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Stability Analysis of Electric Power Systems Using Controllers Facts on Transmission System

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ABSTRACT
Power system stability is a critical factor in maintaining the continuity and quality of energy supply, especially in transmission systems that face load fluctuations and integration of renewable energy sources. The main problems in this study are voltage instability and reactive power oscillations that often occur due to disturbances such as sudden load changes or short circuits, as well as the limited capacity of conventional controllers in reducing these impacts. This study aims to explore the role of Static VAR Compensator (SVC) as part of Flexible AC Transmission Systems (FACTS) technology in improving transmission system stability through a qualitative approach. The research method is carried out with descriptive analysis based on literature studies, mathematical modeling of the power system, and numerical simulations to understand the dynamics of the system response to disturbances. The focus is given to qualitative evaluation of the interaction between SVC, system parameters (voltage, reactive power, and phase angle), and the impact of controller placement on network reliability. Simulation case studies cover small to large disturbance scenarios to assess the effectiveness of SVC in restoring stability. The results show that SVC integration makes a significant contribution to improving the dynamic stability of the transmission system. Qualitative analysis finds that SVC is able to reduce voltage oscillations and accelerate post-disturbance system recovery through adaptive reactive power regulation. However, the limited capacity of SVC in handling extreme disturbances indicates the need for combination with other FACTS controllers (such as STATCOM or UPFC) for more complex systems. This study also reveals the importance of proper SVC placement strategy to optimize its effectiveness.

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INTRODUCTION

The stability of the electric power system is one of the main aspects that must be maintained to ensure the reliability of the electric energy supply to consumers. The transmission system, which functions as a link between power plants and load centers, often faces major challenges due to high loads, sudden disturbances, and the integration of fluctuating renewable energy sources (Kundur et al., 1994). Under these conditions, the system's ability to maintain voltage and frequency stability becomes increasingly important to prevent widespread blackouts or system collapses.

The use of Flexible AC Transmission System (FACTS) technology has been widely identified as one of the potential solutions to improve the performance and stability of the electric power system. FACTS allows more flexible power flow regulation by using power electronics-based controller devices (Hingorani & Gyugyi, 2000). One type of FACTS device that has been widely used is the Static VAR Compensator (SVC), which is designed to regulate reactive power in the transmission network. SVC works by automatically increasing or decreasing reactive power to maintain voltage within the desired limits, thereby helping to improve system stability (Rao, 2018).

Various previous studies have shown that the application of SVC to the transmission system can improve voltage stability and reduce power oscillations after disturbances. For example, Zhang et al. (2011) stated that the use of SVC can improve the dynamic response of the system to sudden load changes and accelerate the system recovery time after disturbances. Another study by Asghar and Iqbal (2019) stated that SVC provides an effective solution in overcoming stability problems, especially in complex interconnected transmission networks.

Based on the above background, this study aims to analyze the role of SVC as a FACTS controller in improving the stability of the electric power system. The main focus of this study is to evaluate the performance of SVC in the transmission system through numerical simulation, especially in dealing with various frequent disturbance scenarios. Thus, this study is expected to provide practical contributions in the development of control strategies to improve the reliability of the electric power system in the future.

Literature Review

Stability of Electric Power System

Power system stability refers to the ability of the system to maintain balanced operation after a disturbance or change in conditions. In this context, system stability can be divided into three main categories: voltage stability, frequency stability, and transient stability (Kundur et al., 1994). Voltage stability is the ability of the system to maintain voltages within acceptable limits at all buses during normal operation as well as after a disturbance (Padiyar, 2012).

