

Review article

A comprehensive review of FACTS devices in modern power systems: Addressing power quality, optimal placement, and stability with renewable energy penetration



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ABSTRACT

Incorporating Flexible AC Transmission Systems (FACTS) devices into modern power systems is a crucial field of study, mainly due to the growing adoption of renewable energy sources. This paper thoroughly examines the role and efficacy of FACTS devices in improving power quality and maintaining stability in both conventional power systems and those that heavily rely on renewable energy sources. At first, the central aspect of the review centers on different FACTS devices, including Static VAR Compensators (SVC), Thyristor Controlled Series Capacitors (TCSC), Unified Power Flow Controllers (UPFC), and distributed power flow controllers (DPFC). A comprehensive analysis of each device's operational principles, benefits, and constraints is provided. The paper assesses the efficacy of these devices in addressing the challenges associated with integrating renewable energy. These functions encompass their involvement in maintaining voltage levels, stabilizing frequency, controlling power flow, and enhancing the power system's ability to respond to sudden changes. This paper compares various FACTS devices in different scenarios to emphasize their efficacy in specific contexts. Furthermore, the paper outlines the emerging difficulties in power systems caused by the incorporation of fluctuating renewable energy sources, such as wind and solar power. The challenges encompass voltage fluctuations, frequency instability, and power flow control issues. Advanced solutions are required to maintain power quality and ensure grid stability due to the variability and unpredictability of renewable energy sources. Furthermore, the paper examines the possibilities and future advancements in FACTS technology. The article explores the potential of utilizing power electronics, control strategies, and artificial intelligence integration to improve the performance and effectiveness of FACTS devices. To summarise, the review emphasizes the crucial importance of FACTS devices in modern power systems, especially concerning the growing integration of renewable energy sources. It emphasizes that the strategic deployment of these devices is essential for guaranteeing power quality and stability, enabling a more seamless shift towards sustainable and resilient power systems.

1. Introduction

The complexity and rising demand for power networks provide utilities with a significant problem sustaining sustainable power quality. Voltage stability and effective power flow management are necessary when deviations from norms in voltage, current, and frequency influence power quality. When generating units cannot provide reactive support or when the active-reactive power balance equation is no longer

valid, instability may result (Gayatri et al., 2018). The most viable reactive power system must be installed to maintain the best possible technical and economic conditions for a power system (Zhou et al., 2018). In transmission and distribution networks, energy-related numbers are called "power." Instantaneous equal power is produced by multiplying voltage by current; reactive power is measured in vars, while real power is measured in watts. Apparent power is the total amount of power consisting of both reactive and active components

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(Tian and Li, 2018). Reactive power demand increases utility power networks' efficiency. Voltage-amp reactive (VAR) compensators, such as series/shunt capacitors and static synchronous compensators (STATCOM), are examples that have recently been employed in the electrical grid's power regulation. Faster time responses are possible with these compensators, which are particularly useful since they simultaneously inject and absorb reactive and active power to maintain loads rather than overloading the main lines. When these devices are used, they change things like frequency, voltage, current, phase angle, and impedance. This makes it seem like transmission lines can carry more power and stabilize the network (Iqbal et al., 2019). Some transmission lines are overloaded, and others are loaded below the threshold at which the voltage profile deteriorates. The system stability degrades, so controlling the transmission line's power flow is essential for power transfer.

Power electronic technology improvements have made devices such as the Flexible AC Transmission System (FACTS) possible (Narain and Srivastava, 2015). In particular, for connected systems, Flexible AC Transmission Systems (FACTS) are effective instruments for managing power flow, improving different aspects of stability, and boosting transfer capacity (Athamneh and Lee, 2006). Many academics have examined different models and methodologies for studying FACTS devices and their optimum functioning and planning within power systems. Important review papers that provide a thorough summary of the research results on FACTS devices and related grid services are also available in addition to research publications. There are reviews explicitly written about a FACTS device (Georgilakis and Hatzigiorgiou, 2019), (Irvani and Maratukulam, 1994). Since their inception, FACTS devices have proven to be very successful in reducing power system difficulties. They are somewhat expensive; however, if not used correctly, their initial costs may outweigh the energy they save. In order to overcome this obstacle and optimize the financial advantages offered by FACTS devices, optimization strategies are required. These strategies primarily aim to allocate FACTS devices optimally to enhance many power system performance elements (Song and Johns, 1999).

The paper thoroughly reviews FACTS devices in modern power systems, emphasizing their importance for power quality, optimal placement, and stability amid increasing renewable energy integration. It analyzes various FACTS devices, such as SVC, TCSC, UPFC, and DPFC, detailing their operational principles, benefits, and limitations. Also, this paper focuses on maintaining voltage levels, stabilizing frequency, controlling power flow, and enhancing system response to sudden changes. This work compares FACTS devices in diverse scenarios to highlight their specific context efficacy and addresses emerging challenges due to renewable energy sources like wind and solar power. It also explores future advancements in FACTS technology, including the potential of integrating power electronics control strategies and artificial intelligence. Compared to other reviews, this paper provides a comprehensive analysis of FACTS devices' functions, optimal placement based on metaheuristic optimization techniques, and their crucial role in supporting high-power renewable energy penetration into power grids, outlining advanced solutions and emphasizing the necessity for sustainable power systems. The primary benefits of this review article include:

1. The paper analyzes various FACTS devices like SVC, TCSC, UPFC, DPFC, and others, detailing their functions, advantages, mitigation of power quality issues, and limitations in modern power systems.
2. The paper discusses the optimal placement of FACTS devices based on optimization techniques with a case study overview of many IEEE standard networks based on a literature review.
3. It evaluates the role of FACTS devices in integrating renewable energy into power grids, focusing on voltage stability, frequency regulation, and power flow control, including a comparative analysis in different scenarios.

4. The paper addresses challenges in power systems due to renewable energy variability, discusses advanced solutions and future FACTS technology enhancements, and emphasizes their importance for sustainable power systems.

The structure of the rest of the paper is outlined as follows. Section 3 provides a detailed examination of the classification of FACTS devices. The various kinds of FACTS devices and their ideal placement and configurations are explored in Sections 4, 5, and 6, accompanied by a summary of optimization techniques. Section 7 delves into the latest advancements and findings related to newly developed FACTS devices and discusses potential avenues for future research.

2. Power quality issues and FACTS devices

Problems such as transients, voltage sags and swells, interruptions, over- and Undervoltage, harmonics, flickers, and frequency variations are considered (Mikkilil and Panda, 2018) and explored in the following sections to summarize the different PQ concerns in power systems as shown in Fig. 1, and Table 1.

Regarding the harmonics compensation by FACTS devices, the harmonic suppression techniques facilitated by FACTS devices represent a cornerstone in modern power systems for enhancing power quality and ensuring efficient operation. Through their advanced control strategies, FACTS devices play a pivotal role in mitigating harmonics and deviations from the ideal power frequency that can lead to inefficiencies and instability in the power grid. Selective Harmonic Elimination (SHE) and Active Power Filtering (APF) are among the numerous techniques. SHE involves the precise control of inverter switching angles to cancel out specific harmonic frequencies, effectively reducing the harmonic content without impacting the fundamental power flow. On the other hand, APF, integrated within FACTS, dynamically compensates for harmonic distortions by injecting counteractive currents, thus neutralizing the effects of undesirable harmonics. These methodologies are bolstered by sophisticated control algorithms, including Direct Current Control and Adaptive Filtering, which adapt to changing network conditions to maintain harmonic levels within acceptable limits. Incorporating these techniques in FACTS devices underscores the technological advancements in power electronics and highlights the ongoing commitment to improving power system reliability and efficiency through innovative harmonic suppression strategies.

3. FACTS devices for mitigating power quality issues

The power system is becoming increasingly complex due to rising power demand, leading to operational uncertainty and an increased risk of blackouts. High-power electronic controllers can address this issue in AC transmission networks. The FACTS family of power electronics devices enhances controllability, stability, and power transfer capacity. These devices combine power system components like transistors, thyristors, transformers, reactors, switches, and capacitors. Thyristors with high current ratings can handle large-power applications. The FACTS controller also enhances the power system's dynamic and transient performance. Electronic-based switches in FACTS devices improve transient stability, voltage stability, controllability, and transmission capacity. They are more flexible and responsive, and their use can increase transmission capacity by 40–50% (Das et al., 2019). Phase angle, current, voltage, phase impedance Z , and oscillation damping are just a few of the operating variables that affect how the transmission system functions and are all controllable by FACTS controllers. A transmission line close to its thermal rating can transmit power thanks to the FACTS controller (Singh and Gupta, 2016). In FACTS devices, impedance and apparent admittance are changed at standard coupling and AC bus points. AC components are added to electrical network nodes, reactive or capacitive current is provided locally, and controlled switching is used to change the equivalent driving point impedance at the interface

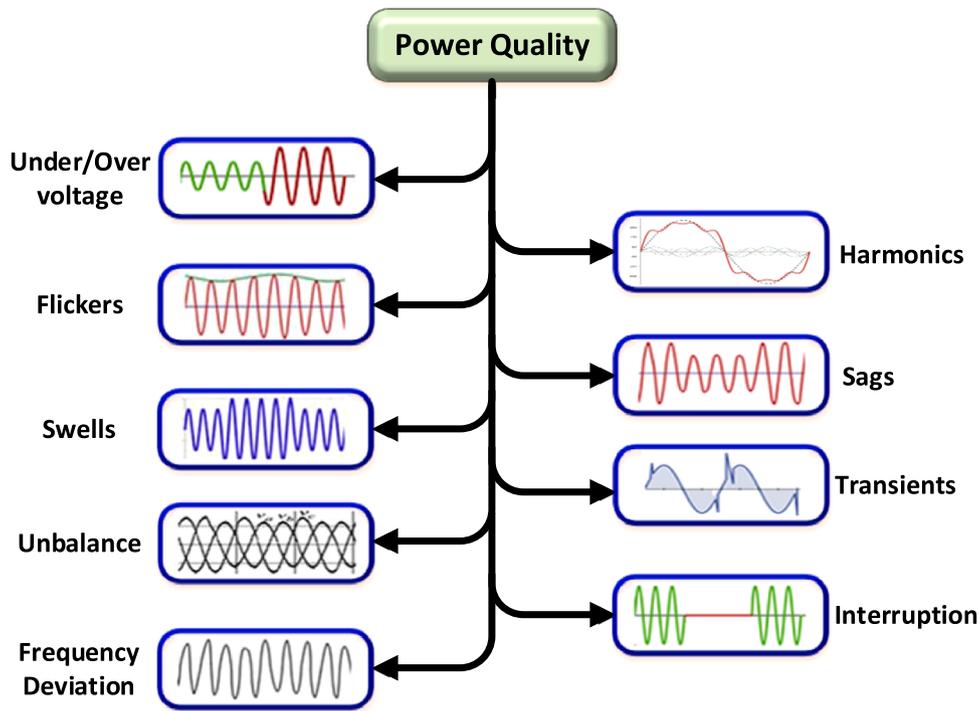


Fig. 1. Typical power quality issues (Mikkili and Panda, 2018).

bus. Control strategies are based on voltage, power, angle, or reactive power flow control. There are two types of converter topologies: voltage source-converter fed, interface for DC-current source injection, switched or modulated inductors or capacitors, and active power filters (Gandoman et al., 2018). In (Marouani et al., 2023; Habur and O’Leary, 2004), fact devices have advantages and disadvantages, as shown in Table 2.

3.1. Classification of (FACTS)

3.1.1. Series controllers

The serial controller can be a variable impedance, such as a condenser, reactor, or static converter with fundamental, sub-synchronous, and harmonic frequencies. In principle, all serial controllers inject a voltage in series with the line since a variable impedance in series, multiplied by the current flow, represents a serial voltage injected into the line. The serial controller only consumes or injects reactive power while the voltage is in quadrature with the line current. Any other phase combination will also involve active power management. Thus, the fundamental effect of this type of equipment is controlling the current in the transmission line (Acha et al., 2004).

An ideal serial controller can be represented as a voltage source connected in the middle of the transmission line, as indicated in Fig. 2. The injected serial Voltage, V_m , can be replaced by a reactive impedance if it is in quadrature with the current, as indicated in Fig. 2. The current equation can be written as follows:

$$I = \frac{\vec{V}_s - \vec{V}_r}{jX(1-r)} \text{ wherer } = \frac{X_{comp}}{X} \quad (1)$$

From this expression, we observe that the total equivalent impedance of the transmission line is modified by adding or subtracting the compensation impedance from the impedance of the line. Factor r is the degree of series compensation, and the absolute value of this factor varies between 0 and 1. Its sign is positive for capacitive compensation and negative for inductive compensation (Acha et al., 2004; Hingoranl and Gyugyi, 2000).

