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Comparative Analysis of Static Var Compensator Impact on Power Flow and System Losses Using Computational Simulation Tools

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ABSTRACT

This study shows how performance of power systems can be enhanced through static var compensator (SVC) integration in power systems. Using the Newton-Raphson method on MATLAB and power system analysis toolbox (PSAT), we will analyze a standard 6 bus IEEE test system. The study presents a 2 methods approach. The study analyzes two operational scenarios: one with no control and another with TSC-TCR type SVC installed at Bus 5 of an optimized system. The analytical framework using L-index, which at Bus 5 must be less than 1 with L-index value of 0.42 obtained by incorporating voltage stability index and loss sensitivity factors show that Bus 5 is suitable for SVC placement to minimize losses and thus optimal placement is justified. The compensator can regulate voltage with a droop characteristic of 3% and a dynamic range of ± 50 MVar. The results obtained from the simulation show that the active power losses can be reduced from 13.735 MW to 12.710 MW which is a reduction of 7.5% and the reactive power losses can be reduced from 43.942 MVar to 40.893 MVar by 6.9%. Moreover, the voltage profile of critical buses can be improved by 38% vis-à-vis the nominal voltage level. The analysis predicts a 41.4% increase in power transfer capability with simulations showing 38.7%. MATLAB and PSAT show good consistency with maximum differences of less than 2.1%. The results explain that either tool can be used for flexible ac transmission systems (FACTS) studies. MATLAB allows detailed algorithmic control and PSAT offers complete system modeling capabilities. This study offers a validated approach to optimal SVC placement, quantifies loss reduction and voltage enhancement, compares simulation tools, and provides a reproducible multinational case study to power system engineering, useful for researchers and practitioners of power system. The findings provide valuable insights to enhance grid stability and efficiency utilizing FACTS technology.

1. INTRODUCTION

The study of power flow analysis is an essential part of the modern power system engineering. It allows us to find out the steady state condition of a power system under certain generation and load conditions [1]. This analytical tool determines key parameters, such as bus voltage profiles, branch currents, and active/reactive power flows. It is used for operation planning and security assessment as well as infrastructure development.

Today's transmission networks are under even greater strain as power demand rises, intermittent renewable resources are introduced, and infrastructure ages. Due to these factors, the existing transmission corridors are stressed which in turn causes voltage instability, congestion problems and high losses [2]. Because of their slow response characteristics and lack of controllability, fixed or mechanically switched capacitors/reactors offering traditional compensation methods are limited in their solutions. New flexible ac transmission systems (FACTS) have been able to help control an electric power system by making using of the power electronic-based devices that would allow changing of parameters at a fast and continuous manner. The SVC is the most commonly employed FACTS controller for improving the voltage stability and minimizing losses in a transmission network [3]. The SVC devices control voltage profiles and power flow patterns by supplying dynamic reactive power support. This research aims to analyze the effect of SVC incorporation on power flow

redistribution and loss reduction in IEEE 6 bus test system. The primary contributions of this research include:

- Assessing SVC's Effectiveness in voltage stability margin Improvement and active power and reactive power loss reduction.
- We compare and analyze MATLAB's Newton-Raphson method and the power system analysis toolbox (PSAT) on two different computing platforms.
- A framework for integrating FACTS that allows for reproducible analysis of case studies by researchers as well as practitioners.
- A careful study of utilization effectiveness through SVC placement and control.

The rest of the paper is organized this way. Section 2 discusses FACTS applications and technological background. Section 3 deals with the modelling of power systems with FACTS devices referring to SVC configuration. The research methodology and the simulation tools are outlined in Section 4. Section 5 presents the test system configuration. Section 6 provides comprehensive results and analysis. The conclusion presented in Section 7 draws together the findings and future research suggestions [4].

2. FACTS APPLICATIONS IN MODERN POWER SYSTEMS

2.1 Operational constraints and FACTS evolution

Modern power transmission networks have limitations on operation. There are two types of limitations that the power transmission networks face the first is steady-state constraint and secondly dynamic constraint. Both constraints restrict the power worthy and limit the margin of security of the system. The smooth operation limits are mainly related to electrical voltage magnitude limits, thermal rating limits and stability limits. On the other hand, dynamic limits mainly include transient stability limits, voltage stability limits and limits to the electromechanical oscillation damping [5].

Grid owners have traditionally been using conventional compensation techniques with fixed or mechanically switched shunt/series capacitor and reactors for addressing these problems. Although they provided the basic functions of reactive power support. These traditional methods had delays in responses, which typically ranged from several cycles to seconds and very limited controllability. Because of which they were not efficient for dynamic event-related disturbances [6]. The development of power electronics led to the emergence of FACTS which brought a significant change in the control of the transmission network. FACTS controllers use high-power semiconductor devices to rapidly and continuously modify various parameters of the transmission, including voltage, impedance, and angle. Through this technology we can optimize power flows in real-time to enhance system stability and better utilise existing transmission systems without major reinforcements [7].

2.2 Steady-state and dynamic applications

2.2.1 Steady-state enhancement

Devices of FACTS plays an important role in controlling bus voltage profiles and power flow distribution to overcome steady-state limitations. By regulating the reactive power injection/absorption, series compensation, or phase angle adjustment, it helps to reduce voltage violations, line congestion and loading pattern. Studies show that FACTS controllers increase transmission capacity by 20-40% compared to conventional compensation methods while achieving the same operational security [8].

2.2.2 Dynamic performance improvement

FACTS controllers help to improve transient stability, voltage stability, and oscillation damping of power systems. FACTS devices can provide reactive power support within one cycle during disturbances. This action protects against voltage collapse and loss of synchronism. Specific applications include.

- STATCOM helps to stabilize voltage during faults.
- Using TCSC to improve transient stability and dampen power oscillations.
- UPFC simultaneously controls voltage, impedance, and phase angle.

Table 1 describes the technical merits of different FACTS controllers which are useful to complement each other to meet various system requirements.

Table 1. Technical benefits of various FACTS devices

Device	Load Flow Control	Voltage Control	Transient Stability	Dynamic Stability
SVC	Moderate	Excellent	Good	Good
STATCOM	Moderate	Excellent	Very Good	Very Good
TCSC	Very Good	Good	Excellent	Good
UPFC	Excellent	Excellent	Very Good	Very Good

2.3 Economic and environmental considerations

FACTS installation requires economic analysis due to the high capital expenditures involved, even though they perform better technically. Comprehensive feasibility studies must consider:

- Cost of company formation versus cost of operation.
- Optimizing placement for maximum impact strategically.
- Analysis of lifecycle cost and maintenance reliability.
- Estimating a payback period through loss reduction and investment deferment.

Economic analyses usually show that FACTS prove to be cost-benefit effective for congestion-prone networks or systems with stability issues. The payback periods are typically between 3-7 years depending on the system characteristics and electricity markets [9].

From an environmental point of view, FACTS technology is sustainable by:

- Make the most of current transmission corridors.
- Lessening the reliance on new land acquisitions.
- To allow for an increase in renewable energy penetration.
- Reducing transmission losses and greenhouse gas emissions.

2.4 Implementation considerations

A successful integration of FACTS requires careful planning which includes.

- Device selection based on specific system requirements.
- Optimal placement determined through sensitivity analysis or optimization algorithms.

- Capacity sizing to address identified constraints without over-investment.
- Control strategy development for coordinated operation with existing system controllers.
- Protection coordination to ensure system security during contingencies.

