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Application of Voltage Source Converter Based Flexible Alternating Current Transmission System Devices for Stability of Electrical Power System: A Review

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Abstract
Breaking innovations in power electronic devices which are alternative to long-distance alternating current transmission line has provided better solution in driving the transition of power systems toward a carbon-free paradigm while maintaining the current standards of quality, efficiency, and resilience. Thus, application of Voltage Source Converter (VSC) based Flexible Alternating Current Transmission System (FACTS) devices such as Static Synchronous Compensators (STATCOM) and Static Synchronous Series Compensator (SSSC) have been widely recognized as most advanced and powerful tools in providing a veritable way to control the stability in power system during disturbance This study therefore, focuses on reviewing these aspects through comprehensive study of integration of STATCOM and SSSC controller in power system

Keywords: *Power Systems, Voltage Source Converter, STATCOM, SSSC, Stability. FACTS*

I. INTRODUCTION

In a deregulated power system, the electric power demand is increasing everyday due to the increasing number of consumers with the addition of sensitive power-electronic equipments which may lead to overloads, loss of generation and constant power failure [1].This high demand of electricity has made the power management to operate power system closer to their limits than ever before which has affected the power system expansion plans and subject it to transient instability, which also resulted in limited supply of reactive power from synchronous generators during disturbance[2,3, 4]

One of the most common technical solutions in dealing with the high demand of electricity and to improve the transient stability is the construction of new transmission lines, but the process is both time-consuming and costly, and may cause short and long-term disruptions to the environment [1, 5]t. Also, incorporation of power generators such as Therm0-Electric Generators (TEGs) and wind generation bring great innovation to transmission expansion planning, but it is necessary to measure and characterise their performance, to understand their dynamic behaviour and interaction with the other parts of the power system for effective planning [3, 6, 7]

However, application of Voltage Source Converter (VSC) based Flexible Alternating Current Transmission System (FACTS) devices such as STATCOM, SSSC have been widely recognized as most advanced and powerful tools in providing a veritable way to control the transient instability in power system during disturbance [4,7] These VSC devices employ self-commutated DC to AC converters, using Gate Turn-Off (GTO) thyristors, which can internally generate capacitive and inductive reactive power for transmission line compensation, without the use of capacitor or reactor banks. They provide unprecedented levels of flexibility and speed of response in comparison with traditional electromechanical devices. The STATCOM provides fast voltage control, reactive power control and power oscillation damping features. The SSSC also improves voltage and transient stability, and effectively improves damping of power oscillations [5, 8,-10].

Their importance has increased due to the increased awareness of energy conservation and quality of supply on the part of the power utility as well as power consumers. The FACTS technologies therefore allow for improved power transfer capabilities of the transmission system operation compared to the construction of new transmission lines [11-15]. However, proper control strategies to identify critical buses in the power system for optimal placement of the VSC is very much useful for power system monitoring and expansion to prevent possible voltage instability and to meet the increasing loads, as improper controller strategies will lead to non-optimal placement of the VSC which could increase the system instability and thwarting the power system expansion planning

A. *Power System Stability*

Power system stability is the capability of power system, for a given initial operating condition, to maintain an operating equilibrium point after being subjected to a disturbance, with most system variables bounded so that practically the entire system remains intact. It deals with the ability to control the voltage level within a narrow band around normal operating voltage. Also, it can be defined as ability of synchronous machine to remain in synchronism with one another after disturbances at various locations in the system. These disturbances could be faults, load changes, generator outages, line outages, voltage collapse or some combination of these [1].

The three major factors contributing to power system instability are: load dynamics, generation and transmission system limitations. In load dynamics, system instability occurs when the load dynamics attempt to restore power consumption beyond the capability of the transmission network and the connected generation [3, 16]. This results in increasing the reactive power consumption which would cause the voltage to drop much further. However, in generation limits, if a disturbance occurs and as a result, some of the generators hit their field or armature current time-overload capability limits, there will not be enough reactive power to support the system voltage. While in transmission system limits, the voltage would drop across the highly inductive transmission lines. This voltage drop limits the power transfer capability and voltage support of the transmission line [11, 17-20].

