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Power System Stability Improvement using Flexible A.C Transmission System (FACTS) Controllers

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Abstract

This article studies power system stability improvement using Flexible Alternating Current Transmission System (FACTS) controllers. FACTS controllers are controllable devices that can efficiently regulate AC transmission, boost power transfer in a given line and react instantaneously to system stability issues. The performance, operations and control characteristics of four types of FACTS controllers – Static VAR Compensator (SVC), Thyristor Controlled Series Compensator (TCSC), Static Compensator (STATCOM), and Unified Power Flow Controller (UPFC) – are analysed. The study includes applications and comparative methods for reactive power compensating devices in terms of stability and the advantages of using them in electrical transmission systems. Results show that SVC provides voltage control, minimises temporary overvoltage, reduces voltage flicker caused by non-linear loads, and improves the power transfer capability of transmission systems. STATCOM demonstrates faster response and better performance during transients, provides voltage control, VAR compensation, voltage stability, better damping oscillations and maintains stable voltage even in very weak AC systems. TCSC acts quickly and is a cost-effective solution for transient stability, dynamic and steady-state stability. VAR compensation, damping of oscillations and voltage stability in long transmission lines; it increases the power transfer limits and significantly improves the stability margin. UPFC offers active and reactive power control, voltage control, VAR compensation, damping of oscillations, transient and dynamic stability, voltage stability, real-time control and dynamic compensation of AC transmission systems. It can adjust bus voltage, transmission line reactance, and phase angle between two buses simultaneously, providing independently controllable shunt reactive compensation.

Keywords: Power systems; reactive power; facts controllers; transient stability and compensation; transmission lines

1. Introduction

Due to the ever-increasing demand for electric power, existing transmission networks have become weak, leading to poor quality of unreliable supply. Furthermore, it requires huge money to develop or strengthen the existing transmission network, and, in some cases, even securing the right-of-way for new lines can be challenging (Grigsby, 2017). The flow of reactive power is a major cause of voltage drop along the line. Power losses in the system expressed as R are primarily due to reactive currents. The fixed voltage profile at any moment determines the maximum reactive power (vars) that can be transferred over the transmission lines (Wadhwa, 2018; Turan, 2019). During peak load, only a small amount of reactive power (var) is needed, and in most cases, the classical methods, including transmission lines,, cannot provide sufficient reactive power. The focus on the quality of power delivered is greater than ever, while the transmission systems are being pushed closer to their stability and thermal limits. Alternating current (AC) in electrical power systemss is commonly generated, transmitted, distributed and used in electrical energy. But AC has its share of downsides. This includes the necessity of reactive power to be supplied alongside e power. The lines used for reactive power can be shunt or series, leading or lagging (Singh, 2018; Hingorani & Gyugyi, 2020). Active power is the actual power used to do work and is used in determining the energy consumed or transmitted, whereas reactive power, measured in VAr,, does not contribute to energy but rather oscillates back and forth between the generator and load. Currently, electricity demand is rising very fast with no major reinforcement projects for building power transmission networks. The electricity market, on the other hand, is directed towards the open market and deregulation,, acquiring conditions for competition and negotiation forces (Song & Allan, 2019). Data availability and capital provide a challenge, wherein smarter network and customer engagement and relationship handling characterise the customer-edge solution. These FACTS controllers should be used in transmission lines when desired; h application can drastically increase the use of existing transmission assets and become a potent tool in deregulating the current industry with little need for new transmission lines (Abdel-Moamen & Padhy, 2021; Acha et al.,, 2016; Gotham & Heydt, 2018). However, different approaches have been proposed to classify the extent of low voltage profile in transmission lines and then allocate reactive power compensation apparatus, each encountering technical and procedural constraints. Four reactive power compensation technologies based on FACTS controllers were suggested in the article. These include Static VAR Compensator, Thyristor Controlled Series Compensator, Static Compensator, and Unified Power Flow Controllers (Acha etal., 2018; Chung etal.,, 2020). FACTS controllers are used to enhance the power transfer capability of the transmission systems. This means that, under suitable online control of power flow during and after system faults to maintain stability of the system, power flow in a given line can be increased up to the thermal limit by injecting the required amount of current through the series line impedance. In recent times,, many researchers,, such as Sahu et al. (2022), Jolfael et al. (2016), Farah et al. (2021), and Ain et al. (2020), have proposed various intelligent methods for improving and enhancing power system stability (PSS) under different fault disturbances using coordinated control of FACTS controllers, such as TCSC, SVC, or SSSC in the literature; however, none of these techniques proved to be able to completely improve power system stability.