The basic equation used in the analysis of the stability of an electric power system is the equation for real and reactive power at a bus i

$$P_i = \sum_{j=1}^{N} V_i V_j \left(G_{ij} \cos \delta_{ij+} B_{ij} \sin \delta_{ij}\right) \ldots \ldots (1)$$

$$Q_i = \sum_{j=1}^{N} V_i V_j \left(G_{ij} \cos \delta_{ij-} B_{ij} \sin \delta_{ij}\right) \ldots \ldots (2)$$

Where Pi and Qi are the active and reactive power at bus i, respectively, Vi and Vj are the voltages at buses i and j, Gij and Bij are the conductance and susceptance components of the line admittance, and δij is the angular difference between buses i and j (Kundur et al., 1994).

Flexible AC Transmission System (FACTS)

Flexible AC Transmission System (FACTS) is a power electronics-based technology designed to improve the flexibility, efficiency, and capacity of the electric power system (Hingorani & Gyugyi, 2000). FACTS includes various controller devices, such as Static VAR Compensator (SVC), Static Synchronous Compensator (STATCOM), and Unified Power Flow Controller (UPFC). These devices can regulate network parameters such as voltage, reactive power, and power flow to improve the overall system stability.

In the context of voltage stability, SVC is one of the most widely used FACTS devices. SVC can automatically regulate reactive power in the transmission network by absorbing or supplying reactive power using thyristor-controlled reactor (TCR) and thyristor-switched capacitor (TSC). The main function of SVC is explained by its reactive power characteristics:

$$Q_{svc} = V^2 . B_{svc} \qquad \dots \dots (3)$$

where Qsvc is the reactive power supplied or absorbed by the SVC, V is the bus voltage where the SVC is attached, and Bsvc is the effective susceptance controlled by the SVC (Hingorani & Gyugyi, 2000).

Static VAR Compensator (SVC)

SVC is an electronic-based reactive power control device that has the ability to improve the stability of the electric power system by dynamically adjusting the bus voltage. The operation of SVC is based on the regulation of susceptance through a combination of TCR and TSC (Rao, 2018). The working principle of SVC can be represented through the effective susceptance equation

$$B_{svc} = B_{TSC} - B_{TCR} \qquad \dots \dots (4)$$

where BTSC is the susceptance of the thyristor-connected capacitor, and BTCR is the susceptance of the thyristor-controlled reactor. Zhang et al.'s (2011) research shows that SVC is effective in improving voltage stability by reducing the amplitude of voltage oscillations and accelerating system recovery time. This is in line with the study of Asghar and Iqbal (2019) which states that the application of SVC to the transmission network provides a better dynamic response, especially in dealing with sudden load changes and short circuit disturbances.

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Figure 1. Static VAR Compensator

The static VAR compensator consists of a controlled reactor and a fixed shunt capacitor connected in parallel. The reactor is controlled by a thyristor switch assembly SVC. The firing angle of the thyristor determines the voltage across the inductor and, as a result, the current flowing through it. This allows you to control the reactive power demand of the inductor.

It is a static form of parallel connected VAR absorber or generator whose output is adjusted to compensate for inductive or capacitive currents, thereby the circuit can regulate or manage the associated current factors, especially the bus voltage factor. Static VAR compensators rely on thyristors that do not have gate switching capability. The functionality and features of thyristors understand the variable reactive impedance of SVCs.

This device includes two important devices: TCR and TSR, which are capacitors and thyristor-controlled reactors. In the case of high-voltage power transmission lines, these devices provide fast reactive power. SVC is classified as a dynamic AC transmission network with voltage regulation and system stability. The fundamental static VAR compensator circuit schematic is illustrated below:

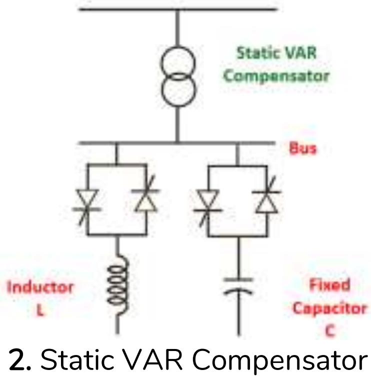

Figure 2. Static VAR Compensator circuit

The thyristor switch assembly controls the reactor, while the firing angle controls the voltage & current values passing through the inductor. This allows the inductor's reactive power to be controlled.