These instability factors have evolved through continuing growth in voltage and power rating due to the load demand. Hence, a classification of the problem of power system stability has become necessary. This is a key issue which needs to be clearly understood to be able to properly design, operate and control an electrical power system. Thus, power system stability can be classified into steady-state stability, transient stability and dynamic stability as shown in Figure 1 [1, 21].

Also, power system stability can be classified as voltage stability (transients, voltage drop, voltage imbalance, short duration and long duration variations), rotor angle stability (waveform distortion such as; dc offset, harmonics, inter harmonics, notching, and noise) and frequency stability (short term and long term stability) and as shown in Table 1 The former is the stability of the system under conditions of gradual or relatively slow change in load while the second refers to the maximum power transfer possible through a point without losing stability with sudden and large changes in the network conditions. However, the main difference between them is that voltage stability depends on the balanced of reactive power demand and generation in the system where as the rotor stability mainly depends on the balanced between real power generation and demand [1, 7, 20, 21]

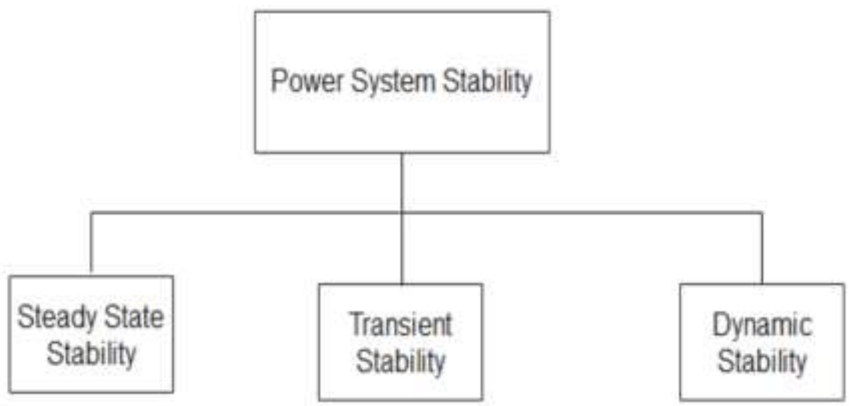

Figure 1: Classification of Power System Stability

Table 1: Power System Stability Classification

Power System Stability		
Voltage Stability	Rotor Angle Stability	Frequency Stability
Transient	Waveform Distortion	Short Term Stability
Voltage Drop	Small-disturbance	Long Term Stability
Voltage Imbalance	Angle Stability	
Short Duration Variation	Transient Stability	
Long Duration Variation		

B. *Flexible Alternating Current Transmission System*

Flexible Alternating Current Transmission System (FACTS) controllers are power electronic based controller circuit configuration and are very effective in regulating power flow on AC transmission lines. FACTS devices are an evolving technology to help electric utility companies. With the applications of FACTS technology, bus voltage magnitude and power flow along the transmission lines can be more flexibly controlled. The main objectives of FACTS are to increase the useable transmission capacity of lines and control power flow over designated transmission routes [3, 16, 19]

Depending on its arrangement and how it will be installed in the power system, FACTS controllers can be classified into four categories as [1, 8, 16]

i. **Series device:** Series devices are used to enhance the stability of electric power system. The device operates as variable capacitive or inductive impedance such as Thyristor Controlled Series Capacitor or Compensator (TCSC) and Static Synchronous Series Compensator (SSSC) that can be adjusted in series with the transmission line to damp oscillation in the system
ii. **Shunt device:** The shunt devices are used to enhance the stability of electric power system. It is variable impedance such as capacitor, reactor or power electronic based variable source such as Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM), which is shunt connected with the transmission line to improve the oscillation damping in the system
iii. **Combined series-series device:** Combined series-series devices: This device could be a combination of separate series controllers, which are controlled in a coordinated manner in a multiline transmission system. It could also be a unified controller, in which series controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link. This include: High Voltage Direct Current VSC (HVDC VSC)
iv. **Combined shunt-series device:** The combined shunt-series devices: This device combines separate shunt and series controllers in a coordinated manner. The devices inject voltage in series in the line with the series part and current into the system with the shunt part. This include; Thyristor Controlled Phase Shifting Transformer (TCPST) and Unified Power Flow Controller (UPFC). In addition, there are two generations for realization of FACTS controllers: Thyristor-controlled group and Voltage Source Converter (VSC) group