The active power transfer on the transmission line can be expressed as follows:

$$P_s = \frac{V_s V_r}{X(1-r)} \sin \delta \quad (2)$$

Furthermore, the reactive power supplied by the controller will be defined by:

$$Q_c = \frac{I^2 X_{comp} (V_s^2 + V_r^2 - 2 * V_s * V_r \cos(\delta)) * r}{X(1-r)^2} \quad (3)$$

From Eqs. (2) and (3), it is observed that for a given offset value between nodes, δ , the variation in the degree of series compensation, r , allows the value of the active power transferred through to be increased. Of the line, it is increasing the reactive power injected by the serial device.

3.1.2. Parallel controllers

Parallel controllers are devices that, by reactive current injection, allow controlling the voltage in a node, regardless of the lines connected to it (unlike a serial controller, which in some cases may require independent controllers for each line, especially in the supposed failure of one of the lines).

Thus, the principle of operation of a parallel controller consists of supplying reactive power to the line, seeking to increase the active power transfer by improving its power factor while maintaining voltage levels within the safety ranges under extreme loading conditions.

For a simple analysis of the principle of parallel compensation, it is convenient to take a circuit diagram, as shown in Fig. 3, where, assuming zero resistive losses, the parallel compensator is located at the midpoint of a transmission line. As indicated in the figure, the line is assumed to be divided into two equal segments.

Considering that the parallel compensator injects a current such that the voltages at the ends and the midpoint of the line are of the same magnitude, that is to say, that $V_s = V_r = V_m = V$, the active and reactive powers in node S would be given by Eq. (5). Their graphic representation corresponds to Fig. 4.

$$P_s^{COMP} = \frac{2 * V^2}{X} \sin\left(\frac{\delta}{2}\right) \quad (4)$$

Table 1
Summary of Power Quality Issues Impact on Electrical Power Systems.

Issue	Causes	Effects	Allowable Range
Overvoltage	Transmission failures, lightning, sudden load changes	Damages electrical devices, stress insulation	Typically, up to 110% of the nominal voltage
Undervoltage	High electrical demand (e.g., multiple ACs running)	This leads to voltage uncertainty, system losses, equipment failure	Typically down to 90% of nominal voltage
Harmonics	Nonlinear loads like power electronics converters, electronic ballasts	Impacts system performance, reliability, and safety	THD < 5% for voltage, < 8% for current
Voltage Flickers	Large loads with abrupt power demand changes	It affects the functionality of household equipment	Pst < 1 (short-term flicker severity)
Voltage Sags	Energizing large loads (refrigerators, AC motors)	Damages sensitive electronics, data loss, malfunctioning of protection equipment	Duration and depth-dependent, often < 90% of nominal voltage
Voltage Swells	Electrical network issues, insulation deterioration, power electronic device malfunctions	It affects electrical system operation, causes flickering	Typically, up to 110% - 120% of nominal voltage
Transients	Incorrect wiring connections, equipment switching	Corrupts computer data, causes electrical equipment failure	Highly variable, dependent on system and equipment tolerance
Voltage Unbalance	Uneven distribution of single-phase loads among three-phase circuits	Overheating of induction device windings, additional power losses	Typically < 2% - 3% unbalance
Interruptions	Control system issues, breaker opening, fuse blowing, power system faults	Disruption in electrical service, categorized as preplanned or accidental	Duration dependent, from milliseconds to hours
Frequency Deviation	Varies	Alters the speed of clocks and motors, affecting traditional electronic equipment	Typically within ±0.5 Hz of the nominal frequency

Table 2
The advantages and disadvantages of FACTS devices.

Advantages of FACTS Devices	Disadvantages of FACTS Devices
1. Enhanced Power Transfer Capacity - Increases transmission lines' capacity. - Allows more power transfer over existing lines.	1. High Cost - Significant installation and maintenance expenses.
2. Increased Stability - Reduces the impact of outages. - Decreases the risk of cascading failures.	2. Complexity - Complex design and operational requirements.
3. Enhanced Efficiency - Reduces power transmission losses. - Lowers operating costs.	3. Potential for Failure - Like any complex system, it is prone to failures.
4. Improved Voltage Regulation and Control - Maintains suitable voltage levels.	-
5. Improved Supply Quality for Sensitive Industries	-
6. Environmentally Friendly - Free from harmful materials and pollution.	-

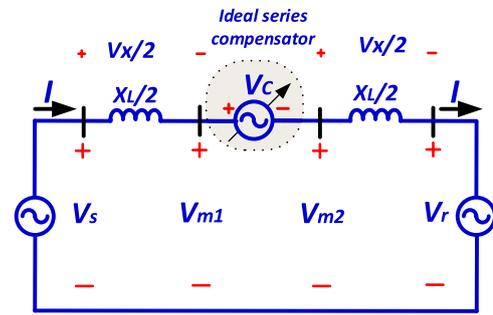


Fig. 2. Ideal series controller (Acha et al., 2004).

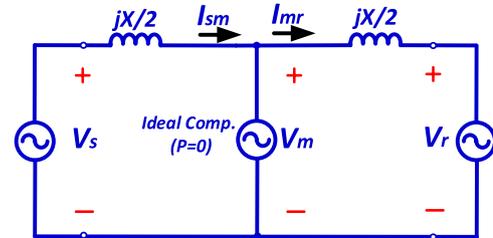


Fig. 3. Ideal parallel controller.

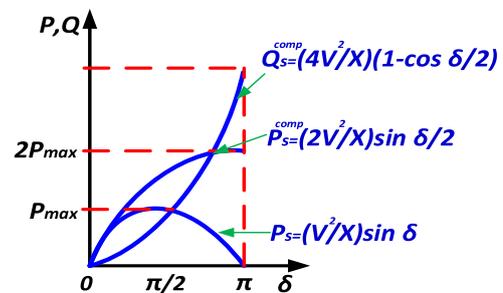


Fig. 4. Power flow variation in a line due to parallel compensation (Acha et al., 2004).

$$Q_s^{COMP} = \frac{4 * V^2}{X} \left(1 - \cos\left(\frac{\delta}{2}\right) \right) \quad (5)$$

The equations in (3) and Fig. 4 show how parallel compensation can increase power transfer in a transmission line.

Classification according to the type of network connection. Series controllers are devices connected in series with the power system network, while shunt controllers are devices connected in a shunt configuration. In some situations, the power system combines Series-Series and Series-Shunt controllers to improve voltage stability and placement (Das et al., 2019). Fig. 5(a) shows how the serial controllers inject a series voltage at the connection point to deal with disturbance voltage situations. The shunt controllers' contact point (Fig. 5(b)) introduced the electrical current into the network, while the combined controller's serial part injected the series voltage. Fig. 5(c) (Zarkani et al., 2021) and the series-series connection Fig. 5(d) allows the shunt controller's electrical current to enter the network. Both series and shunt facts have advantages and disadvantages for each other. The primary purposes of the FACTS series are oscillation damping, current control, and power flow control. Reactive power compensations (RPC) are used in shunt devices to regulate voltage and improve voltage stability. If series-connected controllers are used alone, they need system-specific designs to avoid short-circuit currents and sustain dynamic overloads. Consequently, it is advised that a mix of shunt and series-connected controllers be used to effectively regulate current flow and voltage in

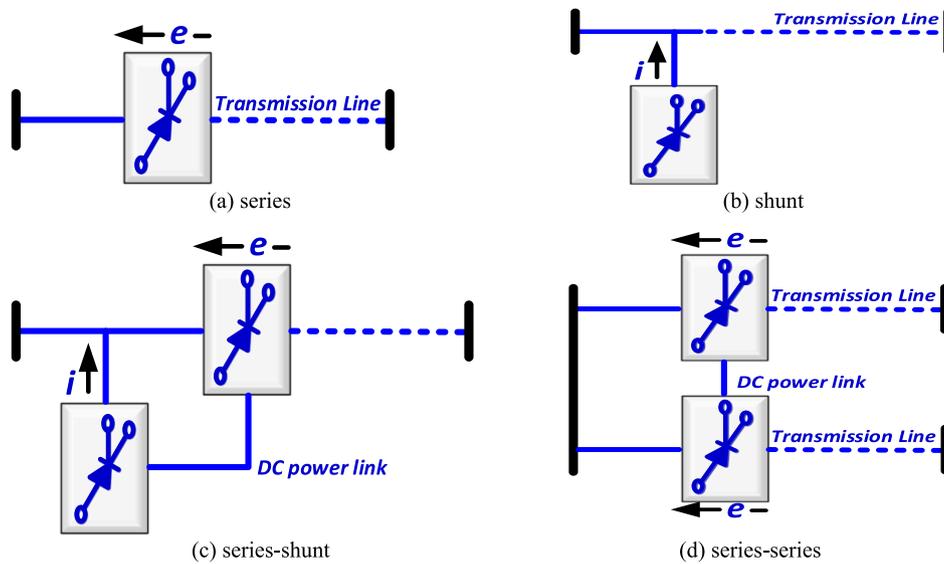


Fig. 5. Classification based on the type of connection.

the system (Shah et al., 2021).

The different types of FACTS Controllers and their control parameters are shown in Table 3 (Singh and Kumar, 2020a), (Singh et al., 2019).

3.2. Classification according to the power electronic devices

FACTS devices are grouped into two generations. The first generation of ignition controlled by gate (SCR) thyristors was used. Second generation: semiconductors (GTOs, MCTS, IGBTs, IGCTS, etc.) with gate-controlled ignition and extinction.

In the first generation of voltage source converters (VSCs), there are reactors, gate turn-off (GTO) thyristor-switched converters, quadrature tap-changing transformers, and regular thyristor-switched capacitors. The first generation produced the Thyristor-Controlled Phase Shifter (TCPS), the Thyristor-Controlled Series Capacitor (TCSC), and the Static Var Compensator (SVC). The second generation includes the Static Synchronous Compensator (STATCOM), Unified Power Flow Controller (UPFC), Static Synchronous Series Compensator (SSSC), and Interline Power Flow Controller (IPFC). The two sets of FACTS controllers have very different operating and performance characteristics (Gupta et al., 2010). Although several groups in the second classification may include devices from one group in the first, these two classes are different. The ability of devices from the first and second generations to produce reactive power and swap out active power is the main distinction between them. The initial generation of FACTS devices employed thyristor-regulated impedances or tap changer transformers to make them passive. Electronic tension sources, like three-phase inverters, auto-switched voltage sources, synchronous voltage sources, and voltage source control, are used in the second generation of FACTS devices. These work similarly to angle- and module-controlled voltage sources but do not have any inertia. These sources provide static synchronous voltage and current and are fast, proportional, and controlled (Parate and Pai, 2016).

Table 3
The different types of FACTS Controllers.

Types of Facts	Regulating Sensitivity	regulated parameters
Series	Control reactance	Real and reactive power
Shunt	Control susceptance	Reactive power
Shunt-Series	Control X, V, and δ	real and reactive power
Series-Series	Control V and δ	real and reactive power

As shown in Fig. 6, the FACTS devices are grouped according to connection and generation.

3.3. FACTS device types

Several of the special-purpose FACTS controllers and their uses will be covered in this section.

3.3.1. Static Var Compensator (SVC)

The Static Var Compensator is one of the FACTS devices (SVC). These consist of reactors and shunt-connected capacitors with thyristors installed or controlled (Levačić et al., 2018). Both capacitive and inductive corrections may be employed with SVC (Vadivelu and Marutheswar, 2014). By quickly adding or removing parallel-connected capacitors and reactors, the thyristor valve can operate in a phase-controlled manner, which regulates reactive power injection and absorption by the SVC into and out of the bus bar. At any given bus-k, the applicable SVC model may be implemented as a shunt-linked variable susceptance B_{svc} . To find the amount of reactive power the SVC sends into the bus, use the formula $Q_{svc} = B_{svc} V^2$, where V is the bus's voltage amplitude at the compensator's installation point (Muhammad et al., 2020). Within the region of ± 100 MVAR, the SVC is employed to control the reactive compensation of a system (Adail et al., 2018). The SVC's device and equivalent circuit are seen in Fig. 7.

The benefits of installing the SVC device may be summarized as follows (COTEANU and GHEORGHE, 2023), (Pathak, 2020), (Elshreef et al., 2021), (Muhammad et al., 2020):

1. Attenuation of oscillation in power.
2. Increasing the stability of power.
3. Control of reactive power dynamically.
4. Improvement of the Under-Voltage Problem utilized to boost renewable energy sources' capacity for integration.

