Sensitivity Analysis was performed to evaluate the responsiveness of each bus voltage to incremental reactive power injections. Buses exhibiting the highest sensitivity were identified as the most vulnerable to voltage instability and, therefore, the most suitable candidates for voltage support through reactive compensation.

Justification of index selection: Voltage Sensitivity Analysis provides a direct, computationally light ranking of weak buses using only standard load-flow outputs ($\Delta V/\Delta Q$) and is therefore well suited for the IEEE 14-bus benchmark and for implementation within PSS®E. Modal (V-Q) analysis and reduced-Jacobian eigenvalue methods can provide deeper insight into voltage collapse proximity [7], and the L-index offers a compact scalar indicator computed from a solved power flow [8]; however, these methods require additional eigen-analysis or network reduction steps that are not necessary for the corridor-screening objective of this paper. Accordingly, VSA is used as the primary weak-bus screening metric, while more advanced indices are recommended as follow-up studies for large or heavily stressed networks.

Voltage limits and “weak bus” criterion: For the screening phase, bus voltages were required to lie within the normal operating range of $0.95 \le |V| \le 1.05$ p.u.; buses approaching the lower bound and/or exhibiting the largest sensitivity factors were tagged as “weak” candidates. For the transfer-capability (RPF) study in Section 4, a more permissive emergency lower limit of $|V| \ge 0.90$ p.u. at the receiving bus was enforced to avoid voltage-collapse conditions while stressing the corridor.

The voltage sensitivity factor, S_V, quantifies the change in voltage magnitude at a bus resulting from a small incremental change in reactive power injection at the same bus. It is mathematically defined as:

$$S_V = \frac{\Delta V}{\Delta Q} \tag{13}$$

where:

ΔV is the change in voltage magnitude (per unit) at the bus,

ΔQ is a small incremental change in reactive power injection (in MVar) at that bus.

A higher S_V indicates that the bus voltage is more sensitive to changes in reactive power, suggesting the bus is weaker and more susceptible to voltage instability. Conversely, a lower S_V signifies a stronger voltage profile that is less affected by reactive power variations. This sensitivity analysis is essential for prioritising buses where reactive compensation devices, such as series or shunt capacitors, will have the greatest effect on enhancing voltage stability and overall system performance.

3.2.2. Line Reactance Screening Test

The Line Reactance Screening Test involved a systematic ranking of all transmission lines in the system based on their series reactance values and the associated voltage drops across their terminal buses. Lines with relatively high reactance were considered less efficient in transferring power and more prone to voltage degradation.

3.3. Simulation Setup

To evaluate the impact of series capacitors on power transfer, voltage stability, and transmission losses, a simulation study was conducted using the IEEE 14-bus test system in PSSE (Power System Simulator for Engineering). The IEEE 14-bus system is a standard test network commonly used for power system studies, including load flow analysis, stability assessment, and compensation techniques.

IEEE 14-Bus System Test Network

The IEEE 14-bus system consists of 14 buses, 5 generators, 11 loads, and 20 branches (transmission lines and transformers) as shown in **Figure 1** [11]. It is often employed for educational and research purposes due to its representative structure and tractable scale. This system was chosen due to its simplicity, yet sufficient complexity, to demonstrate the impact of series compensation on key network parameters [11] [12].

3.4. Simulation Scenarios

Five (5) different simulation scenarios were set up to compare the impact of series capacitors on the IEEE 14-Bus System Test Network:

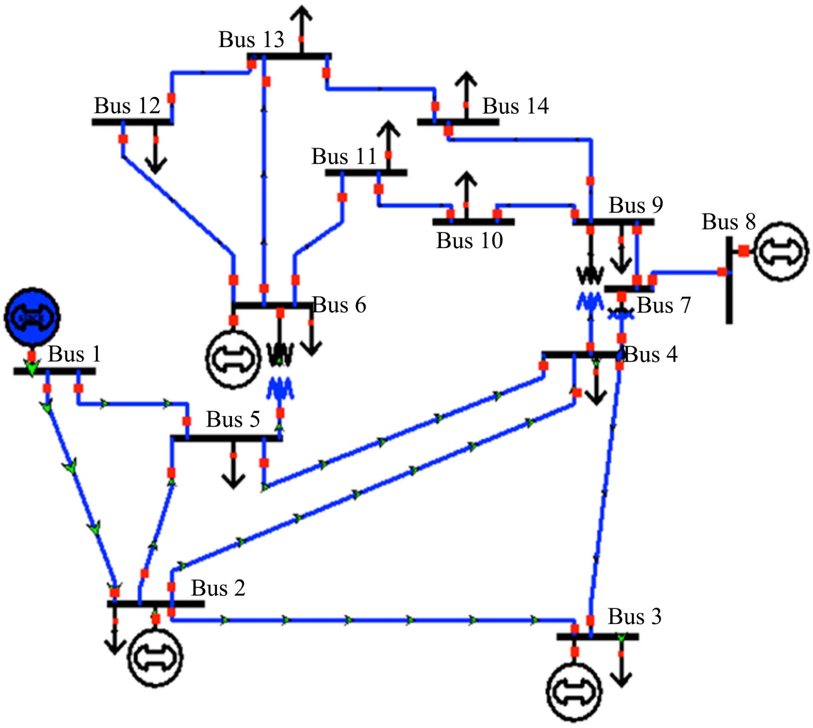

Figure 1. IEEE-14 bus system single line diagram [11].

Topology clarification for corridor studies: Two physical candidate corridors feed Bus 14 (Lines 13 - 14 and 9 - 14). The screening steps (Voltage Sensitivity and Reactance Screening) are performed on the intact IEEE 14-bus topology with all original lines in service. For the compensation-impact tables in Section 4.3, an additional controlled "corridor-isolation" topology is used in which the parallel path is opened (e.g., Line 9 - 14 opened when studying compensation on Line 13 - 14, and vice versa). This is a deliberate sensitivity/stress-test design choice to attribute the performance change to the compensated corridor without parallel-flow sharing. The 0% (base) case reported for each table is computed under the same corridor-isolation topology; therefore, the results should not be interpreted as an $N-1$ security claim but as an isolated corridor benefit assessment.

1) Base Case: No Series Compensation

In the base case, the network operates without any series capacitors. A load flow analysis is conducted to determine the natural power transfer across the network, the voltage profiles at each bus, and the transmission losses within the unmodified system. This serves as the reference case for evaluating the effect of compensation.

2) Scenario 1: 20% Series Compensation

A series capacitor is placed in one of the main transmission lines, effectively reducing the line reactance by 20%. The resulting impact on bus voltages, power transfer, and transmission losses is then analysed and compared to the base case without compensation.

3) Scenario 2: 30% Series Compensation

The compensation level is increased to 30%, further reducing the effective line reactance. This scenario evaluates whether the additional compensation yields incremental benefits in terms of power transfer and voltage stability.

4) Scenario 3: 40% Series Compensation

In this scenario, the series capacitor is tuned to provide 40% compensation, significantly reducing the effective line impedance. The objective is to assess the system's response as compensation approaches high levels. The analysis focuses on improvements in power transfer, voltage profiles, and transmission losses compared to previous scenarios.

5) Scenario 4: 50% Series Compensation

This scenario investigates the effect of applying 50% series compensation. The analysis focuses on the improvements in voltage profile, reduction in line losses, and increase in power transfer capability at this compensation level. Particular attention is given to ensuring system stability and operational security while achieving these performance gains. The results provide valuable insight into the effectiveness of moderate series compensation in enhancing system performance without introducing significant dynamic risks.

4. Simulation and Discussion of Results

4.1. Voltage Sensitivity Analysis

The Voltage Sensitivity Analysis was conducted to identify the load buses most vulnerable to voltage instability by calculating the sensitivity of bus voltages to incremental changes in reactive power injection (Q). For each load bus, a sensitivity factor (S_V) was computed, representing the change in voltage magnitude per unit change in reactive power injection as shown in Table 2 below.