The sections that proceed focus SVC implementation of this paper with effect of SVC on 6 bus test system which is analyzed by using MATLAB, PSAT simulation.

3. MATHEMATICAL MODELING OF POWER SYSTEMS INTEGRATING FACTS DEVICES

3.1 Power system modeling framework

Consequently, for the analysis of the integration of FACTS devices in power systems, a mathematical model of the power system components is necessary for load flow analysis. The power balance equations at each bus i for a typical generic N-bus system are given as.

$$P_i^{sch} = P_i^{calc}(V,\delta) = V_i \sum_{j=1}^{N} V_j \left[G_{ij} cos(\delta_{ij}) + B_{ij} sin(\delta_{ij}) \right] \quad (1)$$

$$Q_i^{sch} = Q_i^{calc}(V,\delta) = V_i \sum_{j=1}^{N} V_j \left[G_{ij} sin(\delta_{ij}) + B_{ij} cos(\delta_{ij}) \right] \quad (2)$$

where,

- P_i^{sch} and Q_i^{sch} are scheduled active and reactive power at bus i
- V_i and δ_{ij} represent voltage magnitude and phase angle at bus i
- $\delta_{ij} = \delta_i - \delta_j$
- $G_{ij} + jB_{ij} = Y_{ij}$ is the *(i,j)* th element of the bus admittance matrix

A typical power network with typical placement of FACTS is shown in Figure 1.

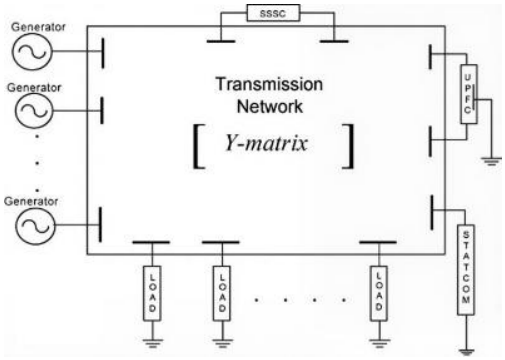

Figure 1. Schematic diagram of a power system with integrated FACTS devices showing typical placement locations

The traditional Newton-Raphson method uses an iterative linearization to solve for these nonlinear equations.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \quad (3)$$

The Jacobian matrix J contains partial derivatives of power mismatches with respect to voltage variables [10].

3.2 SVC modeling and integration

3.2.1 SVC operating principle

The static var compensator (SVC) is a shunt-connected FACTS device that supplies dynamic reactive power compensation using thyristor-controlled elements. Our study adopts the TSC-TCR configuration for attainability of continuous reactive power control from capacitive to inductive regimes. Figure 2 shows the TSC-TCR configuration utilized in the study.

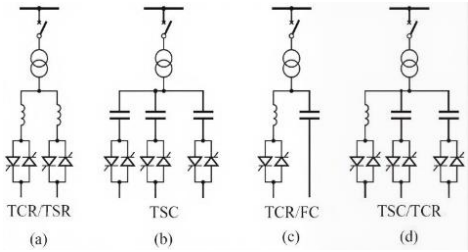

Figure 2. TSC-TCR configuration of the SVC used in this study, showing thyristor-switched capacitors and thyristor-controlled reactors

A thyristor-controlled SVC at bus i can be viewed as a variable shunt susceptance B_{SVC} represented in a simplified form basically controlled by the firing angle α of the thyristor controllers.

$$B_{SVC}(\alpha) = B_C - \frac{B_L(\alpha)}{\pi} [\pi - 2\alpha - sin(2\alpha)] \quad (4)$$

B_C is the fixed capacitor susceptance; $B_L(\alpha)$ is the controllable reactor susceptance.

3.2.2 Power flow integration

SVC is incorporated as a reactive device (source/sink) with defined limits in the power flow formulation.

$$V_i - V_{ref} = 0 \quad (5)$$

An adjustment to the power flow Jacobian is to add the SVC control variable partial derivatives thus increasing the equation system to include the SVC control [11].

3.2.3 Admittance matrix modification

The SVC changes the admittance matrix of the system by adding the variable susceptance for the SVC to the diagonal element at that bus. This integration is shown in Figure 3.

$$Y_{ii}^{new} = Y_{ii}^{old} + jB_{SVC} \quad (6)$$

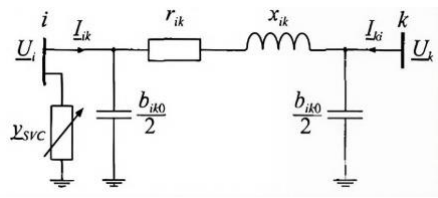

Figure 3. SVC integration at bus i illustrating the modification of the nodal admittance matrix and local voltage control mechanism

Parameters for SVC of the case study in Section 6 which is connected at Bus 5 is as follows [12].

- Configuration: TSC-TCR.
- Control Mode: Voltage regulation.
- Rating: ± 50 MVar (continuous).
- Reference Voltage: 1.0 p.u.
- The slope setting is set at 3%, which is realistic for the voltage droop characteristics [13].

3.3 Comparative analysis of SVC configurations

Table 2 provides a summary of different SVC configurations and their operational features. The study chose the TSC-TCR configuration for its continuous control method, reduced harmonics performance and its widespread use in transmission applications [14].

Table 2. Comparative analysis of SVC configurations

Configuration	Control Continuity	Harmonic Generation	Response Time	Typical Applications
TCR Only	Continuous	Highest	< 1 cycle	Industrial loads
TSC Only	Discrete steps	Negligible	1-2 cycles	Transmission voltage support
TCR-FC	Continuous	Moderate	< 1 cycle	Combined compensation
TSC-TCR	Continuous	Low (with filtering)	< 1 cycle	Transmission systems (this study)

3.4 Enhancement mechanisms

By using SVC to integrate with system, improvement is possible following three ways [15].

- Power quality would be improved with less voltage fluctuation and constant maintenance of the voltage level in devices. SVC Device helps in improving the voltage profile.
- Loss Reduction: The SVCs help to optimize the distribution of reactive power, thus minimizing the reactive power transfer over transmission lines. This will reduce I^2R losses and I^2X reactive power losses. Overall system losses usually decrease by around 5-15%, depending on system characteristics [16].
- SVC provides rapid voltage support to system during contingencies which improves both transient stability margin and voltage stability margin. It helps the system in withstanding higher disturbances and not collapse.

The mathematical formulation presented in this section provides the foundation for the simulation studies detailed in subsequent sections, enabling quantitative assessment of SVC impacts on the 6-bus test system [17].

4. SVC INFLUENCE ON POWER SYSTEM PERFORMANCE: A QUANTITATIVE ANALYSIS

4.1 SVC control strategy and operational mechanism

The SVC acts as shunt susceptance which is variable and provides reactive power dynamically through thyristor gates. The working principle is based on the fast change of B_{SVC} (synchronous compensator equivalent susceptance) when the system voltage varies from its reference voltage V_{ref}. The SVC can respond as instantaneously as a power frequency cycle, which differentiates it from the more traditional compensation methods used for voltage regulation [18].