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This technology has the capacity to eliminate reactive power regulation even over long distances while maintaining zero time delay. And also improves system stability and power factor. Some of the schemes used by SVC devices include:

a. Thyristor regulated capacitor
b. Thyristor regulated reactor
c. Self-contained reactor
d. Thyristor regulated reactor with constant capacitor
e. Capacitors and reactors regulated by thyristors

Design

In the single line diagram of SVC, the reactor can be an internal slider to the circuit through PAM modulation by thyristors, which produces a constantly changing VAR type to the electrical system. In this mode, the capacitor regulates the expanded voltage level, which is well known to provide efficient control.

As a result, TCR mode provides better control and reliability. Thyristors can also be electronically regulated. Thyristors, like semiconductors, dissipate heat and use deionized water to cool them. When reactive loads are fed into the circuit, they create unwanted harmonics, and various filters are usually used to smooth out the waveform. Since filters have capacitive operation, they will transfer MVAR to the power circuit.

The block diagram structure is illustrated as follows:

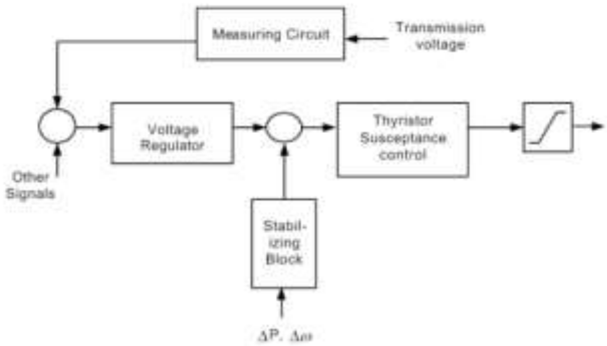

Figure 3. Block diagram of static VAR compensator

This device is equipped with a control system that includes:

a. The distribution section identifies the capacitors and thyristor-activated reactors that need to be activated internally and externally, and calculates the firing angles.
b. The synchronization section includes a phase-locked loop synchronized at the pulse generator and the secondary voltage level, both of which send the required number of pulses to the thyristors.
c. The calculation section determines the positive '+' voltage that needs to be set.
d. A voltage control system that measures the difference between a calculated voltage level and a reference voltage level.

Phasor simulation techniques performed using strong parts are required to operate SVC equipment. This technique can also be used in 3-phase power networks with synchronous generators, dynamic loads for execution, and electromechanical variations of devices. High-end static VAR compensators can also be made for accurate voltage regulation. Closed-loop controllers allow you to control the voltage.

RESEARCH METHODOLOGY

The research methodology includes several main stages, namely system modeling, SVC control implementation, disturbance simulation, and result analysis. At this stage, the modeling of the electric power system consisting of generators, transmission lines, loads, and buses is carried out. Modeling is done by making mathematical equations of the system and then making a block diagram of the modeling.

a. Basic Model of Electric Power System
   The electric power system can be modeled using the active power (P) and reactive power (Q) equations at the buses in the system. The active and reactive power equations at bus i and bus j are as in equations (1) and (2).
b. Dynamic Model of Electric Power System
   To analyze the stability of the system in the time domain, we use a dynamic model that describes the behavior of the system under disturbances. The dynamic equations for the rotor generator system can be written as follows

$$\frac{d\delta_i}{dt} = \omega_i$$

$$\frac{d\omega_i}{dt} = \frac{P_m - P_e}{M} \qquad \ldots..(5)$$

Where:

δi is the rotor angle at bus i,
ωi is the angular velocity of the rotor at bus i,
Pm is the mechanical power that enters the generator,
Pe is the electrical power that comes out of the generator,
M is the inertia constant of the system.
Model with Static VAR Compensator (SVC)

SVC is a controller that regulates reactive power adaptively to maintain voltage within desired limits. The function of SVC to regulate reactive power Qsvc can be described by equation (3)

Total System Equation with SVC

By adding the influence of the SVC to the system, the total reactive power equation at bus i connected to the SVC can be modified to:

$$Q_i = V_i \sum_{j=1}^{n} V_j \left(G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}\right) + Q_{svc} \qquad \ldots..(6)$$

where Qsvc is the reactive power contribution from SVC, which is adjusted based on the voltage condition of bus i.