Table 2. Voltage sensitivity test–IEEE 14-bus system.

Bus No.	Voltage Magnitude (p.u.)	Voltage Sensitivity (S_V) (p.u./MVar)	Remark
4	0.9933	0.0008	Low
5	0.9961	0.0008	Low
7	1.0016	0.0013	Moderate
9	0.9967	0.0017	Moderate
10	0.9899	0.0023	High
11	0.9925	0.0028	High
12	0.9875	0.0038	Very High
13	0.9830	0.0031	Very High
14	0.9715	0.0034	**Very High**

The results indicate that Bus 12, Bus 13 and Bus 14 exhibits the highest voltage sensitivity, meaning they are the most affected by changes in reactive power injection. This implies that providing reactive support near these buses would significantly improve voltage stability in the network. Buses with lower sensitivity values are less affected and thus are lower priority for reactive power interventions.

Bus 14 and Bus 12 with the highest sensitivity values are chosen as the candidate buses to improve through series compensation. However, Bus 14 is supplied by lines connecting Bus 13 to Bus 14 and Bus 9 to Bus 14. Therefore, we need to conduct a further test to determine the candidate route for series compensation. Furthermore, Bus 12 is supplied by lines connecting Bus 6 to Bus 12 and Bus 12 to Bus 13. Therefore, we need to conduct a further test to determine the candidate routes for series compensation.

4.2. Line Reactance Screening Test

To determine the most appropriate line for series compensation in the IEEE 14-Bus system, a Line Reactance Screening Test was conducted. This diagnostic test ranks transmission lines by their series reactance (X), as higher reactance often correlates with significant voltage drops and limited power transfer capability. Table 3 summarizes the findings from this test.

Table 3. Line reactance screening test-IEEE 14-bus system.

From Bus	To Bus	Line Reactance (p.u.)	Voltage Drop Indicator
1	2	0.05917	Low
1	5	0.22304	High
2	3	0.19797	Moderate
2	4	0.17632	Moderate
2	5	0.17388	Moderate
3	4	0.17103	Moderate
4	5	0.04211	Low
6	11	0.19890	Moderate
6	12	0.25581	High
6	13	0.13027	Moderate
7	8	0.17615	Moderate
7	9	0.11001	Moderate
9	10	0.08450	Low
9	14	0.27038	High
10	11	0.19207	Moderate
12	13	0.19988	Moderate
13	14	0.34802	Very High

Among all the lines, the connection between Bus 13 and Bus 14 exhibits the highest series reactance (0.34802 p.u.), categorised as *Very High*. This indicates a major contributor to voltage drop and power flow limitation into Bus 14, which is one of the most voltage-sensitive node in the network and consistent with findings from other studies [13] [14]. Line 9 - 14 also ranks highly, with a reactance of 0.27038 p.u., making it another critical path supplying Bus 14. The reactances of Line 6 - 12 and Line 12 - 13 are significantly lower than those of Line 9 - 14 and Line 13 - 14, making them theoretically unsuitable candidates for series compensation, as lower reactance lines offer limited potential for impedance reduction and performance improvement [1] [9].

Given that both Line 13 - 14 and Line 9 - 14 directly connect to Bus 14, they each play a vital role in determining the voltage profile and transfer capacity of the bus. The location of Bus 14 at the periphery of the system further amplifies the importance of these two lines in ensuring adequate voltage support and power delivery to the outer edge of the grid. Based on the combined results of the Voltage Sensitivity Analysis and Line Reactance Screening, Line 13 - 14 stands out as the most effective route for initial series capacitor deployment. While Line 13 - 14 was selected as the primary candidate for series compensation due to its maximum reactance and stronger alignment with the highest voltage sensitivity, Line 9 - 14 also presents a technically justifiable alternative, particularly where power transfer capacity enhancement is a priority.