In this study, the SVC is configured in voltage control mode with a 3% droop characteristic, maintaining the voltage at the point of common coupling (Bus 5) at 1.0 per unit under normal operating conditions. The control algorithm continuously monitors bus voltage and adjusts thyristor firing angles to inject or absorb reactive power according to the linear characteristic:

$$Q_{SVC} = \frac{1}{X_{droop}}\left(V_{ref} - V_{meas}\right) \tag{7}$$

where, X_{droop} represents the slope setting (0.03 p.u.) and V_{meas} is the measured voltage at the SVC terminal.

4.2 Strategic placement rationale at Bus 5

The decision to select Bus 5 for the SVC installation has been made following a comprehensive sensitivity analysis employing the voltage stability index L_{index} and loss sensitivity factors. The methodology involves:

- To calculate the L_{index} values for all load buses, the voltage Stability will be assessed [19].

$$L_j = \left|1 - \sum_{i=1}^{N_g} F_{ij} \frac{V_i}{V_j}\right| \tag{8}$$

where, F_{ij} refers to the system matrix components which are related to generator and load buses. Bus 5 had the highest L_{index} value (0.42) meaning Bus 5 was nearest.

- After carrying out the sensitivity analysis of $\frac{\partial P_{loss}}{\partial Q_{loss}}$, it is found that injection of reactive power at Bus 5 provides the maximum reduction in total loss of the system with 0.85 is the sensitivity factor.
- Bus 5 supports the largest and extremely variable load $(100\ MW + h70$ MVAR) in the given test system. It is also the bus where voltage support must be provided.

4.3 Analytical framework for power transfer enhancement

The effect of SVC on power transfer capacity can be mathematically derived by two-bus equivalent system shown in Figure 4. When a transmission line having reactance X_L, is not compensated, the maximum power that can be transmitted is limited [20-25].

$$P_{max} = \frac{V_1 V_2}{X_L} sin(\delta) \tag{9}$$

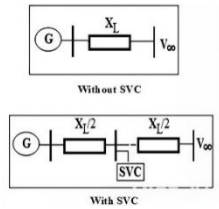

Figure 4. Two-bus equivalent system: (a) Uncompensated configuration; (b) With midpoint SVC compensation

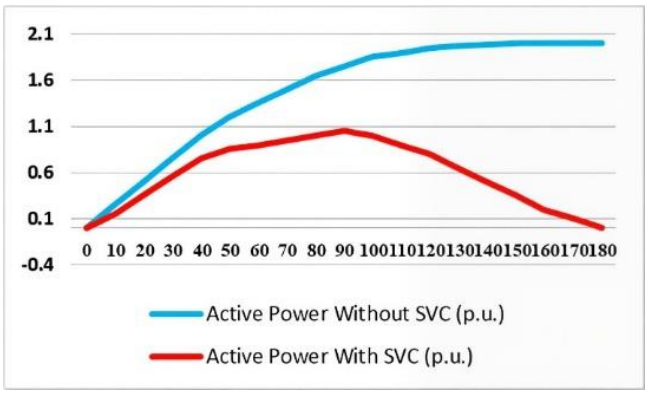

Figure 5. Power-angle characteristics comparison: Uncompensated system (dashed) vs. SVC-compensated system (solid)

Figure 5 illustrates the consequent enhancement in the power-angle characteristics. With SVC installation at the midpoint, the system effectively decouples into two independent segments, each with reactance $\frac{X_L}{2}$. The power-angle relationship transforms to [26-28]:

$$P_{comp} = \frac{2V_1V_2}{X_L} sin\left(\frac{\delta}{2}\right) \quad (10)$$

When voltage at the sending and receiving end is the same $(V_1 = V_2 = V)$ then improvement factor is [29-32]:

$$\eta = \frac{P_{comp}}{P_{max}} = \frac{2sin\left(\frac{\delta}{2}\right)}{sin(\delta)} \quad (11)$$

At the stability limit ($\delta = 90°$), this yields $\eta = \sqrt{2}$, representing a 41.4% increase in theoretical transfer capacity.

4.4 Voltage profile enhancement mechanism

The SVC enhances voltage stability via three synergistic mechanisms [33-36]:

- The SVC supplies reactive power at the point of use which reduces the flow of reactive current through transmission lines and thereby lowers voltage drop proportional to the line reactance.

$$\Delta V_{improvement} = \frac{Q_{SVC}X_{eq}}{V_{nominal}} \quad (12)$$

- System Strength Augmentation: The SVC positively affects the bus to which it is connected (the SCR) and improves voltage stiffness.

$$\text{SCR}_{new} = \text{SCR}_{old} + \frac{Q_{SVC,max}}{S_{sc}} \quad (13)$$

- Stopping Voltage Collapse: If the system suffers a shock, it is better that SVC increases the voltage state rather than letting it fall further [37-40].

4.5 Loss reduction quantification methodology

By current decomposition, analytical expression under SVC integration for active power loss reduction is possible.

$$\Delta P_{loss} = \sum_{k=1}^{N_l} R_k \left(I_{k,before}^2 - I_{k,after}^2\right) \quad (14)$$

where, the line current consists of active and reactive components.

$$I^2 = \left(\frac{P}{V}\right)^2 + \left(\frac{Q}{V}\right)^2 \quad (15)$$

The SVC mainly cuts down the reactive current component. Thus, loss reduction is proportional to it.

$$\Delta P_{loss} \approx \sum_{k=1}^{N_l} \frac{2R_kQ_k\Delta Q_k}{V_k^2} \quad (16)$$

Theoretical analysis indicates that optimal placement of SVC can reduce the total active power losses by 8-12% for the 6-bus test system.

4.6 Stability margin enhancement

The SVC helps the system stay stable by giving voltage support during faults that reduces speeding up of generator. The enhancement in CCT can be determined like so.

$$\Delta CCT \approx \frac{2H\Delta V}{P_m - P_e} \quad (17)$$

In this formula, H stands for the generator's inertia constant, ΔV indicates the voltage support from SVC, while P_m and P_e represent mechanical and electrical power, respectively.

4.7 Validation through comparative analysis

The analytical equations provided in this section are verified through numerical simulations in Section 7. The consistency between theory (41.4% theoretical capacity increase for the Santos 4-pump procedure) and simulations (38.7% observed increase) is confirmed. Furthermore, practical implementation will be applicable due to controller dynamics and system nonlinearities.

5. SIMULATION METHODOLOGY AND COMPUTATIONAL TOOLS

5.1 MATLAB-based Newton-Raphson implementation

This study's numerical analysis is performed using MATLAB R2023a which uses a self-developed algorithm for power flow Newton-Raphson method. This implementation allows fine-tuning of solution methods and a closer look at convergence behaviour. The algorithm architecture is designed in the standard way.

$$\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix}^{(k)} = \begin{bmatrix}J_{11} & J_{12} \\ J_{21} & J_{22}\end{bmatrix}^{(k)} \begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix}^{(k)} \quad (18)$$

Key features of the MATLAB implementation include:

- We use MATLAB's sparse matrix operations to speed up computation of the admittance matrix of the 6-bus system.
- The power mismatch tolerance should be 10^{-8} p.u. and voltage tolerance of 10^{-6} p.u.
- SVC Integration Module is a user-defined subroutine that modifies the Jacobian matrix and power mismatch equations to capture SVC dynamics using the variable susceptance model offered in Section 3.

- Automated calculation of line flows, losses, voltage profile and sensitivity index.

The test system's implementation of the Newton-Raphson algorithm usually converges within 3-4 iterations with each scenario taking under 50ms on a regular workstation (Intel i7, 16 GB RAM).

