Design of Static Var Compensator for Voltage Stability Improvement in 30 bus network

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ABSTRACT

This paper presents a comprehensive study on the application of Static Var Compensator (SVC) devices for voltage stability and load flow optimization in the IEEE 30-bus power system. As modern power networks face increasing demand and complexity, maintaining voltage levels and minimizing power losses are critical challenges. This research investigates the impact of SVC compensation on bus voltage profiles using load flow analysis based on the Newton-Raphson method. The IEEE 30-bus system is simulated in MATLAB, and buses with voltages below 1.0 p.u. are identified as requiring compensation. Results show that SVC implementation stabilizes voltage levels, with buses initially operating at voltages as low as 0.920 p.u. being raised to approximately 1.0 p.u. Furthermore, the generator buses experienced a voltage improvement of up to 0.05 p.u., contributing to a robust and uniform voltage profile across the network. Power losses were also significantly reduced, demonstrating the dual benefits of voltage stabilization and loss minimization. The findings confirm that SVCs are effective in mitigating voltage sags, enhancing system resilience, and optimizing modern power grids.

1. INTRODUCTION

The stability and efficiency of modern power systems heavily depend on effective load flow management and voltage regulation. As power demand continues to grow and networks become more interconnected, maintaining voltage stability while minimizing power losses remains a critical challenge [1]. Voltage instability, if not addressed, can lead to system blackouts and increased operational costs due to inefficient power transfer [2].

Among the most widely adopted methods for ensuring voltage stability and efficient power flow is the load flow analysis, which provides essential insights into voltage profiles, power losses, and the operational conditions of different network components under various load scenarios [3].

Flexible Alternating Current Transmission Systems (FACTS), such as the Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM), have been instrumental in addressing the limitations of traditional grid infrastructure. These devices have become critical tools for addressing voltage instability by controlling reactive power and optimizing power transfer in congested networks [4]. They enable better control of reactive power, mitigate voltage instability, and optimize power transfer in congested networks. Specifically, the IEEE bus system serves as an essential testbed for simulating and analyzing load flow performance under varying conditions of compensation, making it a valuable model for evaluating the impact of FACTS devices on real-world networks [5].

Load flow analysis not only helps in determining the steady-state operation of power systems but also facilitates the strategic placement of compensators to enhance network reliability. Techniques like the Newton-Raphson method have proven effective in solving the nonlinear equations governing power flows, offering accurate and fast convergence for systems of various sizes. Moreover, integrating FACTS controllers, such as SVC, into the IEEE bus system network has been shown to significantly improve voltage profiles and reduce power losses, thus extending the operational lifespan of grid components by preventing overloading [6].

This paper investigates the application of an SVC within the IEEE 30-bus system, a widely used testbed for power system analysis. Using MATLAB-based simulations, we analyze the system's voltage profile and identify the optimal placement of SVCs to improve voltage stability and reduce power losses. The findings of this study offer actionable insights for enhancing the reliability and resilience of power transmission networks.

2. POWER QUALITY CONTROL

Several studies have explored the role of reactive power compensation in improving voltage stability in power systems. The application of FACTS devices, particularly SVCs and STATCOMs, has been extensively analyzed in both transmission and distribution networks. [7,8] demonstrated that the integration of SVCs significantly improved the voltage profile in heavily loaded systems by dynamically controlling reactive power. Similarly, [9] applied an SVC in a multi-bus system and observed a reduction in power losses and improved voltage regulation.

The Newton-Raphson (NR) method remains one of the most popular approaches for solving load flow equations due to its robust convergence properties and computational efficiency. Researchers have used the NR method to model nonlinear power systems with high accuracy, enabling the precise evaluation of voltage profiles under different load conditions [10]. Despite its effectiveness, the placement and sizing of SVCs for optimal performance in power systems remain a challenging problem, often requiring iterative simulation techniques to identify the best locations for compensation devices.

This study builds on these findings by applying the NR method to analyze the IEEE 30-bus system and integrating SVCs for voltage stability. The contribution of this work lies in its detailed assessment of the voltage profile before and after SVC compensation, as well as its recommendations for optimal compensator placement.