This paper,, therefore, proposes four types of FACTS controllers – Static VAR Compensator (SVC), Thyristor Controlled Series Compensator (TCSC), Static Compensator (STATCOM), and Unified Power Flow Controller (UPFC) – for PSS optimisation and compares their operating performances in terms of load flow control, voltage control, transient stability, and dynamic stability.

2. Materials and Methods

2.1 Proposed Methods of FACTS Controllers

Flexible Alternating Current Transmission System (FACTS) are static devices used for the AC transmission of electrical energy. FACTS controllers can be classified into four types: Series controllers; Shunt controllers; Combined series-series controllers; Combined series-shunt controllers.

The primary goal of FACTS device is to improve controllability and increase power transfer capacity. These devices are typically based on power electronics technology. The aims of FACTS controllers are to enhance the power transfer capacity of transmission lines and to support power flow along selected paths. By using fast acting controls, power system margins can be minimized and power system capability better utilized, all while preserving existing quality and reliability levels. In this article the method of reactive power compensation using four types of FACTS controllers is analysed. They include Static VAR Compensator, Thyristor Controlled Series Compensator, Static Synchronous Compensator, and Unified Power Flow Controllers.

The complex power delivered by generators is given in Equation 1:

$$S = P + jQ = V_1 \left(\frac{E_S^{e-j\delta} - V_r}{jX_g}\right)$$

$$S = V_1 x E_s x \frac{(j\cos\delta + \sin\delta) - jV^2}{X_g} \tag{1}$$

where S is the apparent power (KVA), P is the active power (KW), Q is the reactive power (KVAr), V_1 is sending-end voltage, V_r is receiving-end voltage, and X_g is the machine reactance.

Similarly, power flow through a transmission line is shown in Figure 1. The amount of power that is transmitted from sending-end bus 1 to receiving-end bus 2 can be expressed by Equation 2.

$$P_{12} = \frac{V_1 \, x \, V_2}{X_L} \sin\delta \tag{2}$$

where P_{12} is the power transmitted through the transmission system, X_L is the reactance of the transmission line, δ is the phase angle between phasors V_1 and V_2. From Equation 2, it shows that the power transfer/flow between two systems interconnected through a tie-line can be controlled by three parameters: the voltages at the two systems, the reactance of the tie-line, and the difference in the voltage angles at the two ends; and that the real power will be increases when the power angle δ increases. The FACTS devices can be used to control one or more of these parameters. Similarly, with a series capacitor installed in the line, Equation 2 can be rewritten as

$$P = \frac{E_S * E_R * \sin\delta}{X_L - X_C} \quad (3)$$

$$P = \frac{E_S * E_R * \sin\delta}{X_L(1 - K)} \quad (4)$$

where $K = X_C/X_L$ is the degree of compensation, usually expressed as a percentage. For example, a 70% series compensation means that the value of the series capacitor (in ohms) is 70% of the line reactance.

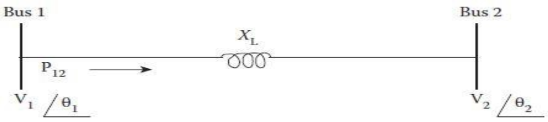


Figure 1: Power flow through transmission line

Also, if we want to minimize real power loss then surely the loadings will not correspond to minimum cost of generation. Thus, if R and X are the series resistance and reactance of the transmission line, and I the current loading the losses in the line are I^2R and I^2X

$$I^2 = \frac{P^2 + Q^2}{V^2} \text{ and}$$

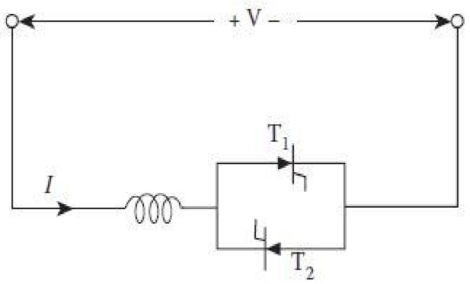
$$P_L = I^2R = \frac{P^2 + Q^2}{V^2}R \quad (5)$$

