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Analysis of FACTS-Based Voltage Regulation Under Harmonic Distortion, Fault Conditions, Stability Constraints, and Transient Overshoot

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ABSTRACT :

The continuous growth in electrical energy consumption has increased the operating stress on modern power transmission networks, making voltage stability and reliable power transfer increasingly important. Flexible AC Transmission System (FACTS) controllers provide an effective means of enhancing the voltage profile, power transfer capability, and overall stability of interconnected power systems. In the present study, a continuous power flow analysis of the IEEE 14-bus test system is performed to identify the buses that are most susceptible to voltage instability under increasing loading conditions. The influence of different FACTS controllers, including the Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC), Static VAR Compensator (SVC), and Static Synchronous Compensator (STATCOM), is subsequently investigated. The voltage magnitude and phase-angle variations at the critical buses are evaluated for both uncompensated and FACTS-compensated operating conditions. X–V curves are employed to determine and compare the maximum loading capability and voltage stability characteristics of the system. Particular emphasis is placed on the performance of SVC and STATCOM for controlling bus voltage through reactive power compensation. The analysis demonstrates the capability of these shunt-connected compensators to either supply or absorb reactive power according to variations in system operating conditions, thereby maintaining the desired voltage level. Furthermore, the study examines the suitability of SVC and STATCOM for dynamic voltage regulation in power systems subjected to changing and nonlinear load demands. The increasing penetration of nonlinear loads can introduce significant voltage disturbances, highlighting the need for fast and flexible reactive power compensation. MATLAB/Simulink is used to develop the models and perform the simulation of SVC and STATCOM under different operating conditions. The comparative analysis provides an assessment of their contribution to voltage regulation and loading capability and demonstrates the potential of FACTS-based compensation for improving the voltage stability and dynamic performance of modern power systems.

Keywords: **Flexible AC Transmission System (FACTS), Voltage Stability, IEEE 14-Bus System, Static VAR Compensator (SVC), STATCOM, Reactive Power Compensation, Dynamic Voltage Control, MATLAB/Simulink, Voltage Regulation.**

INTRODUCTION

The continuous growth of electrical energy consumption has created significant challenges for modern power systems. Increasing industrialization, urban development, electrification, and the widespread use of power-electronic equipment have resulted in rapidly changing and often nonlinear loading conditions. A power system is expected to supply electrical energy reliably while maintaining acceptable values of voltage, frequency, power flow, and power quality under both normal and disturbed operating conditions. Among these requirements, maintaining an appropriate voltage profile is particularly important because excessive voltage deviations can adversely affect electrical equipment, increase system losses, reduce system efficiency, and, under severe conditions, lead to voltage instability or system collapse.

The voltage at different buses of a power network is strongly influenced by the balance between active and reactive power. Changes in load demand can alter this balance and consequently produce variations in bus voltage. The problem becomes more pronounced when the transmission system operates close to its maximum transfer capability. Under such conditions, even a relatively small increase in load may cause a substantial reduction in voltage magnitude. Therefore, increasing the loadability of an existing network while maintaining acceptable voltage levels has become an important area of research in modern power-system engineering.

Sometimes, control systems are unable to keep up with the rise in operational limits, the system could begin to function in an unsafe way. Throughout the process, the security and dependability of the system are compromised, which leads to issues with the system's stability. Power system operation

and control has grown to be a significant problem in the current environment when load demand is always rising and there is little room for generating and transmission system growth. Stability has always been defined as the alternators continuing to operate synchronously with the system.

Need for the Present Study

The increasing complexity of electrical networks has created a requirement for voltage-control techniques that are fast, flexible, and capable of responding to changing system conditions. Conventional compensation methods may not always provide adequate dynamic performance when the network experiences rapidly varying or nonlinear loads.

The present study focuses on the modeling and simulation of SVC and STATCOM for dynamic voltage control. The investigation emphasizes the ability of these devices to regulate a specified bus voltage by supplying or absorbing reactive power according to the system requirement. The study also considers the influence of increasing load conditions on voltage performance and evaluates the improvement achieved through dynamic compensation.