2.1 SVC

A Static Var Compensator (SVC) is a shunt-connected device used to regulate voltage and control reactive power in power systems [12]. As a critical component of Flexible AC Transmission Systems (FACTS), the SVC plays a vital role in enhancing power quality and stability in transmission networks [11]. It is widely employed for dynamic voltage control, power factor correction, and load balancing, all of which are crucial for the optimal operation of modern power systems.

The SVC's ability to provide dynamic voltage support and control reactive power makes it indispensable for improving system stability and mitigating common power system challenges, such as voltage sags, power oscillations, and inefficient transmission capacity utilization [12]. This ensures that transmission systems operate efficiently while maintaining high levels of reliability and power quality.

2.1.1 Principles of Operation

The primary function of an SVC is to regulate voltage levels within acceptable limits by either absorbing or injecting reactive power into the power system. An SVC is mainly composed of two key components [13].

- **Thyristor-Controlled Reactors (TCRs):** These adjust the inductive reactive power.
- **Thyristor-Switched Capacitors (TSCs):** These regulate the capacitive reactive power.

By adjusting the thyristor firing angle, the SVC can dynamically alternate between capacitive and inductive modes of operation. When the system voltage drops below a specified threshold, the SVC injects capacitive reactive power to increase the voltage. Conversely, if the voltage exceeds the set limit, the SVC absorbs reactive power to reduce it to acceptable levels.

2.1.2 SVC Modelling

To accurately model the behavior of an SVC, it is essential to describe its equivalent susceptance Bipolar static var compensator (B_SVC), which depends on the operating states of its components, namely the Thyristor-Controlled Reactor (TCR) and Thyristor-Switched Capacitor (TSC). The operation of the SVC is regulated by adjusting the thyristor firing angle, which consequently alters the system's effective reactance.

2.1.3 Thyristor-Controlled Reactor (TCR) Modelling:

The equivalent inductive reactance of a Thyristor-Controlled Reactor (TCR), modulated by the firing angle α\alphaα, is expressed as in [12]:

$$X_L(\alpha) = \frac{\pi \cdot X_L}{\sin(2\alpha) + 2(\pi - \alpha)} \quad (1)$$

Where:

X_L represents the reactor's inductance and α is the firing angle of the thyristor, typically between 90° *and* 180°.

2.1.4 Thyristor-Switched Capacitor (TSC) modelling

The susceptance of the TSC is constant and can be expressed as in [14]:

$$B_{TSC} = \frac{1}{X_C} \quad (2)$$

Where X_C is the capacitive reactance

2.1.5 Reactive Power Modelling

The reactive power injected or absorbed by the SVC at a voltage V can be expressed as [13]:

$$Q_{SVC} = -V^2 \cdot B_{SVC} \quad (3)$$

This relationship demonstrates that the SVC provides reactive power when the system voltage is low (operating in capacitive mode) and absorbs reactive power when the voltage is high (operating in inductive mode).

2.1.6 Combined Susceptance Of SVC

The total susceptance B_{SVC} of the SVC is derived from the combined contributions of the TCR and TSC. It can be expressed as [14]:

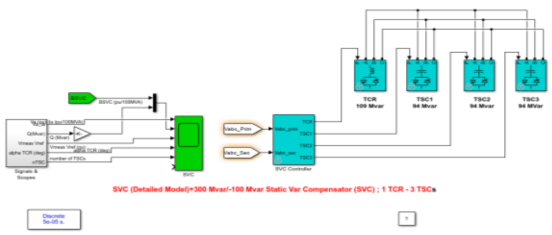

Fig. 1. Simulink Model of SVC

$$B_{SVC} = B_{TSC} - B_{TCR}(\alpha) \quad (4)$$

where B_{TSC} is the constant susceptance of the TSC defined in EQ above, and $B_{TCR}(\alpha)$ is the variable susceptance of the TCR, which depends on the thyristor firing angle α based on EQ as in [12]:

$$B_{TCR}(\alpha) = \frac{1}{X_L(\alpha)} \quad (5)$$

This capability allows the SVC to offer both inductive and capacitive compensation in response to the system's requirements.

2.1.7 Control Strategy

The control of the SVC is achieved by adjusting the thyristor firing angle. By varying the angle α, the SVC regulates the amount of reactive power it either injects or absorbs. The firing angle typically ranges from 90° to 180°, with 90° corresponding to maximum inductive compensation and 180° indicating no inductive compensation. Capacitive compensation is activated when the thyristors in the Thyristor-Switched Capacitor (TSC) are triggered [15].

