Comparative analysis of two static var compensator models in voltage control of transmission network

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ABSTRACT

The static var compensator (SVC) is a member of the family of flexible alternating current transmission systems controllers used in power system engineering to manage specific transmission network characteristics to enhance the performance of the transmission networks and thus increase the networks' reliability. Power system engineers typically find it difficult to choose which SVC model to implement for simulations. This research aims to address this issue by conducting a comparative examination of two key SVC models on a transmission network. The two models of SVC variable shunt susceptance and firing angle were mathematically modeled and methodically included into the Newton-Raphson power flow algorithm for the network power flow solution. The IEEE 30-bus network was adopted as the test case, and the method was implemented in the MATLAB/Simulink environment. The network performance metric utilized was the voltage profile of the network. The two SVC models were successful in enhancing the network's performance; however, the variable shunt susceptance model was computationally faster than the firing angle model, as revealed by the simulation results. Therefore, among the two SVC models, the variable shunt susceptance model may be taken into account for simulation to enhance the performance of the transmission networks.

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1. INTRODUCTION

Several difficulties confront transmission systems, jeopardizing their performance. Among these difficulties are voltage magnitude fluctuations, power losses, and voltage regulation. Researchers from all across the world have devised various solutions to some of these issues. Some of the solutions include shunt capacitor placement [1]-[4], distribution generation incorporation [5]-[7], and the placement of flexible alternating current transmission systems (FACTS) controllers [8]-[10], among others. FACTS devices have found a wide range of applications in transmission systems for voltage control because of their adaptability [11].

FACTS devices are electronic-based reactive compensators that are proficient at supplying or consuming reactive power from networks based on the network requirements so that the performance of the network may be improved [12]-[14]. FACTS devices come in various forms and their connections, as well as their performances, differ from one another. The static var compensator (SVC), which comes in numerous variants, is one of the several types of FACTS devices [15]-[17]. The two primary SVC models are the variable shunt susceptance model and the firing angle model. Both of these models are capable of boosting transmission network performance due to their ability to control the bus voltage magnitudes of the transmission networks [18].

A substantial amount of research has been undertaken to improve the performance of transmission networks utilizing various types of FACTS devices. Particle swarm optimization (PSO) was utilized in [19] to assign a static synchronous compensator (STATCOM) to improve the system voltage magnitudes and decrease the active power loss. As a test case, the IEEE 14-bus network was employed. However, the study focused only on one type of FACTS device and did not compare it with other devices, limiting the scope of optimization techniques to STATCOM.

The application of the firefly algorithm (FA) to optimize SVC and STATCOM for voltage magnitude enhancement and loss mitigation on the IEEE 14-bus network is documented in [20]. According to the analysis, the installation of SVC and STATCOM devices enhanced the system voltage magnitudes while simultaneously lowering active and reactive power losses. Nonetheless, the research did not explore the performance of these devices under different network conditions, which could affect their applicability.

Metaheuristic algorithms were used in [21] to solve reactive power planning problems using FACTS controllers. For the test scenarios, the IEEE 30- and IEEE 57-bus networks were utilized. The load flow analysis technique was utilized to estimate the location of the thyristor-controlled series capacitor (TCSC), and the voltage collapse proximity indication method was employed to obtain the SVC position. This study, however, did not account for dynamic changes in the network load, which might influence the effectiveness of the placement strategies.

Magadum *et al*. [22] solved voltage instability by employing fuzzy logic to optimize unified power flow controller (UPFC) placement. The MiPower software package was used to run the simulation using the IEEE 14 bus system. The UPFC location improved network voltage stability substantially. The limitation here is the reliance on fuzzy logic, which may not capture all the nuances of the network dynamics and might require extensive tuning of the fuzzy rules for different scenarios.

Subramani *et al*. [23] improved UPFC by utilizing PSO for optimal device position and parameter tuning, which reduces active losses and enhances network voltage stability. To validate the proposed approach, simulations were performed using the IEEE 14-bus system. However, the study did not compare PSO with other optimization techniques, leaving open the question of whether PSO is the most effective method for this purpose.

The multi-objective genetic algorithm (MOGA) was used in [24] to analyze overall loss minimization and line congestion enhancement by calculating the appropriate placements and compensation rates of TCSC devices. To confirm the potency of the technique, it was evaluated on the IEEE 30-bus test network. While effective, this approach did not consider the impact of other FACTS devices, such as SVC or STATCOM, on the overall network performance.

