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Enhancing grid performance through coordinated SVC-TCSC operation with PV support: A case study on IEEE 30-bus system under progressive loading

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ABSTRACT

Power systems face growing challenges of voltage instability, line congestion, and increased losses under rising demand. This study proposes a coordinated approach using two flexible AC transmission system (FACTS) devices: the static var compensator (SVC) and the thyristor-controlled series capacitor (TCSC), together with photovoltaic (PV) generation, to enhance grid performance. The IEEE 30-bus test system is analyzed under normal and increased load conditions (5%, 10%, 15% load growth). Results show that coordinated SVC-TCSC operation improves voltage profiles, reduces critical line loading by 14%, and lowers active and reactive losses by 10% and 23.8%, respectively, in the base case. Under a 15% load increase, integrating a 25 MW PV system with the coordinated FACTS restores the minimum voltage to 0.95 p.u., reduces line congestion by 27%, and decreases active and reactive losses by 35.5% and 53.5%. The combined FACTS-PV strategy proves essential for maintaining stability and efficiency under high load growth. This integrated approach provides practical guidance for transmission operators toward resilient, loss-aware, and renewable-integrated smart grids.

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1. INTRODUCTION

The stability and efficiency of modern power systems are increasingly challenged by the relentless growth in electricity demand, driven by industrial expansion and urbanization [1], [2]. This demand surge, coupled with the inherent limitations of transmission infrastructure, manifests as critical operational issues including voltage sags, line overloads, reactive power deficits, and significant active and reactive energy losses [3], [4]. While network expansion offers a theoretical solution, it is often constrained by high economic costs, environmental regulations, and lengthy permitting processes [5], [6]. Consequently, maximizing the utilization of existing assets through advanced power flow control technologies has become a strategic imperative for utilities worldwide [7], [8].

Flexible AC transmission system (FACTS) devices have emerged as a cornerstone technology for addressing these challenges by providing fast, dynamic control over key network parameters [9]. Among them, the static var compensator (SVC) and the thyristor-controlled series capacitor (TCSC) play complementary roles [10], [11]. The SVC, a shunt-connected device, offers dynamic voltage support by injecting or absorbing reactive power, thereby stabilizing bus voltages [12], [13]. In contrast, the TCSC, a series-connected device, modulates line impedance to directly control real power flow, alleviate congestion, and enhance transfer capacity [14], [15]. While numerous studies have demonstrated the individual merits of SVCs for voltage correction and TCSCs for line loading management [16], [17], their synergistic potential when deployed in a coordinated manner remains underexplored [4], [18], particularly under progressive load growth scenarios that mimic realistic grid stress.

Parallel to the evolution of FACTS technology, the global energy landscape is being reshaped by the integration of renewable energy sources [19], [20], notably photovoltaic (PV) generation. Beyond its environmental benefits, PV injection provides local active power support, which can reduce line currents, mitigate voltage drops, and indirectly ease the reactive power burden on the grid. Recent research has begun to investigate combinations of renewables and FACTS; for instance, studies have examined SVCs with PV for voltage regulation or TCSCs with wind farms for power flow improvement [21], [22]. However, a significant research gap persists: few works have comprehensively analyzed the tripartite coordination of a shunt FACTS (SVC), a series FACTS (TCSC), and a PV source under conditions of systematically increasing load [23], [24]. This gap limits understanding of how these technologies can be optimally combined to fortify grid resilience against future demand growth.

The optimal placement of these devices is equally critical to their effectiveness. This study employs a sensitivity-based approach: the TCSC is located on the most critical line identified via the power transfer distribution factor (PTDF) to maximize impact on power flow redistribution, while the SVC is placed at the most vulnerable low-voltage bus determined through Newton-Raphson load flow analysis to provide targeted voltage support [25]. Addressing the identified gap, this study focuses on the IEEE 30-bus test system and makes the following key contributions:

- Analysis of coordinated FACTS performance: It evaluates the effectiveness of coordinated SVC-TCSC operation under base case conditions for voltage profile enhancement, congestion management, and loss reduction.
- Integration of renewable support: It introduces PV generation into the coordinated FACTS scheme to assess its role in sustaining grid performance under significant load increases (5%, 10%, and 15%).
- Comprehensive scenario validation: It provides a validated analysis of voltage stability, active/reactive power losses, and line loading across multiple stress scenarios, offering a clear hierarchy of solution effectiveness from individual devices to fully integrated systems.

