Optimal Placement and Sizing of Static VAR Compensator (SVC) for Voltage Stability Enhancement in Wind Integration Power System

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Abstract- The goal of this project is to utilise MATLAB to model and simulate a Static Var Generation (SVC) for electrical system research. First, we used MathCAD to perform a mathematical rating study of the SVC. The Static Var Compensation (SVC) in power systems was then modelled in order to examine its behaviour both inside and outside of the control range. This involved using analysis of load flow to make the implementation of SVC easier. The SVC transfer operations with open-loop controls for each of the different control elements—such as the voltage regulator, thyristor susceptance control, and measurement modules—were then separately modelled. We set up the open and a closed-l transfer equations by using the lag/lead compensator theories, taking into account their individual phase margins and gain. Lastly, we used the SVC gadget to regulate the power system's reactive power and voltage flow. We were able to evaluate the SVC's performance and behaviour under various operating settings because to this thorough approach, which also gave us important insights into its possible uses in power systems.

***Keywords— Power Factor; Reactive Power*; *FACTS, SVC, Var and Voltage Control etc*.

I. INTRODUCTION

The rapid development of power semiconductors or computer-controlled technologies has led to the development of numerous innovative automatic and quick reactive power compensation systems. Initially, electrical grids employed mechanical switching capacitor units, which were activated and deactivated by circuit breakers or contactors. However, the use of breakers for filter or capacitor implantation resulted in a number of noteworthy changes and challenges, such as the stretching discharge phenomena, which decreased the action durations of the circuit breakers and reduced the frequency of switching.

A significant development in shunt compensating devices is the use of Static Var Compensating elements (SVCs), a device that utilises thyristor-switched technology. SVCs, although built on the concepts of inductor and parallel capacitance processes, differ from mechanical breakers in that they employ large-capacity thyristors for switching. Because SVCs offer precise control over switching durations and nearly limitless operations, they are widely used in distribution systems. By using thyristors, inrush current effects are mitigated and operational issues are reduced. Thyristors provide improved performance, impact-free, quick switching. SVCs have dynamic reaction times ranging from 0.01 to 0.02 seconds.

Static Var compensating elements are essential for compensating for reactive power in power systems, even though they require a larger initial investment and ongoing maintenance expenses. It is frequently not feasible to perform direct power measurements on SVCs because of safety, cost, and technological issues. Therefore, this paper uses MATLAB for simulation & modelling in order to further analyse the characteristics and potential uses of Static Var Compensating elements in power grids.

II. PROPOSED CONFIGURATION WORK

The SVC is a shunt device that is part of the FACTS family. It is used to control power flow and improve transient stability in power grids through the use of power electronics. It was first used in the mid-1970s for arc furnaces flicker compensation, and thereafter it was used in power transmission networks. In 1978, one of the first installations of 40 Mvar SVC took place at the Minnesota Power & Light system's Shannon Substation. The SVC has various advantages, such as,

- Voltage support, and regulation,
- Transient stability improvement, and
- Power system oscillation damping,
- Reactive power compensation,
- Power transfer capacity increase and line loss minimization.

Controlled reactive compensation in electric power systems is usually achieved by means of different configuration choices, such as fixed capacitor (FC), mechanically switched capacitor/reactor SVC, thyristor switched capacitance/reactor (TSC/TSR), and thyristor controlled reactor (TCR). The TCR/TSR SVC combo and the related control system are the main topics of this discussion. Figure 1.

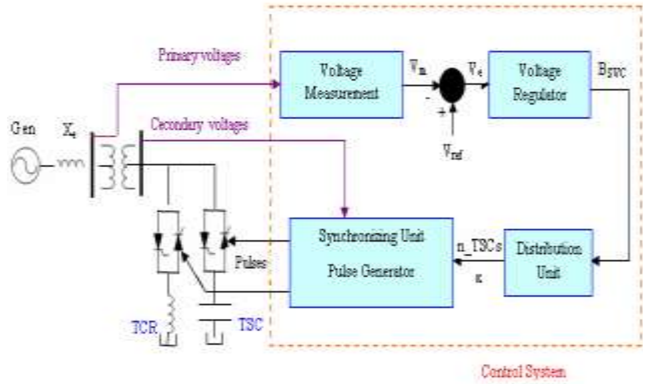

Fig. 1. Single-line Diagram of an SVC and Its Control system.

The compensator's output is modulated step by step by the sequential switching of TCRs and TSCs. This gradual reactor switching, as opposed to continuous control, removes the requirement for harmonic filtering as a component of the compensator scheme.