The disadvantages of SVC devices could be summarised as follows (Qiao et al., 2019), (Igbinovia et al., 2015), (Gadal et al., 2023):

1. Installing SVC devices requires a significant amount of floor area and labor and is expensive.
2. It is comparatively slower than STATCOM.
3. SVC can negatively impact the power system's stability by producing harmonics and voltage oscillations. Real-world applications require matching filtering devices. Accurate capacity and parameters of SVC

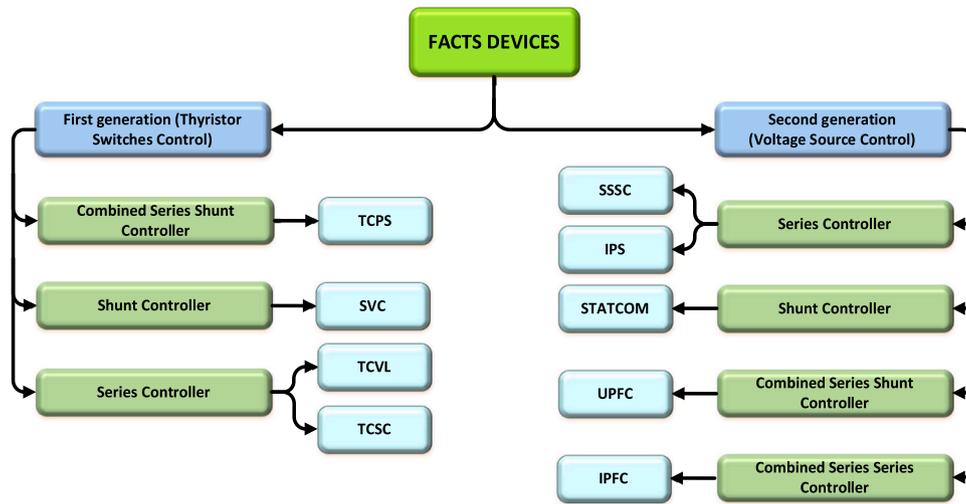


Fig. 6. Classification of FACTS devices (Ismail et al., 2020a).

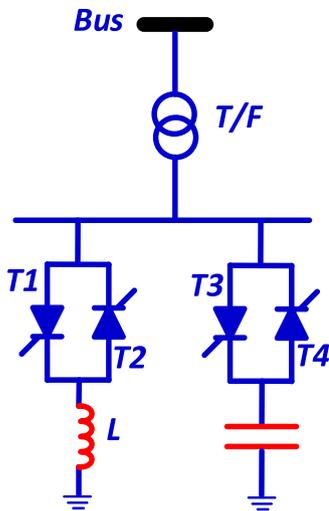


Fig. 7. Static Var Compensator (SVC).

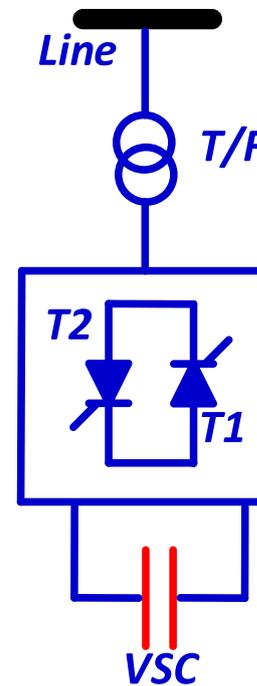


Fig. 8. Static synchronous compensator STATCOM.

are crucial for grid dependability and economy, necessitating continuous improvement in the control strategy.
 4. It ignores active losses caused by SVC components.

3.3.2. Static Synchronous Compensator (STATCOM)

According to IEEE definitions, a static synchronous compensator is a shunt-connected static variable compensator that regulates the output current of an inductive system or capacitor independent of the voltage of the AC system (Siddique et al., 2019). Shunt compensators are often used to raise the system bus’s voltage profile. It gauges the magnitude and angle of the bus voltage it connects to. It may provide the inductive or capacitive current needed to keep the connected bus’s voltage stable and the voltages of other buses (Jaiswal et al., 2021). STATCOM uses the least amount of active power possible from the system to regulate the flow of reactive power by varying the voltage angle output of its converter. Conversely, active power may be exchanged if an available energy storage system is available (Shinde and Pulavarthi, 2017). The STATCOM’s devices and equivalent circuit are seen in Fig. 8.

We can summarize the benefits of installing the STATCOM device as follows (El Zoghby and Ramadan, 2022), (Subramanian et al., 2018), (Singh and Kumar, 2020b), (Muhammad et al., 2020; Kumar et al., 2022), [Shahgholian and Faiz, 2010]

1. Transient stability of the grid.
2. Show three-phase unbalance.
3. Adjusting an arc furnace’s dynamic power factor reduces sudden voltage fluctuations (flicker control).
4. It controls voltage.
5. Lower loss in lines.
6. The STATCOM device enhances the microgrid’s stability by reducing voltage, frequency, and power fluctuations, improving its performance.
7. Integration of wind farms and PV Integration of solar plants.
8. Due to its active nature, STATCOM can quickly provide both actual and reactive power to the system, which helps enhance the system’s voltage profiles and damping.

The disadvantages of STATCOM devices could be summarized as follows (Gadal et al., 2023), (Kynev et al., 2016).

1. Loss and cost are more significant than SVC.
2. Ignores active losses brought on by the components of the STATCOM.
3. When there is a sudden decrease in voltage, the synchronous capacitor responds quickly and pumps current following the change, but the STATCOM is slow.
4. It is slower than a BESS (Battery Energy Storage System).

3.3.3. Thyristor Controlled Series Reactor (TCSR)

The TCSR FACTS Controller is a variable-series reactor that efficiently lowers line current by increasing a line’s reactance. It comprises a series reactance (XL1) and two antiparallel thyristors (T1 and T). The symbols RL and XL, respectively, stand for the resistance and reactance of the transmission line, and the controller is meant to manage both transmitting and receiving buses (Gupta et al., 2020). When the thyristor-controlled reactor shuts down at a 180-degree firing angle, the uncontrolled reactor acts as a fault current limiter. The net inductance decreases as the angle decreases below 180 degrees (Singh et al., 2013). The TCSR equivalent circuit is shown in Fig. 8.(Fig. 9)

We can summarize the benefits of installing the TCSR device as follows (Rao and Mohan, 2014), (Muhammad et al., 2020; Kumar et al., 2022),[(Yuan, 2021)].

1. The electrical system’s stability.
2. Smooth inductive reactance varies.
3. It maintains voltage control.

The drawbacks of TCSR devices: High installation and maintenance costs might be associated with using a TCSR device.

3.3.4. Thyristor Switched Series Capacitor (TSSC)

TSSC is compensation for physical phenomena. It is made up of a bank of sequence capacitance that is thyristor-switched. It is common practice to provide a systematic strategy for handling a series of physical events (Raza and Khatak, 2024). This type of payment is similar to TCSR. The firing angle of a thyristor is used in TCSR to control the power. Therefore, it provides progressive control.

Nevertheless, in the case of TSSC, the thyristor can only be switched on or off, and there is no angle of fire. Consequently, the capacitor’s line connection is either fully connected or disconnected. The controller and thyristor see a decrease in price as a result (Razmi et al., 2023). Fig. 10 shows the device and equivalent circuit of the TSSC.

We can summarize the benefits of installing the TSSC device as follows (Colak et al., 2016), (kumar Reddy and Nireekshana, 2019), (Gheydi and Bagheri, 2019)

1. effective in controlling power flow in the line and in improving the dynamic behavior of the power system
2. By combining a leading capacitive reactance with the trailing line reactance, TSSC may reduce the line reactance during steady, balanced operation.
3. Minimize voltage collapse, lessen under synchronous oscillations, and dampen dynamic oscillations to increase the system’s dependability.

A failure to switch active power across a transmission line is a disadvantage of TSSC devices (Gadal et al., 2023).

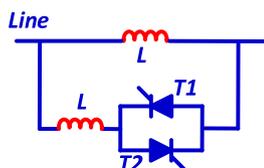


Fig. 9. Thyristor Controlled Series Reactor (TCSR).

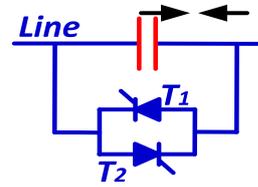


Fig. 10. Thyristor Switched Series Capacitor (TSSC).

3.3.5. Thyristor Controlled Series Compensator (TCSC)

The TCSC is a series-compensating device that modifies the overall impedance of a transmission line through the series connection of a capacitor and a thyristor-controlled reactor. Since an inductive reactor connected in parallel might alter capacitance, this modification is required to control the flow of electrical current (Shelke and Bhole, 2024). A TCSC may generate an inductive or capacitive product, depending on how the total reactance varies (Ambadkar, 2024). The TCSC’s device and equivalent circuit are seen in Fig. 11.

We can summarize the benefits of installing the TCSC device as follows (Elijah et al., 2017), (Shivalingswamy and Anjali, 2019), (Haroon et al., 2020)

1. improve the voltage/angle stability and power transfer capacity of power systems dynamically, as well as their voltage profile and steady-state voltage profile.
2. The Split TCSC is introduced into the grid system line to eliminate power oscillations, moderate subsynchronous resonance, decrease losses, increase voltage range, and enhance system stability by reducing harmonic distortion and minimizing losses.
3. TCSC can enhance the system’s transient stability by providing voltage support, improving dynamic performance by enhancing power transmission capacity, and potentially reducing subsynchronous resonance.

The following can be used to summarize TCSC device disadvantages, such as (Gadal et al., 2023):

1. Not able to exchange active power with the transmission line.
2. It is larger than the SSSC in terms of size.

3.3.6. Static Synchronous Series Compensator (SSSC)

The FACTS device SSSC allows concurrent control of the node’s phase angle, voltage, and line impedance. Sinusoidal reactive voltage can be introduced into the transmission line through a solid-state voltage source inverter connected to a transformer. SSSCs are always linked in series, adjusting line-equivalent impedance and controlling transmission power flow (Dwivedi and Vadhera, 2019). In a system containing a wind farm, an SSSC with an oscillation damping controller simultaneously accomplishes power flow management and low-frequency oscillation damping (Kotsampopoulos et al., 2019). The SSSC devices function similarly to STATCOM, connecting a voltage source converter to a transmission line via a transformer, requiring an energy source to maintain constant voltage across a condenser (Pathak, 2020). Fig. 12 shows the device and equivalent circuit of the SSSC.

We can summarize the benefits of installing the SSSC device as follows (Sharma and Khambra, 2020), (Jadhav and Kulkarni, 2018),

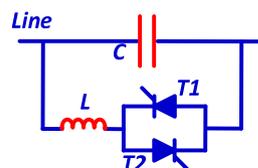


Fig. 11. Thyristor Controlled Series Compensator (TCSC).

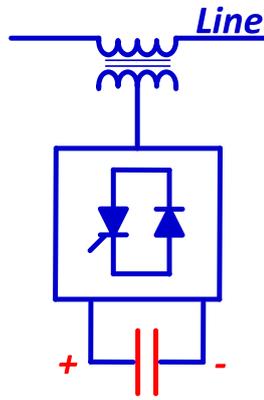


Fig. 12. Static Synchronous Series Compensator (SSSC).

(Venkateswarlu et al., 2018)

1. Power flow control
2. Expand the capacity for both power transmission and loading.
3. Use controllers to enable reactive power adjustment and system security
4. Offers more adaptability
5. It is possible to lessen the issue of voltage oscillations and fluctuations.
6. Reduction in size of the valuable air-cored reactor
7. Compared to other FACTS controllers, SSSC can be used more successfully for power system oscillation dampening since it operates in both capacitive and inductive modes.

The study analyzed the performance of HSC with SSDC using a torque coefficient approach, revealing that SSSC's constant reactive voltage injection mode outperforms constant voltage mode.

The disadvantage of SSSC devices could be summarized as follows (Gadal et al., 2023), (Sharma and Khambra, 2020),

1. Because of the many commutations, the network is at risk of overvoltage.
2. It is expensive in comparison to TCSC.
3. The SSSC's high cost and high installation and maintenance expenses may not make it as cost-effective for various power systems.
4. An SSSC's failure risk is due to its reliance on semiconductors like IGBTs or thyristors, which can overheat or break down at high voltages or currents.