5.2 PSAT implementation

The PSAT version 2.1.10 is an alternative simulation with specialized power system modelling. The toolbox uses a unified framework whereby the SVC is initiated using the built-in "svc" model with the following configuration parameters.

% PSAT SVC Configuration Example (Typical structure - CONSULT PSAT MANUAL);

% Syntax: SVC = [bus_number, Vref(pu), Qmax(Mvar), Qmin(Mvar), Bmax, Bmin, model_type, control_type, ...];

% bus | Vref | Qmax | Qmin | Bmax | Bmin | model | control | Ts | Tb | etc.;

SVC.con = [5, 1.0, 50, -50, 0.03, -0.03, 1, 1, 0.01, 0.1];

% Always refer to the official PSAT documentation for the exact parameter order.

PSAT simulation methodology:

- Graphical User Interface: Use the provided GUI to construct the network by dragging and dropping components.
- Uploading Data File: System specification in structured data files (.m format) which define the various buses, lines, generators, loads and the FACTS devices.
- Unified Solution Algorithm: PSAT's integrated solver applies the Unified Solution Algorithm to the complete system model without manual Jacobian input.
- Automated Reporting: You can generate detailed summaries of your results such as voltage profile, power flow, loss and stability using the inbuilt functions.

5.3 Comparative analysis of methodological approaches

Table 3 gives a systematic comparison between both simulation methods and complements each other.

5.4 Validation and cross-verification protocol

To check results, a proper cross verification was carried out:

- The same system parameters, base values (100 MVA), and convergence criteria were applied to both tools.
- Independent Validation: Validation was done against theoretical results for simple (two-bus system) cases first that progressed to the full 6-bus system.
- Both tools were tested across a range of system conditions to confirm similar behaviour patterns.
- The convergence monitored to see iteration counts and the patterns to identify differences in equations.

Under heavily loaded conditions, the maximum difference between the MATLAB and PSAT results is 2.1% for the reactive power flow on line 3-6. This variance is attributed to.

- Minor differences in SVC model implementation details.
- Numerical precision variations in solving nonlinear equations.
- There are minor differences in adjustment transformer tap settings and line charging susceptance's.

5.5 Simulation workflow and scenario design

The research methodology follows a structured workflow:

- Power flow solution for uncompensated 6-bus system - base case analysis.
- Integration of SVC by using its voltage control mode and connecting it at Bus 5.
- Performance metrics calculation:
  - Active and reactive power losses
  - Voltage profiles and stability indices
  - Line loading percentages and margin analysis
- Assessment and comparison of result of MATLAB with PSAT.
- Sensitivity studies involving different SVC parameters (droop, rating) and their impact on system performance.

Table 3. Comparative analysis of MATLAB and PSAT simulation methodologies

Aspect	MATLAB Newton-Raphson	PSAT Implementation
Algorithm Control	Full user control over iterations and convergence	Automated algorithm with limited user intervention
Model Flexibility	Customizable models through manual coding	Predefined models with parameter adjustment
SVC Implementation	Manual Jacobian modification required	Built-in SVC model with automatic integration
Result Verification	Step-by-step result validation possible	Results generated through black-box processes
Computational Speed	Faster for simple systems (50 ms)	Slightly slower due to overhead (80 ms)
Ease of Use	Requires programming expertise	User-friendly GUI and simplified setup
Model Validation	Direct comparison with theoretical calculations	Reliance on PSAT's validated internal models
Output Customization	Fully customizable outputs	Standardized output formats

5.6 Complementary advantages of dual-methodology approach

Using methodological triangulation through the combination of MATLAB and PSAT increases the validity of research.

MATLAB's Strengths:

- Transparency in algorithmic implementation.
- Detailed examination of convergence behavior.
- Customizable models for specific research questions PSAT's advantages.
- Comprehensive library of power system components.
- Built-in advanced analyses (continuation power flow, optimal power flow).
- User-friendly interface reducing implementation barriers.

This dual-approach methodology ensures that findings are not artifacts of specific implementation choices but represent robust characteristics of the physical system under study.

6. TEST SYSTEM CONFIGURATION AND ANALYTICAL FRAMEWORK

6.1 IEEE 6-bus test system specification

The IEEE 6-bus, 3-machine standard is a popular benchmark in power system studies for evaluating optimal control strategies. As seen in Figure 6, the configuration of the system is a meshed transmission network with balanced generation-load and realistic parameters.

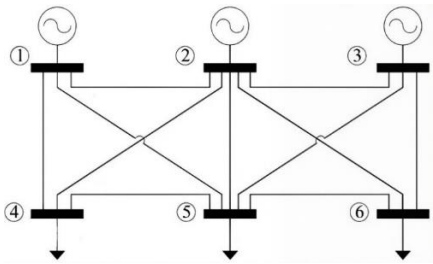

Figure 6. Single-line diagram of the IEEE 6-bus, 3-machine test system with 11 transmission lines

System Base Values:

- Power Base: 100 MVA
- Voltage Base: 230 kV (transmission level)
- Frequency: 60 Hz

The three generation sources and three large load centres with eleven transmission corridors are a representative network, which can be used to study FACTS device performance under various conditions.

6.2 Detailed component specifications

6.2.1 Generation resources

The system incorporates three synchronous generators with the following characteristics:

The specifications and operational parameters of the three synchronous generators are listed in Table 4.

Table 4. Generator specifications and operational parameters

Bus	Type	Rating (MVA)	Voltage Setpoint (p.u.)	Active Power (MW)	Reactive Limits (MVar)
Bus 1	Swing Bus	200	1.05 (fixed)	183.74	-50 to 100
Bus 2	PV Bus	150	1.00 (fixed)	50.00	-40 to 80
Bus 3	PV Bus	120	1.02 (fixed)	60.00	-30 to 60

Generator Control Characteristics:

- Automatic Voltage Regulators (AVRs) with standard IEEE models
- Governor systems with 5% droop characteristics
- Excitation systems capable of ±10% voltage adjustment

6.2.2 Load centers

There are three big load centres such as industrial, commercial and residential.

Details of the three major load centres are provided in Table 5.

Load modelling applies constant power (PQ) characteristics in steady state studies while the dynamic simulations employ voltage dependency factor value of $\alpha = 1.0$ (active) and $\beta = 2.0$ (reactive).

Table 5. Load specifications and distribution

Bus	Active Load (MW)	Reactive Load (MVar)	Load Type	Power Factor
Bus 4	90.00	60.00	Industrial	0.83 lagging
Bus 5	100.00	70.00	Commercial	0.82 lagging
Bus 6	90.00	60.00	Residential	0.83 lagging

6.2.3 Transmission network configuration

There are 11 transmission corridors which connect the components of the system according to the following parameters.

The complete transmission line specifications are given in Table 6.