$$Q_L = I^2X = \frac{P^2 + Q^2}{V^2}X \quad (6)$$

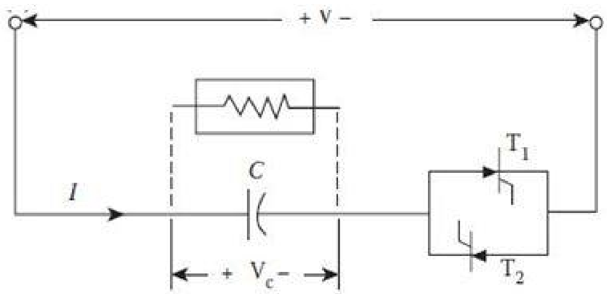
From Equations 5 and 6, it is clear that in order to decrease reactive power loss, we must minimize reactive power transfer over the line and also the operating voltages should be high. Keeping operating voltages high to minimize reactive power loss helps maintain voltage stability.

2.1.1 Static Var Compensation (SVC)

This approach thus affords a compensation that reacts to rapid variations of the load of the system with a minimum of delay of the order of a few milliseconds. Based on needs, it can provide leading or lagging vars. It consists of a reactor shunted across the supply and connected in parallel with a fixed or variable high-voltage bank. The ratio between the lagging and leading vars to be provided is entirely based on the particular demands of a transmission line or system. The configuration consists of two thyristors that are connected in an antiparallel configuration, where the thyristors facilitate a smooth regulation of the current driven through a shunt reactor as shown in Figure 2 (a). However, as the transfer function dictated by a capacitor has a long time constant associated with the charge/discharge cycle of the capacitor, it is not possible to have smooth control of the current; hence, the current can either only be switched on or off, as shown in Figure 2(b).



(a) Thyristor-controlled reactor



(b) Thyristor switch-switched capacitor.

Figure 2: Static Var Compensation diagram

Typically, thyristor firing circuits responsible for SVCs are controlled by a voltage regulator that attempts to maintain the bus voltage at a constant level by regulating both the amount and the polarity of the reactive power injected into the bus. SVC is an automatic controller of impedance matching. It aims to bring the system into the neighbourhood of the unity power factor. When the reactive load of the power system is capacitive (leading), the SVC consumes reactors from the power system and draws VARs from it, resulting in a reduction of system voltage. It is used to have a higher system voltage by automatically switching on capacitor banks under inductive (lagging) conditions. Their usage is limited to those areas of a system where large variations of real power occur and both inductive and capacitive vars are needed as a result. The use of SVC includes voltage control; minimisation of temporary overvoltages; minimisation of voltage flicker used by non-linear loads such as arc furnaces; improving the power transfer capability of transmission systems; increasing the transient stability limit of a power system; and enhancing damping of power oscillations.

2.1.2 Thyristor-Controlled Series Compensation (TCSC)

The thyristor-controlled series capacitor (TCSC) method presents a fast control and the ability to adjust the impedance of a series capacitor bank by using a thyristor-controlled capacitor in series with the transmission line. The TCSC is a FACTS (Flexible Alternating Current Transmission System) device, an application of power electronics for control of the AC system to enhance the power flow, operation, and control of the AC system. TCSC enhances the system performance for SSR damping, power swing damping, transient stability and power flow control. Figure 3 represents a single-line diagram of TCSC. The TCSC power flow controller consists of five identical modules in which high-voltage capacitors and thyristor valves are connected in series (this is done to reduce the voltage rating) and the internal reactor and varistor are connected across the individual thyristor valve in each module.

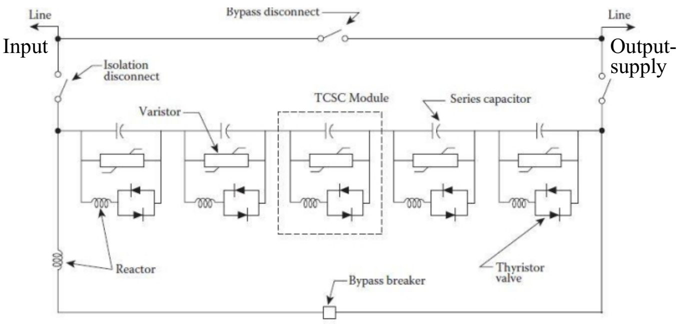


Figure 3: Single line diagram of a Thyristor-controlled Series Compensator (Grigsby, 2012).

