Reactive Power Compensation Using FACTS Devices for Voltage Stability Improvement in Power Systems

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***Abstract*—Reactive power compensation is important for maintaining acceptable voltage profiles and improving the operating performance of electrical power systems under varying loading conditions. This paper evaluates a simplified, bounded reactive-power injection model representing Static Synchronous Compensator (STATCOM) support in the IEEE-30 bus test system. Two equivalent compensators are considered at buses 26 and 30, with a reference voltage of 1.00 p.u. and an assumed reactive-power injection limit of ±10 MVAr per device. The system is evaluated at loading levels from 80% to 150% of the base load using Newton–Raphson power-flow analysis. The uncompensated and compensated cases are compared in terms of minimum bus voltage, voltage magnitudes at the controlled buses, active and reactive power losses, reactive-power injection, voltage-regulation error, convergence, and operating-limit status. At 100% loading, minimum voltage increases from 0.98256 p.u. to 0.99307 p.u. At 150% loading, it increases from 0.70724 p.u. to 0.84967 p.u.; active power losses decrease from 63.370 MW to 54.928 MW, and reactive power losses decrease from approximately 219.15 MVAr to 182.48 MVAr. However, the assumed reactive-power limits are reached under high loading, and voltage references cannot always be maintained. The results show the potential benefits and capacity limitations of the implemented simplified model and should not be interpreted as validation of a detailed converter-based STATCOM.**

***Index Terms*—Reactive power compensation, FACTS devices, STATCOM, IEEE-30 bus system, voltage profile, power losses, loading variation.**

I. INTRODUCTION

The increasing demand for electrical energy places significant pressure on power transmission networks to operate efficiently and reliably while maintaining acceptable voltage levels. As electrical loads increase, networks may experience voltage deviations, higher transmission losses, and greater reactive-power demand. Maintaining a satisfactory voltage profile under changing operating conditions is therefore an important aspect of power-system planning and operation.

Reactive power supports the establishment of bus-voltage magnitudes and influences the transfer capability of an AC network. Inadequate reactive-power support can contribute to low voltages and deteriorating operating conditions, particularly during heavy loading. Conveyntional compensation equipment, including shunt capacitors and reactors, is widely used; however, the response and controllability of such equipment depend on its design and operating arrangement. Flexible compensation methods are consequently important for managing voltage and reactive-power requirements.

Flexible AC Transmission Systems (FACTS) devices use power-electronic or controlled-reactance technologies to influence selected power-system variables. Shunt-connected FACTS controllers, including the Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM), are used for reactive-power compensation and voltage regulation. A STATCOM can inject or absorb reactive power at its connection point, subject to its control strategy and capability limits. The resulting effect on the wider network depends on system topology, loading, device location, and available compensation capacity [1], [2].

Power-flow analysis provides a steady-state method for examining bus voltages, phase angles, generation, and network losses under specified operating conditions. The Newton–Raphson method is widely used to solve the nonlinear power-balance equations in power systems. Comparing a base case with a compensated case at the same loading level provides a

way to quantify the changes associated with reactive-power support [2], [3].

This study examines the IEEE-30 bus test system using MATLAB-based power-flow scripts. Two equivalent STATCOM devices are represented at buses 26 and 30, and the system loading is varied from 80% to 150% of the original load. The main objective is to evaluate changes in minimum bus voltage, voltages at the controlled buses, active and reactive power losses, reactive-power injection, and controller performance. The work is limited to the implemented bounded reactive-power injection model; it does not claim to reproduce the complete electrical dynamics or converter equations of a practical STATCOM.

II. LITERATURE REVIEW

Shunt FACTS Devices for Voltage Regulation

Shunt FACTS devices are used to provide reactive-power support and influence the voltage magnitude at or near their point of connection. SVC models are commonly represented using a controllable shunt susceptance, while detailed STATCOM power-flow models may represent a voltage-source converter connected to the AC network through an equivalent coupling impedance. The mathematical representation affects the network equations and the behaviour captured by the simulation.

Studies Using the IEEE-30 Bus System

Berrouk et al. studied shunt FACTS controllers for voltage-stability improvement and presented SVC and STATCOM models for power-flow analysis of an IEEE-30 bus system. Their work considered compensation at buses 26 and 30 and examined voltage-profile changes with and without the controllers [1]. This provides relevant background for selecting the benchmark network and connection buses in the present study. The present implementation differs in its device representation and should not be interpreted as a direct reproduction of the detailed models described in that paper.