Despite these advances, there remains a need for a focused comparison between different types of SVCs in controlling bus voltage magnitudes to improve transmission network performance. This research was conducted to compare the capabilities of two key types of SVCs in controlling the voltage magnitudes at the buses where they are placed to boost the performance of the transmission network. The two basic types of SVCs were modeled mathematically and added to the Newton-Raphson load flow algorithm. MATLAB codes were developed to implement the technique and were executed on the IEEE 30-bus transmission system.

The primary contribution of this paper extends to offering comprehensive insights into the performance variations among static var compensator models, facilitating a nuanced understanding of their effectiveness under diverse transmission network conditions. This analysis aids in not only identifying optimal models for precise voltage control but also lays the groundwork for refining voltage control strategies, thus bolstering the stability and efficiency of transmission networks. This study's novelty rests in a focused comparison between two SVC models, emphasizing their computational speed and effectiveness in regulating bus voltage magnitude within transmission networks.

2. METHOD

In its simplest form, the static var compensator (SVC) consists of a parallel connection between a bank of capacitors and a thyristor-controlled reactor (TCR). This configuration operates similarly to a parallel-connected variable susceptance, where the SVC regulates the voltage magnitude at the connection point to the system by either generating or absorbing reactive power. This capability allows the SVC to provide rapid adjustments to reactive power and voltage levels as needed [25]. The thyristor’s firing angle control mechanism enables the SVC to react almost instantaneously to changes in system conditions.

Figure 1 illustrates the schematic representation of the SVC. The SVC is connected to the transmission network through a three-phase, three-winding transformer. This transformer features two secondary windings: one configured as a delta connection for the six-pulse TCR, and the other configured as a star connection for the three-phase capacitor bank, with a floating star point [18]. It is also assumed that all three windings of the transformer are star-connected, with the star points floating to allow for effective reactive power compensation and voltage regulation. Since transmission network lines are transposed at regular intervals, which results in the assumption that these networks operate as balanced systems, the following sub-sections describe the two single-phase models of SVC.

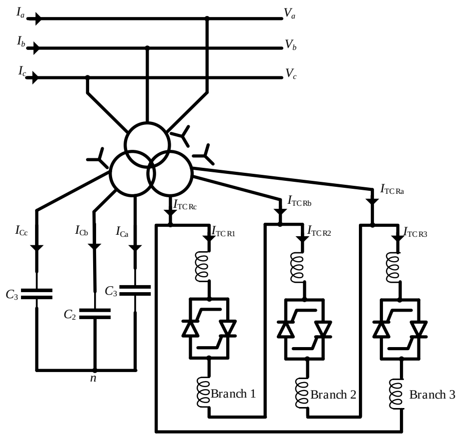

Figure 1. Three-phase SVC representation consisting of thyristor-controlled reactors and fixed capacitors [18]

2.1. Shunt variable susceptance mode

The SVC may really be thought of as a controllable reactance with either reactance limitations or firing angle constraints [26]. The analogous circuit seen in Figure 2 is used to develop both the linearized equations needed by Newton's approach and the SVC nonlinear power equations. Referring to Figure 2, the SVC's current draw is:

$$I_{\mathrm{SVC}} = jB_{\mathrm{SVC}}V_k \quad (1)$$

and the reactive power injected at bus k, as well as the reactive power extracted by the SVC, is given as (2).

$$Q_{SVC} = Q_k = -V_k^2 B_{\mathrm{SVC}} \quad (2)$$

The equivalent susceptance B_{SVC} is assumed to represent the state variable and the linearized equation is given as (3).

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix}^{(i)} = \begin{bmatrix} 0 & 0 \\ 0 & Q_k \end{bmatrix}^{(i)} \begin{bmatrix} \Delta Q_k \\ \frac{\Delta B_{\mathrm{SVC}}}{B_{\mathrm{SVC}}} \end{bmatrix}^{(i)} \quad (3)$$

The variable shunt susceptance B_{SVC} is revised after each repetition in accordance with (4).

$$B_{\mathrm{SVC}}^{(i)} = B_{\mathrm{SVC}}^{(i-1)} + \left(\frac{\Delta B_{\mathrm{SVC}}}{B_{\mathrm{SVC}}}\right)^{(i)} B_{\mathrm{SVC}}^{(i-1)} \quad (4)$$

The total SVC susceptance required to keep the bus voltage magnitude at the desired level is represented by the changing susceptance [27]. The thyristor firing angle is determined once the level of correction has been established. However, due to the nonlinear relationship between the SVC susceptance and the thyristor firing angle, this computation requires an iterative solution [28].