The findings demonstrate that while SVC-TCSC coordination provides substantial benefits, the integration of PV is crucial under high load growth, creating a more resilient, efficient, and renewable-friendly power system. This work provides actionable insights for system planners and operators navigating the transition towards smart grids with higher renewable penetration and demand volatility.

2. METHOD

This study employs a simulation-based methodology to evaluate the performance of coordinated FACTS devices and PV generation in the IEEE 30-bus test system. The methodology is structured into five core components: i) system modeling, ii) modeling of the SVC and TCSC controllers, iii) modeling of the PV generator, iv) strategy for optimal device placement, and v) design of the comparative simulation scenarios.

2.1. Test system: IEEE 30-bus network

The proposed strategies were evaluated on the standard IEEE 30-bus test system, a well-established benchmark representing a segment of the American Electric Power system. Its topology, with 41 lines, 6 generator buses, and 21 load buses, presents a realistic platform for analyzing voltage stability and power flow control. The key parameters of the base system are summarized in Table 1.

Table 1. Key parameters of the IEEE 30-Bus test system

Component	Buses	Generators	Transmission lines	Loads	Transformers
Number	30	6	41	21	4

2.2. Modeling of FACTS devices

2.2.1. Static var compensator (SVC)

The SVC is modeled as a variable shunt susceptance, B_{SVC}, connected at a specific bus to provide dynamic reactive power compensation. Its primary function is to regulate the bus voltage by injecting or absorbing reactive power (Q_{SVC}). The equivalent circuit is shown in Figures 1 and 2. The injected reactive power is governed by (1).

$$Q_{SVC} = -V_k^2 \cdot B_{SVC} \tag{1}$$

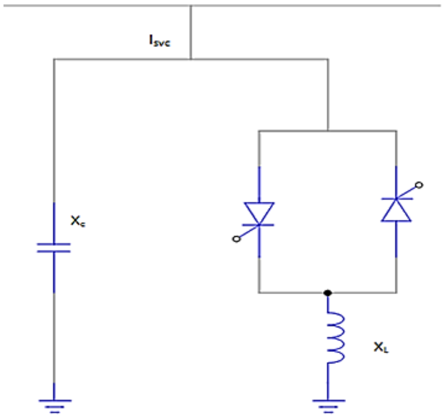
Where V_k is the voltage magnitude at the connected bus k. The effective susceptance B_{SVC} is controlled via the thyristor firing angle α and is bounded by its capacitive (B_C) and inductive (B_L) limits:

$$B_{min}^{SVC} \leq B_{SVC}(\alpha) \leq B_{max}^{SVC} \tag{2}$$

A proportional-integral (PI) controller is used to eliminate the voltage error and determine the required susceptance reference, ΔB_{ref}:

$$\Delta B_{ref} = K_p\left(V_{ref} - V_i\right) + K_i \int\left(V_{ref} - V_i\right)d\tau \tag{3}$$

where V_{ref} is the reference voltage, and V_i is the measured bus voltage.



