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A Survey of Flexible AC Transmission System (FACTS) Devices Applied to Photovoltaic Grid Systems for Improved Stability

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ABSTRACT: In recent decades, the rapid rise in electricity demand has obligated transmission and distribution systems to perform at their maximum capacity. Photovoltaic (PV) system is widely used to meet the increased claim for electrical power. The grid connected PV system has emerged with its simplicity, reliability and insurability, but it pretence limitations in maintaining power quality and steadiness of the power system network. On the other hand due to some restrictions in the construction of transmission lines, there is a possibility of generating block in new transmission lines which results in the blackout of the system. To avoid such critical conditions researchers originate devices to increase the power flow capacity of existing systems, this paper presents a review on Flexible Alternating Current Transmission System (FACTS) devices and its applications. FACTS devices minimizes active power losses while succeeding reactive power flows to keep the voltages within their respective limits.

Key Words: PV grid, SCADA, FACTS devices: STATCOM, SVC, TCSC and UPFC.

1. Introduction

In recent years PV is applied at fast-tracking rate and linked to both transmission and distribution/utilizations by means of power electronic converters. The nature of these resources, oscillation is the common issue. This oscillation issue is severe in PV because the power obtained from PV has numerous challenging difficulties, such as active and reactive power, voltage swell, sag, glimmers, harmonics, power quality characteristics of switching operation [1]. A grid-connected PV system uses series connected panels producing DC power converted into AC by an inverter and fed to an electrical grid. The main objective of grid capacity analysis evaluate the grid to ensure safe, reliable, and capable of accepting PV systems. In addition, reverse power flow (RPF), which cause transformer and line overload condition is prompted by high-level PV penetrations. The RPF produce high voltages in the feeders, and results in limited power factor, distribution network losses. Consequently, grid integration of PV systems offers several challenges which has to be addressed for effective and reliable integration into the electricity grid [2].

To overcome such limitations of PV grid in early period, some of the conventional methods relied on mechanical devices and simpler control methods to improve power factor and manage power flow, the devices like synchronous condensers, capacitor banks, and basic Supervisory Control and Data Acquisition

(SCADA) systems are applied in power system. Synchronous condenser is used to maintain grid voltage stability owing to fast reactive power regulation. It not only absorbs the under-excitation operation of reactive power but also emits over excitation of reactive power. It has a smooth two way voltage regulation with no additional investments. If the system fails or has a heavy inductive loads, the bus voltage of the system has decreased. The synchronous condenser uses this bus voltage and increase the excitation current, thereby improving the permanence of the system. The synchronous condensers are deployed in weak areas to enhance fault current and voltage for mitigating inverter-based generation that lack the inherent short-circuit capacity. It compensates for reduced short-circuit strength increasing the cost [3-4]. SCADA system is widely used for remote monitoring and control of power generation, transmission and distribution. It optimizes power flow, maintains desired voltages, improving grid efficiency and alerts operators while faults arises in power system, thereby enlightening the overall performance of power system. It monitors the PV system for tracking and analysing performance of several scheme mechanisms to guarantee it is optimally operating. Some of the SCADA devices are sensors, Programmable-Logic Controllers (PLCs) and Remote Terminal Units that collects, process, transmit data to a central master unit for monitoring and controlling through Human-Machine Interface (HMI). Nevertheless it needs to improve the precision of PV utility and it uses power meters for continuously monitoring power factor. High initial and ongoing cost, complexity, data overloaded issues for operators and a high reliance on technology which makes the system failures very impactful [5]. To compensate those drawbacks in existing methods, and to improve power factor efficiently and minimizing losses in power system FACTS devices are introduced in power system.

FACTS is power electronic-based device used to boost power transfer ability for AC system. FACTS devices are crucial to improve the performance, reliability of modern power grids by improving power transfer capability, voltage stability. It provides voltage balance, power quality enhancement, and harmonic mitigation [6].The optimal power flow contests becomes progressively composite while allowing for the nature in an electrical grid. The power system issues are subjected to some restrictions, largely restricting somatic limitations forced on the system's hardware and operational parameters. Furthermore, the application exposes the overview of FACTS devices which has a substantial effect on optimal power flow solutions whenever the system enlarges to unite it. Additionally to attain cost-effective power supply determinations, novel optimal methods used to improve power by integrating renewable energy resources and defining the optimal position and dimension of FACTS devices [7]. Furthermore based on the construction of power system. FACTS technologies incorporate a wide array of devices, like Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Thyristor Controlled Series Capacitor (TCSC), Unified Power Flow Controller (UPFC) each adapted to address the specific challenges in reactive power recompense, voltage support, and real power flow control.