II. VOLTAGE SOURCE CONVERTER GROUP FACTS DEVICES

The Voltage Source Converter (VSC) group FACTS device is the most advanced type among the FACTS controllers, employs self-commutated DC to AC converters, using Gate Turn-Off (GTO) thyristors, which can internally generate capacitive and inductive reactive power for transmission line compensation, without the use of capacitor or reactor banks. It can supply required reactive current even at low values of the bus voltage and can be designed to have in built short term overload capability. The converter with energy storage device can also exchange real power with the system. The VSC devices include Static Synchronous Series Compensator (SSSC), Static Synchronous Compensator (STATCOM) and High Voltage Direct Current (HVDC) VSC device among others [2, 4, 9, 17]

A. *Static Synchronous Series Compensator*

The Static Synchronous Series Compensator (SSSC) is a series voltage source equipped with a source of energy in the DC link that can supply or absorb the reactive and active power to or from the line. The SSSC is one of the most used FACTS devices for power transmission series compensation. It can be considered as a synchronous voltage source as it can inject an almost sinusoidal voltage of variable and controllable amplitude and phase angle, in series with a transmission line. [3, 20, 21]

The basic configuration of a SSSC is shown in Figure 2. It consists of a solid state VSC which generates a controllable alternating voltage at fundamental frequency. The injected voltage is almost in quadrature with the line current. A small part of the injected voltage that is in phase with the line current provides the losses in the inverter. Most of the injected voltage, which is in quadrature with the line current, provides the effect of inserting an inductive or capacitive reactance in series with the transmission line. The variable reactance influences the electric power flow in the transmission line [13, 17]

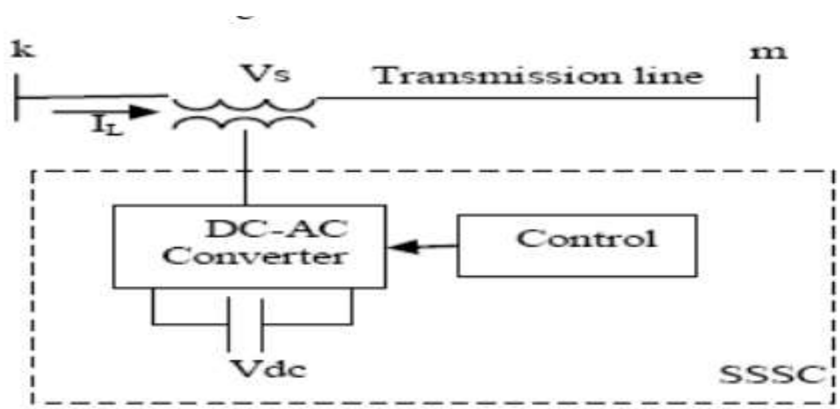

Figure 2: .Basic Configuration of Static Synchronous Series Compensator

The SSSC compensation level can be controled dynamically by changing the magnitude and polarity of injected voltage and the device can operate both in capacitive and inductive mode (Maryam, 2012). In the practical applications of the SSSC, it may be used to control any of the following parameters; the active power flow of the transmission line, reactive power flow of the transmission line, bus voltage and impedance of the transmission line [2, 20].

The active power flow contraints of SSSC is given in Equations (1) to (3) as [17]:

$$P_{ij} - P_{ij}^{ref} = 0 \tag{1}$$

$$P_{ij} = V_i^2 g_{ii} - V_i V_j \left(g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij}\right) - V_i V_{se} \left(g_{ij} \cos(\theta_i - \theta_{se}) + b_{ij} \sin(\theta_i - \theta_{se})\right) \tag{2}$$

where; $g_{ij} + jb_{ij} = \frac{1}{Z_{se}}$, $g_{ii} = g_{ij}$, $b_{ii} = b_{ij}$, $g_{jj} = g_{ij}$, $b_{jj} = b_{ij}$ (3)