III. SVC MATHEMATICAL MODEL WITH MATHCAD

The method for determining the SVC's parameters is demonstrated in the example below. Assume that the 735 kV bus is connected to the SVC, which consists of three 94 MVAr TSC banks and one 109-MVAr TCR bank, through a 333 MVA, 735/16 kV distributor on the other side of the bus. The transformer's leakage reactance is 15%. The regulator has a voltage drop of 0.01pu/100VA (0.03pu/300 VA). The SVC voltage fluctuates between when the SVC operating point shifts from entirely capacitive to fully inductive 1 - 0.03 = 0.97 p.u and 1+ 0.01 = 1.01 p.u.

The SVC rating is as follows:

$$Q_{TSC} = 3.\ 94\,\text{Mvar},\quad Q_{TCR} = 109\,\text{Mvar},$$

The nominal inductive & capacitive currents for SVC referring to the primary side are calculated as follows at graded line-to-line voltage Urated:

$$Q_{L\,rated} = \sqrt{3}\,U_{rated} \cdot I_{L\,rated} = U^2_{rated} \cdot B_{L\,rated} \quad (1)$$

$$I_{L\,rated} = \frac{Q_{L\,rated}}{\sqrt{3}\,U_{rated}} = \frac{Q_{3\,TSC} - Q_{TCR}}{\sqrt{3}\,U_{rated}} = 135.89\ A$$

$$Q_{C\,rated} = \sqrt{3}\,U_{rated} \cdot I_{C\,rated} = U^2_{rated} \cdot B_{C\,rated} \quad (2)$$

$$I_{C\,rated} = \frac{Q_{C\,rated}}{\sqrt{3}\,U_{rated}} = \frac{Q_{3\,TSC}}{\sqrt{3}\,U_{rated}} = 221.51\ A$$

At the maximum line-to-line voltage Umax=742.35 kV

$$Q_{L\,max} = \sqrt{3}U_{max} \cdot I_{L\,max} = U^2_{max} \cdot B_{L\,rated}$$

$$I_{L\,max} = I_{L\,rated}\frac{U_{max}}{U_{rated}} = 137.24\,A \quad (3)$$

At the minimum line-to-line voltage Umin=712.95 kV

$$Q_{C\,min} = \sqrt{3}U_{min} \cdot I_{C\,min} = U^2_{min} \cdot B_{C\,rated} \quad (4)$$

$$I_{C\,min} = I_{C\,rated}\frac{U_{min}}{U_{rated}} = 211.86\,A$$

The reactive of the TCR and TSC are calculated as

$$X_{L\,rated} = \frac{U^2_{rated\,S}}{Q_{L\,rated}} = \frac{16^2}{109} = 2.348\,\Omega$$

$$X_{transf} = 0.15\frac{U^2_{rated}}{P_{transf}} = \frac{16^2}{333} = 0.115\,\Omega$$

$$X_{L\,TCR}(\Delta) = X_{L\,rated} - X_{transf} = 2.233\ \Omega \quad (5)$$

$$X_{L\,TCR}(1\Phi) = 3.\ 2.233 = 6.67\,\Omega$$

$$L_{L\,TCR} = \frac{6.67}{2.\pi.60} = 17.7\,mH$$

$$X_{C\,rated} = \frac{U^2_{rated}}{Q_{C\,rated}} = \frac{16^2}{282} = 0.9078\ \Omega \quad (6)$$

$$C = \frac{1}{2.\pi.60.0.9078} = 2.92\,mF$$

IV. SVC V-I CHARACTERISTICS

The fluctuation of SVC bus voltage having SVC current or reactive energy is described by the steady-state and dynamical characteristics of SVCs; Fig. 2 shows the terminal voltage-SVC flow characteristic with a particular slope.

$$Slope = \frac{\Delta V_{C\max}}{I_{C\max}} = \frac{\Delta V_{L\max}}{I_{L\max}} \quad (7)$$