4.3. Impact of Series Compensation

This section presents the results of load flow simulations performed using PSS®E (Power System Simulator for Engineering) to analyse the impact of series compensation on the IEEE 14-Bus System. A series capacitor was installed on the transmission line between Bus 13 and Bus 14, a strategic location selected to improve the voltage profile at Bus 14, which is typically the weakest node in the system. Compensation levels ranging from 20% to 50% of the line's reactance were applied to assess their effect on system performance.

As detailed in Section 3.4, the compensation-impact simulations are reported using a controlled corridor-isolation topology (opening the parallel path) to prevent flow sharing and to make the incremental effect of compensating a given corridor observable in a small benchmark system. Although opening the parallel line resembles an $N-1$ outage, it is used here strictly as a sensitivity/stress-test setup—not as a contingency security assessment. The 0% (base) case for each compensated corridor is solved using the same corridor-isolation topology; hence, the differences across compensation levels in **Table 4** and **Table 5** primarily reflect the effect of series compensation. A dedicated $N-1$ study that separately evaluates: 1) line outages without compensation and 2) line outages with compensation is recommended as future work to fully quantify contingency benefits.

The results from the series compensation study provide insightful information on how increasing compensation levels influence key system parameters such as voltage magnitude, power angle difference ($\Delta\delta$) between buses, line losses, and power transfer capacity. The results from **Table 4** and **Table 5** confirm the theory based on the voltage sensitivity analysis and the reactance screening that the line connecting Bus 13 to 14 is the preferred candidate for series compensation. However, the performance of Line 9 - 14 in the simulations affirms its potential as a secondary or complementary compensation path in future system upgrade strategies.

Table 4. Impact of series compensation on line 13 - 14 (with Line 9 - 14 opened for corridor isolation).

No.	Scenarios	Voltage at Bus 14 (p.u.)	$\Delta\delta$ (°) (Bus 13 - Bus 14)	Line Losses (MW)	Power Transfer Capacity (MW)
1	Base Case (No Compensation)	0.9969	2.38	0.4249	36.9
2	Scenario 1 (20% Compensation)	1.0011	1.81	0.4213	39.1
3	Scenario 2 (30% Compensation)	1.0032	1.52	0.4196	40.2
4	Scenario 3 (40% Compensation)	1.0052	1.23	0.4179	41.3
5	Scenario 4 (50% Compensation)	1.0071	0.95	0.4162	42.5

Table 5. Impact of series compensation on line 9 - 14 (with Line 13 - 14 opened for corridor isolation).

No.	Scenarios	Voltage at Bus 14 (p.u.)	$\Delta\delta$ (°) (Bus 9 - Bus 14)	Line Losses (MW)	Power Transfer Capacity (MW)
1	Base Case (No Compensation)	1.0190	2.57	0.3024	57.3
2	Scenario 1 (20% Compensation)	1.0222	2.14	0.3005	61.1
3	Scenario 2 (30% Compensation)	1.0237	1.92	0.2996	62.85
4	Scenario 3 (40% Compensation)	1.0252	1.71	0.2987	64.72
5	Scenario 4 (50% Compensation)	1.0267	1.49	0.2978	66.55

4.3.1. Voltage at Bus 14 (p.u.)

In **Table 4**, the voltage magnitude at Bus 14 shows a consistent upward trend with increasing levels of series compensation for both Line 13 - 14 and Line 9 - 14. For Line 13 - 14, the base case voltage starts at 0.9969 p.u., rising steadily to 1.0071 p.u. at 50% compensation, representing an approximate 1.02% improvement. Similarly in **Table 5**, for Line 9 - 14, the voltage increases from a higher base of 1.0190 p.u. to 1.0267 p.u. at 50% compensation, yielding a smaller relative improvement of about 0.76%. These results demonstrate that while both lines contribute to enhanced voltage stability at Bus 14, compensation on Line 13 - 14 offers a more significant relative voltage boost. Consequently, series compensation on Line 13 - 14 is more effective in improving the voltage profile and ensuring stable operation under load conditions.