Also, the reactive power flow control constraint is given in Equation (4) as:

$$Q_{ij} - Q_{ij}^{ref} = 0 \quad (4)$$

The bus voltage control constraint is given in Equation (5) as:

$$V_i - V_i^{ref} = 0, \; V_j^{ref} - V_j = 0 \quad (5)$$

In reactance control, V_{se} is regulated to control equivalent reactance of the SSSC to a specified reactance reference as in Equation (6):

$$X_C - X_C^{ref} - 0 \quad (6)$$

where; P_{ij} is the active power flow, P_{ij}^{ref} is the specified active power flow control reference along the line between bus *j* and *i*., V_{se} and Z_{se} are the voltage source and impedance sources respectively. *g* and *b* are SSSC conductance and susceptance, respectively, Q_{ij}^{ref} is the SSSC specified reactive power flow reference, Q_{ij} is the branch reactive power flow, V_i^{ref} and V_j^{ref} are the bus voltage references, X_C is the function of state variables V_i, V_j and V_{se}, X_C^{ref} is the reference reactance

In addition, the SSSC is typically applied to correct the voltage during a fault in the power system. Thus, some of advantages of employ SSSC in power system during normal conditions are [4, 21]:

i. Power factor correction through continuous voltage injection and in combination with a properly structured controller.
ii. Load balancing in interconnected electric power networks.
iii. It can also help to cover the capacitive and reactive power demand.
iv. Power flow control and
v. Reduces harmonic distortion by active filtering.

B. Static Synchronous Compensator

The Static Synchronous Compensator **(**STATCOM) is a VSC electronic device with Gate Turn Off (GTO) thyristor and Direct Curent (DC) capacitor coupled with a step down transformer as shown in Figure 3 [5, 18, 21]

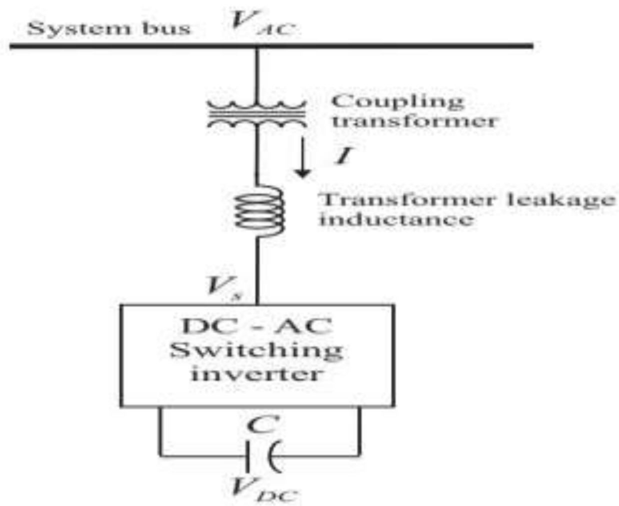

Figure 3: Static Synchronous Compensator

The STATCOM is a capable of generating or absorbing reactive power in a dynamic fashion. The controller exists for both high-voltage transmission application and low voltage distribution system. It improves the damping power oscillation in transmission system, and provides the desired reactive power compensation of a power system. The STATCOM employs solid state power switching devices, providing rapid controllability of the voltage magnitude. The AC voltage difference across the leakage reactance is regulated to produce reactive power exchange between the STATCOM and the power system, the objective is to regulate the AC voltage at the bus bar as to improve the voltage profile of the power system [3, 19].

The basic principle of STATCOM operation is as follows. The VSC generates a controllable Alternating Current AC) voltage source behind the leakage reactance. The exchange of reactive power between the converter and the AC system can be controlled by varying the amplitude of the 3-phase output voltage. If the amplitude of the output voltage is increased above that of the utility bus voltage, then current flows through the reactance from the converter to the AC system and the converter generates capacitive-reactive power for the AC system. If the amplitude of the output voltage is decreased below the utility bus voltage, then the current flows from the AC system to the converter and the converter absorbs inductive-reactive power from the AC system [4, 20, 21].

However, if the output voltage equals the AC system voltage, the reactivepower exchange is zero, in which case the STATCOM is said to be in floating state. The reactive and the real-power exchange between the STATCOM and the AC system can be controlled independently of each other. Any combination of real power generation or absorption is achievable if the STATCOM is equipped with an energy-storage device of suitable capacity [3].