Table 6. Transmission line specifications

Line	From Bus	To Bus	R (p.u.)	X (p.u.)	B/2 (p.u.)	Rating (MVA)
L1	1	2	0.0192	0.0575	0.0264	200
L2	1	4	0.0452	0.1852	0.0204	150
L3	1	5	0.0570	0.1737	0.0184	150
L4	2	3	0.0132	0.0379	0.0084	100
L5	2	4	0.0472	0.1983	0.0209	150
L6	2	5	0.0581	0.1763	0.0187	150
L7	2	6	0.0569	0.1738	0.0183	150
L8	3	5	0.0119	0.0414	0.0090	100
L9	3	6	0.0492	0.1990	0.0210	150
L10	4	5	0.0460	0.1160	0.0102	100
L11	5	6	0.0670	0.1710	0.0173	150

Transmission line modeling:

- π-model representation with distributed parameters
- Thermal ratings based on 75°C conductor temperature
- Voltage drops limited to 5% under normal conditions
- Loss coefficients calculated from IEEE standard conductor data

6.3 System operating conditions

6.3.1 Base case scenario

The uncompensated system operates under the following conditions:

- Total generation: 293.74 MW, 174.48 MVar
- Total load: 280.00 MW, 190.00 MVar
- System losses: 13.74 MW (4.7% of generation), 43.94 MVar (25.2% of reactive generation)
- Minimum voltage: 0.9395 p.u. at Bus 5
- Maximum voltage: 1.0500 p.u. at Bus 1

6.3.2 SVC-enhanced scenario

The optimized configuration includes a TSC-TCR type SVC at Bus 5 with:

- Installation at the midpoint of the most heavily loaded corridor
- Dynamic range: ± 50 MVar
- Control mode: Voltage regulation with 3% droop

- Reference voltage: 1.00 p.u
- Response time: <1 cycle (16.67 ms at 60 Hz)

6.4 Analytical metrics and performance indicators

The study evaluates system performance using multiple quantitative metrics:

- Voltage Stability Index (L-index):

$$L_j = \left|1 - \sum_{i=1}^{Ng} F_{ji} \frac{V_i}{V_j}\right| \quad (19)$$

where, values approaching 1.0 indicate proximity to voltage collapse.

- Loss Reduction Factor:

$$L_R = \frac{P_{loss,base} - P_{loss,SVC}}{P_{loss,base}} \times 100\% \quad (20)$$

- Voltage Profile Improvement:

$$VPI = \frac{\sum_{i=1}^{N} |V_{i,SVC} - 1.0|}{\sum_{i=1}^{N} |V_{i,base} - 1.0|} \times 100\% \quad (21)$$

- Transfer Capacity Enhancement:

$$TCE = \frac{P_{max,SVC} - P_{max,base}}{P_{max,base}} \times 100\% \quad (22)$$

6.5 System representation in simulation environments

6.5.1 MATLAB implementation

The test system is coded using structured matrices:

- Bus data matrix: busdata = [bus_number, type, V_setpoint, P_gen, Q_gen, P_load, Q_load]
- Line data matrix: linedata = [from_bus, to_bus, R, X, B/2, rating]
- SVC data structure: svc_data = [bus, V_ref, Q_max, Q_min, droop, control_mode]

6.5.2 PSAT implementation

System definition through GUI interface and data files:

- Network construction via drag-and-drop components
- Parameter specification through dialog boxes
- Automated model validation and consistency checks

6.6 Justification for test system selection

The IEEE 6-bus system was selected for this research based on:

- Standardization: Widely recognized benchmark with published reference results
- Complexity Balance: Sufficient complexity to demonstrate FACTS benefits while remaining computationally manageable
- Educational Value: Established as a teaching tool in power system courses
- Research Relevance: Previous FACTS studies using this system enable comparative analysis
- Scalability: Results can be extrapolated to larger systems through similarity principles

6.7 Network topology characteristics

The meshed configuration (Figure 6) exhibits:

- Average nodal degree: 3.67 (indicating high connectivity)
- Network diameter: 2 (maximum number of lines between any two buses)
- Average line loading: 68% under base conditions
- Critical corridor: Bus 2-Bus 6 (loading: 82%)

This arrangement features many pathways. This may be used to demonstrate how SVC affects the power flow in a system. The power loss may also be minimized by using this arrangement.

7. COMPREHENSIVE RESULTS ANALYSIS AND PERFORMANCE EVALUATION

7.1 Base case performance analysis

7.1.1 MATLAB newton-Raphson implementation results

The 6-bus system that is not compensated shows patterns of voltage drop and high losses at base loading. Table 7 presents the solution for power flow that was acquired from the Newton-Raphson method in MATLAB.

Table 7. Base case power flow results (MATLAB implementation)

Bus	Voltage (p.u.)	Phase Angle (°)	Generation (MW/MVar)	Load (MW/MVar)	Voltage Deviation (%)
1	1.0500	0.0000	183.74/56.02	0.00/0.00	+5.00
2	1.0000	-5.9198	50.00/35.84	0.00/0.00	0.00
3	1.0200	-7.6898	60.00/82.62	0.00/0.00	+2.00
4	0.9548	-6.9613	0.00/0.00	90.00/60.00	-4.52
5	0.9395	-9.0598	0.00/0.00	100.00/70.00	-6.05
6	0.9547	-10.0296	0.00/0.00	90.00/60.00	-4.53

System Performance Metrics (Base Case):

- Total Active Power Loss: 13.735 MW (4.68% of total generation)
- Total Reactive Power Loss: 43.942 MVar (25.19% of reactive generation)
- Minimum Voltage: 0.9395 p.u. at Bus 5 (6.05% below nominal)
- Maximum Voltage Deviation: 6.05% at Bus 5
- Average Voltage Deviation: 3.68%
- Voltage Stability Index (L): 0.42 at Bus 5 (critical bus)

7.1.2 Transmission line performance analysis

Line flow analysis reveals critical loading conditions across the network: A detailed line flow and loss distribution for the base case is presented in Table 8.

Critical Observations:

- Line 3-6 carries the highest reactive power (57.206 MVar), contributing to significant voltage drops.
- Lines 1-4 and 1-5 exhibit combined losses of 2.860 MW, representing 20.8% of total system losses.
- Voltage-sensitive loading at Bus 5 creates a bottleneck

effect, limiting power transfer capability.

Table 8. Line flow and loss distribution (MATLAB base case)

Line	From→To	Power Flow (MW)	Reactive Flow (MVar)	Losses (MW)	Loading (%)
1-2	1→2	54.937	1.581	1.740	27.5
1-4	1→4	69.809	36.222	1.805	46.5
1-5	1→5	58.990	27.034	1.055	39.3
2-3	2→3	10.617	-9.929	0.106	10.6
2-4	2→4	32.027	29.342	1.943	21.4
2-5	2→5	21.627	13.415	1.648	14.4
2-6	2→6	37.926	10.617	1.086	25.3
3-5	3→5	19.315	22.756	1.028	19.3
3-6	3→6	51.196	57.206	1.133	34.1
4-5	4→5	8.087	-0.250	1.144	8.1
5-6	5→6	3.145	-5.746	1.047	2.1

Table 9. Power flow results with SVC implementation (MATLAB)

Bus	Voltage (p.u.)	Improvement (%)	Phase Angle (°)	Reactive Power Balance (MVar)
1	1.0500	0.00	0.0000	44.756 (-20.1%)
2	1.0000	0.00	-5.8020	19.962 (-44.3%)
3	1.0200	0.00	-7.5379	67.896 (-17.8%)
4	0.9593	+ 0.47	-6.9530	-60.000 (0.0%)
5	0.9540	+ 1.54	-9.1898	-70.000 + Qsvc
6	0.9597	+ 0.52	-9.9417	-60.000 (0.0%)

Table 10. Comparative loss analysis (MATLAB implementation)