Need for Loading-Dependent Evaluation

Performance at a single loading point does not show how reactive-power requirements and controller capability change as demand increases. A loading-dependent assessment can reveal the evolution of minimum voltage, network losses, voltage-regulation error, and device saturation. It is also important to distinguish numerical convergence of the power-flow equations from successful voltage control and from compliance with operating limits. This study applies those separate checks to the base and compensated cases over eight loading levels.

Scope of the Present Study

The study compares only two cases: the uncompensated base network and the same network with two equivalent STATCOM devices. It does not present a comparative simulation of SVC, TCSC, UPFC, or other FACTS devices. The conclusions are specific to the network data, bounded injection limits, and control procedure implemented in the MATLAB scripts.

III. FACTS DEVICES AND STATCOM OPERATING PRINCIPLE

Reactive Power and Voltage Regulation

In an AC power system, active power is primarily associated with energy transfer, while reactive power is closely related to the magnetic and electric fields required by network components. Reactive-power imbalance can affect voltage magnitudes, especially in electrically weak or heavily loaded areas. Local reactive-power compensation can reduce the reactive demand supplied through parts of the transmission network and can therefore improve voltage conditions and influence losses.

STATCOM Principle

A practical STATCOM is a shunt-connected power-electronic compensator based on a voltage-source converter. By controlling the magnitude and phase relationship of its AC-side voltage relative to the network voltage, the device exchanges reactive power with the system. Depending on the operating condition, it can operate in a capacitive mode to inject reactive power or in an inductive mode to absorb reactive power. Its real-world capability depends on converter rating, DC-link conditions, current limits, coupling impedance, and the controller design.

A practical VSC-based STATCOM uses a voltage-source converter, a DC-link capacitor, a coupling transformer, and a controller. The transformer couples the converter output to the AC network, while its leakage reactance limits and shapes the exchanged

current. The controller measures the AC-bus voltage and adjusts converter modulation to regulate voltage or reactive-power exchange. The conceptual arrangement in Fig. 1 illustrates this practical architecture; it is not a circuit model implemented directly in the present MATLAB study.

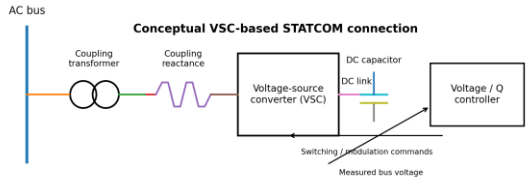


Fig. 1. Conceptual configuration of a practical VSC-based STATCOM.

Equivalent-circuit interpretation

In a conventional steady-state equivalent circuit, the converter is represented by a controllable AC voltage source $E\angle\delta$ connected to the network bus $V\angle\theta$ through coupling impedance $Z = R + jX$. The current flowing from the converter toward the bus can be written as $I = (E\angle\delta - V\angle\theta)/(R + jX)$. The complex power injected at the bus is $S = P + jQ = V I^*$, where I^* is the complex conjugate of the injected current. This voltage-source representation is commonly used in detailed STATCOM power-flow models [4].

For a predominantly inductive coupling reactance and a small angle difference, exchanged active power is strongly related to the phase-angle difference, while reactive-power exchange is strongly related to the difference between converter-voltage magnitude and bus-voltage magnitude. An idealized lossless approximation is $P \approx (VE/X)\sin(\delta - \theta)$ and $Q \approx [V(E\cos(\delta - \theta) - V)]/X$, under the stated current/power sign convention. These equations explain the physical operating principle; they are not the equations used to calculate STATCOM output in the present simplified model.

Reactive-power control and capability limits

A voltage controller compares measured voltage with its reference. The voltage error at controlled bus i is $e_i = Vref_{,i} - V_i$. A controller adjusts reactive-power injection to reduce $|e_i|$, subject to the device capability. For the present study, the assumed bound is -10 MVAr $\leq Qinj_{,i} \leq +10$ MVAr for each device. If the required injection falls outside this interval, the device saturates and the reference voltage may not be achieved. The bounded injection can be expressed as $Qinj_{,i} = \min(Qmax, \max(Qmin, Qcmd_{,i}))$, where $Qcmd_{,i}$ is the controller-requested injection, Qmax = +10 MVAr, and Qmin = −10 MVAr.

The distinction between a practical converter model and the model used here is important. The circuit diagram and voltage-source equations describe the general engineering principle of a practical STATCOM. In contrast, the simulations reported in this paper use a simplified bounded reactive-power injection at buses 26 and 30. They do not explicitly solve converter switching, DC-link dynamics, internal converter losses, or the complete voltage-source converter equations. Therefore, the numerical results demonstrate the behaviour of the implemented equivalent injection model, rather than validating a full converter-based STATCOM.