2.2. Firing-angle model

By addressing the thyristor-controlled reactor (TCR) firing angle α as a state variable in the power flow derivation, an alternative α_{SVC} model may be used to avoid the extra iterative procedure [29]. Here, "SVC" is used to refer to the variable. The SVC's positive sequence susceptance is provided as in (5).

$$Q_k = \frac{-V_k^2}{X_C X_L}\left\{XL - \frac{XC}{\pi}\left[2(\pi - \alpha_{\mathrm{SVC}}) + sin(2\alpha_{\mathrm{SVC}})\right]\right\} \quad (5)$$

The linearized SVC equation is provided from (5) as (6).

$$\begin{bmatrix}\Delta P_k \\ \Delta Q_k\end{bmatrix}^{(i)} = \begin{bmatrix}0 & 0 \\ 0 & \frac{2V_k^2}{\pi X_L}\left[cos(2\alpha_{\mathrm{SVC}}) - 1\right]\end{bmatrix}^{(i)} \begin{bmatrix}\Delta Q_k \\ \Delta \alpha_{\mathrm{SVC}}\end{bmatrix}^{(i)} \quad (6)$$

The variable firing angle α_{SVC} is revised after each iteration in accordance with (7).

$$\alpha_{SVC}^{(i)} = \alpha_{SVC}^{(i-1)} + \Delta\alpha_{SVC}^{(i)} \quad (7)$$

The Newton-Raphson power flow technique was implemented for both SVC models based on their mathematical formulations, and MATLAB scripts and functions were developed to perform the simulations. The data required for the simulations were obtained from [30].

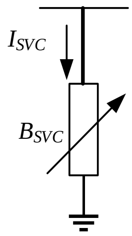

Figure 2. Variable shunt susceptance [18], [26]

3. RESULTS AND DISCUSSION

The investigation results of the two SVC models are presented. The simulations used a precision level of 1e-10 and were performed over 20 iterations. Figure 3 shows the IEEE 30-bus power flow solution. It was discovered that some buses had voltage magnitudes less than 1.0 p.u. Therefore, SVCs were installed on these buses to explore the capabilities of the two types of SVC models in regulating the voltage to the desired level. In the network under investigation, simulations were conducted by sequentially adding SVCs. Initially, one SVC was installed at the first selected bus, followed by two SVCs at the first two selected buses, three SVCs at the first three selected buses, and finally four SVCs at the first four selected buses. Buses numbered 18, 20, 24, and 25 were chosen because their voltage magnitudes were less than 1.0 p.u., as depicted in Figure 3. The voltage magnitudes at these buses were initially adjusted to 1.0 p.u. and subsequently to 1.05 p.u. to assess the performance of the SVCs in regulating the voltage levels.

The simulation results for the two different SVC models are shown in Table 1, with the SVC voltage magnitudes regulated to 1.0 p.u. The susceptance values for both models, as presented in Table 1, were found to be identical, indicating consistent reactive power compensation capabilities. Figure 4 further elucidates the comparison of voltage profiles between the base case and the scenarios where the two different SVC models were deployed on the selected buses. This comparison demonstrates how both models effectively enhanced the network's voltage stability by maintaining the bus voltage magnitudes within the desired range. The identical susceptance values suggest that both models provide comparable reactive power support under steady-state conditions.

However, as shown in Table 1, the variable shunt susceptance model exhibited superior performance over the firing angle model in terms of computational efficiency. Specifically, the variable shunt susceptance model required fewer iterations to converge and achieved shorter simulation times, highlighting its efficiency in reaching a steady-state solution. This indicates that the variable shunt susceptance model is more computationally efficient, which can be particularly advantageous in real-time applications where quick response times are critical.