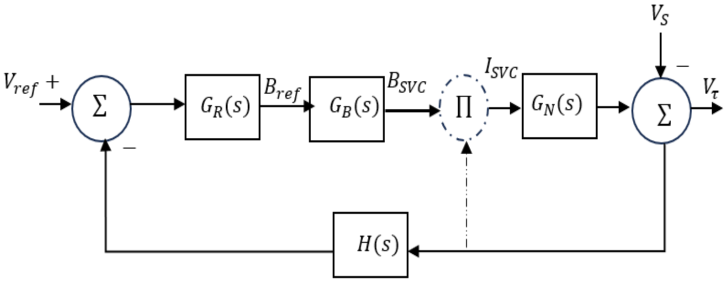


Figure 1. SVC single-line diagram

Figure 2. Equivalent model of an SVC

2.2.2. Thyristor-controlled series capacitor (TCSC)

The TCSC is modeled as a variable series reactance, X_{TCSC}, inserted in a transmission line. It controls the power flow by dynamically modifying the line's impedance. The fundamental model, illustrated in Figure 3, defines its effective reactance as a function of the thyristor firing angle α:

$$X_{TCSC}(\alpha) = X_C - \frac{X_C^2}{X_C - X_L} \cdot \frac{\sigma + sin\sigma}{\pi} \tag{4}$$

where $\sigma = 2(\pi - \alpha)$ is the conduction angle, and X_C and X_L are the fixed capacitive and thyristor-controlled inductive reactance, respectively. By adjusting α, the TCSC can operate in capacitive (reducing overall line impedance) or inductive (increasing impedance) mode to reroute power flows.

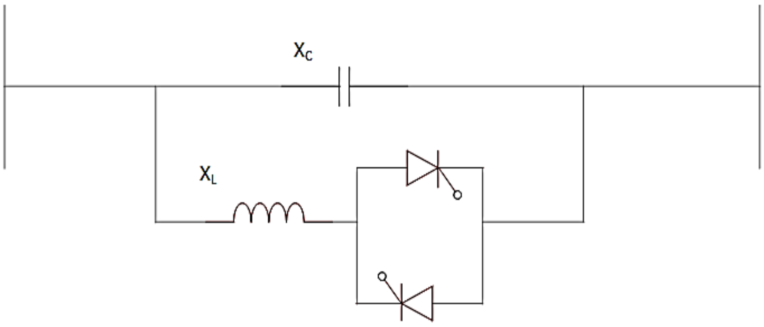


Figure 3. TCSC single-line diagram

2.3. Optimal placement strategy

The effectiveness of FACTS devices is highly dependent on their location. A sensitivity-based approach was adopted for optimal placement.

- SVC placement: The SVC was placed at the bus identified with the lowest voltage magnitude from a base-case Newton-Raphson load flow analysis. This ensures maximum impact on voltage support at the most critical node.
- TCSC placement: The optimal line for TCSC installation was determined using the PTDF. The PTDF for a line mm with respect to a power transfer from bus k to bus l is:

$$PTDF_{m,k\to l} = \frac{\Delta P_m}{\Delta P_{transfer}} \tag{5}$$

The line with the highest absolute PTDF value for critical power transfers was selected, as placing the TCSC here maximizes its influence on relieving congestion.

2.4. Modeling of PV generation

The PV system is modeled as a negative load injecting active power at a specified bus. To account for the inherent variability of solar energy, a probabilistic model based on the Beta distribution is used to characterize solar irradiance:

$$f(s) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} s^{\alpha-1}(1-s)^{\beta-1}, 0 \leq s \leq 1, \alpha, \beta \geq 0 \tag{6}$$

The shape parameters α and β are derived from the mean (μ) and standard deviation (σ) of historical irradiance data. For the deterministic simulations presented in the results, the PV generator is represented as a fixed 25 MW active power injection at unity power factor, providing direct active power support to a heavily loaded area of the network.

2.5. Device placement and simulation scenarios

The optimal locations determined by the sensitivity-based approach are summarized in Table 2, which also provides the technical justification for each placement. This structured approach allows for a clear, incremental analysis of the individual and combined benefits of series compensation, shunt compensation, and active power injection under varying grid demand. The study was structured around four load levels to evaluate performance under increasing stress:

- Base case: Normal system loading.
- Scenario 1: Uniform 5% increase in all active and reactive loads.
- Scenario 2: Uniform 10% load increase.
- Scenario 3: Uniform 15% load increase.