Therefore, the focus of this paper is to analyse and deliberate about FACTS devices in PV grids:

1. FACTS devices and control systems in electrical power system, challenges in power quality and voltage regulation.
2. Benefits and limitations of each type of FACTS devices.
3. Power quality enhancement in electrical networks.

The paper is prearranged as follows. In Section II-FACTS devices are briefly described.

In Section III- Modelling of FACTS, Section IV benefits of FACTS devices. Section V-Comparative analysis. Finally, section VI discusses conclusion.

2. Comprehensive review analysis of FACTS devices

The FACTS devices are developed for attaining steady power flow in power system. The power flow basically obeys Kirchoff's law. The active and reactive power transferred through power lines among the buses is given by the following equation;

$$P_{12} = \frac{V_1 V_2}{X_{12}} sin\, \theta_{12} \quad (1)$$

$$Q_{12} = \frac{1}{X_{12}} \left(V_1{}^2 - V_1 V_2 \cos \theta_{12} \right) \quad (2)$$

Where V_1, V_2 is the voltage, at terminal 1 and 2, X_{12} is the line reactance, θ_{12} is the angle among bus voltages. The control of X_{12} modifies the active and reactive power flow.

Types of FACTS

SVC is a first generation of FACTS which is a shunt device used to regulate voltage and stabilize electrical power system. For a long distance power transmission, it is applied in the lines to sustain a constant voltage which ensures balancing of grid reactive power. It decreasing voltage flicker produced by heavy loads, increase power transmission capacity, transmission losses, and prevent from load losses during overvoltage. However the initial cost is high, the conductors are big in size to handle very high currents associated with lower voltage and a major drawback is the induction of harmonic current produced in the system [8]. STATCOM is the second generation of FACTS using shunt device which is used to regulate voltage, increase the grid stability, regulate reactive power flow. It functions like a variable reactive power source controlled by power electronic converters to improve power factor and voltage stabilization. STATCOM has a parallel features to PV system linked to the grid. To discover the possibility of application of STATCOM in PV system by increasing power system solidity, the device is essential to examine synchronverter as a PV-STATCOM. The power factor correction method is triggered to improve the system capacity. This devices faces some drawbacks of high transmission losses, need to improve power quality. SSSC controls power flow in transmission lines by injecting a controllable quadrature-phase voltage with the line. It enhances the stability of power system or damping power oscillation that occurs after fault or sudden load changes. Nevertheless it has potential power losses, high component cost [9-10]. TCSC device is used to resist the power flow by capacitive reactance in electrical power grids. TCSC technology is a robust and reasonably priced series FACTs device through unique performance which is, dependable on power flow regulation of power lines. It provides series compensating characteristics, is one of the most affordable approaches to increase the transmission network's real electrical carrying capacity. Lots of equality and inequalities limitations relating to both dependent and independent variables are satisfied in order to address the TCSC allocation problems includes maintaining balance between active and reactive power while minimizing network losses [11].

To address such limitations among all the FACTS devices which is described above are overcome by UPFC device.

3. Modelling of FACTS devices

3.1 TCSC

TCSC is a FACTS device used for enhancing power flow capability and facilitate the transfer of inertia and non-inertia supporting regions by connecting the tie-line between two regions [12]. TCSC operation in two modes which is capacitive and inductive. These modes enables the device to either increase or decrease the reactance of transmission lines. It improves the power flow, enhances the system stability. The capacitive mode enhances the power supply while inductive mode restrict it. The structure of TCSC is shown in Figure 1.

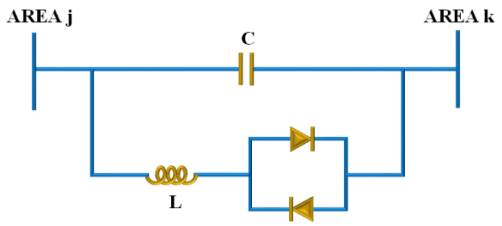

Figure 1(a): *TCSC structure-circuit model*

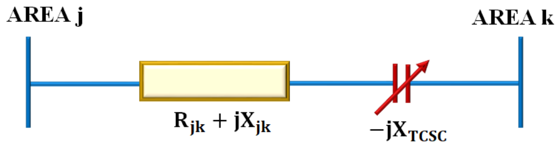

Figure 1(b): *TCSC tie-line diagram*

TCSC compensator works as a controllable capacitor for the purpose of controlling the reactance of transmission lines. Accordingly the power flow increment is illustrated in a first order model with time constant.

$$T_{TCSC}\frac{d(\Delta P_{TCSC})}{dt} = \Delta x_{TCSC}(s) - \Delta P_{TCSC}(s) \quad (3)$$

The time constant of TCSC unit is T_TCSC, where ΔP_{TCSC} is the real power flow, and $\Delta x_{TCSC}$is the control signal for TCSC which is produced by frequency deviation.