Additionally, Table 1 documents the firing angles for each simulation corresponding to the firing angle model. This data provides further insight into the operational characteristics of the firing angle model, showing the adjustments needed to achieve the desired voltage regulation. The detailed recording of firing angles aids in understanding the control mechanism and the extent of modulation required for effective voltage control. In summary, while both SVC models enhance the voltage profile and provide effective voltage regulation, the variable shunt susceptance model offers significant advantages in terms of computational speed and efficiency. These findings underscore the importance of selecting the appropriate SVC model based on the specific requirements of the transmission network and the operational constraints.

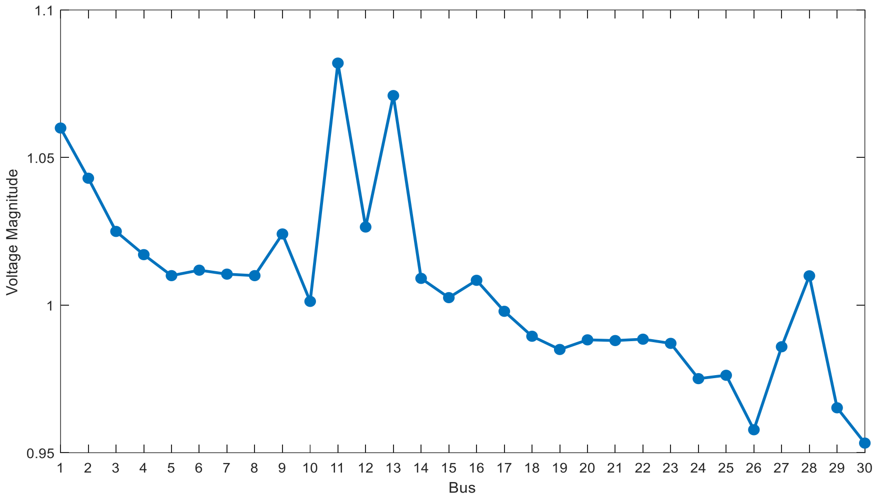

Figure 3. Voltage profile in the IEEE 30-bus network's base scenario

Table 1. Simulation results when the SVC voltage was adjusted to 1.0 p.u.

SVC model		1 SVC	2 SVCs	3 SVCs	4 SVCs
Variable susceptance model	Susceptance (p.u.)	0.0441	0.0182 0.0391	0.0119 0.0305 0.0558	0.0095 0.0273 0.0388 0.0531
	Simulation time (s)/iteration	0.004124/5	0.004195/5	0.004233/5	0.022763/5
Firing angle model	Susceptance (p.u.)	0.0441	0.0182 0.0391	0.0119 0.0305 0.0558	0.0095 0.0273 0.0388 0.0531
	Firing angle (degree)	186.3	154.8 180.2	147.2 169.6 200.7	144.3 165.7 179.8 197.4
	Simulation time (s)/iteration	0.006313/7	0.006578/7	0.012756/7	0.024010/7

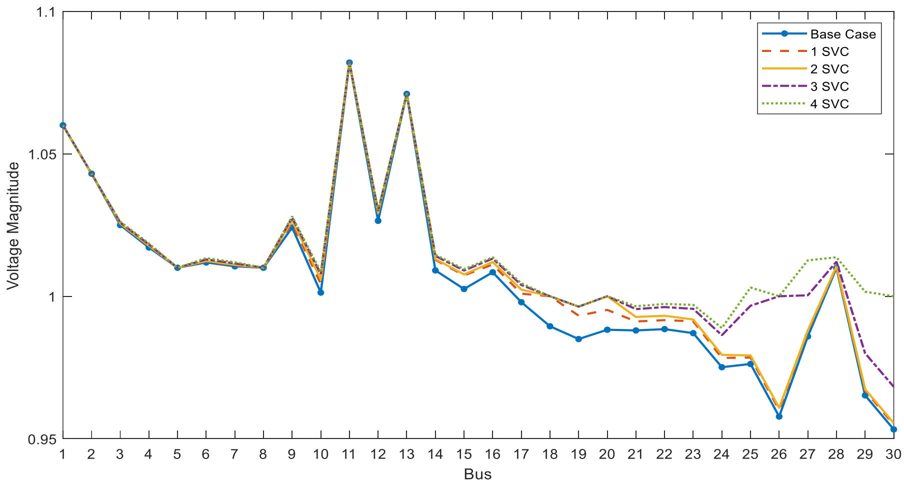

Figure 4. Voltage profile comparison when the two SVC models voltage was adjusted to 1.0 p.u.