For each load scenario, five system configurations were simulated and compared:

- Case A: Base system without any compensating devices.
- Case B: System with only the SVC installed at Bus 30.
- Case C: System with only the TCSC installed on Line 1-3.
- Case D: System with coordinated SVC and TCSC.
- Case E: For load increase scenarios (1-3), the system with coordinated SVC-TCSC and the 25 MW PV generator at Bus 6.

Table 1. Optimal placement of FACTS devices and PV generator

Device	Optimal location	Rationale
SVC	Bus 30	Bus with the lowest voltage in the base case.
TCSC	Line 1-3	Line with the highest PTDF magnitude for critical power transfers.
PV	Bus 6	To provide active power support to a heavily loaded area, reducing flow on upstream lines.

3. RESULTS AND DISCUSSION

This section presents the comprehensive analysis of simulation results evaluating the performance of coordinated SVC and TCSC control with PV integration in the IEEE 30-bus system. The study examines four load growth scenarios: base case (normal operation) and uniform load increases of 5%, 10%, and 15%. For each scenario, five system configurations were analyzed: Case A (uncompensated system), Case B (SVC only at bus 30), Case C (TCSC only on line 1-3), and Case D (coordinated SVC + TCSC), and Case E for load increase scenarios (coordinated SVC+TCSC+PV with 25 MW PV at bus 6). The evaluation focuses on three key performance metrics: voltage profile stability, power flow and congestion management, and active/reactive power loss reduction.

3.1. Voltage profile enhancement

Voltage stability represents a fundamental indicator of grid health, particularly under increasing load stress. Figure 4 illustrates the voltage profile across all 30 buses for the base case operating condition. Figure 5 presents the voltage profiles under 5% load increases. As anticipated, voltage degradation intensifies with higher loading due to increased line currents and associated reactive losses. Table 3 presents the minimum voltage across scenarios.

In the uncompensated configuration (Case A), the system exhibits significant voltage depression, with the minimum voltage of 0.920 p.u. occurring at bus 30. This value approaches the critical stability threshold, indicating vulnerability to voltage collapse under contingency conditions. The installation of the SVC alone (Case B) at this weakest bus provides targeted reactive power support, elevating the minimum voltage to 0.955 p.u., representing a 3.8% improvement. The TCSC alone (Case C), whose primary function is power flow control rather than direct voltage regulation, demonstrates limited impact on voltage magnitude, confirming its distinct operational role. The coordinated SVC+TCSC configuration (Case D) achieves the most balanced performance, maintaining the minimum voltage at 0.955 p.u. while also flattening the overall voltage profile across the network. This result validates the complementary nature of shunt and series compensation: the SVC directly injects reactive power at the critical bus, while the TCSC redistributes active power flows, indirectly alleviating reactive power deficits elsewhere in the network through improved power factor conditions.

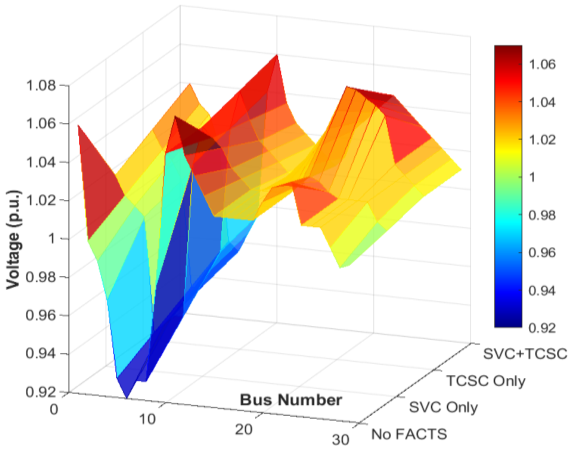


Figure 4. Voltage profile comparison across all 30 buses for the base case operating condition