System Model with Disturbances

To analyze the stability against disturbances, we must include disturbance models such as load changes or short circuits. The equation for voltage changes in a system experiencing a disturbance can be written as:

$$\Delta V_i = \frac{\Delta P_i}{V_i} + \frac{\Delta Q_i}{V_i} \quad .....(7)$$

where ΔPi and ΔQi are the changes in active and reactive power due to the disturbance, and ΔVi is the change in bus voltage i. This model is used to calculate the system response to disturbances and analyze whether the SVC is effective in returning the system to a stable state after a disturbance.

After we create a mathematical model of the equation above, we can create a block diagram of the equation model as shown in the image below.

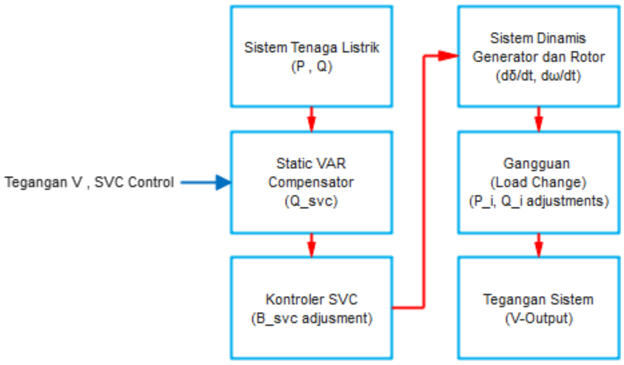

Figure 4. Block diagram of transmission system modeling with the addition of SVC.

Explanation of Each Block:

a. Electric Power System: Calculates the active and reactive power distributed across the network based on parameters such as line conductance and susceptance.
b. SVC: Filters the reactive power supplied or absorbed to regulate the voltage on the connected bus.
c. SVC Controller: Optimize Bsvc based on voltage error to maintain system stability.
d. Dynamic System (Generator and Rotor): Modeling the change in rotor angle and rotor speed after a disturbance.
e. Disturbance: Applying a disturbance to the system, such as a sudden load change, to check the system response.
f. System Voltage (V): The output of the system, namely the voltage stabilized by the SVC after a disturbance.

This block diagram illustrates the process flow and relationships between elements in the electric power system that are influenced by the FACTS controller (SVC).

Numerical Calculation

Calculation Steps:

1. System Parameter Identification
   a. Voltage on the transmit bus (V1) and receive bus (V2).
   b. Phase angles (δ1 and δ2).
   c. Conductance (Gij) and susceptance (Bij) of the channel.
   d. Active load (Pload) and reactive load (Qload).
   e. Reactive power range (Qsvc,min , Qsvc,max) that can be set by the SVC.
2. Calculate Initial Power Flow Without SVC

Use the active power equation:

$$P_i = \sum_{j=1}^{N} V_i \left(G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}\right) \quad \ldots..(8)$$

Calculate reactive power:

$$Q_i = \sum_{j=1}^{N} V_i \left(G_{ij} \cos \delta_{ij} - B_{ij} \sin \delta_{ij}\right) \quad \ldots..(9)$$