3.3.7. Unified Power Flow Controller (UPFC)

An advanced FACTS device, the UPFC is a two-voltage source converter. They may be characterized using both shunt and series controllers. A DC connection capacitor connects these controllers. A coupling transformer linked These complete assemblies to the gearbox line (Chorghade and Deodhar, 2020). FACTS' unified power flow controller (UPFC) is a unique device providing dynamic power system offset and

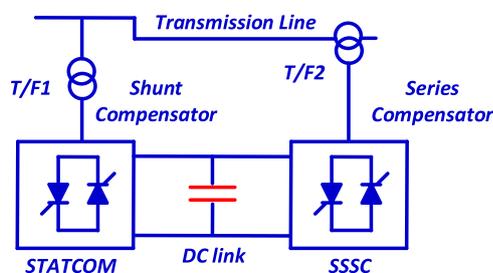


Fig. 13. Unified Power Flow Controller (UPFC).

concurrent control over all parameters (Ananda and Shivakumar, 2018).

The UPFC's device and equivalent circuit are seen in Fig. 13.

We can summarize the benefits of installing the SSSC device as follows (Alsammak and Mohammed, 2018), (Patil and Mahajan, 2017)

1. It is Increasing the power systems' active and reactive control power flow.
2. It improves transient stability.
3. It improves subsynchronous resonance damping.
4. It is Regulating the dynamic or steady state performance.
5. It is Improving the flow of power.
6. UPFC integration has proven to be successful in maintaining voltage stability.

The disadvantages of UPFC devices could be summarized as follows (Gadal et al., 2023)

1. Because of its complex configuration, it is rather expensive.
2. Due to the management of two inverters functioning concurrently, the operating principle is complex.

4. Distributed power flow controller (DPFC)

Both series and shunt converters will be linked between the distribution line's alternating current terminals to create a closed-loop arrangement. Active power exchange conversion will be done via alternating current terminals (Goud et al., 2021; Malleswara Reddy et al., 2020). When the non-sinusoidal voltage and current are considered, the mean value of the product of the two is defined as the absolute power.

It is not easy to calculate when the frequencies are different; the cross-products of the components vary. As a result, the following is a possible definition of absolute power:

$$P = \sum_{i=1}^{\infty} V_i I_i \cos \phi_i \tag{6}$$

When the "ith harmonic frequency is reached, V_i and I_i are the voltage and current at the ith harmonic frequency, respectively. ϕ_i is the angle between the voltage and current". Being independent of frequency, active power increases the flexibility and possibility of generating even in the absence of external energy, actual power at any frequency source, which has the additional advantage of allowing precisely the same amount of energy to be absorbed in different frequencies, which is a significant added benefit.

Shunt Active Power Filters inject an equal but opposite amount of harmonic compensating current to correct for current harmonics. A current source injects the harmonic components created by the load, but the phase is altered by 180 degrees by the shunt active power filter. Since the active filter cancels out and keeps source and load currents sinusoidal and phase, harmonic components in the load current are no longer an issue. Harmonic sources of all kinds can benefit from applying this idea. In addition, the active power filter can correct the load power factor using a suitable management scheme. As a result, the power distribution system views the active power filter and the nonlinear load as an ideal resistor. The filter will produce a closed-loop for these harmonic current converters (Naidu et al., 2020; Chaudhary et al., 2019).

Furthermore, the DPFC has a robust controlling capability since it comprises several small-rated series converters. The failure of one converter has little effect on the system's operation. Because other converters continue to contribute to the regular running of the overall design, there is no need to shut down the system. The provision of bypass protection increases the dependability of the system.

The high-pass channel inside the DPFC blocks the main frequency segments while allowing the consonant sections to pass through. As a result, the harmonic frequency segments are provided with a path to

arrive at. Harmonic current is controlled by a closed loop formed by the ground, the shunt and series converters, and the high pass channel. The difference in configuration between UPFC and DPFC is illustrated in Fig. 14.

4.1. DPFC Advantages

The DPFC is analogous to a UPFC, engaging in power trading via consonants and employing the FACTS concept. As detailed below, all the UPFC and D-FACTS benefits are transferred to the DPFC, as demonstrated in Fig. 14. The main advantages of DPFC are summarized below.

- High control capability:** The DPFC can test the power grid’s line resistance, transmission angle, and transport voltage simultaneously. A more convincing placement for both the shunt and series converters is impossible. DPFC’s great control capacity can alter power quality and system stability in various ways, such as reducing the amplitude of low-frequency control oscillations, restoring voltage after a drop, or compensating for asymmetry.
- High efficiency and reliability:** Better reliability is achieved through the series converter’s repetition. If the series converter fails, the sidestep guarantee will cut power to it before it can cause any damage to the system. If the shunt converter fails, the series converter will stop providing dynamic compensation and function as the D-FACTS controller. At that point, the shunt converter will be activated.
- Low cost:** The series converter does not provide isolation between stages of the power supply. Also, the individual converters have low power ratings, allowing them to be efficiently manufactured in series.

There are some review papers regarding FACTS devices. Table 4 briefly reviews some of the existing works and the most essential aspects investigated in the articles.

Table 5: a brief overview of some of the essential review articles already published on FACTS devices.

5. Control Method of Shunt and Series Facts Devices

This section presented the general control method used to control the shunt and series of FACTS devices with the primary grid always 400 V, 50 Hz. The control model of FACTS, which consists of both series and shunt controllers, is utilized to alleviate problems with PQ. A PID controller is utilized to manage FACTS operations. The metaheuristic optimization approach tunes the PID controllers, resulting in the most significant gain values. The shunt controller is utilized to minimize voltage-related issues, whereas the series controller is utilized to reduce current-related issues.

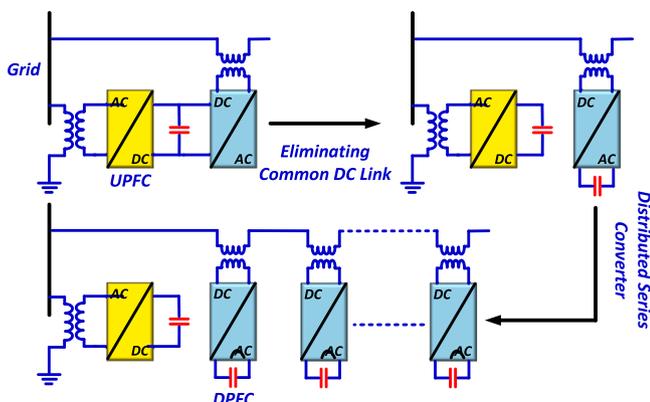


Fig. 14. Basic concept of UPFC to DPFC.

Table 4

provides a basic overview of the construction of standard FACTS devices (Abasi et al., 2021).

Type connection	FACTS devices
series	TCSC (Thyristor Control Series capacitor) SSSC (Series Synchronous Static Compensator) IPC (Interphase Power Controller)
shunt	UIPC(Unified Interphase Power Controller) SVC (Static VAR Compensator) STATCOM (Static Synchronous Compensator)
Series-Series	IPFC (Interline Power Flow Controller)
Series-shunt	UPFC Unified Power Flow Controller

As shown in Fig. 14, the FACTS comprises three primary controllers: a central controller, a series controller, and a shunt controller. The central controller is the principal controller in this system since it is the one that sends signals to the other controllers that are contained within the same device. At the same time, shunt and series controllers are used to make the necessary adjustments to correct current harmonics for voltage.

The management in series is the most common controller used for operating the FACTS. They are used to control their converters, which are located in different locations. This controller controls indications relating to the frequency component of the fundamental. The functions of the FACTS application include balancing asymmetrical details, controlling low-frequency power oscillations, and controlling the flow of electrical power, to name a few examples. In addition, this control gives the shunt converter the appropriate current signal.

5.1. Central Control

As illustrated in Fig. 15, all of the series and shunt controllers are under the direction of this controller, which also provides reference signals for both controllers.

5.2. Design of shunt control

A three-phase shunt converter is connected to two single-phase shunt converters in a back-to-back configuration. The grid’s fundamental frequency gathers active power from this converter. It adjusts the DC voltage between a capacitor and a single-phase converter. Additionally, it provides the shunt converter with a third-harmonic current through the neutral wire of a -Y transformer. Fig. 15 shows the shunt converter block diagram.

Fig. 15 illustrates the control method used with the proposed controller for the active power filter. The currents and voltages in three phases are converted into $(\alpha\beta)$, which are outlined in the following Eqs. (7) and (8) (Goud et al., 2021; Mayer et al., 2020). Calculations of the real and unconsidered powers of the instantaneous values are carried out using the phase neutral voltages and load currents as inputs. The real and reactive powers are determined using Equation in the active shunt filter (9).

$$\begin{bmatrix} V^{s0} \\ V^{s\alpha} \\ V^{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V^{sa} \\ V^{sb} \\ V^{sc} \end{bmatrix} \quad (7)$$

Table 5
overview of some essential works related to FACTS devices.

Ref.	Devices	Review Goal	Conclusion	Recommendations & Difficulties
(Ordóñez et al., 2021)	TSSC, TCSC, SSSC, DSSC	Examines the evolution of series compensation technologies.	DSSC is cost-effective and offers better control and installation benefits.	Explore new applications and protection strategies for DSSC and SSSC.
(Saberian et al., 2013)	FACTS	Investigate FACTS devices in integrating renewable energy into power systems.	FACTS devices enhance the integration of renewables, improving system performance.	Design FACTS carefully for renewable energy plants considering weather impacts.
(STOCHITOIU and UTU, 2020)	SVC, STATCOM, IPFC, UPFC, SSSC, TCPS, TCSC	Compares various FACTS devices for improving power system efficiency.	Improved grid stability, reduced losses, and better power flow control.	No recommendations or difficulties were mentioned.
(Bharambe, 2021)	UPFC, STATCOM, SSSC	Evaluates FACTS regulators in power systems for stability and power management.	FACTS regulators effectively address voltage stability with advanced technology.	No recommendations or difficulties were mentioned.
(Gawande and Mohaney, 2022)	SVC	Discusses SVC design and operation in power systems using MATLAB.	Detailed insight into SVC's role in managing voltage and reactive power.	No recommendations or difficulties were mentioned.
(Ahmed, 2024)	FACTS	Analyzes smart grid technology and the role of FACTS devices.	FACTS are crucial for smart grid technology deployment and integration.	No recommendations or difficulties were mentioned.
(Choudante and Bhole, 2018)	UPFC	Compares FACTS devices and analyzes UPFC for power control.	UPFC enhances power transmission capacity and system stability.	No recommendations or difficulties were mentioned.
(Gadal et al., 2023)	UPFC	Overview of voltage stability techniques, comparing FACTS devices.	UPFC efficiently controls power system stability.	Research FACTS device compatibility with network designs and voltage stability.

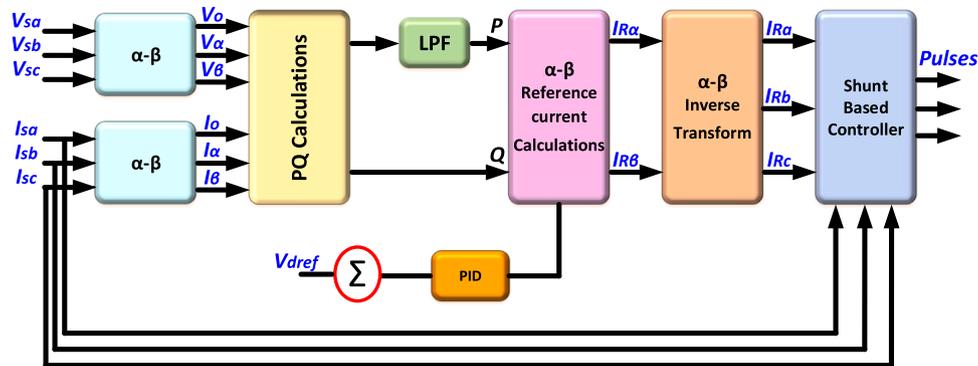


Fig. 15. The strategy of shunt converter control.

$$\begin{bmatrix} I^{l0} \\ I^{l\alpha} \\ I^{l\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V^{L\alpha} \\ V^{L\beta} \\ V^{Lc} \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V^{S\alpha} & V^{S\beta} \\ -V^{S\beta} & V^{S\alpha} \end{bmatrix} \begin{bmatrix} I^{l\alpha} \\ I^{l\beta} \end{bmatrix} \quad (9)$$

5.3. Design of Series Control

Each single-phase converter is controlled by a separate series control throughout the line. A sequence of capacitor voltages, a line current, and a series voltage reference are used as controller inputs during the dq-frame (Chaib et al., 2017). A Diagram of the series converters is shown in Fig. 16 as a block diagram.