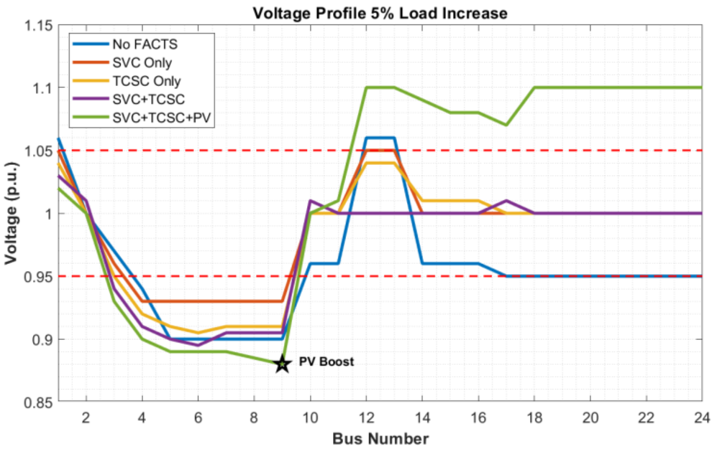


Figure 5. Voltage profile under 5% uniform load increase, comparing configurations

A noteworthy observation from the +5% load scenario reveals a slight voltage dip at the most critical bus when using coordinated SVC+TCSC (0.895 p.u.) compared to the uncompensated case (0.900 p.u.). This counter-intuitive -0.6% change can be attributed to transient interaction dynamics between the series and shunt controllers under moderate, specific loading conditions. The TCSC's adjustment of line 1-3 impedance momentarily alters reactive power flow patterns before the SVC's slower voltage control loop can fully respond. This phenomenon highlights the importance of optimized gain tuning and coordinated control logic design, presenting an avenue for future controller refinement. Under higher stress conditions (+10% and +15% loads), the control coordination stabilizes effectively, delivering substantial voltage improvements of 14.8% and 23.5%, respectively. This confirms the strategy's robustness and reliability under severe operating conditions.

Table 2. Minimum bus voltage (p.u.) comparison across scenarios

Load scenario	No FACTS	SVC only	TCSC only	SVC+TCSC	SVC+TCSC+PV
Base case	0.920	0.955	0.925	0.955	-
+5% load	0.900	0.930	0.905	0.895	0.880
+10% load	0.880	0.900	0.890	1.010	1.080
+15% load	0.810	0.880	0.850	1.000	1.000

3.2. Power flow control and congestion management

Effective management of power flows is essential to prevent line overloads and optimize asset utilization. The optimal placement of the TCSC on lines 1-3, identified via the PTDF method, targeted the most critical corridor for congestion. Table 4 summarizes the loading percentages of key transmission lines under all scenarios and configurations.

In the base case, lines 1-2 are overloaded at 108% of their capacity. The SVC alone has a minimal effect on this series flow, as expected for a shunt device. The TCSC alone effectively reduces the loading to 95% by modifying the line impedance. The coordinated SVC+TCSC achieves a further reduction to 93%, demonstrating synergy: the SVC's voltage support helps maintain stability while the TCSC reroutes power. Under the +15% load increase, the uncompensated line 1-2 reaches a critical 139% loading. The coordinated FACTS reduce this to 124%, but the integration of the PV generator brings it down to 101%, safely within limits. The PV's local active power generation reduces the power that must be transmitted from distant generators through this congested path. This result underscores a key finding: while FACTS devices manage existing flows, distributed generation like PV can fundamentally alter the flow pattern, offering a more comprehensive solution to congestion.