The SVC's rapid response time, typically within the range of milliseconds, enables real-time voltage regulation, making it highly effective for stabilizing power systems during dynamic load conditions.

2.1.8 Application of SVC in Power Systems

SVCs serve several critical functions in power systems:

- **Voltage Stabilization:** By providing fast and dynamic voltage regulation, SVCs help maintain voltage levels within safe operational limits.
- **Reactive Power Compensation:** SVCs provide reactive power support, which improves power factor and reduces transmission losses.
- **Increased Transmission Capacity:** By mitigating voltage drops and regulating power flows, SVCs enable the transmission of more power over long distances.
- **Damping Power Oscillations:** SVCs help dampen oscillations that can occur during disturbances, thus enhancing system stability.

Fig. 1. Shows the circuit diagram of the SVC device which consist of several components and a control section.

2.2 Power Flow Control

Load flow analysis is a critical component of power system analysis and design. It plays a vital role in power planning, economic scheduling, and the distribution of electricity among utilities. In such systems, power transfer between different areas can take unexpected routes due to the varying voltages and impedances of the transmission lines that make up the grid [13].

Flexible Alternating Current Transmission Systems (FACTS) devices are particularly effective in optimizing power flow across various regions of the grid and between parallel power corridors with differing voltages and line impedances. The nonlinear equations governing load flow can be resolved using iterative methods. In this study, the Newton-Raphson method is utilized because its convergence is independent of system size, and the number of iterations does not depend on the selection of the slack bus [16].

Load flow analysis allows for the determination of voltage magnitudes and angles at each bus in a steady-state condition. Maintaining these voltage magnitudes within a specified range is essential for system stability. Once the voltage values and angles are established, the real and reactive power flow in each line can be calculated [15]. Power losses in a given line can also be determined by assessing the difference in power flow between the sending and receiving ends. Furthermore, line flow analysis enables us to manage both overload and underload conditions effectively.

In a steady-state power network, the real and reactive power supplied by a bus is expressed through nonlinear algebraic equations. As a result, iterative methods are necessary to solve these equations accurately.

2.2.1 Real and Reactive Power Injected in A Bus

To formulate the real and reactive power entering a bus, it is necessary to define the following quantities. Let the voltage at the i^{th} bus be represented as in [17]:

$$V_i = |V_i| < \delta_i = |V_i|(cos\delta_i + jsin\delta_i) \quad (6)$$

Additionally, let the self-admittance at the i^{th} bus be defined as in [17]:

$$Y_{ii} = |Y_{ii}| < \theta_{ii} = |Y_{ii}|(cos\theta_{ii} + jsin\theta_{ii}) = G_{ij} + jB_{ii} \quad (7)$$

Similarly, the mutual admittance between buses i and j can be expressed as in [17]:

$$Y_{ij} = \left|Y_{ij}\right| < \theta_{ij} = \left|Y_{ij}\right|\left(cos\theta_{ij} + jsin\theta_{ij}\right) = G_{ij} + jB_{ii} \quad (8)$$

Assuming the power system comprises a total of n buses, the current injected at bus i is given by [17]:

$$I_i = Y_{i1} \cdot V_1 + Y_{i2} \cdot V_2 + \cdots + Y_{in} \cdot V_n = \sum_{k=1}^{n} Y_{ik} \cdot V_k \quad (9)$$

It is important to note that the current entering a bus is considered positive, while the current leaving the bus is deemed negative. Consequently, the incoming active and reactive power at a bus are also assumed to be positive. Therefore, the complex power at bus i can be expressed as in [18]:

$$P_i - jQ_i = V_i^* \cdot I_i = V_i^* \cdot \sum_{k=1}^{n} Y_{ik} \cdot V_k$$
$$= |V_i|(cos\delta_i - jsin\delta_i) \sum_{k=1}^{n} |Y_{ik} \cdot V_k|(cos\theta_{ik} + jsin\theta_{ik}) \cdot (cos\delta_k + jsin\delta_k)$$
$$= \sum_{k=1}^{n} |Y_{ik} \cdot V_i \cdot V_k|(cos\delta_i - jsin\delta_i)(cos\theta_{ik} + jsin\theta_{ik})(cos\delta_k + jsin\delta_k) \quad (10)$$