Each module consists of reactors connected in series with the thyristor valves, limiting the di/dt through the thyristors. The ability to control the current passing through the reactor also alters the total capacitance of the capacitor–reactor and provides variable impedance. TCSC (Thyristor Controlled Series Capacitor) is a controllable capacitive reactance in series which is capable of providing continuous power flow control on the AC line over a wide range. The thyristor-controlled series compensation controller uses a thyristor-controlled reactor (TCR) in parallel with capacitor segments of the series capacitor bank. The combination of TCR and capacitor allows the capacitive reactance to be smoothly controlled over a wide range and switched upon command to a condition where the bi-directional thyristor pairs conduct continuously and insert an inductive reactance into the line. TCSC is an effective and economical means of solving problems of transient stability, dynamic stability, steady-state stability and voltage stability in long transmission lines.

2.1.3 Static Synchronous Compensator (STATCOM)

STATCOM is a static synchronous generator operated as a shunt-connected static VAR compensator whose capacitive or inductive output current can be controlled independently of the AC system voltage. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. Figure 4 shows a single-line diagram of a current-controlled STATCOM. It is a three-phase inverter that is driven from the voltage across a d.c. storage capacitor and whose three-phase output voltages are in phase with ac system voltages; the current flow is caused to lead or lag, and the difference in the voltage amplitudes determines how much current flows. Therefore, controlling the voltage can change reactive power and its polarity. STATCOM functions as a shunt-connected synchronous voltage source, whereas a thyristorised compensator operates as a shunt-connected, controlled reactive admittance.

This difference accounts for the STATCOM's superior functional characteristics and greater application flexibility. The ability of the STATCOM to maintain full capacitive output current at low system voltage also makes it more effective in improving the transient stability limit. Some of its attributes include faster response (within milliseconds) and better performance during transients; voltage control, VAR compensation, and voltage stability; it provides better damping oscillations; it can maintain a stable voltage even with a very weak AC system; and it is insensitive to transmission system harmonics.

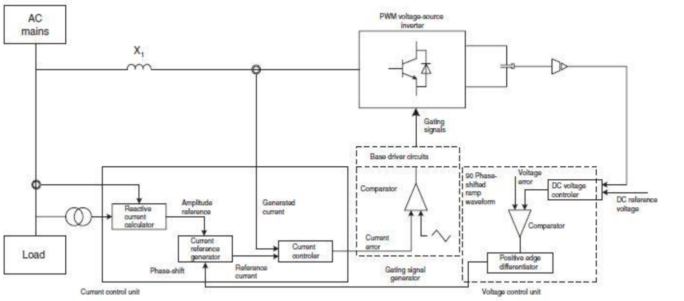


Figure 4: The block diagram of a current controlled STATCOM (Grigsby, 2012).

2.1.4 Unified Power Flow Controller (UPFC)

A unified power flow controller (UPFC) method is a combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC), which are coupled via a common d.c. link to allow bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminal of the STATCOM and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source. A sample model of UPFC is shown in Figure 5, comprising two identical three-phase voltage-source inverters coupled to two sets of DC capacitor banks. The two inverters are interfaced with the AC system via two transformers, a set of magnetically coupled windings configured to construct a 48-pulse sinusoidal wave shape. Inverter 1 connected in parallel can operate as a STATCOM with either one of the two main shunt transformers, while inverter 2 connected in series operates as an SSSC. This method, by means of angular unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance and angle. UPFC has the following attributes, which include active and reactive power control, voltage control, VAR compensation, damping oscillations, transient and dynamic stability, voltage stability and fault current limiting.

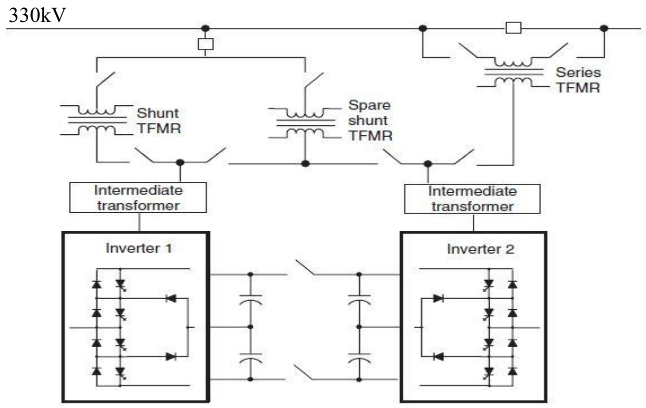


Figure 5: Unified Power Flow Controller at substation.