Problem Statement

The continuous increase in electrical demand and the growing presence of nonlinear and power-electronic loads can result in significant variations in reactive-power requirements and bus voltages. When the available reactive-power support is inadequate, voltage deviations may increase with loading and can eventually threaten the stability of the system.

Therefore, there is a need to develop an effective dynamic compensation approach capable of maintaining acceptable voltage levels while allowing the system to operate at higher loading conditions. The central problem addressed in this research is to determine how effectively SVC and STATCOM can provide dynamic reactive-power compensation and voltage regulation under changing load conditions.

Literature Review

The increasing penetration of nonlinear loads, renewable energy sources, and variable electrical demand has made voltage stability an important concern in modern power systems. Voltage instability generally occurs when the transmission network is unable to maintain acceptable bus-voltage levels under increasing loading or following disturbances. Consequently, considerable research has been directed toward improving voltage profiles, increasing loadability margins, and enhancing reactive-power management through Flexible AC Transmission System (FACTS) controllers. FACTS technologies provide rapid and controllable compensation and can improve the operating characteristics of transmission networks without requiring major changes to the existing infrastructure [1]–[4].

Adnan and Alsammak [23] presented a comparative assessment of different FACTS technologies and discussed their applications for controlling voltage and power-flow characteristics. Their work highlights the importance of selecting an appropriate FACTS configuration according to the required compensation and operating conditions. Mosheer *et al.* [24] specifically examined the influence of FACTS controllers on voltage stability and compared compensated and uncompensated operating conditions. Their investigation demonstrated that FACTS devices can improve the voltage profile and increase the loading capability of a power system. Such findings establish the significance of FACTS-based compensation for voltage-stability enhancement.

Several studies have subsequently concentrated on the optimal location and sizing of FACTS devices. Pati and Karajgi [25] investigated the optimized placement of multiple FACTS devices using population-based optimization techniques. Their results indicated that appropriate placement can reduce transmission losses while improving the voltage profile and overall system performance. Zhang *et al.* [26] investigated the optimum location and parameter selection of STATCOM using an improved optimization algorithm. The study emphasized that the effectiveness of STATCOM depends not only on its control capability but also on its location and operating parameters. These findings are important because the impact of a compensator varies considerably among different buses of an interconnected network.

The application of STATCOM for voltage regulation has also received significant attention. Anichebe and Ekwue [29] investigated the improvement of bus-voltage profiles using STATCOM in a practical power-network environment. Their results demonstrated the ability of STATCOM to provide rapid reactive-power compensation and improve voltage conditions. Kumar *et al.* [30] investigated a STATCOM-based control strategy for a wind-energy-

integrated power system and reported improved system stability under changing operating conditions. These studies indicate that the fast reactive-power response of STATCOM makes it suitable for systems subjected to variable generation and load fluctuations.

Key Research Gap Addressed by the Present Study

The present work therefore attempts to address the following gaps:

1. Identification of critical buses using continuous power-flow analysis rather than evaluating voltage stability only at a fixed operating point.
2. Comparison of compensated and uncompensated systems under progressively increasing loading conditions.
3. Comparative investigation of SSSC, UPFC, SVC, and STATCOM within a common IEEE 14-bus framework.
4. Evaluation of voltage-stability characteristics using X–V/P–V curves to determine the loading capability of critical buses.
5. Specific assessment of SVC and STATCOM for dynamic voltage regulation through reactive-power compensation.
6. MATLAB/Simulink-based modelling and simulation to evaluate the dynamic voltage-control characteristics of the selected compensators.

This literature review establishes the technical foundation for the proposed investigation and demonstrates that a comparative CPF-based evaluation of multiple FACTS technologies can provide useful information for improving voltage stability and increasing the loadability of transmission networks.