Note that

$$(cos\delta_i - jsin\delta_i)(cos\theta_{ik} + jsin\theta_{ik})(cos\delta_k + jsin\delta_k)$$
$$= (cos\delta_i - jsin\delta_i) \cdot [\cos(\theta_{ik} + \delta_k) + jsin(\theta_{ik} + \delta_k)]$$
$$= \cos(\theta_{ik} + \delta_k - \delta_i) + jsin(\theta_{ik} + \delta_k - \delta_i) \quad (11)$$

Substituting into equation (5), we obtain the expressions for the real and reactive power as follows as in [18]:

$$P_i = \sum_{k=1}^{n} |Y_{ik} \cdot V_i \cdot V_k| \cos(\theta_{ik} + \delta_k - \delta_i) \quad (12)$$
$$Q_i = -\sum_{k=1}^{n} |Y_{ik} \cdot V_i \cdot V_k| \sin(\theta_{ik} + \delta_k - \delta_i) \quad (13)$$

Where, V_i = voltage at ith bus and V_j = voltage at jth bus

2.3 Load Flow by Newton Raphson

This method is named in honor of Isaac Newton and Joseph Raphson. The Newton-Raphson method originated and was formulated in the late [19]. It is an iterative method that approximates a set of non-linear simultaneous equations to a set of linear simultaneous equations by using Taylor series expansion, limiting the terms to the first approximation. It is the most commonly used iterative method for load flow analysis because its convergence characteristics are relatively stronger than other methods. The Newton-Raphson approach is also considered more reliable, as it can solve cases that might lead to divergence with other popular methods [16]. This is another widely used iterative load flow method for solving nonlinear equations. The admittance matrix is used to write equations for currents entering a power system. Equation (14) is presented in polar form, where j includes bus i as in [13].

$$I_i = \sum_{j=1}^{n} |Y_{ij}||V_i| < \theta_{ij} + \delta_j \quad (14)$$

The real and reactive power at bus i are seen in [21]

$$P_i - jQ_i = V_i^* \cdot I_i \quad (15)$$

Replacing I_i in equation (14) with the expression from equation (15) yield the power equation at bus i as stated below as in [21].

$$P_i - jQ_i = |V_i| < -\delta_i \cdot \sum_{j=1}^{n} |Y_{ij}| \cdot |V_j| < \delta_{ij} + \delta_i \quad (16)$$

The real and imaginary parts of the power equation are separated as in [18]:

$$P_i = \sum_{j=1}^{n} |V_i| \cdot |V_j| \cdot |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad (17)$$
$$Q_i \sum_{j=1}^{n} |V_i| \cdot |V_j| \cdot |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \quad (18)$$

Equations (17) and (18) above form a set of non-linear algebraic equations in terms of |V| (in per unit) and δ (in radians).

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \left[\begin{array}{ccc|ccc} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \\ \hline \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{array}\right] \begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} \quad (20)$$

In the above equation, the element of the slack bus variable voltage magnitude and angle are omitted because they are already known. The elements of the Jacobian matrix are obtained after partial derivatives of equations (18) and (19) are expressed which gives linearized relationship between small changes in voltage magnitude and voltage angle. The equation can be written in matrix form as in [20]:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (21)$$

J_1, J_2, J_3 and J_4 are the elements of the Jacobian matrix.

The difference between the calculated and the scheduled values known as power residuals for the terms are represented as in [20].

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \quad (22)$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \quad (23)$$

The new estimates for bus voltages are presented below:

$$\delta^{(k+1)} = \delta_i^{(k)} + \Delta \delta_i^{(k)} \quad (24)$$

$$\left|V^{(k+1)}\right| = \left|V_i^{(k)}\right| + \Delta \left|V_i^{(k)}\right| \quad (25)$$

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3. METHODOLOGY

This study employs the Newton-Raphson (NR) method to conduct load flow analysis on the IEEE 30-bus system. The NR method was selected for its superior convergence characteristics and ability to handle nonlinear equations. MATLAB's Power Systems Toolbox was used to simulate the network, and the system's base voltage was set at 132 kV. All voltage measurements are expressed in per-unit (p.u.) values.