Typical applications of the STATCOM are [5, 8, 13]

i. Effective voltage regulation and control;
ii. Improvement of steady-state power transfer capacity;

iii. Improvement of transient stability margin;
iv. Damping of power system oscillations;
v. Damping of sub-synchronous power system oscillations'
vi. Flicker control and
vii. Power quality improvement,

In addition, there are mainly two models of STATCOM that have been well tested in power systems for power flow solution. They are the Current Injection Model (CIM) and the Power Injection Model (PIM). The CIM model the STATCOM as a current source connected in shunt to the bus for voltage magnitude control. Whereas, the PIM model the STATCOM as shunt voltage source behind an equivalent reactance or impedance, which is also referred to as Voltage Source Model (VSM). This steady state PIM of STATCOM has proved reliable when incorporated in power systems [2, 10,12].

The PIM mathematical model of STATCOM in power flow algorithms are given in Equations (7) to (10) [12, 17]:

$$V_{STC} = V_k + Z_{SC} I_{STC} \tag{7}$$

$$I_{STC} = I_N - Y_{SC} V_k \tag{8}$$

$$I_N = Y_{SC} V_{STC} \tag{9}$$

$$S_k = V_{STC} V_{SC}^* V_k^* - V_k^2 Y_{SC}^* \tag{10}$$

The active and reactive power equations of the STATCOM are given in Equations (11) and (12):

$$P_{STC} = V_{STC}^2 G_{STC} + V_{STC} V_k \left[G_{STC} Cos(\delta_{STC} - \theta_k) + B_{STC} Sin(\delta_{STC} - \theta_k) \right] \tag{11}$$

$$Q_{STC} = -V_{STC}^2 G_{STC} + V_{STC} V_k \left[G_{STC} Sin(\delta_{STC} - \theta_k) + B_{STC} Cos(\delta_{STC} - \theta_k) \right] \tag{12}$$

where; V_{STC} is STATCOM voltage m, Y_{STC} is STATCOM phase angle, I_{STC}^* is STATCOM reference current, Y_{SC}^* is admittance of the source converter, V_{STC}^* is STATCOM reference voltage, I_N is Norton current, I_{STC} is STATCOM current, and V_k is bus voltage, δ_{STC} is STATCOM phase angle, Y_{STC}^* is STATCOM reference admittance, G_{STC} is STATCOM conductancem θ_k is the firing angle,

III. RELATED WORKS ON APPLICATION OF FACTS ON POWER SYSTEM

Significant efforts have been directed at examining the integration of VSC of TACTS controller into electrical power. Table 2 provides a summary of the reviewed studies, highlighting their methods and limitations.

Table 2: Summary of various research and their limitations

Author/Year	Title of the Paper	Algorithm used	Shortcoming
Bera *et al* (2010) [1]	Tuning of excitation and TCSC based	Mode controllability and Genetic Algorithm	The method was not efficient enough for optimal solutions of

Author/Year	Title of the Paper	Algorithm used	Shortcoming
	stabilizers for multi machine power system		transient stability of power system.
Sidhartha (2010) [2]	Modelling, simulation and Optimal Tunning of SSSC-based Controller in a Multi-Machine Power system	Real coded genetic algorithm	The model was not sufficient enough to find optimum solution for transient stability in transmission system.
Badran and Abulanwar (2011) [3]	Dynamic Performance Comparison between STATCOM and SVC	Dynamic performance index	The approaches failed to guarantee transient stability of restoration actions
Ambafi *et al* (2012) [4]	Performance Evaluation of PSS and STATCOM on Oscillation Damping of a North-Central Power Network of Nigeria Grid System	Genetic algorithm	The convergence ability of the method used was not efficient.
Safari *et al* (2013) [5]	Controller Design of STATCOM for Power System Stability Improvement	Honey bee mating optimization	The approach failed to guarantee transient stability of restoration actions.
Sasongko *et al.* (2013) [6]	Multi-Objective Function GA for Modal Optimal Control Design in PSS and UPFC Power Oscillation Damping Coordination	Genetic algorithm	The crucial issues regarding PSS and POD control schemes and the necessary improvement that needed to be addressed were not highlighted
Siddiqui and Deb (2014) [7]	Voltage Stability Improvement using STATCOM and SVC	Voltage stability margin	The approach failed to guarantee transient stability of restoration actions.