Research Objectives

The major objectives of the present study are:

1. To investigate the impact of increasing and nonlinear electrical loads on voltage stability and voltage profiles of the power system, with particular emphasis on the system load-carrying capability and voltage regulation requirements.
2. To develop and model SVC and STATCOM-based compensation systems for dynamic voltage regulation and analyze their capability to supply or absorb reactive power according to variations in system loading conditions.
3. To evaluate and compare the performance of SVC and STATCOM in improving voltage stability, voltage profile, reactive power compensation, and loadability of the electrical power system under different operating conditions.
4. To perform MATLAB/Simulink-based modeling and simulation of the compensated power system and determine the effectiveness of SVC and STATCOM in maintaining the desired bus voltage and enhancing the overall dynamic performance of the system.

FACTS CONTROLLER

A power electronic-based system and additional stationary apparatus that manages one or more characteristics of the AC transmission system. electrical power. Fig. 1.2a displays the generic symbol for the FACTS Controller. FACTS Controllers fall into four categories:

i) FACTS Controllers in Series

ii) Shunt FACTS Regulators

iii) Series-Series FACTS Controllers Combined

iv) Series-Shunt Combined FACTS Controllers

i) Series FACTS Controllers: - These DESCRIPTIONS As seen in Fig. 1.2b, controllers can be variable impedance devices like capacitors, reactors, or power electronic-based variable sources that, in theory, inject voltage in series with the passage. Only variable reactive power can be supplied or consumed by the series controllers, provided that the voltage and line current are in phase Quadrature. Any other phase relationship will involve handling of real power as well.

ii) Shunt FACTS Controllers: - The shunt Controllers may be variable impedance such as capacitor, reactor or power electronic based variable source, which is shunt connected to the line in order to inject variable current, as shown in Fig. 1.2c. When the injected current is in phase Quadrature with the line voltage, shunt controllers are the only devices that can produce or consume variable reactive power. Real power handling will be a part of any other phase interaction.

iii) Series-Series FACTS Controllers combined: These controllers are made up of many independent Series FACTS controllers that are coordinated in their control. manner in a multiline transmission system, as illustrated in Fig. 1.2d. This configuration provides independent series reactive power compensation for each line but also transfers real power among the lines via power link. The presence of power link between series controllers names this configuration as “Unified Series-Series Controller”.

iv) Series-Shunt Combined FACTS Controllers: These are either a Unified Power Flow Controller with series and shunt components (Fig. 1.2f) or a collection of independent shunt and series controllers that are coordinated (Fig. 1.2e). Real power exchange via a power link is possible between the series and shunt controllers when the unified Shunt and Series FACTS Controllers are in place.

PROPOSED MODAL

STATCOM and SVC are connected middle point of the transmission line. In that test model two generators are connected both end side. The first generator is linked in series with the three-phase mutual inductance. Transmission line voltage and current are measured using B1, B2, and B3. We are considering in test model the three phase PI section line and three phase distributed parameter line. The three loads are connecting parallel with transmission line that is l0 KW, 2KW, 10KW. We are also connected fault impedance for creating fault in transmission line by manually. After creating a fault the disturbances in transmission line can be compensated by STATCOM and SVC. In this chapter shows the implementation of the proposed method with the help of MATLAB Simulink modal. Figure 4.1 shows the STATCOM on a 500KV Transmission Line. This is the first modal of proposed work.