3. System Error
   Add disturbances in the form of changes in reactive load (ΔQload) on certain buses.
4. Correction with SVC:
   a. Calculate the reactive power that must be supplied by the SVC to maintain a stable voltage: Qsvc = Qload − Qi.
   b. Check SVC operating limits: Qsvc,min ≤ Qsvc ≤ Qsvc,max.
5. Final Voltage Evaluation
   Calculate the voltage after disturbance with SVC correction

$$V = \sqrt{\frac{P_i^2 + Q_i^2}{B_{ij}}} \quad \ldots..(10)$$

Numerical Problem Examples
Two Bus System:

1. Nominal voltage
   Bus 1 (V1): 1.0 pu.
   Bus 2 (V2): 1.0 pu.
2. Phase angle: δ1 = 0°, δ2 = −10°
3. Transmission channel parameters
   Gij= 0 , Bij = 10 pu.
4. Load on bus 2
   Upload= 0.8 pu.
   Qload= 0.6 pu.
5. Disturbance: Add a reactive load of ΔQload = 0.3 pu.
6. SVC operating range
   Qsvc,min= – 0.5Q pu,
   Qsvc,max= + 0.5Q pu.

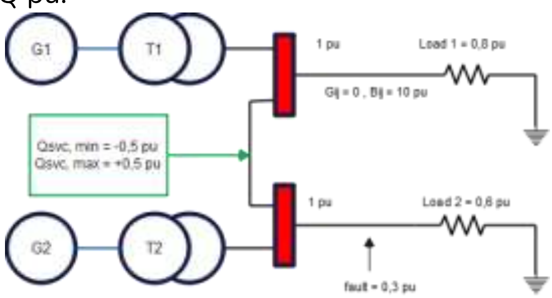

Figure 5. One line diagram system with SVC

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Solution

1. Calculate Initial Reactive Power Without SVC:

$$Q_1 = V_2 \sum_{j=1}^{n} V_j.(-B_{ij}) = 1{,}0 \,.\, 1{,}0 \,.\, (-10) = -10\, pu$$

The total reactive power at bus 2 is:

$$Q_{total} = Q_{load} + Q_i = 0{,}6 + (-10) = -9{,}4\, pu$$

2. After Disturbance: Add *ΔQload*:

$$Q_{new} = Q_{load} + \Delta Q_{load} = 0{,}6 + 0{,}3 = 0{,}9\, pu$$

Total reactive power after disturbance:

$$Q_{total.new} = Q_{new} + Q_i = 0{,}9 + (-10) = -9{,}1\, pu$$

3. Role of SVC: Reactive power that must be supplied by SVC to maintain voltage:

$$Q_{svc} = -Q_{total.new} = -(-9{,}1) = 9{,}1\, pu$$

Check SVC operating limits:

$$Q_{svc.max} = 0{,}5\, pu$$

Since Qsvc exceeds the limit Qsvc,max, the SVC cannot compensate all the reactive power. The system still experiences voltage drop.

4. Final Voltage: Calculate the voltage at bus 2 after the fault:

$$V_2 = \sqrt{\frac{P_{load^2} + Q_{svc}^2}{B_{ij}}}$$

$$V_2 = \sqrt{\frac{0{,}8^2 + 0{,}5^2}{10}} = \sqrt{\frac{0{,}64 + 0{,}25}{10}} = \sqrt{0{,}089} = 0{,}943\, pu$$

Conclusion Results

a. Before the disturbance, the voltage was stable at 1.0 pu.
b. After a fault, without SVC, the voltage drops drastically below 0.9 pu.
c. With SVC, the voltage can be partially restored to 0.943 pu, but not completely restored to nominal due to the reactive power limit Qsvc,max.

ANALYSIS AND DISCUSSION

Initial Calculation Without SVC

At the beginning of the simulation, the power system is analyzed without the use of Static VAR Compensator (SVC). This system operates under normal conditions where active power (Pload = pu) and reactive power (Qload = 0.6 pu) are present on bus 2, while bus 1 functions as a sending bus. The voltage on both buses is set at 1.0 pu, and the system is in a stable state.

a. Reactive Power Calculation of System Without SVC:In the initial reactive power calculation, the Qi value is calculated using the power flow equation model. As a result, the reactive power at bus 2 is -10 pu. This shows that without external reactive power control, the voltage in the system becomes unstable, and we need additional solutions to restore the system to normal conditions.