It offers potential advantages for the static and dynamic operation of transmission lines; the real-time control and dynamic compensation of AC transmission systems; and the ability to adjust the three control parameters, *i.e.,* the bus voltage, transmission line reactance, and phase angle between two buses, either simultaneously or independently, all the parameters affecting power flow in transmission lines. It can also provide independently controllable shunt reactive compensation.

3. Results and Discussion

3.1 Performance and Application Analysis of FACTS Controllers for Power System Stability and Reactive Power Compensation.

Results revealed that the SVC provides compensation that responds to rapid fluctuations in system load with a minimal delay, on the order of a few milliseconds. SVC provides both leading and lagging VAR compensation and can be used in the following applications: Voltage control and regulation; voltage stability; reduction of temporary overvoltage; reduction of voltage flicker caused by varying loads such as arc furnaces; increased power transfer capacity of transmission systems; increased transient stability limits of a power system; increased damping of power oscillations. TCSC is an effective and economical means of solving problems related to transient and dynamic stability, damping oscillations, current control, fault current limiting and voltage stability in long transmission lines. STATCOM has the ability to maintain full capacitive output current at low system voltage and is more effective in improving the transient stability limit. Its attributes include faster response (within milliseconds) and better performance during transients; voltage control; VAR compensation and voltage stability; improved damping of oscillations; maintenance of stable voltage even with very weak AC systems; as well as insensitivity to transmission system harmonics. The UPFC method, by means of angular unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance and angle. Its control attributes include active and reactive power control, voltage control, VAR compensation, damping oscillations, transient and dynamic stability, voltage stability and fault current limiting.

The technical benefits and dynamic applications of the studied FACTS controllers in addressing issues related to transient stability, post-contingency voltage control and dynamic stability are summarised in Table 1. The levels of their performance are illustrated by the number of points allotted to each device – the higher the points, the better the performance.

Table 1: Technical benefits of the different FACTS controllers

FACTS devices	Load flow control	Voltage control	Transient stability	Dynamic stability	The Higher the Better
SVC	●	●●●	●	●●	●
STATCOM	●	●●●	●●	●●	●●
TCSC	●●	●	●●●	●●	●●● ↓
UPFC	●●●	●●●	●●	●●	

The implementation of high-performance FACTS controllers enables power supplies to increase the capacity of existing transmission network capacity while maintaining or improving the operating margins necessary for grid stability. Consequently, more power can reach consumers with a minimal impact on the environment. When applied to transmission lines, FACTS controller methods present the following advantages:Increasing the loading capability of lines to their thermal limits over short and seasonal periods; reducing reactive power flow, thus allowing the lines to carry more active power; preventing ccascading black outs by minimizing the impact of faults and equipment failures; improving power system stability and power flow control mechanism; enhancing dynamic and transient stability of the grid and reducing loop flows; supplying higher quality power for sensitive industries; better utilization for existing transmissions system facilities; eliminating the need to supplement transmission lines with new system assets; and providing flexible and controllable inter-tie connection with neighbouring utilities thereby minimizing overall generation reserve requirements. Reserve requirements through the two sides; also damping out from the oscillations of the power systems in such a way as to respect the flow dynamic, which could damage equipment and also restrict the useable capacity by dynamic modulation for the effective impedance adjusting constantly to the power system dynamics.

4. Conclusion

This research work proposes four types of FACTS controllers – SVC, TCSC, STATCOM, and UPFC – for reactive power compensation control in transmission systems at substations. A brief review of FACTS applications to optimal power flow and deregulated electricity markets was presented. Their principles of operations and control attributes were analysed. A performance comparison of the different FACTS controllers was reviewed and discussed. Finally, the applications and benefits of power systems control using FACTS controllers in electrical transmission systems were examined and highlighted.

Conflict of Interest

Authors declare no conflict of interest associated with this work.

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