3.2 SSSC

SSSC controls power flow in transmission lines by injecting a controllable quadrature-phase voltage with the line in series. It increases or decreases power flow and stabilize the system. When attached to a capacitor SSSC absorbs or generate reactive power to the system. It operates as a series compensator without external energy source whose output is controlled within the quadrature line. From [13]. The single line diagram for SSSC is shown in Figure 2.

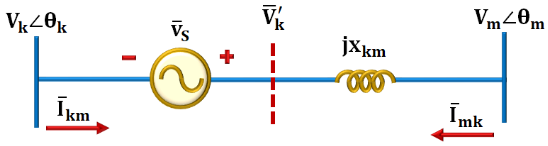

Figure 2: *SSSC-single-line diagram*

The total power flows in the transmission lines considering SSSC is given by,

$$P_{km} = (1+\varepsilon)\frac{V_k V_m}{x_{km}} sin(\theta_k - \theta_m) \quad (4)$$

$$Q_{km} = (1+\varepsilon)\frac{V_k}{x_{km}}[V_k - V_m\, cos(\theta_k - \theta_m)] \quad (5)$$

$$P_{mk} = -P_{km} \quad (6)$$

$$Q_{mk} = (1+\varepsilon)\frac{V_m}{x_{km}}[V_m - V_k\, cos(\theta_k - \theta_m)] \quad (7)$$

$$\varepsilon = \frac{V_s}{\sqrt{V_k{}^2 + V_m{}^2 - 2V_k V_m \cos\theta_{km}}} \quad (8)$$

The equivalent reactance value of the line gets decreases, in this case the power flowing in transmission line will increase. Equation (3) and (4) gives the power flow in transmission line.

3.3 UPFC

UPFC is the third generation of FACTS devices which is a most comprehensive device in power system, with combination of series and shunt side which independently controls real and reactive power flow in transmission lines by inserting a controlled voltage in power lines. The series converter is applied to regulate power flow in the transmission line while the shunt converter control voltage at UPFC terminal and DC link capacitor voltage. The most sensitive bus-bars is determined for the optimal location of UPFC which produces increase in the voltage stability. UPFC is chosen for its ability to adjust power flow in transmission line, progress the system performance. In most cases UPFC architecture depends on Pulse Width Modulation (PWM) fixed in series with a tie line. The block diagram interconnected power grid with UPFC is shown in Figure 3.

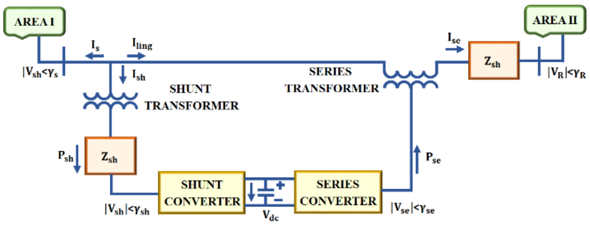

Figure 3: *UPFC combination of dual-area linked power system*

The shunt converter provides the real direction of current flowing through shunt division is a true equilibrium power which is required for the series converter. The Mathematical Representation of UPFC is expressed as:

The formula used when calculating the composite power at receiving station is derived in equation (7). This formula is determined from Figure1, for calculating magnitude of series voltage is given in equation (8).

$$P_{real} - jQ_{reactive} - \vec{V}_r^{\,*} I_{line} = \vec{V}_r^{\,*}\left\{\frac{(\vec{V}_s+\vec{V}_{se}-\vec{V}_r)}{j(X)}\right\} \tag{9}$$

$$\vec{V}_{se} = |V_{se}|\angle(\gamma_s - \vartheta_{se}) \tag{10}$$

The power component is determined by using the equation (9) calculated using equation (3)

$$P_{real} = \frac{|V_s||V_r|}{(X)}\sin(\gamma) + \frac{|V_s||V_{se}|}{(X)}\sin(\gamma - \vartheta_{se})$$

$$= P_{o(\gamma)} + P_{se}(\gamma, \vartheta_{se}) \tag{11}$$

The magnitude of ratio in voltage is represented by V_{se}/V_{sh}, where V_S/V_R is sending and receiving end voltage, $\gamma_{se,}\gamma_{sh,}$ indicates the phase angle and X indicates the line inductance. From equation (9) it is noted that the voltage V_{se} is zero then the true power implies on the system [14].