The control procedure based on the series active power filter is illustrated in Fig. 16. The phase-locked loop, abbreviated as PLL, is utilized to establish the reference voltage. Using the dq transformation technique (also known as the Clarke transformation), the three-phase voltage data is transformed so that it may be plotted along the d–q axis. In addition, the power filter was utilized to monitor the FACTS and address the problems with the system's power quality (Mikkili and Panda, 2018). The formal representation of the mechanism behind the transition of dq voltage from three-phase voltage is shown in Eq. (10),

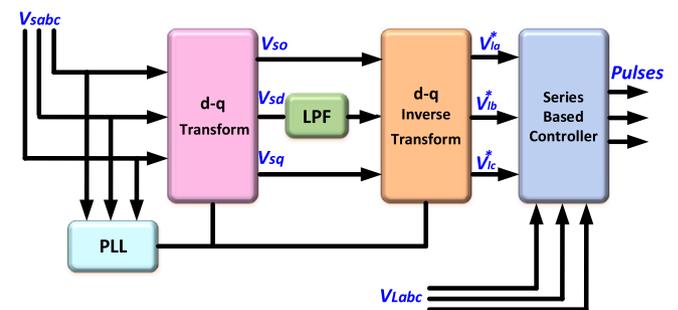


Fig. 16. The strategy of series converter control.

$$\begin{bmatrix} V^0 \\ V^d \\ V^q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1/2 & 1/2 & 1/2 \\ \sin(\alpha t) & \sin(\alpha t - 2\pi/3) & \sin(\alpha t + 2\pi/3) \\ \cos(\alpha t) & \cos(\alpha t - 2\pi/3) & \cos(\alpha t + 2\pi/3) \end{bmatrix} \begin{bmatrix} V^a \\ V^b \\ V^c \end{bmatrix} \quad (10)$$

The voltage along the d-axis is shown both as a direct voltage and as the voltage associated with the alternating component. The low-pass filter (LPF), whose mathematical formulation is as follows, can smooth out the voltage along the d-axis.

$$V^{d(dc)} = V^d - V^{d(ac)} \quad (11)$$

After that, the voltage is divided into three phases. The voltage control loop is regulated by the PI controller and adjusted by PID in conjunction with the optimization method presented in Section 5. Finally, the voltage reference converts to three-phase voltage to

compare with the sawtooth signal to produce the optimal gate signal for an inverter.

$$\begin{bmatrix} V^{Ra} \\ V^{Rb} \\ V^{Rc} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(\alpha t) & 1/2 & 1 \\ \sin(\alpha t) & \sin(\alpha t - 2\pi/3) & 1 \\ \cos(\alpha t) & \cos(\alpha t - 2\pi/3) & 1 \end{bmatrix} \begin{bmatrix} V^{d(dc)} \\ V^g \\ V^0 \end{bmatrix} \quad (12)$$

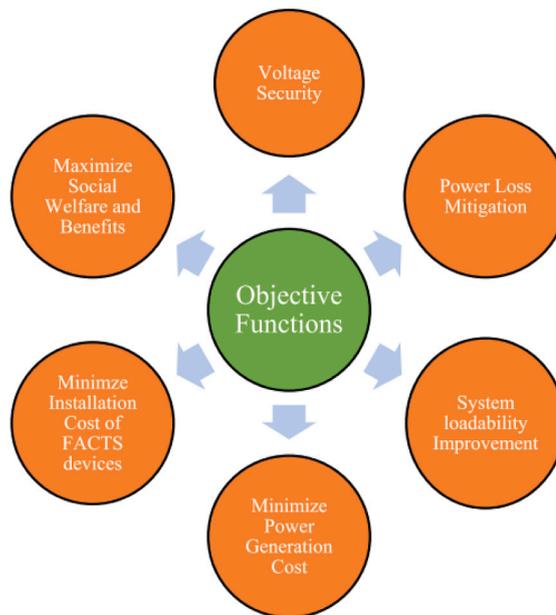
6. Methods of optimal placement and settings of FACTS devices

FACTS devices may increase power system performance and fix issues (Zhang et al., 2012). Due to high installation costs, electricity systems are being updated using the fewest FACTS devices possible. Determining the best position and size for each item to be placed is crucial. Several research studies supported this idea and offered ways to determine the appropriate size and location (Gabl et al., 2018). Researchers have presented several methods and algorithms for FACTS device location, setup, and parameter tuning (Roshan et al., 2020). Numerous optimization methods have been proposed and used in recent decades. The complexity of power system optimization and new computer engineering advances need programming approaches to determine the appropriate FACTS device position (Madhuranthaka and Manohar, 2016). Fig. 17 (a and b) shows four types of optimum placement methods: analytical, conventional optimization-based, metaheuristic, objectives, and hybrid (Ismail et al., 2020a). The figure represents a set of objective functions central to the strategic implementation of FACTS devices within a power network. It emphasizes a multi-objective approach to optimize power system operations. The core objective

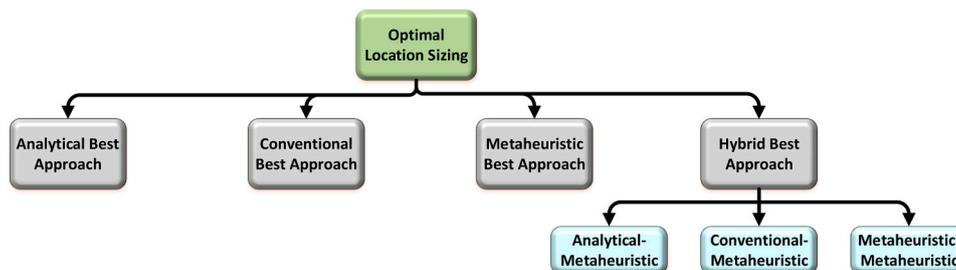
functions include enhancing voltage security to maintain acceptable voltage levels across the network, mitigating power loss to improve efficiency, and improving system loadability to maximize the power transfer capability.

Additionally, it focuses on minimizing the cost of power generation and the installation costs of FACTS devices, underscoring the economic aspect of power system management. Surrounding these technical and economic objectives is the overarching goal of maximizing social welfare and benefits, indicating that deploying FACTS devices should ultimately contribute to the broader good by ensuring a reliable, cost-effective, and efficient power supply. The diagram reflects a holistic view where each objective is interrelated, suggesting that improvements in one area may impact others, and the effective management of FACTS devices requires balancing these diverse goals to optimize overall system performance.

Numerical formulation is used in analytical or sensitive-based techniques. Conventional approaches, also called traditional methods, include Newton-Raphson (NR), linear programming, nonlinear programming, sequential quadratic programming, dynamic programming, and many more. Typically, these approaches begin with the random determination of an initial solution and aim to achieve the optimal solution in every solution (Zubidi et al., 2023). Metaheuristic algorithms are dynamic algorithms that may produce a global optimal solution and are independent in tackling any issues. Typically, the algorithms are nature-inspired techniques that fall into one of three dominant disciplines: (i) algorithms based on biology, (ii) algorithms based on physics, and (iii) algorithms based on chemistry (Slowik and Kwasnicka, 2017),



(a) objective functions of optimal location (Ahmad and Sirjani, 2020).



(b) shows the optimization location classification

Fig. 17. optimal location based on optimization techniques.

(Siddique and Adeli, 2017). Computational techniques known as heuristic or meta-heuristic approaches optimize several candidate solutions in an equation system by repeatedly attempting to raise the objective function. The 18 heuristic and metaheuristic techniques for the ideal placement of FACTS are examined in the following references: Sequential Annealing (SA), Tabu Search (TS), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Differential Evolution (DE), Harmony Search (HS), Bees Optimization (BO), Fuzzy Logic (FL), Trajectory Sensitivity Analysis (TSA), Dual Programming (DP), Gravitational Search Algorithm (GSA), Curve Space Optimization (CSO), Decomposition Coordination Method (DCM), and ELECTRE are some examples of evolutionary strategies, evolutionary programming (EP), genetic algorithms, and simulated annealing (SA) (Hernandez et al., 2013). Analytical and metaheuristic approaches and metaheuristic and

traditional optimization techniques are examples of hybrid approaches. Reducing the search space of the suggested metaheuristic optimization strategy mostly depends on applying analytical techniques or traditional optimization approaches with metaheuristic optimization techniques.

Consequently, less calculation is required, and the structure is more straightforward (Ahmad and Sirjani, 2020). Modern metaheuristic-based algorithms (MMBAs) are the most widely used optimization approaches suitable for solving multi-objective problems because they may find several optimum solutions in a single run (Mir-saeidi et al., 2022). Metaheuristic algorithms are shown below.(Fig. 18)

The use of many Metaheuristic methods in the FACTS optimization issue will be covered in the following sections.

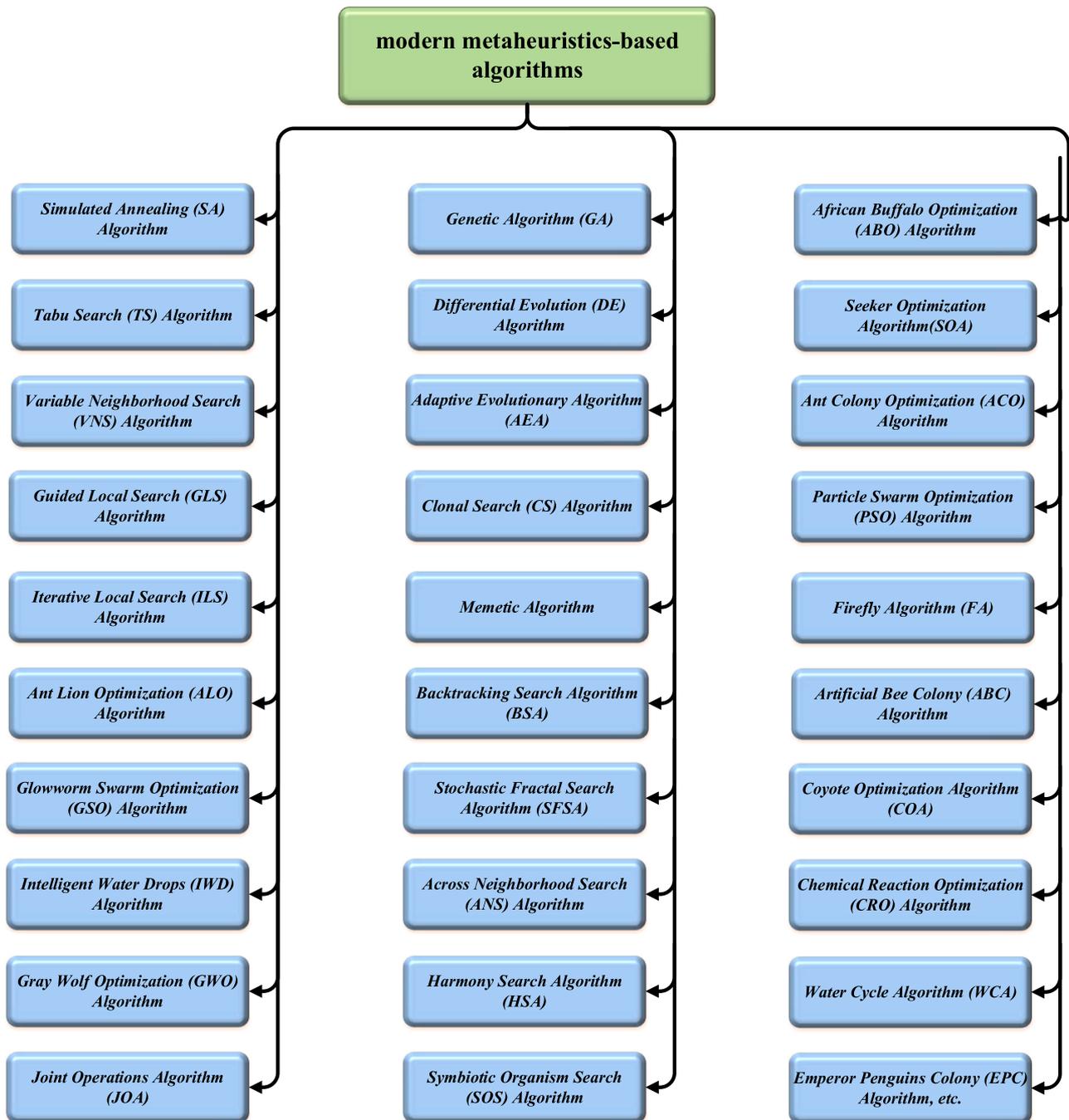


Fig. 18. shows modern algorithms based on metaheuristics.