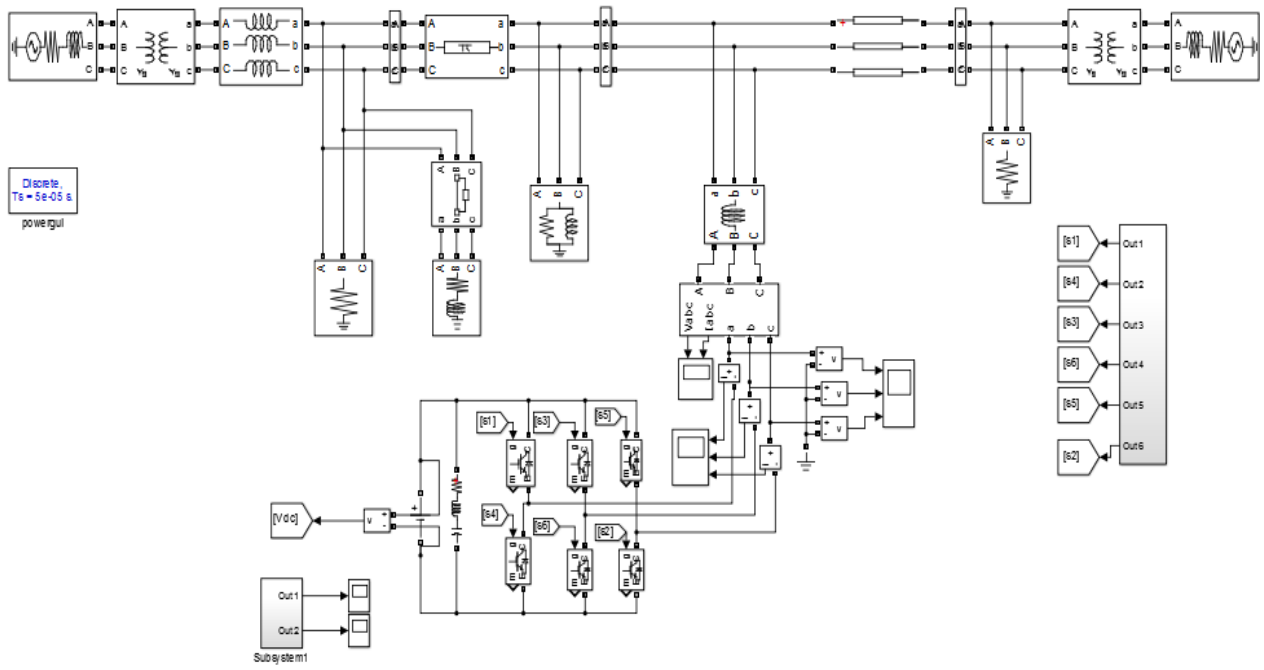


Fig: Proposed STATCOM on a 500KV Transmission Line

RESULT ANALYSIS

Electrical fault condition is required to deploy proper different protective relays in different locations of electrical power system. Information regarding values of maximum and minimum fault currents**,** voltages under those faults in magnitude and phase relation with respect to the currents at different parts of power system, to be gathered for proper application of protection relay system in those different parts of the electrical power system. Collecting the information from different parameters of the system is generally known as electrical fault calculation.

Fault calculation broadly means calculation of fault current in any electrical power system. Essentially, there are three phases for calculating faults in a system.

1. Rotations of impedance options.
2. A single equivalent impedance replaces the complex electrical power system network.
3. Computation of electrical fault currents and voltages using symmetric component theory.

Result parameters

The Power block computes the active power (P), in watts, and the reactive power (Q), in a voltage-current pair at fundamental frequency. To perform this computation, the block first determines the fundamental values (magnitude and phase) of the two input signals V & I. The following P and Q are then calculated:

$$P= (V/2)^2\times (I/G)^2\times\cos(\varphi)$$

$$Q= (V/2)^2\times (I/G)^2\times\sin(\varphi)$$

$$\varphi=\angle V-\angle I \quad (5.3)$$

As this a running average window, one cycle of simulation must complete before the outputs give the correct value. For the first cycle of simulation, the

outputs are held constant using the values specified by the Voltage initial input and current initial input parameters.