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b. Reactive Loads Imposed:The load on bus 2 is disturbed by the addition of reactive power of ΔQload = 0.3 pu. This causes the system reactive power to be -9.1 pu, which is greater than before.

Analysis of the Impact of Disturbances

When a fault occurs, reactive power increases at bus 2. Without any control over the reactive power supplied to the system, the voltage at bus 2 decreases further, creating instability in the power system. System Voltage After Disturbance:The voltage at bus 2 drops to about 0.943 pu, although it is still higher than the uncontrolled condition. This shows that even though there is a voltage drop due to the disturbance, the use of SVC can help improve the system voltage, but does not completely restore it to the nominal condition (1.0 pu).

The Role of Static VAR Compensator (SVC)

SVC is responsible for regulating reactive power in real-time. This system is designed to provide reactive power compensation when there is a change in load power, either an increase or decrease, so that the system remains stable.

a. SVC Provides Reactive Power:After the disturbance, the value of reactive power required by the system to maintain voltage stability is calculated as Qsvc = 9.1 pu. However, due to the SVC operating limit Qsvc,max = 0. pu, the system cannot compensate all the required reactive power.
b. SVC Capability Limits:In the calculation above, SVC is only able to supply reactive power up to 0.5, which means the system cannot fully restore the voltage to its nominal value (1.0 pu). This shows the limitations of SVC in overcoming the problem of voltage instability that is greater than its capacity.

Evaluation of SVC Success

a. Final Voltage with SVC:With the presence of SVC, the voltage at bus 2 is restored to 0.943 pu, although it does not fully return to the nominal value of 1.0 pu. Although SVC cannot fully restore the voltage to the desired stable condition, the voltage recovery that occurs is quite significant. The voltage at bus 2 remains higher than without SVC, which shows that although SVC cannot handle all the reactive power needed, its role is still important in reducing instability.
b. Limitations in SVC Capabilities:As a reactive power controller, SVC has a limit in its ability to supply reactive power. In this example, the required Qsvc exceeds the maximum capacity of the SVC (Qsvc,max = 0.5 pu), which limits its effectiveness in maintaining voltage. Therefore, although SVC serves to reduce voltage oscillations and accelerate recovery, when a larger disturbance occurs or the SVC operates at maximum capacity, the system may still face significant voltage sags.

Practical Implications and Recommendations

a. SVC Capacity Optimization:From the above analysis, it can be concluded that for larger and more complex systems, the capacity and arrangement of SVCs need to be carefully considered to accommodate larger reactive power fluctuations. In this case, using SVCs with larger capacities or placing multiple SVC units in strategic locations can help improve the overall system performance.

b. Limitations of SVC in Handling Major Disturbances:SVC is effective in improving voltage stability after small to moderate disturbances. However, for large disturbances or in systems with very large reactive power requirements, other FACTS technologies such as STATCOM or UPFC may be more effective because they have higher capabilities in dynamically regulating reactive power.
c. Implementation in Real System:For implementation in real systems, it is important to conduct system planning studies and stability analysis using further simulations, especially to examine the interaction between SVCs and other system components. Placing SVCs at appropriate locations in the transmission network can optimize voltage and reactive power control, reducing the possibility of blackouts or major disturbances.

CONCLUSION

The conclusion of this paper are: The use of SVC can improve voltage stability in the electric power system, although it does not completely restore the voltage to the nominal value, especially if the required reactive power exceeds the SVC capacity. The limitations of SVC capacity in handling reactive power need to be taken into account in the design and operation of the electric power system to ensure system reliability. SVC is effective in handling small to moderate disturbances, but for large disturbances, other FACTS technologies may be required to ensure better system stability.

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