6.1. Genetic Algorithm (GA)

GA uses multi-objective optimum power flow to arrange FACTS devices optimally (Rasmitha and Ratnamala, 2019). Genetic algorithms, or adaptive heuristic search algorithms, are population-based optimization methods predicated on natural selection and evolutionary genetic theories. They use the principles of mutation, selection, reproduction, and recombination to determine the optimal solutions to search problems. A generational shift in the population results from the algorithm's matching of fit individuals and the mutation of some of them (Shahakar and Shahakar, 2019). An optimization technique that is often used is the genetic algorithm. Its name comes from the way real-world creatures evolve biologically. In a specific setting, this algorithm seeks to mimic the mechanisms involved in natural selection (Keskes et al., 2017). GAs provide many advantages over conventional optimization techniques, including a more extensive solution space, better handling of multi-objective functions, more straightforward global optimum discovery, and more accessible adaptation for different problems. They work effectively in noisy functions, large search regions, and multi-modal situations. GAs have many uses, are robust against local optima, and perform well in large-scale optimization problems. Because they utilize probabilistic transition rules and objective function information, they are suitable for power system applications such as hydro-thermal scheduling, transmission expansion planning, capacitor placement, operational voltage/reactive power regulation, and so on (Haldurai et al., 2016).

6.2. Evolution strategies

Evolution strategies (ES), a robust optimization method introduced in the 1960s, are used in hydrodynamics. Rechenberg and Schwefel enhanced it in the 1970s, and it can handle complex, multimodal, and large-scale nonlinear scenarios (Jordehi and Joorabian, 2011). A distinct class of heuristics known as evolution strategies (ES) uses selection and mutation as search operators. The mutation rate is not directly controlled by the $(\mu+\lambda)$ and (μ, λ) techniques developed for ES. As it progresses through evolution, it alters. One of ES's most potent features is its capacity for self-adaptation to change the parameters of its strategies (Prakash and Khatod, 2016). Evolution strategies have already been implemented to address several power system issues, with encouraging results. These algorithms, for instance, provide up-and-coming optimization methods for handling complex parameter optimization problems (Miranda et al., 1998).

6.3. Evolutionary Programming (EP)

Evolutionary programming (EP) is a stochastic optimization technique focusing on the interaction between parents' behavior and their children's (Risi et al., 2022). David B. Fogel developed the artificial intelligence paradigm known as evolutionary programming (EP) in 1960. It uses computer simulations of fundamental evolutionary processes such as selection, initiation, mutation, and reproduction. When maximizing TCSC size, it performs better than artificial immune systems (AIS). Fogel's technique, which optimizes power systems' total transfer capability (TTC) by considering slack buses, actual power loads, and generation bus voltages, establishes the optimal position for FACTS devices. This includes locations, FACTS parameters, and power generators (Dixit et al., 2015).

6.4. Differential evolution (DE)

DE was first explained in a technical paper that Storn (1996) conceptualized. A year later, in May 1996, during the First International Contest on Evolutionary Optimization, which was a component of the IEEE International Conference on Evolutionary Computation (CEC) (Pant et al., 2020). Differential evolution (DE) is a crucial optimization

technique to find the optimal solution for complex problems. It uses the differences of randomly sampled objective vectors for mutation, providing efficient global optimization capabilities. DE is accurate, fast, robust, and simple to solve optimization problems requiring real-valued and multimodal objective functions. Its main advantage is its ability to search with floating point representation, making it a fast and robust alternative to the evolutionary algorithm EA (Mohamed, 2017). Differential evolution (DE) tests candidates repeatedly using a predefined standard (a mutant vector) to find the answer or solutions that best match the challenge. The difference vector directs the mutant vector toward the global optimum (Qiao and Liu, 2020).

6.5. Simulated Annealing (SA)

Statistical approximation (SA) is a flexible method that combines optimization with statistical mechanics to solve challenging optimization issues. The primary benefit of SA is that, unlike conventional optimization approaches, it is not limited by continuity, convexity, or differentiability, making it applicable to large-scale systems (Sirjani et al., 2012). A stochastic computer method called "simulated annealing" was developed using statistical mechanics to provide almost universal minimum-cost solutions to challenging optimization issues (Gall, 2020). Applications in power systems include planning for the development of generation and transmission (Kirkpatrick et al., 1983), unit commitment generator maintenance scheduling, and load forecasting. Unit commitment, economical dispatch, and automated generation control of two-area power systems are examples of applications in power systems (Mohamed, 2017).

6.6. Tabu Search (TS)

Fred Glover introduced the Tabu Search meta-heuristic optimization technique in 1986. Adaptive memory is an algorithm's primary means of generating the most versatile search behavior. It functions sequentially, with algorithms selecting a new point in the search space at the subsequent current point when the search begins at a specific location (Prakash and Khatod, 2016). Artificial intelligence is one of the domains that the TS algorithm investigates as part of its introductory search space study. Thus, using intelligence, the TS improves its adaptive memory and responsiveness to memory-related tasks, such as scheduling and workshop challenges. It approached the problem at hand directly and iteratively (Prajapati et al., 2020). To solve the problem of the best power flow, a linear state estimator model of a system was used to show how to get a fully observable power system and the right amount of redundancy using TS. Some power system applications include fault diagnostics, hydrothermal scheduling, unit commitment, distribution system planning and operation, and optimal capacitor placement (Shahakar and Shahakar, 2019).

6.7. Fuzzy Logic

1964, Zadeh created fuzzy logic to solve ambiguity and imprecision in engineering difficulties. It is a kind of classical set theory that was first introduced in 1979 to address issues with power systems. Using fuzzy set theory, element linkages may alter throughout time, resulting in a more precise and seamless comprehension of the surroundings. A mathematical mapping from the discourse world to a closed interval is called a fuzzy set (Singh et al., 2010). Fuzzy logic has two benefits over crisp constraints regarding FACTS optimization: it can more accurately characterize power system restrictions, and fuzzified constraints are softer (Jordehi and Jasni, 2011).

6.8. Bacterial Foraging Optimization Algorithm BFOA

In (Passino, 2002), Passino introduced the BFOA, significantly advancing the use of swarm-based algorithms. The fundamental idea of

the novel method is to use the group foraging strategy of a swarm of *E. coli* bacteria for multi-optimal function optimization. Bacteria seek out nutrients to accumulate the most energy in a given period. Furthermore, individual bacteria may communicate with one another by sending signals. When a bacterium chooses what to forage, it considers the abovementioned factors. The method by which a bacteria moves in search of nourishment is known as chemotaxis. To mimic the chemotactic movement of virtual bacteria in the problem search space is the fundamental principle underlying BFOA (Das et al., 2009).

6.9. Particle Swarm Optimization (PSO)

It is based on the social behavior of creatures related to fish and mammal schooling (Maskar et al., 2017). A population of people is used in particle swarm optimization (PSO), a population-based stochastic optimization method, to look for promising regions in a search space. PSO is based on natural phenomena in socially structured colonies, including flocks of birds or schools of fish. Based on its optimal experience and particle at that particular instant, each particle travels across the decision space and modifies its location (Khamees et al., 2016). By integrating SVC and TCSC at the optimal location, PSO has been utilized to optimize branch loads and voltage stability while minimizing losses on an IEEE 30 bus network. PSO demonstrated a more significant loading factor (182%) and a lower minimum number of FACTS devices in comparison to evolutionary programming (EP) (Gaur and Mathew, 2018).

6.10. Artificial Bee Colony (ABC)

simulates the astute foraging activity of a swarm of honeybees. ABC has a concept that is easy to understand, has fewer control settings, and is easier to execute (Khamees et al., 2016). Studies have shown that ABC works better than several other popular optimization strategies. Many ABC algorithms are developed based on honey bee feeding behaviors for various optimization problems. The original ABC is only applicable to continuous surfaces (Marcus, 2013).

6.11. Harmony Search (HSA) Algorithm

The HSA algorithm is an optimization technique created in response to musicians who want to obtain more harmony by varying the pitches of their instruments (Sirjani et al., 2012). The HS algorithm has been used to determine the optimal location for FACTS devices, such as UPFC, TCSC, and SVC, in a power system to improve power system security. For the deployment of multi-type FACTS devices, such as SVC, UPFC, and Thyristor Controlled Phase Angle Regulators (TCPARs), an alternative method using the HS algorithm was shown (Kazemi et al., 2009), (Parizad et al., 2009).

6.12. grey wolf optimizer (GWO) algorithm

The programmer imitates the leadership style and hunting strategy grey wolves use to follow their prey until it runs out of fuel. GWO is similar to other population-based metaheuristic algorithms in that it mimics the social behavior of grey wolves in their social lives while foraging for food by adhering to the group hierarchy. Alpha and beta are the two levels of the grey wolf social order. While beta assists alpha in decision-making, alpha stands for the group's leaders (El-Fergany and Hasaniien, 2015). Considered a successful metaheuristic, the GWO has been used to solve many optimization issues in various domains, including bioinformatics, machining learning, engineering, and medicine (Nadimi-Shahraki et al., 2021).

7. Optimal Placement Techniques: A Case Study Overview

Researchers proposed several optimization strategies for FACTS

devices' ideal placement and dimensions. This section offers a succinct assessment of critical contributions to the current methodologies. Each method's benefit and performance metric are detailed in Table 5 (Bhayani and Pandya, 2019). (Table 6)

Table 7 Summary of FACTS devices based on the recent studies and their methodologies and outcomes.

8. Power Electronic Based Facts Controllers

In power electronics, inverters play a pivotal role, particularly in the context of FACTS controllers, which are instrumental in enhancing the stability and efficiency of electrical power systems. Through their ability to convert DC to AC, these inverters enable precise control over power flow, voltage, and reactive power, thus fortifying the grid against disturbances and fluctuations. However, different types of inverters, namely Voltage Source Inverters (VSI), Current Source Inverters (CSI), Multilevel Inverters, and Pulse Width Modulated (PWM) Inverters, each come with their own set of challenges that can impact their performance and reliability in FACTS applications (Gayatri et al., 2018; Zhou et al., 2018; Tian and Li, 2018).

Voltage Source Inverters (VSI) are widely recognized for their flexibility and fast dynamic response, making them suitable for various applications, including FACTS controllers. Despite their advantages, VSIs face challenges such as harmonic generation, which can degrade power quality, and switching losses, which can reduce efficiency and increase thermal stress on components. Furthermore, the complexity of their control systems can be a significant barrier, requiring sophisticated algorithms to manage their operation effectively under varying load conditions (Irvani and Maratukulam, 1994).

On the other hand, current Source Inverters (CSI) are known for their robustness and simplicity in high-power applications. However, they struggle with reactive power management, necessitating additional compensatory mechanisms to balance the reactive power in the system. Their limited overload capability and the complexity of designing appropriate protection schemes also present considerable challenges, especially in environments with fluctuating load demands (Gandoman et al., 2018).

Multilevel Inverters represent an advanced class of inverters that can produce high-quality voltage waveforms with reduced harmonic distortion. While they offer improved performance and lower voltage stress across each semiconductor device, they are plagued by challenges such as component stresses due to uneven voltage sharing, control and modulation complexity, and the need for a large number of components, which can drive up costs and complicate maintenance and fault diagnosis.

Pulse Width Modulated (PWM) Inverters are renowned for their ability to control the amplitude and frequency of the output voltage, making them ideal for applications requiring precise control. Despite their versatility, they face issues like electromagnetic interference (EMI), which can affect nearby electronic equipment, and significant switching losses that necessitate efficient heat dissipation methods. Additionally, achieving real-time control to respond effectively to rapid changes in grid conditions can be challenging, requiring fast and accurate control systems.

Addressing these challenges is critical for ensuring inverters' reliable and efficient operation in FACTS applications. Solutions range from advanced filtering techniques to mitigate harmonic distortions in VSIs to integrating reactive power compensation devices in CSIs. For multilevel inverters, balanced voltage sharing and modular design principles can enhance performance and ease of maintenance. Meanwhile, PWM inverters can benefit from EMI filtering, advanced semiconductor materials to reduce losses, and sophisticated digital control systems to handle dynamic grid conditions.

In conclusion, while inverters are crucial for power systems' dynamic control and stability in FACTS applications, they come with inherent challenges that must be addressed. These challenges can be overcome

Table 6
shows some of the FACTS devices and utilized optimization algorithms in the literature.