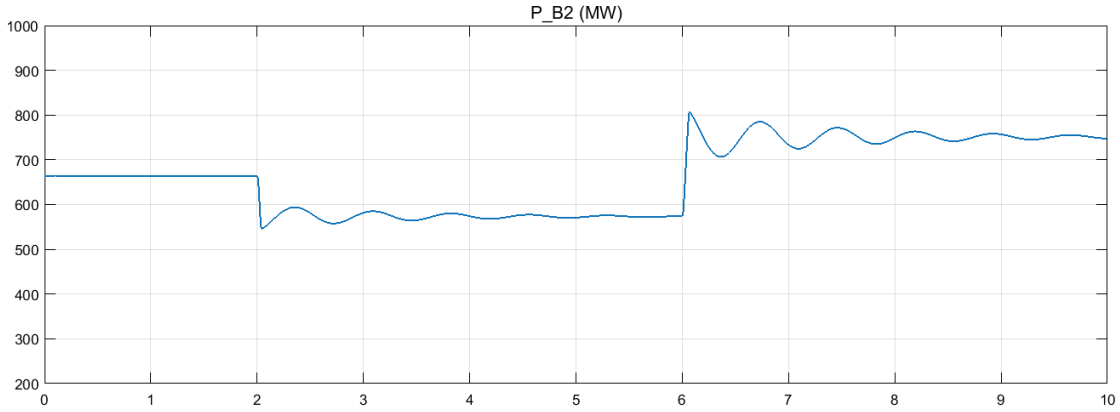


Fig: Shows the Voltage (PU) with Respect to Time(s) of STATCOM Base paper result with STATCOM

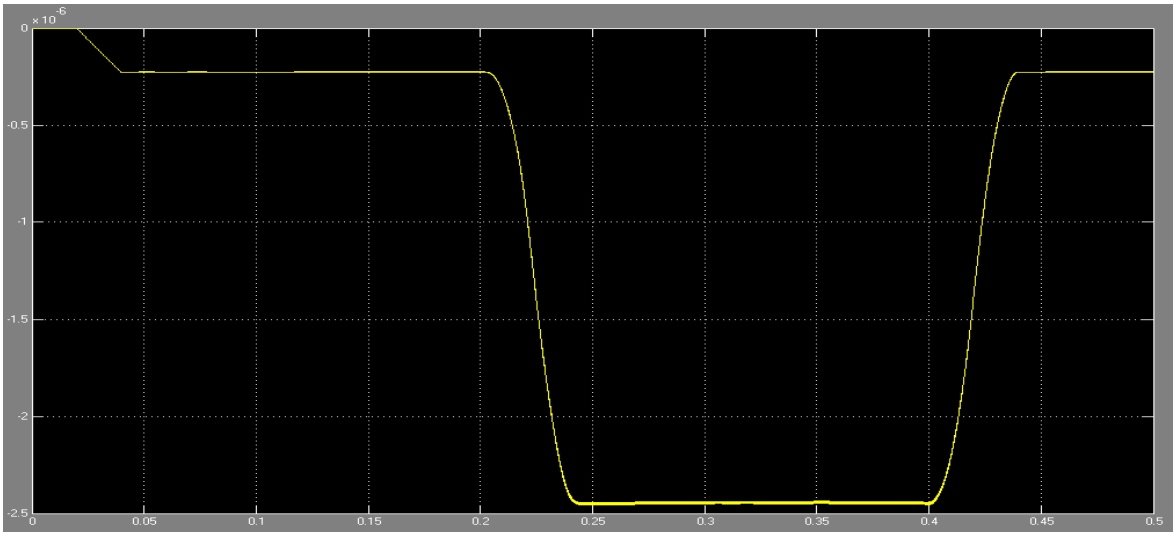
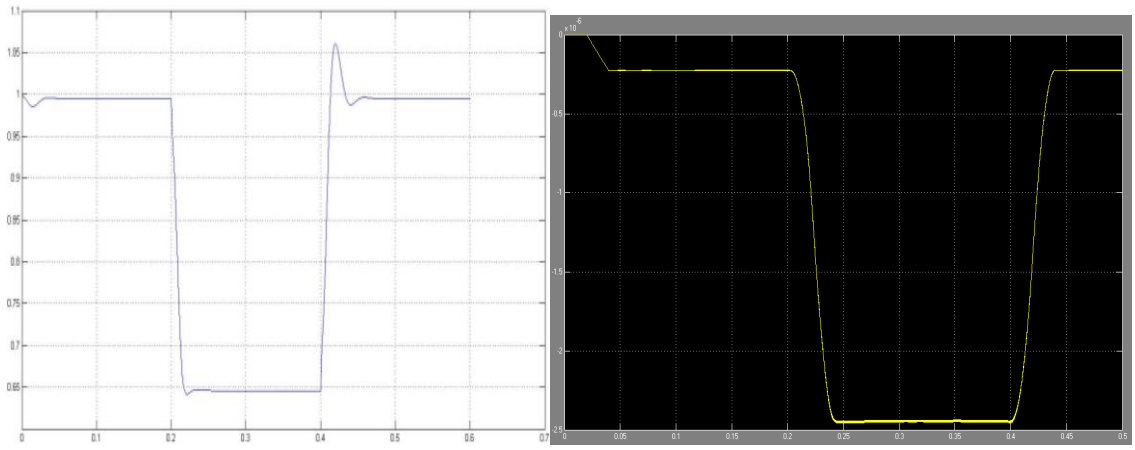