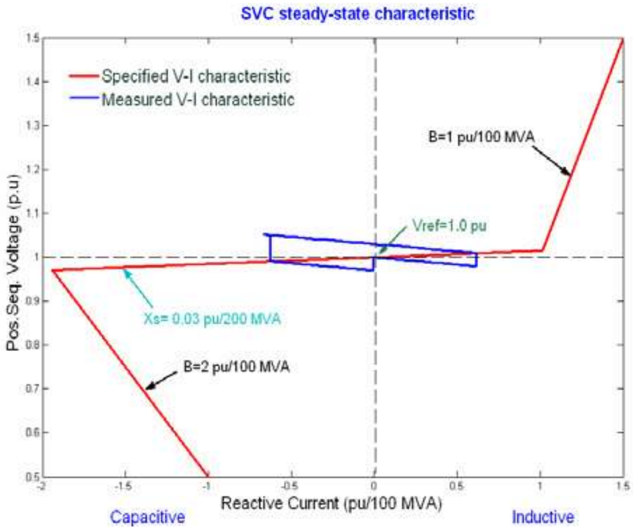

Fig. 2. SVC steady-state control characteristics.

The regulation slope makes it possible to:

•Increase the voltage regulation loop's stability; and • Increase the compensator's linear operating range.

•To mandate automatic load sharing among other voltage-regulating devices and the static variable compensator.

The following equations describe the V-I characteristic:

$$V = V_{ref} + X_s \cdot I \quad (8)$$

SVC is in regulation rang;

$$V = \frac{I}{-B_{C\max}} \quad (9)$$

SVC is fully capacitive , $B = B_{C\max}$

$$V = \frac{I}{B_{L\max}} \quad (10)$$

SVC is fully inductive, $B = B_{L\,max}$

The voltage Vref, as shown in figure (2), is the reference voltage where the SVC neither accepts nor produces reactive power. This voltage can be practically altered within the usual ±10% range. Slope reactance XSL, which results in the SVC response to a voltage fluctuation, can be seen of as the characteristics' slope since it represents a change in voltages and compensator current.

V. MODELING OF STATIC VAR COMPENSATOR IN POWER SYSTEM STUDIES

Appropriate electrical system models and research techniques addressing the specific issues that the SVC application is intended to address are necessary for SVC application studies. From the initial stages of planning to implementation, the following studies are often needed for an SVC application.

- Load flow studies.
- Small and large disturbance studies.
- Harmonic studies.
- Electromagnetic transient studies.
- Fault studies.

Model for load flow analysis :

Determining the node voltages, reactive and active electrical flow in the network limbs, generations, and loss is the primary goal of load flow analysis. The following are the power flows studies pertaining to SVC applications: • Locate the SVC and establish its initial rating.
• To provide data regarding how the SVC affects power flows and system voltages.
• To offer the starting point for the transient analysis of the system.
• As well as operating boundaries, which are either inside or outside the control range.

SVC Operating within the control range :

The control range of the SVC is defined as:

$$I_{min} < I_{SVC} < I_{max} \; ..... \; V_{min} < V < V_{max}$$

With P=0, V = Vref, SVC is represented in this range as a PV-node (the generator node) at a secondary bus. At the auxiliary nodes and the system coupling node, there is extra reactance equal to the slope of the V-I characteristics. As seen in Fig. 3, the node at the centre that has common coupling constitutes a PQ node of P=0, Q=0:

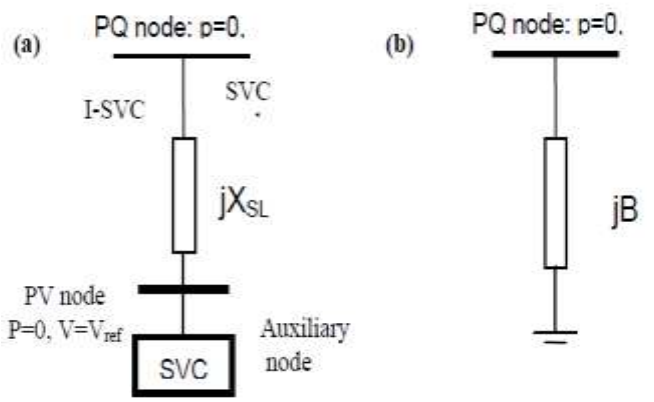

Fig.3. SVC model for operation , a) within control range, b) outside control range