Ref.	FACTS Device	Optimization Algorithm	Bus System	Finding
(Shaik and Reddy, 2016)	SVC	Artificial Bee Colony (ABC) Algorithm	IEEE 30-bus	Preserves voltage profile and minimizes power losses.
(Gabl et al., 2018)	TCSC, STATCOM, SVC	Genetic Algorithm (GA)	IEEE 30-bus	Identifies ideal sizes and locations; STATCOM outperforms SVC in various scenarios.
(Karami et al., 2009)	SVC, TCSC	None Specified	IEEE 14-bus	Emphasizes careful selection of FACTS for practical use.
(Rahman et al., 2014)	TCSC, TCPAR, SVC	Genetic Algorithm	IEEE 30 and 118 bus	Reduces transmission loss; influences optimal power flow.
(Nadeem et al., 2020)	TCSC, UPFC, SVC	Whale Optimization Algorithm (WOA)	IEEE 14 and 30 bus	WOA reduces transmission line losses, and system costs effectively.
(Sarda et al., 2012)	TCSC, UPFC, SVC	Genetic Algorithm (GA)	IEEE-30	It enhances readability and reduces transmission loss.
(Lin et al., 2012)	UPFC with Equivalent-Current-Injection model	Modified PSO with GA and EP algorithms	IEEE-30	Improves voltage stability; enhances computation efficiency.
(Shehata et al., 2021)	SVC	Autonomous Groups Particle Swarm Optimization (AGPSO)	IEEE 14 and 30 BUS	Reduces total active power losses significantly.
(Sulaiman and Mustafa, 2022)	SVC, TCSC	Various algorithms, including BMO, MPA, MFO, PSO, GSA, TLBO, HBO	IEEE 14-bus	HBO and TLBO perform best for optimal power flow (OPF).
(Coronado de Koster and Domínguez-Navarro, 2020)	FACTS and DG units	Tabu search algorithm	300-node network	DG improves the network at a lower cost; FACTS is also necessary but more expensive.
(Salkuti, 2019)	DG and D-STATCOM	Artificial Fish Swarm Optimization Algorithm (AFSOA)	33 and 69 bus systems	Reduces power losses; improves voltage profiles.
(Pati and Karajgi, 2020)	TCSC, UPFC, SVC	Particle Swarm Optimization (PSO) and Cuckoo Search Algorithm (CSA)	IEEE 14 bus	CSA outperforms PSO and reduces total generation cost.
(Khan et al., 2021)	SSSC	Salp Swarm Algorithm (SSSA)	IEEE 30-bus and 57-bus	MSSA is efficient and superior for ORPD; it improves system performance.
(Zhang et al., 2020)	STATCOM	Harmony Search (HS)	IEEE 30-bus	Enhances voltage profile and reduces power losses.
(Daealhaq and Tukkee, 2021)	TCSC, UPFC, SVC	Differential Evolution (DE)	IEEE 30 bus	Identifies optimal locations for devices; reduces power losses.
(Ahsan et al., 2014)	SVC	GA, PSO, and ACO algorithm	IEEE 14 and 57 bus	ACO performs best, especially for larger bus systems.
(Zhang and Milanovic, 2007)	SVC, STATCOM, DVR	Genetic Algorithm (GA)	295-bus	GA effectively reduces network sag number and loss costs.
(Gerbex et al., 2003)	TCSC, TCVR, TCPST, SVC, UPFC	SA, TS, GA	IEEE 118-bus	Increased security with more devices; TS and GA converge faster.
(Malakar et al., 2010)	TCSC and SVC	NSGA-II	IEEE-30 bus	Efficient solutions for nonlinear multi-objective optimization.
(Nusair and Alomoush, 2017)	STATCOM	TLBO	IEEE 14-bus and modified 30-bus	TLBO reduces active power loss effectively; superior convergence.
(Ismail et al., 2020b)	STATCOM	Various indices, including LSF, PI, VPI, PLI	IEEE 14 and 30 bus	Optimal positioning near the load center improves power loss and voltage profile.
(Singh et al., 2017)	TCSC and TCPS	Grey Wolf Algorithm (GWO)	IEEE 30 bus	Fast convergence outperforms others in OPF problems.
(Kumar et al., 2019a)	SVC, shunt capacitor, TCSC	GSA	IEEE-30 bus	Enhances load ability; GSA is effective for coordinating FACTS devices.
(Archana and Vidhyapriya, 2016)	STATCOM, UPFC	Modified ABC algorithm	IEEE 14 and UPSEB 75 bus	Improved load ability and reduced power losses with FACTS installation.
(Shah et al., 2016)	TCSC, SVC, UPFC	Real Coded GA	IEEE-30 bus	It enhances system load ability and minimizes losses.
(Aghaebrahimi et al., 2016)	TCSC, UPFS, SVC	HBMO	IEEE-30 bus	Improves cost, voltage profile, and system load ability.

through innovative design, advanced control strategies, and integration of complementary technologies, leading to more stable, efficient, and reliable power systems. Table 8 presents the summary of the challenge and solution of each inverter.

9. Role of FACTS Devices in Enhancing Voltage Stability in Renewable Energy Power Grids

9.1. wind energy integration

Wind energy, as the most significant variable renewable energy source, has prompted extensive research into its impact on the stability of electrical grids, especially when integrated in large amounts. A variety of wind energy conversion systems (WECS), including Permanent Magnet Synchronous Generator (PMSG) based WECS, Doubly-Fed Induction Generator (DFIG), and Squirrel-Cage Induction Generator (SCIG), have been the focus of many studies. The SCIG-WECS, in

particular, tends to draw reactive power from the grid rather than supply it, necessitating using a capacitor bank at its stator terminals for reactive power support. On the other hand, DFIG-WECS can supply and absorb reactive power, which aids in maintaining the voltage at the grid's connection points. Consequently, SCIG-WECS are more likely to negatively impact grid voltage stability than DFIG-WECS (Heetun et al., 2016).

In one notable study, researchers compared the voltage stability in power systems integrated with SCIG-WECS and DFIG-WECS. They utilized PV curves to demonstrate the maximum load capacity for each type of WECS. The study also examined two types of FACTS (Flexible AC Transmission Systems) devices, specifically SVC (Static Var Compensator) and STATCOM (Static Synchronous Compensator), for their effectiveness in reactive power compensation. This comparison was conducted using a modified version of the IEEE 14-bus test system. The findings indicated that STATCOM was more effective than SVC in providing voltage support. Furthermore, another study compared the

Table 7
Summary of FACTS and their methodologies and outcomes.

Ref.	Methodology	Outcomes
(Zand et al., 2023)	Sensitivity analysis was used to place UPFC in the power grid, examining the IEEE 14-bus network.	An ideal UPFC location was found, reducing 55% active and 11% reactive losses and optimizing network current flow.
(Roy et al., 2023)	Presentation of a hybrid shunt compensator (HSC) for EHV systems to prevent voltage instability.	HSC maintains bus voltage, provides reactive current, and prevents voltage drop at PCC.
(Osama abed el-Raouf et al., 2023)	Use of FOPID controller with Atomic Search Optimization (ASO) technique for UPFC in hybrid renewable energy systems (HRES).	Enhanced voltage and power stability in HRES, demonstrating the FOPID-ASO controller's effectiveness.
(Mishra and Chatterjee, 2022)	Small-signal analysis of the DFIG system's response to wind speed changes, comparing DFIG and SSSC.	Better power quality under low wind speeds with more considerable inductive series compensation.
(Wang et al., 2023)	Multistage moving target defense (MMTD) technique to optimize detection and balance security and economics.	MMTD accurately detects FDI attacks with minimal power loss, and future studies on its hiddenness are planned.
(Dandotia et al., 2023)	Locating a static variable regulator using voltage drop analysis and Genetic Algorithm in IEEE 14-bus system.	Identification of weakest buses for SVC installation, optimizing size to minimize costs.
(Zadehbagheri et al., 2023)	Technical and economic analysis for optimal placement and capacity of TCSC in transmission networks.	TCSC placement reduces power loss by 4.17% and increases the load capacity by 23.02%, validated with MATLAB simulations.
(Sahoo et al., 2023)	Optimal power dispatch model using moth flame optimization to reduce power curtailment and congestion.	Reduced congestion costs in 14- and 30-bus systems, improved transaction deviations and customer costs.
(Paredes et al., 2023)	Integration of FACTS controllers into microgrids for dynamic voltage stability, with design and modeling.	DSTATCOM is more effective than SVC in enhancing microgrid voltage stability and operational resilience.

reactive power control abilities of STATCOM and SVC in conjunction with DFIG-WECS during short circuit faults, with results favoring the performance of STATCOM over SVC.

In the research in (Heetun et al., 2016), static and dynamic voltage stability analyses were conducted on grid-connected wind farms that included FACTS (Flexible AC Transmission Systems) devices. The static analysis utilized methods like power flow, PV curve analysis, and QV modal analysis to assess the voltage stability of the IEEE 14-bus test system. Dynamic analysis was then performed to evaluate the performance of SVC (Static Var Compensator) and STATCOM (Static Synchronous Compensator) under normal and contingency conditions. The findings revealed that both SVC and STATCOM contribute to improved steady-state voltage stability and increased network loadability margins. However, STATCOM was more effective in enhancing dynamic voltage stability.

Additionally, in (Rashad et al., 2018), the study focused on the stability improvement of power systems integrated with different wind energy conversion systems: SCIG-WECS (Squirrel-Cage Induction Generator), DFIG-WECS (Doubly-Fed Induction Generator), and a combined wind farm incorporating both SCIG and DFIG WECS. In this scenario, the SCIG-WECS and DFIG-WECS were equipped with an SSSC (Static Synchronous Series Compensator) controller, while the combined wind farm operated without any FACTS device. The Voltage Stability Index (VSI) was used to assess the voltage stability in each case. The results indicated that while the SSSC controller enhanced the

Table 8
Challenges and Solutions for Different Types of Inverters in FACTS Controllers.

Inverter Type	Challenge	Solution
Voltage Source Inverters (VSI)	Harmonic Generation	Use of advanced filtering techniques and harmonic compensation strategies.
	Switching Losses	Implementation of efficient cooling systems and use of low-loss switching devices.
	Control Complexity	Development of robust and adaptive control algorithms that can handle dynamic conditions.
Current Source Inverters (CSI)	Reactive Power Management	Integration of reactive power compensation devices like capacitors or synchronous condensers.
	Limited Overload Capability	Design of inverters with higher overload capacity or implementation of overload protection schemes.
Multilevel Inverters	Complexity in Protection	Development of advanced protection schemes that can quickly identify and isolate faults.
	Component Stresses	Ensure balanced voltage sharing and use protection circuits to prevent component overstress.
Pulse Width Modulated (PWM) Inverters	Control and Modulation Schemes	Utilization of sophisticated modulation techniques and real-time control systems for optimal performance.
	Large Number of Components	Use of modular design principles to simplify maintenance and enhance fault tolerance.
	Electromagnetic Interference (EMI)	Implementing EMI filtering and shielding techniques to minimize interference.
Real-Time Control Challenges	Switching Losses and Heat Dissipation	Utilization of advanced semiconductor materials like SiC or GaN to reduce losses and improve thermal performance.
	Real-Time Control Challenges	Employing fast and efficient digital controllers to adapt to changing grid conditions effectively.

performance of the SCIG-WECS and DFIG-WECS setups, the combined wind farm without the SSSC controller exhibited the best overall performance. It is important to note that this study only considered the SSSC controller and did not explore the impact of other FACTS devices.

Further advancements in analytical tools and methodologies have been made to study voltage stability, such as continuation power flow and eigenvalue analysis. For instance, in (Chaib et al., 2017), these methods were applied to evaluate the voltage stability of Kerala's 220KV, 26-bus grid system, which includes wind power integration and the application of SVC.

These studies collectively demonstrate that STATCOM generally outperforms SVC in enhancing voltage stability in power systems integrated with wind energy conversion systems.

9.2. Solar photovoltaic (SPV) Integration

Numerous studies have examined the impact of Solar Photovoltaic (SPV) integration on the voltage stability of power systems, as referenced in publications (Adetokun and Muriithi, 2021; Komiyama and Fujii, 2019; Tbaileh et al., 2017; Kumar et al., 2019b; Varma et al., 2014); (Gayatri et al., 2018; Iqbal et al., 2019; Narain and Srivastava, 2015; Athamneh and Lee, 2006; Georgilakis and Hatzigiargyriou, 2019). In one such study (Tbaileh et al., 2017), researchers analyzed the influence of SPV integration on the dynamic voltage stability of a power system, using the Dominion Virginia Power system as a model. They explored various PV penetration scenarios and found that high SPV penetration can significantly affect the dynamic voltage stability of a power grid.

In a novel approach presented in (Varma et al., 2014), researchers introduced the concept of using an SPV inverter as a Static Synchronous Compensator (STATCOM), termed PV-STATCOM. This device enhances power transmission limits both during the day and at night. The study conducted transient stability analysis using a realistic single-machine infinite-bus power system model, where the PV-STATCOM was located at the midpoint of the system. The analysis, performed using EMTDC/PSCAD software, indicated that PV-STATCOM could substantially improve stable power transmission limits, irrespective of whether it was the day (with high active power generation) or night.