Power-flow equations and network losses

For an n-bus network, the complex bus injection is $S_i = P_i + jQ_i = V_i I_i^*$, with $I_i = \Sigma_{j=1}^{n} Y_{ij}V_j$. Separating real and imaginary parts gives the nonlinear active- and reactive-power balance equations used in the Newton–Raphson method. At each iteration, the mismatch vector is $\Delta f = [\Delta P; \Delta Q]$, and the state correction is obtained from $J\Delta x = \Delta f$, where J is the power-flow Jacobian and Δx contains corrections to voltage angles and applicable voltage magnitudes. Iterations continue until the mismatch is below the selected tolerance or the iteration limit is reached.

The active-power loss over a branch connecting buses i and j is evaluated from the branch-end power flows as $PLOSS,ij = Pij + Pji$. The total network active loss is $PLOSS = \Sigma branches(Pij + Pji)$. Reactive loss can similarly be evaluated as $QLOSS = \Sigma branches(Qij + Qji)$, with interpretation affected by branch charging and shunt elements. In this paper, the reported losses are those calculated by the project's power-flow implementation and are compared at identical loading levels.

Equivalent Model Used in This Work

For the present study, each STATCOM is represented as a bounded equivalent reactive-power injection rather than a complete converter-based voltage-source model. The controlled buses are 26 and 30, both with a voltage reference of 1.00 p.u. The assumed reactive-power injection range is −10 MVAr to +10 MVAr for

each device. These limits are modelling assumptions for this study and are not presented as verified manufacturer ratings. Positive injection represents capacitive reactive-power support, while negative injection represents reactive-power absorption.

The simplified representation is useful for investigating the effect of bounded reactive-power support in a steady-state loading study. However, it does not represent all converter, switching, DC-link, or dynamic-control characteristics of a practical STATCOM. Accordingly, the results are interpreted as a study of the implemented equivalent model.

IV. SYSTEM MODEL AND METHODOLOGY

IEEE-30 Bus Test System

The test network contains 30 buses, six generators, and 41 branches, with a system base of 100 MVA. The original total active and reactive loads are 283.4 MW and 126.2 MVAr, respectively. The network model includes bus, generator, branch, transformer, and shunt data used to form the bus-admittance matrix. The base-case power flow is solved before applying the loading variation and compensation cases.

TABLE I. IEEE-30 BUS SYSTEM AND STUDY PARAMETERS

Parameter	Value
Test network	IEEE-30 bus system
Buses / generators / branches	30 / 6 / 41
System base	100 MVA
Base active load	283.4 MW
Base reactive load	126.2 MVAr
STATCOM locations	Buses 26 and 30
Voltage reference	1.00 p.u. per device
Assumed Q limit	±10 MVAr per device

Newton–Raphson Power-Flow Formulation

The steady-state power flow is governed by nonlinear active- and reactive-power balance equations. For bus i, the calculated injections can be expressed as:

$P_i = V_i \Sigma_j V_j [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)]$

$Q_i = V_i \Sigma_j V_j [G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)]$

where V_i and δ_i are the voltage magnitude and phase angle at bus i, and G_{ij} and B_{ij} are the conductance and susceptance elements of the bus-admittance matrix. The Newton–Raphson algorithm updates the unknown voltage magnitudes and angles using the power mismatch and Jacobian matrix until the specified convergence criterion is met or the iteration limit is reached.

Loading Variation

The original active and reactive demands are uniformly scaled by the loading factor λ. For each load bus i:

$P_{D,i}(\lambda) = \lambda P_{D,i}(0)$ and $Q_{D,i}(\lambda) = \lambda Q_{D,i}(0)$

The loading levels considered are 80%, 90%, 100%, 110%, 120%, 130%, 140%, and 150% of the base load. At each level, the base and STATCOM cases use the same scaled load demands so that the effect of compensation can be compared consistently.

STATCOM Control Procedure

In the compensated case, the two equivalent devices are placed at buses 26 and 30. Each controller attempts to move the local bus voltage toward 1.00 p.u. by adjusting reactive-power injection within its assumed limits.