The IEEE 30-bus system consists of 30 buses and 41 transmission lines, with buses 1, 2, 5, 8, 11, and 13 serving as generator buses. Bus 1 is designated as the slack bus, and the rest of the buses are considered load buses. For this study, we focused on identifying buses with voltage levels below 1.0 p.u., which indicates voltage instability.

SVC devices were modeled and applied to these load buses to compensate for reactive power imbalances. The SVC was designed using a combination of Thyristor-Controlled Reactors (TCRs) and Thyristor-Switched Capacitors (TSCs), enabling it to inject or absorb reactive power as needed. The following assumptions were made during the simulation:

Power factor: 0.9 lagging.

Load buses are considered to have real and reactive power demands.

The system is assumed to operate under steady-state conditions.

The goal of the load flow analysis was to calculate the voltage profile of the system, both with and without the SVC compensation, and evaluate the impact on voltage stability and power loss reduction on voltage stability and power loss reduction.

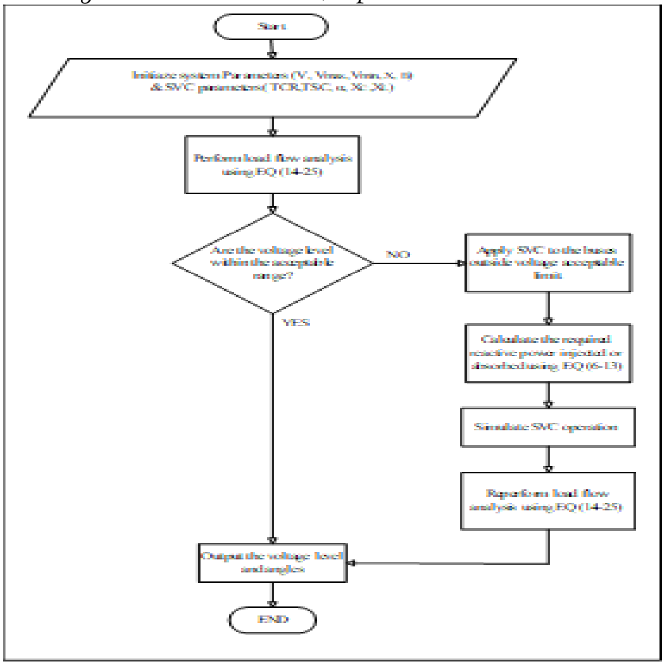

Fig. 2. Research Flowchart

Fig. 2 shows the flowchart that serves as a guide for implementing the research work.

4. SIMULATION RESULTS

The initial load flow analysis revealed several buses with voltages below 1.0 p.u., including buses 3, 4, 9, 10, 13, etc. These low voltage levels were primarily observed in buses farther from the generators, indicating that insufficient reactive power support was being provided to maintain voltage stability. This is typical in power systems where long transmission lines and high loads lead to voltage drops. The simulated results are shown in Table 1.

Table 1a. Voltage Profile before compensation

Bus	Voltage (p.u)	Voltage Level (KV)	Angle (degrees)	Bus Type
1	1.060	139.92	0.00	Slack
2	0.980	129.36	-5.00	Generator
3	0.950	125.40	-13.00	Load
4	0.960	126.72	-10.50	Load
5	0.970	128.04	-9.00	Generator
6	1.020	132.64	-14.50	Load
7	0.980	129.36	-13.50	Load
8	1.030	135.96	-13.40	Generator
9	0.950	125.40	-15.00	Load
10	0.940	124.08	-15.10	Load
11	0.930	122.76	-15.00	Generator
12	0.950	125.40	-15.20	Load
13	0.920	121.44	-15.30	Generator
14	0.940	124.08	-16.10	Load
15	0.930	122.76	-16.20	Load