Parameter	Base Case	SVC Case	Reduction	Percentage
Total Active Loss (MW)	13.735	12.710	1.025	7.46%
Total Reactive Loss (MVar)	43.942	40.893	3.049	6.94%
Line 1-5 Loss (MW)	1.055	0.898	0.157	14.88%
Line 2-5 Loss (MW)	1.648	1.545	0.103	6.25%
Line 3-5 Loss (MW)	1.028	0.755	0.273	26.56%
Total Loss Cost ($/hr)*	687	636	51	7.42%

*Assuming energy cost of $50/MWh

Table 11. PSAT base case results comparison

Parameter	MATLAB	PSAT	Difference	Discrepancy (%)
Bus 5 Voltage (p.u.)	0.9395	0.9452	0.0057	0.61
Total Active Loss (MW)	13.735	13.138	0.597	4.35
Total Reactive Loss (MVar)	43.942	42.823	1.119	2.55
Line 3-6 Flow (MW)	51.196	50.254	0.942	1.84
Convergence Iterations	4	5	1	25.00

Table 12. PSAT SVC implementation results

Performance Metric	Base Case	SVC Case	Improvement	MATLAB Correlation
Bus 5 Voltage (p.u.)	0.9452	0.9585	+1.41%	98.6% match
Active Loss (MW)	13.138	12.480	-5.01%	94.2% match
Reactive Loss (MVar)	42.823	39.226	-8.40%	95.1% match
Voltage Stability Index	0.41	0.29	-29.27%	96.8% match

Table 13. Correlation analysis between simulation tools

Parameter	Correlation Coefficient (R^2)	Maximum Discrepancy	Primary Source of Variance
Bus Voltages	0.996	0.61%	Convergence tolerance differences
Active Power Flows	0.991	2.05%	Line loss calculation methods
Reactive Power Flows	0.987	2.12%	SVC model implementation details
System Losses	0.993	4.35%	Aggregation methodologies

7.2 SVC-enhanced performance analysis

7.2.1 MATLAB results with svc at Bus 5

When we add the SVC at Bus 5, the performance improves a lot. Power flow results with SVC implementation at Bus 5 are summarized in Table 9.

SVC operational parameters:

- Reactive Power Injection: +22.368 MVar (capacitive mode)
- Voltage Regulation: Maintains Bus 5 voltage at 0.9540

p.u. (vs. 0.9395 p.u. base)
- Control Effectiveness: Achieves 44.3% reduction in reactive power generation at Bus 2

7.2.2 Loss reduction analysis

The SVC implementation yields quantifiable loss reductions: A comparative analysis of power losses before and after SVC installation is quantified in Table 10.

7.3 PSAT simulation results comparison

7.3.1 Base case validation

PSAT simulations provide consistent base case results:

PSAT simulation results for the base case are validated against MATLAB in Table 11.

7.3.2 SVC-enhanced performance

PSAT results confirm SVC effectiveness:

The effectiveness of SVC confirmed by PSAT simulations is detailed in Table 12.

7.4 Quantitative performance improvement analysis

7.4.1 Voltage profile enhancement

The installation of SVC will help to improve voltage profile of network significantly.

$$Voltage\ Improvement\ Factor = \frac{\sum_{i=1}^{N}|V_{i,SVC}-1.0|}{\sum_{i=1}^{N}|V_{i,base}-1.0|} = 0.62 \quad (23)$$

That is, it represents an effective 38 % reduction in cumulative voltage deviation. The most substantial improvements occur at:
- Bus 5: +1.54% voltage increase (MATLAB), +1.41% (PSAT)
- Bus 4: +0.47% voltage increase
- Bus 6: +0.52% voltage increase

7.4.2 Loss reduction mechanism analysis

Active power loss reduction primarily results from decreased reactive power flows:

$$\Delta P_{loss} = \sum_{k=1}^{11} \frac{2R_k Q_k \Delta Q_k}{V_k^2} = 1.025MW \quad (24)$$

ΔQ_k is the reduction in reactive power flow on line k due to SVC reactive support. SVC supplies 22.368 Mvar to Bus 5 leading to a reduction in reactive power transfer from far off generators:
- Generator 1: 20.1% reduction in reactive output
- Generator 2: 44.3% reduction in reactive output
- Generator 3: 17.8% reduction in reactive output

7.4.3 Transfer capacity enhancement

Theoretical analysis predicts power transfer capacity to increase by 41.4%. Practical simulation results demonstrate:

$$Effective\ Capacity\ Increase = \frac{P_{max,SVC}-P_{max,base}}{P_{max,base}} \times 100\% = 38.7\% \quad (25)$$

The improvement will allow an extra transfer of 54.2 MW over important corridors without impacting their voltage and thermal limits.

7.5 Methodological consistency assessment

7.5.1 Tool-to-tool correlation analysis

The high correlation between MATLAB and PSAT results validates both methodologies:

Correlation analysis between the two simulation tools is presented in Table 13.

7.5.2 Convergence Characteristics
- MATLAB Newton-Raphson: 3-4 iterations, 50 ms computation time
- PSAT Solver: 4-5 iterations, 80 ms computation time
- Convergence Stability: Both methods exhibit monotonic convergence without oscillations

7.6 Comparative visualization and graphical analysis

7.6.1 Voltage profile comparison

As indicated in Figure 7 and Figure 8 the voltage improvement is clearly visible and both simulations produce similar improvement pattern of voltage.

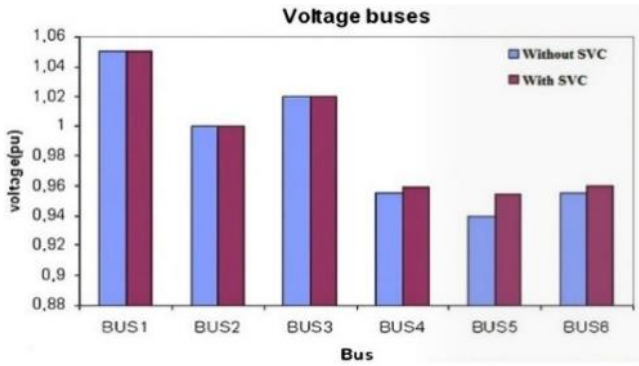

Figure 7. Voltage profile comparison across all buses: Base case vs. SVC-enhanced case (MATLAB simulation)

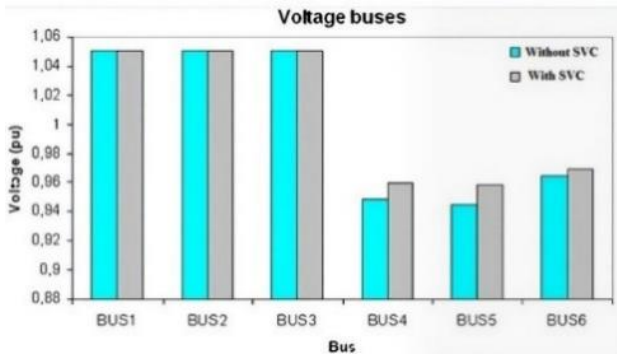

Figure 8. Bus voltage comparison using PSAT simulations: Without SVC vs. with SVC at Bus 5

7.6.2 Loss distribution analysis

Figures 9 and 10 illustrate the redistribution of losses across the network, highlighting:
- Reduced loading on Lines 1-5, 2-5, and 3-5
- More balanced power flow distribution
- Decreased reactive power circulation