4.3.2. Power Angle Difference ($\Delta\delta$)

In **Table 4** and **Table 5**, the power angle difference ($\Delta\delta$) between Bus 13 and Bus 14 consistently decreases with increasing levels of series compensation on both Line 13 - 14 and Line 9 - 14, reflecting improved system performance. For Line 13 - 14, $\Delta\delta$ drops from 2.38˚ in the base case to 0.95˚ at 50% compensation, representing a substantial 60.08% reduction. This decline indicates that series compensation effectively reduces the line reactance, thereby lowering the phase shift required to transfer power and enhancing transmission efficiency and stability [15]. Similarly, for Line 9 - 14, $\Delta\delta$ decreases from 2.57˚ in the base case to 1.49˚ at 50% compensation, amounting to a 42.02% reduction. Although the reduction is significant, it is less pronounced than that observed on Line 13 - 14. The consistently greater percentage reduction in $\Delta\delta$ for Line 13 - 14 reinforces its effectiveness in minimising impedance-related stress and supports its selection as the more suitable line for series compensation aimed at stabilising power flow to Bus 14.

4.3.3. Line Losses (MW)

In **Table 4** and **Table 5**, line losses exhibit a gradual decline with increasing levels of series compensation in both Line 13 - 14 and Line 9 - 14, reflecting improvements in transmission efficiency. For Line 13 - 14, losses reduce from 0.4249 MW in the base case to 0.4162 MW at 50% compensation, representing a 2.05% reduction. Similarly, for Line 9 - 14, losses decrease from 0.3024 MW to 0.2978 MW, a smaller but notable 1.52% reduction. While the absolute reductions may appear modest due to the IEEE 14-bus system's short line lengths and simplified loss modelling, they are consistent with the expected effects of series compensation. By lowering the line reactance, series compensation reduces the current flow required for the same power transfer, thereby decreasing I^2R losses and improving overall system efficiency. Notably, Line 13 - 14 exhibits a slightly greater percentage improvement, further supporting its suitability as the preferred path for compensation aimed at reducing transmission losses.

4.3.4. Power Transfer Capacity (MW)

The power transfer capacity, calculated using the Repeated Power Flow (RPF) method while respecting line thermal limits, bus voltage thresholds, and generator operating constraints [16]. For Line 13 - 14, as shown in **Table 4**, transfer capacity increases from 36.9 MW at zero compensation to 42.5 MW at 50% compensation, representing an approximate 15.17% enhancement. This clearly demonstrates the core advantage of series compensation in boosting the line's ability to deliver more power without breaching stability or thermal margins. Likewise, in **Table 5**, Line 9 - 14 exhibits a power transfer increase from 57.3 MW to 66.55 MW under the same compensation range, equating to a 16.14% improvement. Although the absolute capacity is higher in Line 9 - 14, the relative improvements in both cases highlight how series compensation effectively reduces line impedance, allowing the transmission path to carry greater power flows. Throughout the analysis, a minimum voltage limit of 0.9 p.u. at Bus 14 was maintained, ensuring compliance with voltage stability standards. By lowering the effective reactance of the compensated lines, the system can leverage existing infrastructure more efficiently, enabling higher power transfer while maintaining acceptable voltage and thermal conditions.

4.3.5. Evaluation and Comparative Discussion

The choice between Line 13 - 14 and Line 9 - 14 for series compensation is informed by a multi-criteria assessment that combines: 1) diagnostic indicators (voltage sensitivity and reactance ranking) and 2) simulation-based performance metrics. Line 13 - 14 aligns more strongly with Bus-14 weakness indicators and shows superior relative improvements in voltage support, angle reduction, and loss reduction, while still achieving a comparable gain in transfer capability. Line 9 - 14 offers a slightly higher absolute transfer capability in this benchmark case. **Table 6** summarises the key comparative metrics at 50% compensation.

Table 6. Comparative summary of series compensation performance at 50% compensation.