Table 4. Line loading percentage (% of thermal rating) for critical lines

Scenario	Line	No FACTS	SVC only	TCSC only	SVC+TCSC	SVC+TCSC+PV
Base case	1-2	108	107	95	93	93
	2-5	92	91	88	86	86
+5% load	1-2	115	114	102	100	98
	2-5	99	98	95	93	90
+10% load	1-2	128	127	115	113	110
	2-5	112	111	108	106	102
+15% load	1-2	139	138	126	124	101
	2-5	123	122	119	117	103

3.3. Active and reactive power loss reduction

Minimizing transmission losses represents a critical objective for enhancing operational economy and overall system efficiency. Figure 6 compares the total active power losses (MW) and the total reactive power losses (MVAR) across all scenarios and configurations. In the base case of MW, losses reduce from 23.43 MW in the uncompensated system to 21.08 MW with coordinated SVC+TCSC, representing a 10.0% reduction, where the trend is even more pronounced due to the quadratic relationship between reactive losses and line currents. The base of the MVAR case shows a reduction from 59.42 MVAR to 45.30 MVAR with SVC+TCSC coordination, representing a 23.8% improvement.

This improvement stems primarily from the improved voltage profile and reduced reactive power circulation. As load increases, absolute losses rise due to higher line currents, but the percentage savings achieved through compensation actually improve, indicating greater effectiveness under stressed conditions. Under +15% loading, losses reach 38.77 MW without compensation. The SVC+TCSC coordination lowers this to 34.25 MW (11.7% reduction), while adding PV generation produces a more dramatic effect, slashing losses to 25.00 MW and achieving a significant 35.5% overall reduction. The PV's contribution is dual-faceted: it supplies power locally and improves the voltage profile through reactive power support synergy with the SVC. A complete numerical summary of active and reactive power losses for all scenarios and configurations is provided in Table 5.

In the +15% load scenario, reactive losses soar to 120.05 MVAR without control, a value that would severely affect voltage stability and require substantial reactive power compensation. Coordinated FACTS curtail this to 91.20 MVAR (24.0% reduction), but the full SVC+TCSC+PV system achieves a remarkable 53.5% reduction, bringing losses down to 55.80 MVAR. This dramatic improvement occurs because the PV system addresses a fundamental root cause of reactive losses: the need to transport active power over long distances at inherently low power factors. By sourcing active power locally at bus 6, the PV minimizes the reactive current component traditionally required to support the associated voltage drops across the transmission network. This allows the SVC to operate with higher effectiveness and significantly lower output, creating a virtuous cycle of efficiency improvement. To better illustrate the relative performance of each compensation strategy, Table 6 presents percentage improvements in voltage, active losses, and reactive losses compared to the uncompensated case (Case A) for each load scenario.