Table 1b. Voltage Profile before compensation

Bus	Voltage (p.u)	Voltage Level (KV)	Angle (degrees)	Bus Type
16	0.940	124.08	-16.00	Load
17	0.950	125.40	-16.00	Load
18	0.930	122.76	-16.30	Load
19	0.940	124.08	-16.40	Load
20	0.950	125.40	-16.50	Load
21	0.930	122.76	-16.40	Load
22	0.920	121.44	-16.50	Load
23	0.930	122.76	-16.50	Load
24	0.940	124.08	-16.60	Load
25	0.930	122.76	-16.50	Load
26	0.920	121.44	-16.60	Load
27	0.930	122.76	-16.50	Load
28	0.940	124.08	-16.50	Load
29	0.950	125.40	-16.50	Load
30	0.960	126.72	-16.40	Load

From Table 1, it is observed that several buses have voltage levels below 1.0 p.u., indicating the need for compensation to stabilize the voltage. Specifically, buses 2, 3, 4, 7, 9, 10, 11, and 13 are identified as potential candidates for Static Var Compensator (SVC) compensation, as their voltage levels are below 1.0 p.u. These buses are ideal for voltage stabilization, and an SVC will be installed at one or more of them to inject reactive power and boost voltage levels, improving system stability. Additionally, buses 2, 5, 8, 11, and 13, which are generator buses, show voltage levels close to 1.0 p.u. but still below optimal levels. These buses could also benefit from SVC compensation to further stabilize and improve voltage levels.

After the installation of the SVC, the buses that initially had voltages below 1.0 p.u. experienced significant improvements, with all buses reaching acceptable voltage levels around 1.0 p.u. The reactive power injected by the SVCs helped mitigate the voltage sags by providing dynamic reactive power support in real-time. As shown in Table 2, buses 3, 9, 10, and 13 were raised to 1.0 p.u., and the generator buses also experienced slight increases in voltage, which enhanced the overall system robustness.