Fig: Shows the Voltage (PU) with Respect to Time(s) of STATCOM

In the above figure shows the Voltage (PU) with Respect to Time(s) of STATCOM Base paper result with STATCOM. The figure the voltage (PU) with Respect to Time(s) of STATCOM. The first graph displays the measured positive-sequence voltage Vm at the STATCOM bus .The second graph displays the reactive power absorbed or generated by the STATCOM. At the initial stage transmission line is inductive. Because of the inductive load transmission line voltage decreases of the desire value, to maintain the desire voltage level STATCOM act as capacitive (0-0.2 sec.).At the instant 0.2 Z-fault occur and voltage falls down (02-0.4 sec.) at that time STATCOM is act as more capacitive and goes more negative to regulate voltage. At the instant 0.4 fault is suddenly remove at that time STATCOM take one overshoot and comes at desire level same as the before fault occur. The figure having a problem of over shoot. The previous method recover the voltage but having error of peak over, that is clearly shown in figure. This problem is over come in the proposed STATCOM system. That is shown in figure

CONCLUSION

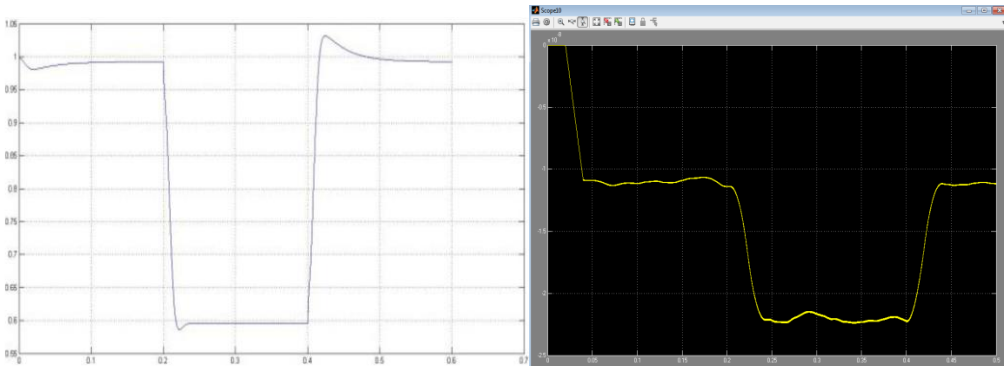
This proposed work employs a Simulink model created in MATLAB to describe a power system with many loads linked at different busses. According to the suggested research, STATCOM has been successfully used to regulate system voltage in the power system. Because STATECOM-based systems have less harmonics than SVC-based systems, we have established in this suggested study that STATCOM is superior than SVC. The results of the suggested work are superior than those of the earlier effort.



(a) Result of Previous STATCOM **(b) Result of proposed STATCOM**

Fig: Shows the STATCOM performance of proposed and previous work

In the above figure clearly see that the STATCOM shows better result as compare to SVC, SVC figure shown in below. SVC poor result in terms of harmonics. That is shown in below figure. The effectiveness of SVC in enhancing the transient stability of the aforementioned model has been investigated. SVC has a significant impact on the system's transient stability. Thus, it can be said that employing SVC enhances the power system's transient stability when various loads are applied to various busses.



(a) Result of Previous SVC (b) Result of proposed SVC

Fig: Shows the SVC performance of proposed and previous work

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