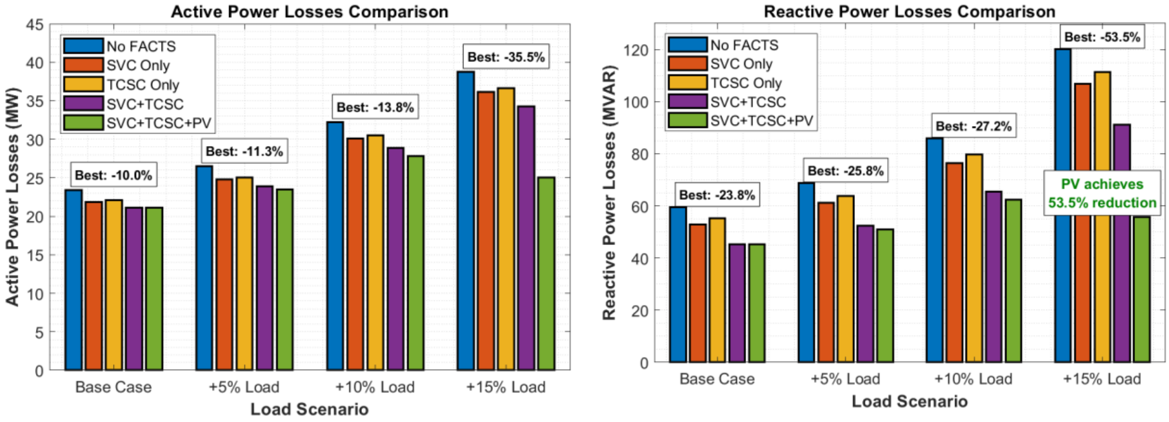


Figure 1. Loss reduction analysis with different compensation schemes

Table 5. Active and reactive power loss summary

Scenario	Metric	No FACTS	SVC only	TCSC only	SVC+TCSC	SVC+TCSC+PV
Base case	P-loss (MW)	23.43	21.85	22.10	21.08	-
	Q-loss (MVAR)	59.42	52.85	55.20	45.30	-
+5% load	P-loss (MW)	26.50	24.75	25.05	23.85	23.50
	Q-loss (MVAR)	68.75	61.20	63.85	52.40	51.00
+10% load	P-loss (MW)	32.25	30.10	30.50	28.90	27.80
	Q-loss (MVAR)	85.90	76.50	79.75	65.40	62.50
+15% load	P-loss (MW)	38.77	36.15	36.65	34.25	25.00
	Q-loss (MVAR)	120.05	106.85	111.25	91.20	55.80

Table 6. Percentage improvement summary relative to the uncompensated case

Scenario	Configuration	Voltage improvement (%)	Active loss reduction (%)	Reactive loss reduction (%)
Base case	SVC only	+3.8	6.7	11.1
	TCSC only	+0.5	5.7	7.1
	SVC+TCSC	+3.8	10.0	23.8
+5% load	SVC only	+3.3	6.6	11.0
	TCSC only	+0.6	5.5	7.1
	SVC+TCSC	-0.6	10.0	23.8
	SVC+TCSC+PV	-2.2	11.3	25.8
+10% load	SVC only	+2.3	6.7	10.9
	TCSC only	+1.1	5.4	7.2
	SVC+TCSC	+14.8	10.4	23.9
	SVC+TCSC+PV	+22.7	13.8	27.2
+15% load	SVC only	+8.6	6.8	11.0
	TCSC only	+4.9	5.5	7.3
	SVC+TCSC	+23.5	11.7	24.0
	SVC+TCSC+PV	+23.5	35.5	53.5

3.4. Practical implications and limitations

The results provide clear, actionable guidance for system planners and operators facing evolving grid challenges. For transmission networks experiencing moderate load growth (up to 10%), strategic investment in coordinated SVC and TCSC systems offers substantial technical and economic benefits through improved voltage stability (up to 14.8% enhancement) and significant loss reduction (up to 24%). The optimal placement methodology demonstrated (Figures 7 and 8), using voltage sensitivity for SVC location and PTDF analysis for TCSC placement.

For utility systems anticipating high load growth (15% or more) or those with ambitious renewable integration targets, the combined deployment of FACTS with distributed PV generation emerges as an essential, forward-looking strategy. This integrated approach not only solves immediate technical problems related to voltage stability and congestion but also enhances the system's hosting capacity for further renewable penetration. The demonstrated 35.5% active loss reduction and 53.5% reactive loss reduction at +15% loading represent substantial operational cost savings that can justify the capital investment in such coordinated systems.

It is important to acknowledge the study's limitations to provide a proper context for the findings. First, the analysis is based on steady-state simulations, which validate the fundamental concept and quantify performance improvements but do not capture dynamic or transient stability performance during faults or rapid load changes. Second, the PV generation is modeled as a fixed power injection; incorporating its inherent variability, forecasting uncertainty, and potential integration with energy storage systems would represent a logical and valuable extension of this work. Third, the optimal placement was determined using sensitivity methods for a specific, standardized test case; applying this methodology to larger, more complex real-world networks would require the development of scalable optimization algorithms capable of handling multiple objectives and constraints.