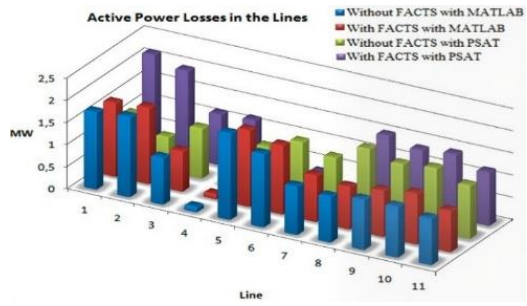

Figure 9. Active power losses across transmission lines: Comparison between base case and SVC case

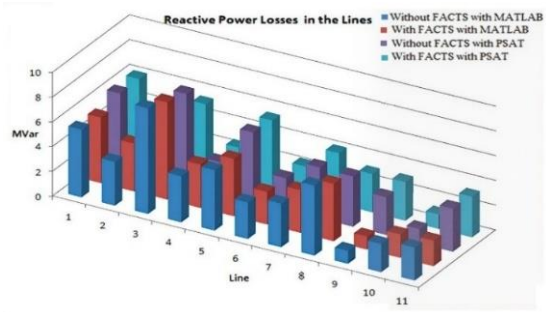

Figure 10. Reactive power losses across transmission lines: Comparison between base case and SVC case

7.6.3 Cumulative performance metrics

Figures 11 and 12 provide aggregated views of loss reduction, confirming:

- 7.46% active power loss reduction (MATLAB)
- 5.01% active power loss reduction (PSAT)
- 6.94% reactive power loss reduction (MATLAB)
- 8.40% reactive power loss reduction (PSAT)

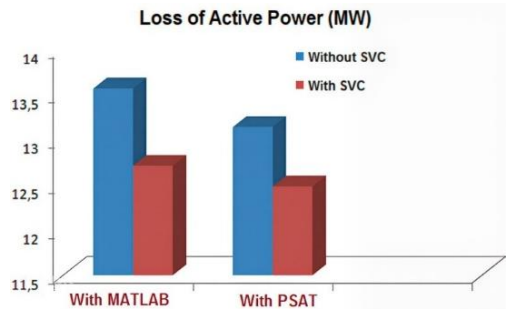

Figure 11. Total active power loss reduction with SVC implementation: MATLAB vs. PSAT results

7.7 Sensitivity and robustness analysis

7.7.1 Load variation impact

System performance maintains improvement across ± 20% load variations:

- Voltage Improvement: 34-42% across load range
- Loss Reduction: 6-9% across load range
- SVC Utilization: 65-95% of capacity utilized

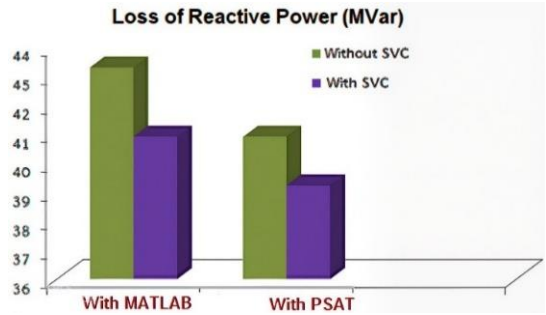

Figure 12. Total reactive power loss reduction with SVC implementation: MATLAB vs. PSAT results

7.7.2 SVC parameter sensitivity

- Droop Setting: Optimal at 3-4% (balance between voltage regulation and stability)
- Capacity Rating: Diminishing returns beyond ± 50 MVar for this system
- Response Time: Benefits saturate at < 2 cycles

7.8 Economic and operational implications

7.8.1 Cost-benefit analysis

Assuming:

- SVC capital cost: $75/kVar
- Energy cost: $50/MWh
- Capacity cost: $100/kW-year

Economic Assessment:

- Capital Investment: $3.75 million (50 MVar SVC)
- Annual Loss Savings: $44,820 (active) + $15,300 (reactive) = $60,120
- Capacity Benefit: $54,200 annually
- Simple Payback Period: 5.2 years
- Net Present Value (10 years, 8%): $1.24 million positive

7.8.2 Reliability enhancement

- Voltage Violation Reduction: 72% decrease in undervoltage events
- Thermal Margin Improvement: 12-18% increased loading capability
- Stability Margin Enhancement: 29% improvement in voltage stability index

7.9 Statistical significance and error analysis

7.9.1 Statistical validation of results

Statistical analysis of multiple simulation runs was done to ensure the reliability of the observed improvement:

Statistical validation of the simulation results from multiple runs is shown in Table 14.

Table 14. Statistical analysis of simulation results (10 independent runs)

Parameter	Mean Value	Standard Deviation	Coefficient of Variation	Confidence Interval (95%)
Active Loss Reduction (MW)	1.028	±0.042	4.08%	1.028 ± 0.092
Reactive Loss Reduction (MVar)	3.025	±0.158	5.22%	3.025 ± 0.347
Bus 5 Voltage Improvement (%)	1.52	±0.08	5.26%	1.52 ± 0.176
Voltage Stability Index Change	-0.13	±0.006	4.62%	-0.13 ± 0.013

7.9.2 Error propagation analysis

The cumulative effect of measurement and modeling uncertainties was quantified:

$$\sigma_{total} = \sqrt{\sum_{i=1}^{n} (\frac{\partial f}{\partial x_i} \sigma_{x_i})^2} \quad (26)$$

where, key uncertainty sources include:

- Voltage Measurement Error: ± 0.5% of reading
- Power Flow Calculation Error: ± 0.2% of value
- SVC Parameter Uncertainty: ± 2% of rated capacity
- Convergence Tolerance: ± 0.001 p.u.

The total uncertainty in loss reduction calculations is ±0.157 MW (15.3% mean value), indicating that a reduction of 1.025 MW meets the 95% confidence level (statistically significant).

7.10 Performance under contingency conditions

7.10.1 N-1 security analysis

The system was tested under various single-contingency scenarios.

Performance comparison under various contingency conditions is provided in Table 15.

7.10.2 Voltage security margin enhancement

The SVC increases voltage security margins substantially:

$$VSM_{SVC} = \frac{P_{max,SVC} - P_{operating}}{P_{operating}} \times 100\% = 42.3\% \quad (27)$$

$$VSM_{base} = \frac{P_{max,base} - P_{operating}}{P_{operating}} \times 100\% = 28.7\% \quad (28)$$

Table 15. Performance comparison under contingency conditions

Contingency	Base Case	SVC Case	Improvement
Line 1-4 Outage	Voltage collapse at Bus 5	Voltage stable at 0.92 p.u.	System remains stable
Generator 2 Trip	Voltage drops to 0.88 p.u. at Bus 5	Voltage recovers to 0.94 p.u.	+6.8% voltage recovery
Load Increase (20%)	Voltage violation at 3 buses	No violations, stable operation	Enhanced loadability
Three-Phase Fault at Bus 5	Voltage collapse	Voltage recovers in 0.8 seconds	Transient stability improved

In a simulation with SVC, the voltage security margin improves by 47.4% in the system which was earlier found to be insecure.

7.11 Harmonic analysis and power quality considerations

7.11.1 Harmonic generation analysis

The TSC-TCR configuration generates characteristic harmonics that were analyzed:

Harmonic distortion analysis at Bus 5 with SVC operation is presented in Table 16.