Metric (at 50% compensation)	Line 13 - 14	Line 9 - 14
Bus 14 voltage $\lvert V_{14} \rvert$ (p.u.)	1.0071 (+1.02%)	1.0267 (+0.76%)
Angle difference $\Delta\delta$ (deg)	0.95 (−60.08%)	1.49 (−42.02%)
Line losses (MW)	0.4162 (−2.05%)	0.2978 (−1.52%)
Transfer capacity (MW)	42.5 (+15.17%)	66.55 (+16.14%)

4.5. Subsynchronous Resonance Screening of Proposed Compensation Levels

Series compensation can introduce an electrical resonance between the series capacitor and the line inductance. A common first-level screening computes the electrical resonance frequency as:

$$f_r = f_s\sqrt{k}$$

where f_s is the system frequency and $k = X_c/X_l$ is the degree of compensation. For the IEEE 14-bus test case (60 Hz base frequency), **Table 7** reports the resulting subsynchronous resonance frequencies for $k = 0.2 - 0.5$ (20% - 50% compensation). The complementary (slip) frequency $f_{slip} = f_s - f_r$ is also shown because torsional interactions are often discussed in terms of slip frequency.

Table 7. First-level SSR frequency screening for 20% - 50% series compensation (f_r = 60 Hz).

Compensation level k	Electrical resonance f_r (Hz)	Slip frequency, $f_{slip} = f_s - f_r$ (Hz)
20%	26.8	33.2
30%	32.9	27.1
40%	37.9	22.1
50%	42.4	17.6

The calculated f_r values (≈26.8 - 42.4 Hz) fall within the subsynchronous range (<60 Hz). Whether these frequencies pose a practical SSR risk depends on the presence of turbine-generator torsional modes near f_r or f_{slip} and on the network damping. The IEEE 14-bus benchmark used for this steady-state study does not include detailed multi-mass shaft models; therefore, the results above are provided as an initial screening rather than a definitive SSR assessment. In real applications, an electromagnetic transient and/or torsional interaction study is recommended before deploying high series compensation levels.

5. Conclusion and Recommendation

This study has demonstrated that moderate series compensation provides measurable and technically meaningful improvements in voltage support, transmission efficiency, and power transfer capability within the IEEE 14-bus benchmark system. Using a structured two-stage placement approach—Voltage Sensitivity Analysis followed by Line Reactance Screening—the analysis identified Line 13 - 14 and Line 9 - 14 as the most impactful candidate corridors supplying the weakest bus.

Across 20% - 50% compensation levels, both corridors exhibited consistent performance gains. For Line 13 - 14, Bus 14 voltage increased to 1.0071 p.u., the power angle difference reduced by 60.08%, line losses declined by 2.05%, and transfer capability improved by 15.17%. Line 9 - 14 achieved a comparable 16.14% increase in transfer capacity with moderate reductions in angle stress and losses. Although Line 9 - 14 delivered slightly higher absolute transfer capacity, Line 13 - 14 demonstrated stronger alignment with the identified weak-bus condition and produced greater relative improvements in voltage stability and impedance stress reduction.

Accordingly, Line 13 - 14 emerges as the technically preferred compensation corridor when the primary objective is voltage reinforcement and stability enhancement, while Line 9 - 14 remains a viable alternative for capacity-oriented reinforcement strategies.

While the absolute magnitude of improvements is naturally constrained by the compact scale and light loading of the IEEE 14-bus test system, the results validate the engineering principle that targeted series reactance reduction increases transfer margins, reduces angular stress, and improves receiving-end voltage performance. The proposed screening workflow therefore provides a practical and reproducible framework for corridor selection and moderate compensation assessment prior to large-scale deployment in real transmission networks.

Finally, the first-level SSR screening reported in Section 4.5 (**Table 7**) shows that 20% - 50% series compensation corresponds to electrical resonance frequencies of approximately 26.8 - 42.4 Hz on a 60 Hz system. Because practical SSR risk depends on generator shaft torsional modes and damping, a detailed SSR study (EMT and torsional interaction modelling) is recommended prior to deploying high series-compensation levels in real networks.

Disclaimer

The views and opinions expressed in this article are those of the author and do not reflect the official position of ASR.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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