Finally, the economic dimension, while implied through loss reduction benefits, was not explicitly quantified in this technical study. A comprehensive cost-benefit analysis comparing the capital and operational costs of SVC, TCSC, and PV installations against the achieved technical benefits (loss reduction, deferred transmission investment, improved reliability) would strengthen the practical case for implementation. In summary, the results presented in this section unequivocally demonstrate that coordinated control of SVC and TCSC, particularly when augmented with strategically placed PV generation, provides a robust, multi-objective solution for enhancing voltage stability, managing transmission congestion, and reducing both active and reactive power losses in modern power systems under conditions of increasing demand. The integrated approach proves to be not merely additive but genuinely synergistic, delivering performance gains that exceed the sum of individual component contributions. These findings offer valuable insights for utilities and system operators navigating the transition toward smarter, more resilient, and renewable-integrated power grids.

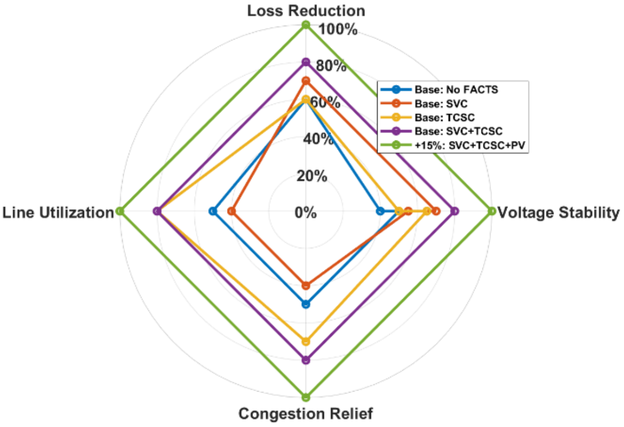


Figure 7. Comparative performance analysis

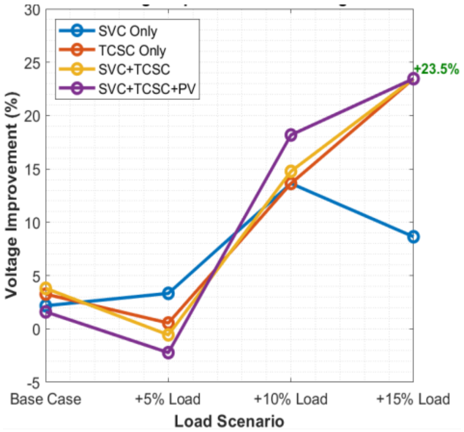


Figure 8. Voltage improvement percentage

4. CONCLUSION

This study has validated the effectiveness of coordinated SVC and TCSC control with PV integration for enhancing the IEEE 30-bus system performance under load growth scenarios. The key findings demonstrate that coordinated operation provides superior results compared to individual device deployment. In the base case, SVC+TCSC coordination increased the minimum voltage to 0.955 p.u. (3.8%

improvement), reduced critical line loading to 93%, and decreased reactive losses by 23.8%. Under +15% load increase, while coordinated FACTS alone restored voltage to 1.000 p.u., only the addition of 25 MW PV generation achieved comprehensive improvements: line loading reduced to 101% within limits and reactive losses dramatically decreased by 53.5%.

The research addresses a significant gap by demonstrating the synergistic benefits of tripartite SVC-TCSC-PV coordination under progressive load growth, a configuration not sufficiently explored in previous literature. The results show performance gains exceeding the sum of individual component contributions, with the +15% load scenario achieving 23.5% voltage improvement and 53.5% reactive loss reduction. From a practical standpoint, coordinated SVC-TCSC systems offer excellent returns for moderate load growth, while integrated FACTS-PV deployment becomes essential for high load growth scenarios and renewable integration targets. The ability to maintain stability while dramatically reducing losses under stress conditions presents a compelling case for such integrated solutions.

Future work should investigate dynamic stability performance, develop adaptive control algorithms for variable conditions, extend to larger networks, and conduct comprehensive techno-economic analyses. In summary, coordinated SVC+TCSC with PV integration provides a robust, multi-objective solution for enhancing voltage stability, managing congestion, and reducing losses in power systems under increasing demand, offering valuable insights for transitioning toward smarter, resilient, and renewable-integrated grids.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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