3.4 Power quality issues

Power quality issues including transient, voltage sag, swell, over and under voltage, harmonics, flickers. FACTS plays a vital part in overcoming power quality issues by enhancing the power quality. It recompenses harmonic distortions by inserting counter active currents and thus defusing the possessions of adverse harmonics [15]. FACTS devices emphasizes technological progressions in power electronics and point-out current assurance to improve power system efficiency and reliability via advanced harmonic destruction approaches.

4. Benefits of Facts Devices

The welfares of FACTS devices are described below [16]:

- ❖ Reliability of transmission lines increase rapidly.
- ❖ Improved dynamic stability of the system.
- ❖ It minimizes short circuit problems and faulty instant switches in the lines.
- ❖ It prevents blackouts, cascading outages and swings in power system and Power quality is highly improved.
- ❖ It accomplishes power flow control and refining transient stability.
- ❖ Mitigate the faults effects and more safe by reducing the number of line trips.

5. Comparative analysis

Table 1: *Comparison of FACTS devices*

Sl.No	Author/Year of publication	Methodology	Advantages	Limitations
1.	Bikash Kumar Saw *et al* (2025) [17]	This study introduces a techno-enviro-economic analysis of modernized practical DN with the impacts of Solar-integrated DSTATCOM-FACTS devices	It has the benefits including voltage stability with reduced power losses.	It faces limitations confined to a technical factors as Total harmonic distortion (THD) and less power factor.

2.	Noor Zanib *et al* (2022) [18]	This paper offers a detailed presentation analysis of a distributed generation system that assimilates solar PV system using UPQC.	This method improves THD, load voltage and current with low cost of components.	It has limited power factor, power produced from PV is insufficient, low convergence.
3.	Kai Hu *et al* (2024) [19]	The paper presents the STATCOM for enhancing power quality using one cycle controller.	This method has robustness, simplicity and flexibility	High THD value, increased power losses.

Table 1. Shows the comparative analysis of FACTS devices using various methods. Comparing other FACTS devices, UPFC is the most versatile device providing superior control over power flow.

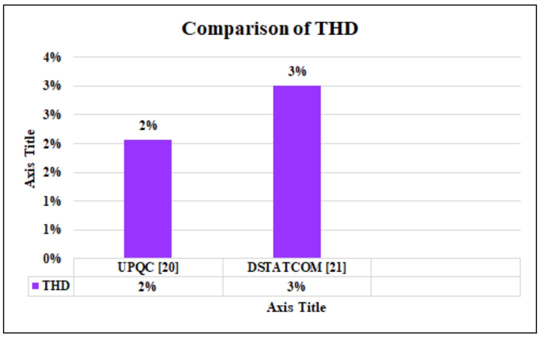

Figure 4: *THD comparison*

Figure 4 shows the comparative analysis of FACTS devices. Comparing FACTS devices, UPQC [20] shows THD level of 2.06% and D-STATCOM [21] shows the THD level of 3% respectively where UPQC has the lower THD value which is more accurate for controlling power quality issues in power system.

Table 2: *Power factor comparison*

FACTS devices	Power Factor
UPQC[20]	0.78
DSTATCOM[21]	0.967

Table 2 represents the power factor comparison between FACTS devices. Here UPQC [20] has the power factor of 0.78 and D-STATCOM [21] has 0.967 value of power factor respectively.

6. Conclusion

This review explains the dynamic role of FACTS devices for power quality enhancement and firmness in power grids with combined PV sources. FACTS devices including SVC, TCSC, STATCOM, SSSC, are studied and it effectively address power quality issues in PV grid. The research highlights the enrolment of FACTS devices in voltage regulation, power factor correction, and power quality enhancement, which is important for unified combination of renewable energies. This paper similarly deliberates the progressions in FACTS technology, which includes the acceptance of innovative power electronics, inventive control strategies, and harmonic distortion, additional growth in performance and efficiency in upcoming difficulties of power systems.

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