Author/Year	**Title of the Paper**	**Algorithm used**	**Shortcoming**
Berrouk *et al* (2014) [8]	Applications of Shunt FACTS Controller for Voltage Stability Improvement	Newton-Raphson iterative technique	The approach was not sufficient enough to find optimum solution for transient stability in transmission system.
Poonia and Shekhawat (2016) [9]	Modeling of STATCOM and SVC for Power System Steady State Operation and Enhancement of Transient Stability of a Multi-Machine Power System by STATCOM	Review on trnsient stability index	The study was only based on review, no practical system was implemented.
Abubakar *et al* (2018) [10]	Enhancement of Power Quality and Transient Stability Margin in Coordination with UPFC and MB-PSS Controller	Multiple band controller index	The crucial issues regarding PSS and POD control schemes and the necessary improvement that needed to be addressed were not highlighted.
Salman *et al.*, (2021) [11]	Improvement the voltage stability margin of power system using the optimal values of FACTS devices	Voltage stability margin factor and the Voltage Collapse Prediction Index	The system generator power limit and their optimal operating conditions were not considered
Joseph and Dattesh (2018) [12]	Comparative Survey of STATCOM and SVC Integration for Power System Stability Improvement	Comparative study	The result was inconclusive as the STATCOM model used was not specified in the study
Nkan *et al* (2019) [13]	Investigating the Steady State Stability of the Nigerian 48- Bus Systems using FACTS Devices	Continuation power flow	The approach could not be guaranteed for global optimal solution for optimal placement of FACTS devices.

Author/Year	Title of the Paper	Algorithm used	Shortcoming
Gandotra and Pal (2022) [14]	FACTS technology: A comprehensive review on FACTS application in power system	Review on FACTS optimal placement	The study was only based on review, no practical system was implemented.
Sayed *et al* (2019) [15]	Multi-Shunt VAR Compensation SVC and STATCOM for Enhance the Power System Quality	Comparative study	The study was only based on review, no practical system was implemented
Kalunta and Ngwu (2022) [16]	Optimal location of VSC-HVDC system in Nigerian 330kV power network using a short circuit voltage violation index and line loss Technique.	Short circuit voltage violation indicator	The approach was not sufficient enough to find optimum solution for transient stability in transmission system
Chodura *et al.*, (2023) [17]	Investigation of the impact of embedded VSC-HVDC active and reactive power control on power system stability	Maximum transfer capability of permanent fault	The approaches failed to guarantee transient stability of restoration actions.
Nkan *et al.*, (2023) [18]	[Optimum location of shunt FACTS devices for enhancement of power system loadability	Continuation power flow and Voltage Stability Factors (VSF)	The system generator power limit and their optimal operating conditions were not considered
Ojo *et al.*, (2023) [19]	An optimal placement of STATCOM controller on test transmission network	Particle Swarm Optimization (PSO)	The system generator power limit and their optimal operating conditions were not considered
Alajrash *et al.*, (2024) [20]	A comprehensive review of FACTS devices in modern power systems: addressing power quality, optimal	Review on placement of FACTS devices	The study was only based on review, no practical system was implemented.

Author/Year	Title of the Paper	Algorithm used	Shortcoming
	placement, and stability		
Ekpa *et al.*, (2024) [21]	Power transfer capability enhancement of the Nigerian 330kv network with SVC	R-square with Genetic Algorithm (GA)	The approach was not sufficient enough to find optimum solution for stability analysis

IV. RESULTS OF THE REVIEWS

This research provides an in-depth review of various applications of FACTS controller methods for improving stability of electrical power system. Different approaches have been employed to analyze, predict, identify and find solution to system stability and system collapse. Each technique has tried to solve the problem with various objectives and constraints. However, most of the techniques employed showed a non -linear behavior near the collapse point and in the presence of system control limits, they are computationally expensive, especially for very large power systems as several matrix and vector manipulations are required. Moreover, several of the existing techniques experience malfunctions caused by blinding issues, leading to failures in system protection with application of FACTS controller. Consequently, there is a clear need for a reliable method that ensures an optimal and accurate solution for power system stability with the VSC controller. This help to maintain the system power quality (PQ) for efficient compensation of the voltage imbalances in order to meet the load growth

V. CONCLUSION

This study reviews the benefits, challenges, and impacts of integrating VSC type of FACTS controller such as STATCOM and SSSC into electrical power systems. VSC FACTS controller offers advantages such as improved system reliability, reduced line losses, enhanced voltage and stability. Thus, the reviews verified the effectiveness of the applications of STATCOM and SSSC controllers in improving the stability of power system during disturbances..

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