The effective reactive demand at a controlled bus is represented as $Q_{D,i,eff} = Q_{D,i} - Qinj_{,i}$. The power flow is solved iteratively during the control process. Power-flow convergence and voltage-control convergence are recorded separately, because a converged network solution does not necessarily mean that the voltage reference has been achieved. When a device reaches its injection limit or no further improving control correction is found, the controller may stop with a residual voltage error. The study records injection levels and saturation flags to identify such cases.

Performance Measures

The comparison uses minimum system voltage, the bus at which the minimum occurs, voltages at buses 26 and 30, active power losses, reactive power losses, STATCOM injections, voltage-regulation error, convergence status, and operating-limit indicators. The change in minimum voltage is $\Delta V_{min} = V_{min,STATCOM} - V_{min,Base}$. Percentage active-loss reduction is $RP = 100(P_{LOSS,Base} - P_{LOSS,STATCOM})/P_{LOSS,Base}$, and percentage reactive-loss reduction is $RQ = 100(Q_{LOSS,Base} - Q_{LOSS,STATCOM})/Q_{LOSS,Base}$. Positive loss-reduction values indicate lower losses in the compensated case. The absolute voltage-regulation error is $E_i = |V_{ref,i} - V_i|$.

V. RESULTS AND DISCUSSION

Minimum Bus Voltage

The minimum bus voltage declines as loading increases in the uncompensated base case. At 100% loading, the minimum voltage improves from 0.98256 p.u. in the base case to 0.99307 p.u. with STATCOM support. At 110% loading, it increases from 0.96864 to 0.98743 p.u.; at 120%, from 0.94105 to 0.97144 p.u.; and at 130%, from 0.88719 to 0.94653 p.u. At 140% loading, the minimum voltage changes from 0.81802 to 0.90757 p.u. At 150%, it changes from 0.70724 to 0.84967 p.u. These results show improved minimum voltage in the compensated case across the reported loading range, but the remaining voltage depression at heavy loading indicates that compensation does not remove all operating concerns.

TABLE II. MINIMUM BUS VOLTAGE COMPARISON

Loading	Base Vmin	STATCOM Vmin
80%	0.9971	0.9970
90%	0.9922	0.9951
100%	0.9826	0.9931
110%	0.9686	0.9874
120%	0.9410	0.9714
130%	0.8872	0.9465
140%	0.8180	0.9076
150%	0.7072	0.8497

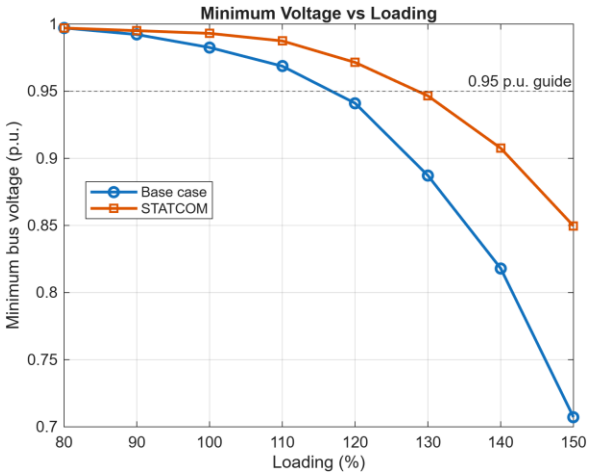


Fig. 2. Minimum bus voltage versus loading.

Voltage at the Controlled Buses

At 100% loading, the base-case voltages at buses 26 and 30 are approximately 0.99085 p.u. and 0.98256 p.u., respectively. With STATCOM control, both buses are brought close to the 1.00 p.u. reference. At 130% loading, the control process also approaches the references, although the bus-30 device is close to its assumed upper injection limit. At 140% and 150% loading, the available reactive-power injection is insufficient to maintain both voltage references. Thus, the controlled-bus results show both the regulation benefit and the effect of finite compensation capability.

Active and Reactive Power Losses

At 100% loading, active losses decrease from approximately 17.684 MW to 17.620 MW, while reactive losses decrease from 34.171 MVAr to 33.894 MVAr. At 120% loading, active losses decrease from 27.359 MW to 26.918 MW and reactive losses from 72.869 MVAr to 70.478 MVAr. At 140% loading, active losses decrease from 45.295 MW to 42.018 MW and reactive losses from 145.74 MVAr to 130.64 MVAr. At 150% loading, active losses decrease from 63.370 MW to 54.928 MW, while reactive losses decrease from approximately 219.15 MVAr to 182.48 MVAr. The calculated reductions suggest that the equivalent reactive-power support changes network operating conditions in a way that lowers the losses in these cases. The magnitude of the benefit depends on the loading level and the resulting power-flow solution.