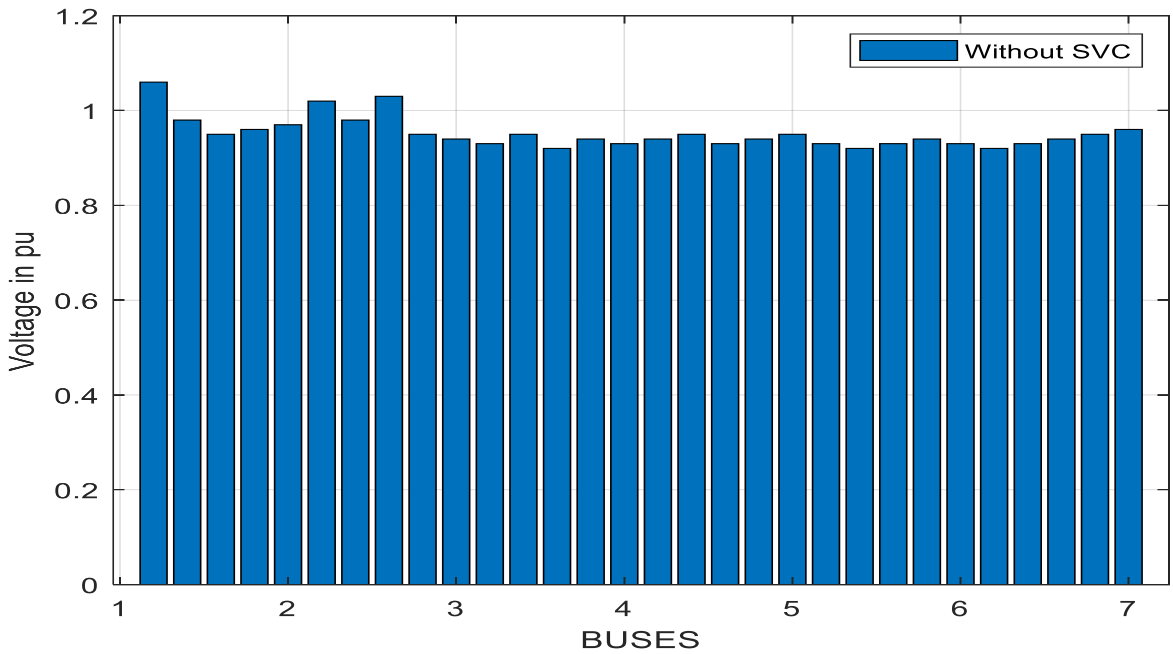

Fig. 3. Voltage profile without compensation

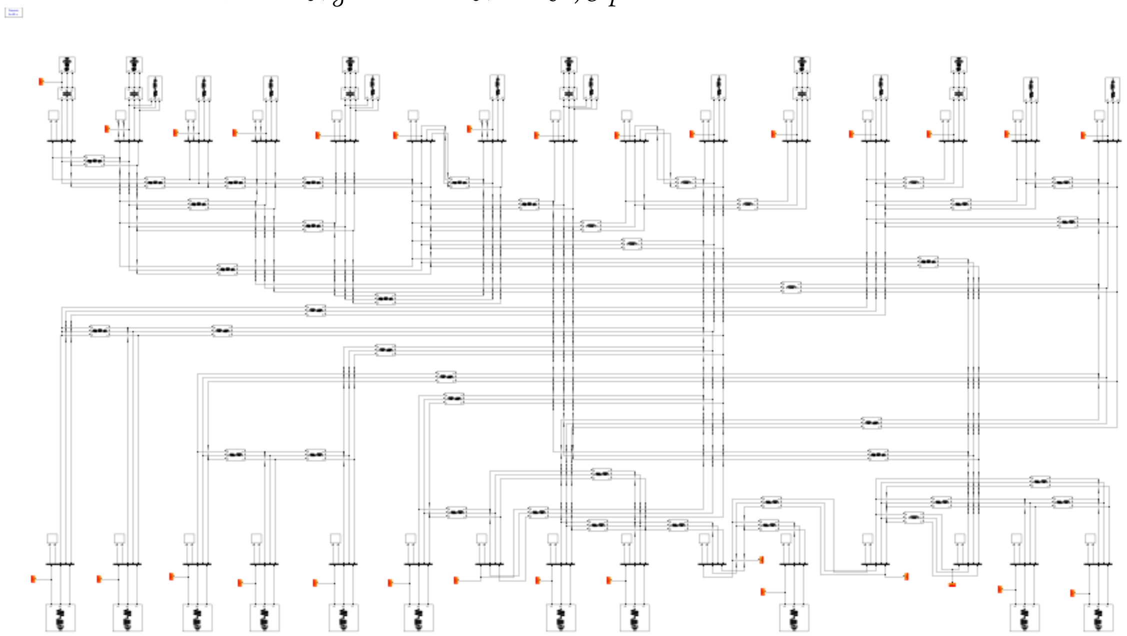

Fig. 4 Simulink Model of IEEE-30 bus network

Fig. 4 shows the 30-bus network implemented in this study.

Table 2a. Voltage profile after compensation with SVC

Bus	Voltage (p.u)	Voltage Level (kV)	Angle (degrees)	Bus Type
1	1.060	139.92	0.00	Slack
2	1.030	135.96	-4.50	Generator
3	1.000	132.00	-12.00	Load
4	1.000	132.00	-10.00	Load
5	1.020	134.64	-8.50	Generator
6	1.020	134.64	-13.00	Load
7	1.000	132.00	-12.50	Load
8	1.030	135.96	-12.20	Generator
9	1.000	132.00	-14.00	Load
10	1.000	132.00	-14.70	Load
11	1.030	135.96	-14.40	Generator
12	1.000	132.00	-14.80	Load
13	1.020	134.64	-14.90	Generator
14	1.000	132.00	-15.50	Load
15	1.000	132.00	-15.80	Load

Table 2b. Voltage profile after compensation siwth SVC

Bus	Voltage (p.u)	Voltage Level (kV)	Angle (degrees)	Bus Type
16	1.000	132.00	-15.60	Load
17	1.000	132.00	-15.70	Load
18	1.000	132.00	-15.90	Load
19	1.000	132.00	-16.00	Load
20	1.000	132.00	-16.00	Load
21	1.000	132.00	-16.00	Load
22	1.000	132.00	-16.00	Load

23	1.000	132.00	-16.00	Load
24	1.000	132.00	-16.00	Load
25	1.000	132.00	-16.00	Load
26	1.000	132.00	-16.00	Load
27	1.000	132.00	-16.00	Load
28	1.000	132.00	-16.00	Load
29	1.000	132.00	-16.00	Load
30	1.000	132.00	-16.00	Load

Time. As shown in Table 2, the voltages of buses 3, 9, 10, and 13 were raised to 1.0 p.u., and the generator buses also saw a slight increase in voltage, enhancing overall system robustness