VI. SIMULATION AND RESULT ANALYSIS

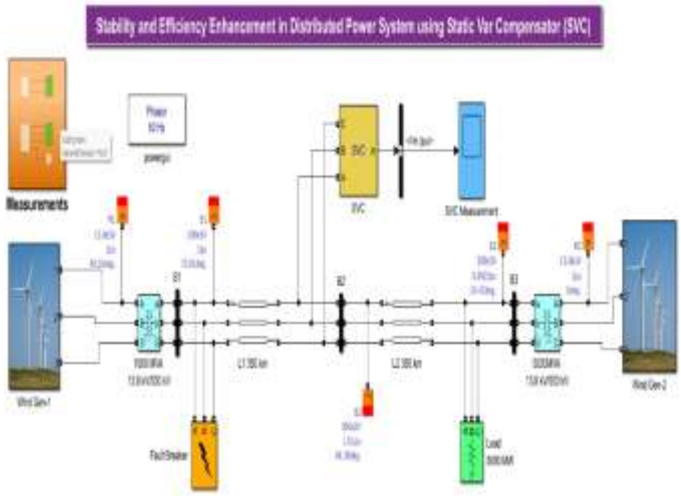

Fig. 4. Simulation model of With Static Var Compensator

Figure 4 illustrates the simulation model of a distributed power system integrated with a Static Var Compensator (SVC) for stability and efficiency enhancement. The system consists of two wind generation units (Wind Gen-1 and Wind Gen-2) connected through two long transmission lines (L1 and L2), each 350 km in length. High-voltage transformers (13.8 kV/500 kV) link the wind farms to the transmission network. An SVC is connected at Bus B2 to provide dynamic reactive power compensation. By regulating voltage magnitude (Vm), the SVC helps maintain voltage stability during varying load and generation conditions. A 5000 MW load is connected near Bus B3 to represent consumer demand. The model also includes measurement blocks for monitoring voltage, current, and phase angles, along with a fault breaker to analyze transient response. This setup evaluates improved voltage profile and system reliability with SVC control.

With SVC Output:

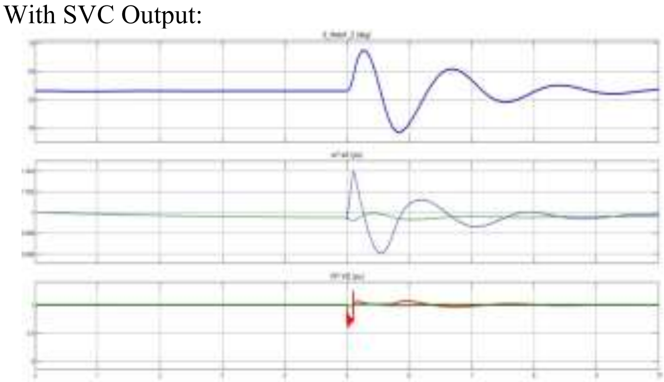

Fig. 5. Machine signals after fault disturbances

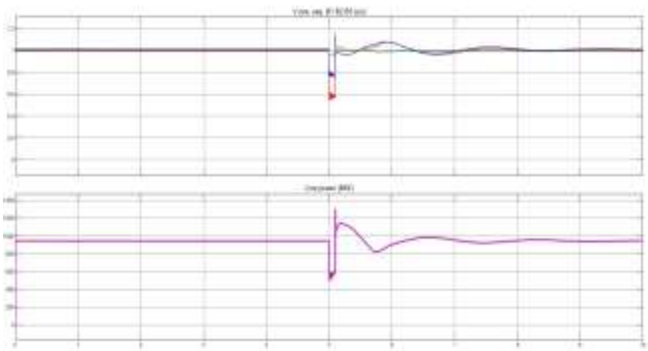

Fig. 6. RMS Bus measurements after fault disturbances

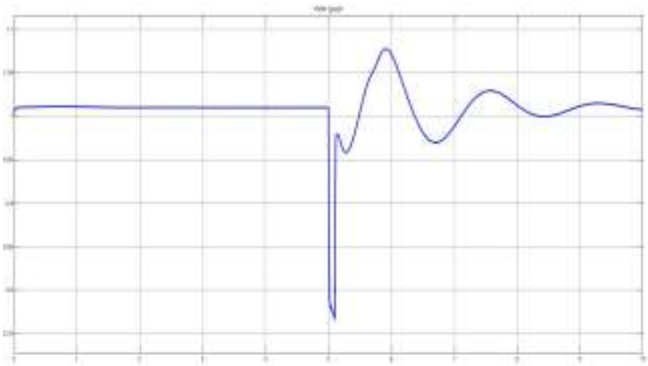

Fig. 7. SVC measurements

Without SVC :