Similarly, additional simulations were performed with the SVC voltage magnitudes adjusted to 1.05 p.u. to evaluate the impact of this voltage setting on network performance. The outcomes of these simulations are summarized in Table 2, which presents a detailed comparison of the performance metrics for both the variable shunt susceptance and firing-angle SVC models. Figure 5 illustrates the resulting voltage profiles from these simulations, providing a clear visual representation of how the adjusted SVC voltages influenced the voltage regulation across the network.

The results depicted in Figure 5 reveal a marked improvement in the voltage profile when the SVC voltage magnitudes were set to 1.05 p.u. Both SVC models effectively enhanced the voltage stability at the specified buses, as evidenced by the improved voltage profiles. However, a closer comparison of the two models shows that, while both achieved similar outcomes in terms of voltage regulation, the variable shunt susceptance model demonstrated superior computational efficiency compared to the firing-angle model. This superiority was evident through fewer iterations and faster convergence in the power flow calculations, consistent with observations made when the SVC voltages were controlled to 1.05 p.u. These findings underscore the variable shunt susceptance model's advantage in both practical applications and simulation scenarios for effective voltage control in transmission networks.

Table 2. Simulation results when the SVC voltage was adjusted to 1.05 p.u.

SVC model		1 SVC	2 SVCs	3 SVCs	4 SVCs
Variable susceptance model	B_{SVC} (p.u.)	0.2427	0.1301 0.1697	0.1184 0.1537 0.1034	0.1177 0.1527 0.0981 0.0170
	Simulation time (s)/iteration	0.004963/6	0.013045/6	0.014362/6	0.022763/6
Firing angle model	B_{SVC} (p.u.) (p.u.)	0.2427	0.1301 0.1697	0.1184 0.1537 0.1034	0.1141 0.1479 0.0723 0.0962
	Firing angle (degree)	86.7	294.6 346.7	279.6 325.5 260.3	274 317.9 221.2 251.3
	Simulation time (s)/iteration	0.015616/7	0.016468/7	0.028005/7	0.024010/7

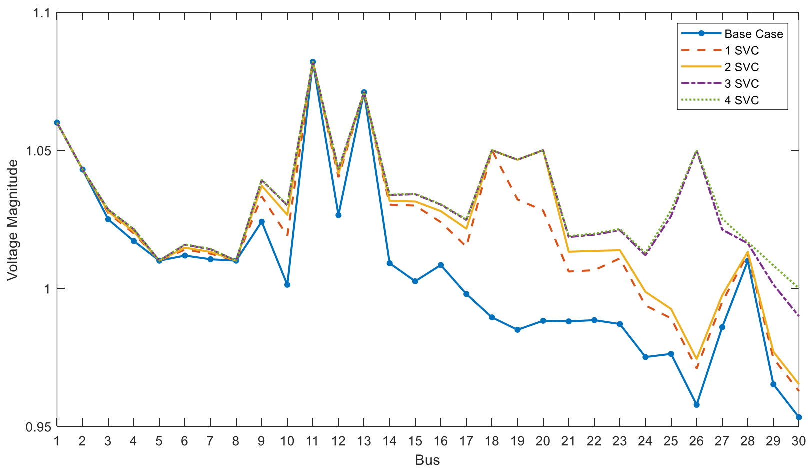

Figure 5. Voltage profile comparison when the two SVC models voltage was adjusted to 1.05 p.u.

4. CONCLUSION

This study explored the effectiveness of two different types of SVC models variable shunt susceptance and firing-angle models in regulating voltage magnitudes in transmission networks. Both models were systematically developed and integrated into the Newton-Raphson power flow algorithm, demonstrating their capability to stabilize voltage levels across the network. The simulations revealed that while both models were effective in improving voltage stability, the variable shunt susceptance model exhibited superior performance compared to the firing-angle model. Specifically, the variable shunt susceptance model achieved faster computational times and required fewer iterations to reach convergence, highlighting its efficiency for voltage control applications.

The results suggest that the variable shunt susceptance model is a more advantageous tool for power system engineers seeking to enhance voltage regulation in transmission networks. Its superior computational performance and effectiveness make it a preferred choice for simulation and practical implementation. Future research could extend these findings by investigating the model's performance under dynamic conditions and exploring its integration with advanced optimization techniques to further improve transmission network management.

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