TABLE III. ACTIVE AND REACTIVE POWER LOSSES

Load	Base P loss	STATCOM P	Base Q loss	STATCOM Q
80%	10.72	10.75	7.53	7.63
90%	13.94	13.93	19.86	19.80
100%	17.68	17.62	34.17	33.89
110%	22.02	21.87	51.02	50.23
120%	27.36	26.92	72.87	70.48
130%	34.79	33.30	103.14	95.88
140%	45.29	42.02	145.74	130.64
150%	63.37	54.93	219.15	182.48

Reactive-Power Injection and Saturation

At 100% loading, the reported reactive-power injections are approximately 0.482 MVAr at bus 26 and 2.381 MVAr at bus 30. At 130% loading, injections rise to approximately 7.023 MVAr and

9.999 MVAr, respectively, placing the bus-30 device effectively at its assumed upper limit.

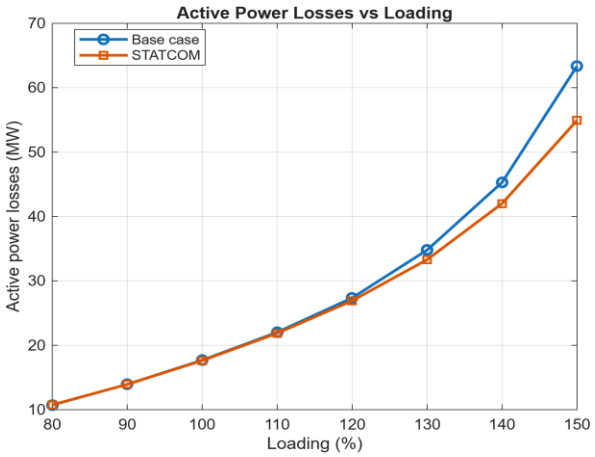


Fig. 3. Active power losses versus loading.

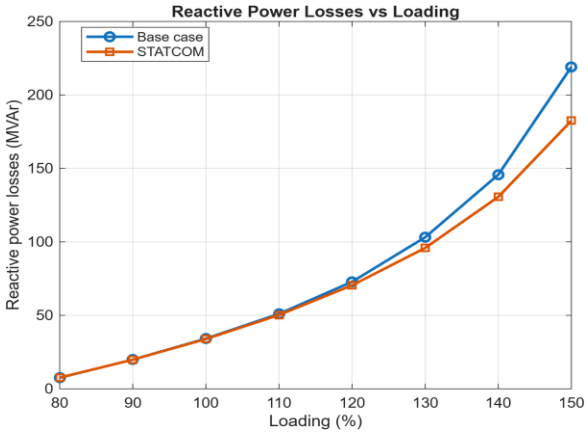


Fig. 4. Reactive power losses versus loading.

At 140% and 150% loading, both devices reach approximately +10 MVAr, while the voltage-control targets remain unmet. The saturation results indicate that the available compensation capacity in the selected model becomes insufficient for the requested voltage regulation under the heaviest loading conditions.

TABLE IV. STATCOM REACTIVE-POWER INJECTION

Load	Q26	Q30
80%	-1.41	0.28
90%	-0.48	1.31
100%	0.48	2.38
110%	1.65	3.75
120%	3.60	6.18
130%	7.02	10.00
140%	10.00	10.00
150%	10.00	10.00

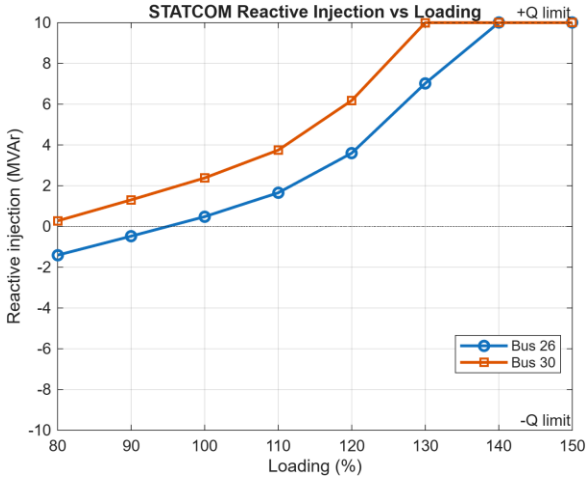


Fig. 5. STATCOM reactive-power injection versus loading.