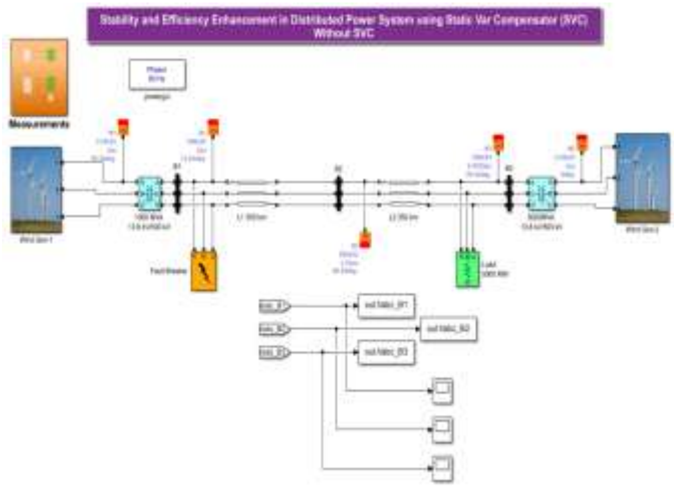

Fig. 8. Simulation model of Without Static Var Compensator

Figure 8 illustrates the simulation model of a distributed power system operating without a Static Var Compensator (SVC). The system includes two wind generation units, Wind Gen-1 and Wind Gen-2, connected through high-voltage transformers (13.8 kV/500 kV) and two long transmission lines (L1 and L2), each 350 km in length. Busbars B1, B2, and B3 serve as key monitoring points for voltage and phase angle measurements. A 5000 MW load is connected near Bus B3, representing the system's demand. A fault breaker is placed near Bus B1 to analyze the system's transient and dynamic response under fault conditions. In this configuration, the absence of SVC results in limited reactive power compensation, making the system more susceptible to voltage instability and fluctuations during load variations or disturbances. This model serves as a baseline for comparison with the SVC-enhanced system.

Without SVC Output:

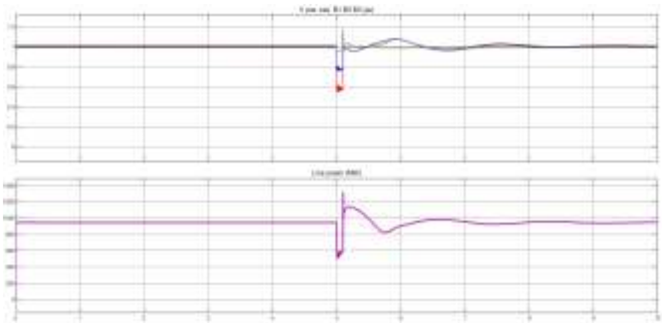

Fig. 9. Bus measurements

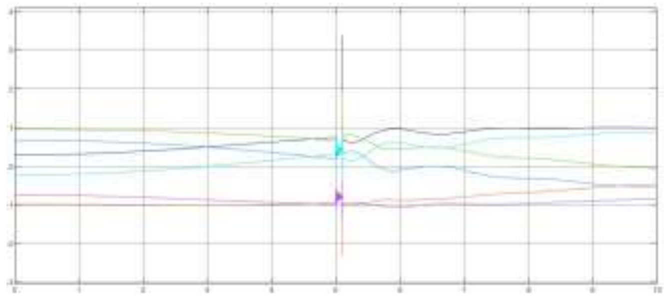

Fig. 10. Bus1 voltage measurement After Fault

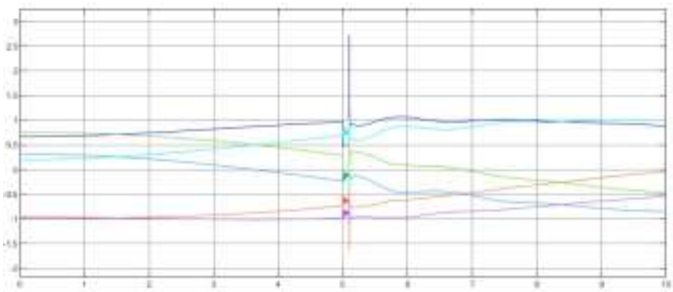

Fig. 11. Bus2 voltage measurement After Fault

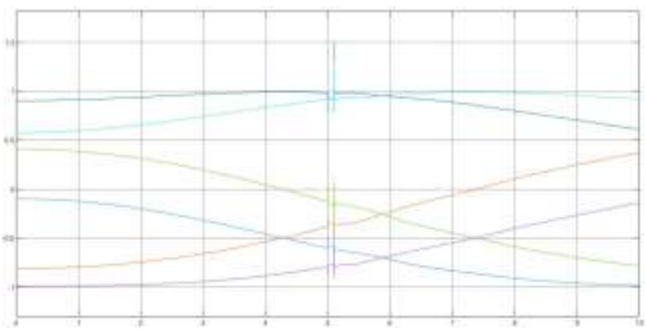

Fig. 12. Bus3 voltage measurement After Fault

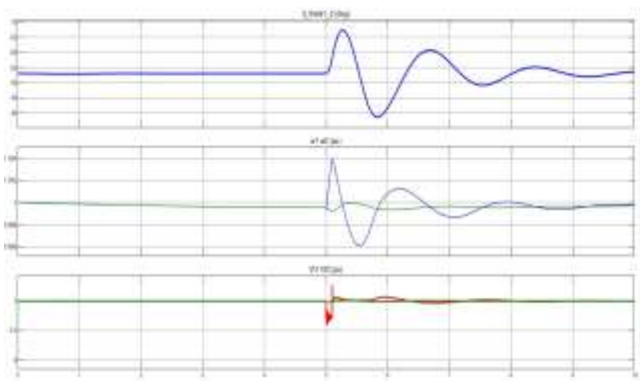

Fig. 13. Machine Signals after Faults disturbance

Optimization Results:

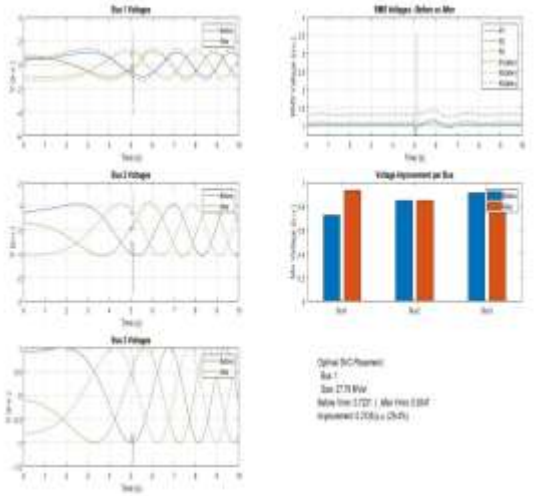

Fig. 14. Optimization Results

Optimization Results illustrate the effect of integrating a Static Var Compensator (SVC) into the distributed power system. The voltage waveforms at Bus 1, Bus 2, and Bus 3 are compared before and after SVC placement under fault disturbance conditions. Prior to compensation, the buses experience noticeable voltage fluctuations and oscillations, indicating instability and poor reactive power support. After installing the SVC, the oscillations are significantly reduced, and voltage profiles become smoother, demonstrating improved dynamic stability.
The RMS voltage comparison plot shows that the voltage levels at all buses are more regulated after compensation. The bar graph indicates a clear increase in minimum voltage values at each bus, confirming enhanced voltage security. The optimal location for SVC placement is determined to be Bus 1, with an optimal compensating capacity of 27.79 MVar. The minimum voltage improved from 0.7221 p.u. to 0.9347 p.u., indicating an enhancement of 0.2126 p.u. (29.4%). Overall, the optimization results confirm that SVC implementation significantly enhances voltage stability and system performance.

VII. CONCLUSION

We can infer from the aforementioned simulation results that the Static Var Compensation is capable of resolving a wide range of reactive compensation issues in power systems. The quality of electricity in the power grid can be significantly improved by installing a static voltage rectifier. Additionally, this technology offers faster response times and continuous regulation and control from inductive to capacitive. Additionally, it features improved phase-and voltage-control capabilities. Reducing network losses, maintaining grid voltage stability, enhancing power quality, lessening the dampening effect of low frequency oscillation, and controlling harmonics in power systems are all made possible by the Static Var Compensator. However, in future analysis, the thyristor's simulation of metal oxide arresters gadgets implanted within it can survive significant over-voltage and over-current shocks. In summary, this cutting-edge, reasonably priced, and energy-efficient technology can be utilised as a significant tool that will be extensively employed in the power grid in the future.

This article models minor disturbances, including control action, to establish the required SVC rating for the chosen subject matter.

In addition, we have ascertained the suitable control signal for sufficient transient stability and control structures corridors in order to offer the most feasible and comprehensive understanding of the SVC control system. Consequently, voltage regulation at the point of SVC attachment to the system is described by power system stability. This method can be applied to confirm if the control parameters are adequate. In order to regulate the voltage and reactive power, we lastly connect an SVC to the power grid.

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