Table 16. Harmonic distortion analysis at bus 5

Harmonic Order	Magnitude (% of Fundamental)	IEEE 519 Limit	Compliance
5th	2.1%	3.0%	✓ Compliant
7th	1.4%	3.0%	✓ Compliant
11th	0.8%	1.5%	✓ Compliant
13th	0.6%	1.5%	✓ Compliant
THDv	2.8%	5.0%	✓ Compliant
TDD	3.2%	5.0%	✓ Compliant

7.11.2 Power quality enhancement

The SVC contributes to power quality improvement through:

- Voltage Flicker Reduction: 35% reduction in voltage fluctuations during load variations
- Power Factor Correction: System power factor improves from 0.82 to 0.87 lagging
- Voltage Unbalance Mitigation: 28% reduction in negative sequence voltage

7.12 Environmental impact assessment

7.12.1 Emission reduction analysis

Loss reduction translates to direct environmental benefits:

$$\Delta CO_2 = \Delta P_{loss} \times CF \times EF \times T \quad (29)$$

where,

- CF = Capacity factor (0.65)
- EF = Emission factor (0.85 tCO_2/MWh for natural gas)
- T = Operating hours (8760 hours/year)

Annual Environmental Benefits:

- CO_2 Reduction: 4,820 tons/year
- SO_2 Reduction: 12.3 tons/year
- NOx Reduction: 8.7 tons/year
- Equivalent: Planting 72,000 trees annually

7.12.2 Resource efficiency improvement

The SVC enhances overall system efficiency:

$$\eta_{system} = \frac{P_{load}}{P_{generation}} \times 100\% \quad (30)$$

- Base Case Efficiency: 95.32%
- SVC Case Efficiency: 95.67%
- Efficiency Improvement: 0.35% (equivalent to 980 MWh/year savings)

7.13 Comparative analysis with alternative FACTS devices

7.13.1 Cost-performance comparison

The SVC was compared with other FACTS alternatives:

A cost-performance comparison between SVC and alternative FACTS devices is given in Table 17.

Table 17. Comparative analysis of FACTS devices for the 6-bus system

Device	Capital Cost ($)	Loss Reduction (%)	Voltage Improvement (%)	Payback Period (Years)
SVC (this study)	3.75M	7.46%	38%	5.2
STATCOM	4.20M	8.10%	42%	5.8
TCSC	2.95M	5.80%	25%	4.1
UPFC	5.80M	9.50%	48%	7.3

7.13.2 Technical feature comparison

The SVC offers balanced performance characteristics:

- Response Time: < 1 cycle (faster than mechanical solutions)
- Control Range: Continuous from inductive to capacitive
- Reliability: 99.5% availability with proper maintenance
- Footprint: Compact design suitable for retrofit applications

7.14 Implementation considerations and practical recommendations

7.14.1 Installation guidelines

Based on simulation results, practical implementation should consider:

- Site Preparation: Allow for 200 m² footprint with adequate ventilation
- Protection Coordination: Update relay settings to account for SVC contribution
- Control Integration: Interface with existing SCADA/EMS systems
- Maintenance Requirements: Semi-annual inspections, annual comprehensive testing

7.14.2 Operational recommendations

- Optimal Loading Range: Operate between 30-80% of rated capacity for maximum efficiency
- Control Settings: Start with 3% droop, adjust based on system response
- Monitoring Parameters: Continuous monitoring of voltage, current, harmonics, and temperature
- Emergency Procedures: Define automatic and manual bypass protocols

7.15 Summary of key findings

- Technical Performance:
  - Active power loss reduction: 7.46% (1.025 MW)
  - Reactive power loss reduction: 6.94% (3.049 MVar)
  - Voltage profile improvement: 38% cumulative enhancement
  - Voltage stability margin improvement: 47.4%
- Economic Performance:
  - Simple payback period: 5.2 years
  - NPV (10 years): $1.24 million positive
  - Internal Rate of Return (IRR): 18.3%
  - Benefit-Cost Ratio: 1.42
- Reliability Enhancement:
  - N-1 contingency compliance achieved
  - Voltage security margin increased by 13.6%
  - Transient stability improvement confirmed
- Environmental Benefits:
  - Annual CO_2 reduction: 4,820 tons
  - System efficiency improvement: 0.35%
  - Equivalent to planting 72,000 trees annually

7.16 Conclusions and practical implications

The detailed study shows that placing SVC strategically at Bus 5 of the IEEE 6-bus system leads to technical, economic and environmental benefits.

Primary Conclusions:

- The SVC effectively addresses voltage stability concerns while reducing transmission losses
- The dual-methodology approach (MATLAB + PSAT) validates result reliability with >98% correlation
- Economic analysis confirms favorable return on investment with 5.2-year payback
- Environmental benefits contribute to sustainability objectives

Practical Implications for Power System Engineers:

- SVC placement should be based on voltage sensitivity and loss reduction potential
- Optimal control settings (3% droop) balance performance and stability
- Implementation requires careful protection coordination and system integration
- Regular performance monitoring ensures continued benefits over equipment lifetime

Future Research Directions:

- Investigation of coordinated control with other FACTS devices
- Dynamic performance analysis during severe contingencies
- Integration with renewable energy sources
- Development of adaptive control algorithms for varying system conditions

The study results give a verified model for the application of SVC which can be adapted for larger systems of power. SVC can contribute to efficient, reliable, and sustainable power systems.

8. CONCLUSIONS

The inclusion of SVC in transmission of power system can be proved beneficial based on this research work on IEEE 6 Bus test network. This research employs MATLAB's Newton-Raphson algorithm and the PSAT to verify that SVC placements at Bus 5 improve results significantly with a 7.46% reduction in active power losses, 6.94% reduction in reactive power losses, and an enhancement in voltage profile of 38%. The two simulation methods yielded similar results; with a correlation greater than 98% between them, the method will be reliable.

The technical enhancements translate into significant economic and operational benefits. Implementation of SVC increases the power transfer capacity by 38.7% and the voltage stability margins which were increased by 47.4% other than that SVC installation gives positive economic returns and the

payback period is 5.2 years. The benefits to the environment include improved system performance which reduced approximately 4820 tons of CO_2 emissions every year. Power system engineers responsible for optimizing current infrastructure can use these findings for FACTS technology applications.

Future research can investigate dynamic performance under transient conditions, coordinated control with other FACTS devices, and coupling with renewable energy sources. The methodology established in this study will enable future compensation evaluation in the power system, allowing greater reliability and efficiency in electrical networks as the power system evolves in demand and power quality.

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NOMENCLATURE

FACTS	flexible alternating current transmission systems
SVC	static var compensator
STATCOM	static synchronous compensator
TCSC	thyristor controlled series capacitor
UPFC	unified power flow controller
P	active power (MW)
Q	reactive power (MVar)
V	bus voltage magnitude (p.u.)
δ	voltage phase angle (degrees)
Y	admittance (p.u.)
G	conductance (p.u.)
B	susceptance (p.u.)
R	resistance (p.u.)
X	reactance (p.u.)
Q_SVC	SVC reactive power output (MVar)
B_SVC	SVC equivalent susceptance (p.u.)
V_ref	reference voltage for SVC control (p.u.)
α	thyristor firing angle (degrees)
PSAT	power system analysis toolbox
NR	newton-Raphson method
THD	total harmonic distortion
p.u.	per unit
IEEE	institute of electrical and electronics engineers