The data in Table 2 demonstrates that the buses, which initially had voltages below 1.0 p.u., have been stabilized to approximately 1.0 p.u. after compensation with the SVC. Additionally, the voltage at the generator buses has seen a slight increase, leading to a more stable and robust voltage profile across the network. As a result, system stability has been significantly enhanced, and all buses are now operating within the acceptable voltage range. A comparison of the voltage levels before and after compensation is provided in Figure 5, which highlights the improvement in the voltage profile across the network.

reactive power and stabilize the voltage profile, with all buses reaching acceptable voltage levels. As shown in Fig. 5, all buses that had a voltage profile below 1.0 p.u were maintained at 1.0 p.u. after compensation, except for the generator buses, which exhibited slightly higher voltages than 1.0 p.u. In addition to stabilizing voltage levels, the introduction of SVCs reduced transmission losses. By controlling reactive power flow and maintaining voltage at desired levels, the SVCs allowed for more efficient power transmission, minimizing the losses typically associated with voltage instability.

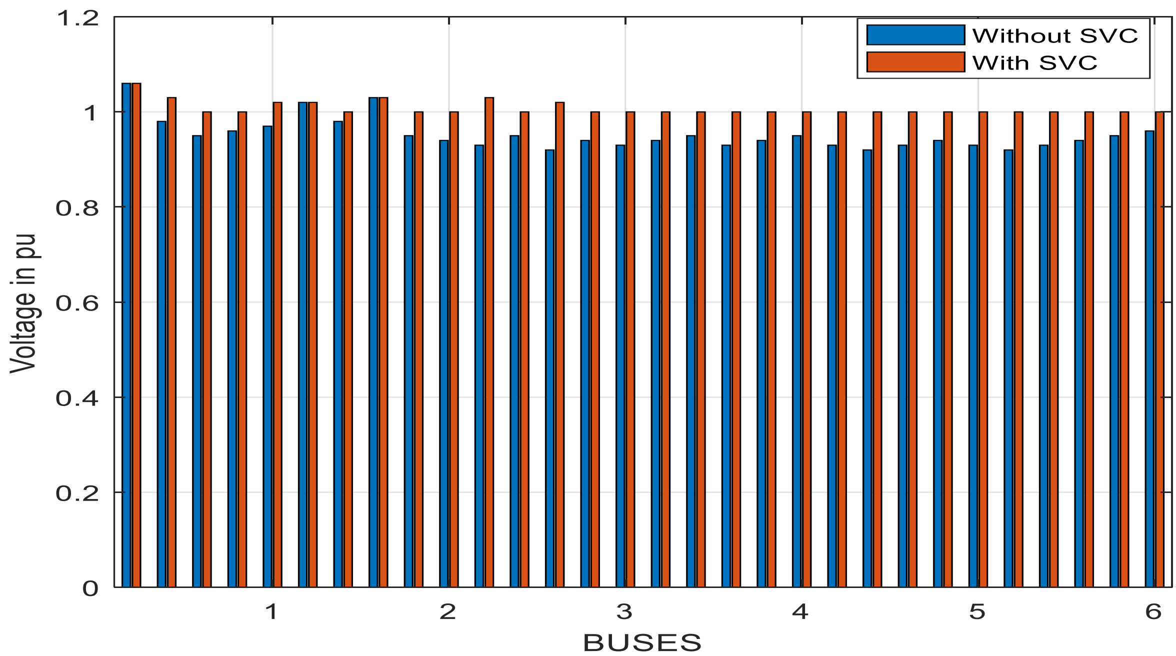

Fig. 5. Voltage profile with and without compensation

5. CONCLUSION

This study successfully applied Static Var Compensators (SVCs) to enhance voltage stability and optimize load flow in the IEEE 30-bus system. The initial load flow analysis identified several buses with voltage levels below 1.0 p.u., signaling the need for compensation to prevent voltage instability. By integrating SVCs into the system, we were able to inject

The results demonstrate that SVCs are highly effective in improving system stability and reducing power losses, particularly in networks with long transmission lines and heavy loads. This research provides practical insights into the optimal placement of SVCs for voltage regulation and suggests that further studies could explore the integration of other FACTS devices, such as STATCOM, for even greater network stability.

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