Convergence and Operating Limits

The power-flow solver reports numerical convergence at all eight loading levels for both cases. However, convergence of the power-flow equations is not equivalent to successful voltage regulation or full compliance with all operating limits. The controller reaches its voltage targets at six of the eight loading levels; at 140% and 150%, it cannot maintain the references because both devices reach their assumed upper reactive-power limits.

At 150% loading, the minimum voltage in the compensated case is 0.84967 p.u. at bus 19, and the study reports voltage and reactive-power-limit violations. These cases should therefore be described as numerically converged power flows with unsuccessful voltage control and/or operating-limit violations, rather than as fully satisfactory operating states.

Overall Interpretation

Across the tested cases, the simplified STATCOM representation improves the minimum voltage and reduces calculated active and reactive losses. The benefit becomes especially noticeable at heavy loading, but the finite injection limits constrain voltage regulation as demand rises. The results are specific to the selected network data and simplified bounded-injection controller. They do not establish a formal voltage-stability margin, transient stability performance, or the performance of every practical STATCOM implementation.

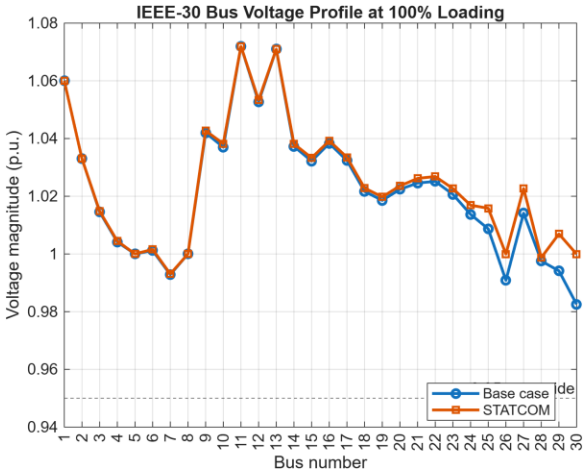


Fig. 6. IEEE-30 bus voltage profile at 100% loading.

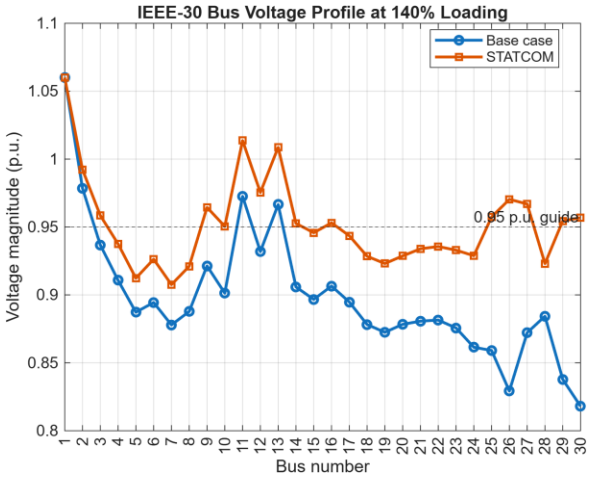


Fig. 7. IEEE-30 bus voltage profile at 140% loading.

VI. CONCLUSION AND FUTURE SCOPE

This paper evaluated reactive-power compensation using two equivalent STATCOM devices at buses 26 and 30 of the IEEE-30 bus test system. The uncompensated and compensated cases were compared under loading levels from 80% to 150% using MATLAB-based Newton–Raphson power-flow analysis. The evaluated measures included minimum bus voltage, controlled-bus voltages, active and reactive power losses, reactive-power injection, controller convergence, and operating-limit status.

The results show that the implemented STATCOM model improves minimum bus voltage and reduces calculated active and reactive power losses in the reported cases. At 100% loading, minimum voltage increases from 0.98256 p.u. to 0.99307 p.u. At 150% loading, it increases from 0.70724 p.u. to 0.84967 p.u.; active losses decrease from 63.370 MW to 54.928 MW, and reactive losses decrease from approximately 219.15 MVAr to 182.48 MVAr. Nevertheless, at 140% and 150% loading, both devices reach their assumed +10 MVAr limits and the voltage references cannot be maintained. The study therefore demonstrates both the potential benefit and the capability limitations of the selected simplified model. Future work should implement and validate a detailed converter-based STATCOM model, investigate alternative device locations and ratings, and enforce generator reactive-power limits directly within the power-flow formulation. Additional voltage-stability analysis, such as continuation power flow, could provide a more direct estimate of loading margin. Further comparison with trusted benchmark software would also strengthen validation of the numerical results.

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