Further research in (Nivedha et al., 2016) focused on applying PV-STATCOM equipped with voltage and damping controllers to increase the power transfer capacity of transmission lines. This study also included harmonic analysis, finding that situating PV-STATCOM at the center of a transmission line effectively enhances system stability by reducing Total Harmonic Distortion (THD) during fault conditions.

Another significant study (Swandaru et al., 2016) explored optimizing additional reactive and active power control strategies in SPV plants. It used the particle swarm optimization (PSO) technique to tune the real and reactive power support, considering the rates of change in frequency, voltage, and voltage phase angle. This research concluded that while active and reactive power support from SPVs can adversely

affect grid stability post-fault, the PSO-based tuning of SPV parameters could counteract these negative impacts. FACTS devices effectively remedy power quality issues by integrating high-power renewable energy sources with conventional power grids. Their rapid compensation of active and reactive power positions them as a viable replacement for earlier methods. These devices contribute to maintaining voltage stability and managing power flow control. Moreover, they play a significant role in boosting transient stability and augmenting the damping of power oscillations, as demonstrated in Fig. 19.

Table 9 provides a detailed look at the functional characteristics of various FACTS devices and their strategic importance in modern power systems that rely heavily on renewable energy sources. These devices are pivotal in maintaining grid stability, quality, and efficiency as the world moves towards more sustainable energy solutions.

10. Future research directions for FACTS device applications in improving voltage stability in high-renewable energy power systems

The upcoming research avenues and areas that require additional exploration involve using FACTS devices to augment voltage stability in power systems with a growing emphasis on renewable energy sources.

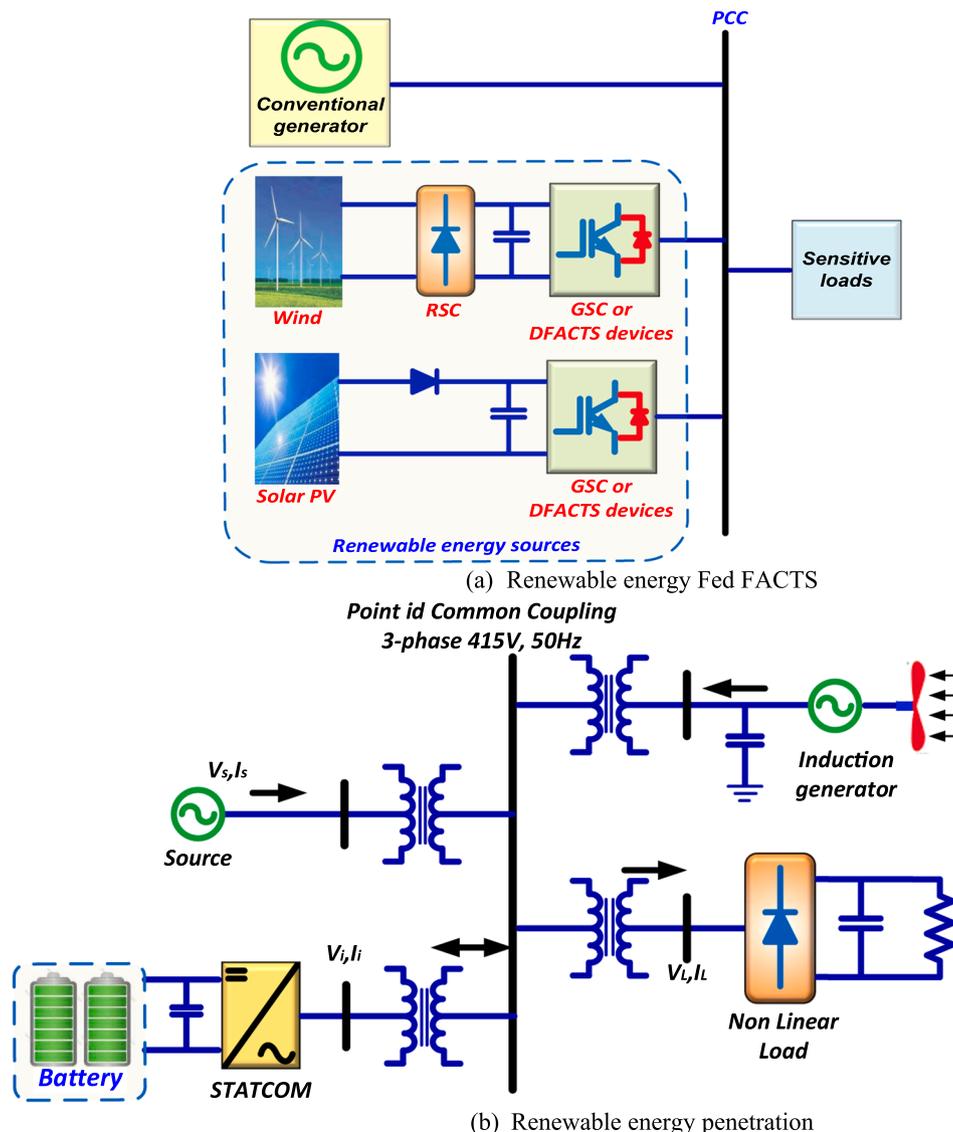


Fig. 19. Placement of FACTS Devices in Enhancing Renewable Energy Integration.

Table 9
FACTS Devices in Renewable Energy Grids: Functions and Applications.

Type of FACTS Device	Primary Function	Applications in Renewable Energy Grids (Expanded)
SSSC (Static Synchronous Series Compensator)	Injects compensating voltage in series with transmission line	<ul style="list-style-type: none"> Enhances voltage stability by regulating power flows. Supports high renewable penetration by balancing variable power outputs. Mitigates power quality issues such as voltage sags or swells caused by renewable intermittency.
TCSC (Thyristor Controlled Series Capacitor)	Provides controllable series capacitive reactance	<ul style="list-style-type: none"> Improves voltage stability through controlled reactance. Enables higher renewable penetration by smoothing power transfers from variable sources. Reduces transmission losses and harmonics, improving overall power quality.
IPFC (Interline Power Flow Controller)	Manages power flow between multiple interconnected transmission lines	<ul style="list-style-type: none"> Stabilizes voltage in interconnected lines, which is crucial for grids with multiple renewable sources. Enhances renewable penetration by efficiently managing power among different lines. Alleviates power quality issues like voltage flicker and harmonic distortion.
STATCOM (Static Synchronous Compensator)	Provides fast-acting reactive power compensation	<ul style="list-style-type: none"> Rapidly compensates for voltage variations, ensuring stability Vital for grids with intermittent renewables like wind and solar. It helps in mitigating issues like voltage instability and reactive power imbalances.
UPFC (Unified Power Flow Controller)	Simultaneously controls voltage, impedance, and phase angle in transmission lines.	<ul style="list-style-type: none"> Crucial for voltage regulation and transient stability. Facilitates integration of large-scale renewables by managing multi-directional power flows. Addresses power quality issues by compensating for fluctuations and disturbances.
DPFC (Distributed Power Flow Controller)	Distributes power flow control among multiple transmission lines	<ul style="list-style-type: none"> Maintains voltage levels across different lines, enhancing stability. Supports diverse renewable sources, optimizing power distribution. Improves power quality by reducing congestion and balancing loads.

This section identifies potential directions for future studies in this field.

10.1. Investigating robust and efficient ancillary services for enhanced renewable energy penetration

With the potential for a future where energy systems rely almost entirely on renewable sources, it is imperative to conduct comprehensive studies on the essential support services required, like voltage regulation, reactive power balancing, and improving power quality.

These analyses ensure that these future power grids are technologically sound and economically feasible. Additionally, there will be a significant need to create more advanced and resilient Flexible AC Transmission System (FACTS) devices. These devices are vital for the stability of such power grids. Moreover, it is essential to tackle the power quality challenges that come with the widespread use of devices based on power electronics in these highly renewable energy-dominated systems (Ade-tokun and Muriithi, 2021).

10.2. Expanding the scope: considering multiple renewable energy sources

There is a noticeable shortage of research focusing on enhancing the voltage stability of power systems through FACTS devices, especially in scenarios where multiple renewable energy (RE) sources are incorporated into the system. Current studies primarily concentrate on wind energy conversion systems (WECS) connected to the grid or solar PV systems integrated into the grid. Consequently, there is a need for more detailed and extensive analysis to understand the voltage stability of grids that integrate two or more types of renewable energy sources.

10.3. Balancing cost and performance: trade-off analysis

Research indicates varying degrees of effectiveness among different FACTS (Flexible AC Transmission System) devices in enhancing voltage stability. For example, STATCOMs offer better voltage support than SVCs (Static Var Compensators) but are more expensive than SVCs of the same capacity. This makes SVCs a more affordable option for developing economies. Therefore, balancing cost and performance is essential to determine the optimal and cost-effective FACTS device for specific grid applications.

11. Recommendations for future studies

Most recent studies have employed the metaheuristic optimization technique to ascertain the ideal location and capacity of FACT devices. Nevertheless, certain studies have not conducted a comparative analysis between the suggested approach and alternative metaheuristic optimization techniques concerning simulation outcomes, computational duration, convergence features, and accuracy of results (Ahmad and Sirjani, 2020).

Considering multiple objectives: Future studies could optimize multiple conflicting objectives simultaneously, such as minimizing power losses while maximizing voltage stability or system reliability.

The sentence highlights the need to identify new uses for various series technologies, such as DSSC and SSSC, so that people in charge of developing plans for the growth of electrical transmission grids will be more inclined to consider them. To achieve seamless integration with actual power system protection methods, new protection schemes and control techniques must also be developed for these technologies. The objective is to achieve flexibility and facilitate the decarbonization of power systems by optimizing their performance through broad area coordinated control approaches and maximizing their capabilities once implemented (Ordóñez et al., 2021).

The study in the review (Hailu et al., 2023) explores methods to improve static security in power systems, contrasting machine learning with traditional methods. It recommends using Flexible AC Transmission System devices and deep learning algorithms for reliable security assessment in complex power networks influenced by renewable energy sources and electric cars.

Renewable energy integration in power systems may pose future voltage regulation and stability challenges, necessitating further advancements in FACTS devices or other technologies.

Case studies with other benchmark systems: To further test the effectiveness of various optimization techniques, expand experimental investigations to include benchmark systems beyond the IEEE 14 busbar system and IEEE 57 busbar system (do Nascimento and Gouvêa Jr,

2017).

Studies on advanced modeling methods that faithfully represent harmonics, nonlinear behavior, and interactions between different parts in a transmission system while using static compensators (Mohamed and Abdel-Rahim, 2019).

The best placement of FACTS devices faces challenges such as determining targets, optimization criteria, managing system parameters, and developing computationally practical algorithms. Future research should explore integrating renewable energy sources into power systems and improving FACTS device performance. Focusing on sophisticated optimization strategies or hybrid algorithms using meta-heuristic methodologies could also enhance device placement studies (Kamarposhti et al., 2021).

The high initial cost of FACTS controllers is a challenge. Sophisticated algorithms must be used for searching. Most of the effort focuses on lowering the devices' production costs; consumer cost reduction is not considered. Advanced algorithms that lower generating and consumer costs are required (Gandotra and Pal, 2022). Extending the research to consider several real-world networks in diverse geographic areas enables a more thorough assessment of the suitability and efficacy of the suggested strategy (Karmakar et al., 2020).

12. Conclusion

This study examines the crucial role of FACTS devices in enhancing power quality and stability in power grids incorporating renewable energy sources. Analyzing devices like SVC, TCSC, UPFC, and DPFPC highlights their effectiveness in addressing voltage fluctuations, frequency instability, and power flow issues from integrating renewables like wind and solar. The research emphasizes the vital functions of FACTS devices in voltage regulation, frequency stabilization, and power flow management, which are essential for the seamless integration of renewable energies. It also discusses the need for future advancements in FACTS technology, including the adoption of advanced power electronics, innovative control strategies, and artificial intelligence, to further enhance their performance and efficiency in facing the growing complexities of power systems with renewable energy sources. **Conclusively, the paper points out:**

- FACTS devices are crucial for managing voltage, frequency, and power flow challenges inherent in integrating renewable energy sources, thus ensuring grid reliability.
- FACTS devices effectively address emerging challenges posed by renewable integration, critical to the seamless adoption of wind and solar energies.
- Future technological advancements in FACTS devices are anticipated to significantly elevate their performance and efficiency, meeting the evolving needs of modern power systems.
- The DPFPC, with its distributed approach, is particularly recommended for enhancing stability in complex, renewable-rich power grids due to its flexibility, comprehensive control capability, and contribution to system resilience and reliability.

CRediT authorship contribution statement

Mohamad Kamarol: Writing – review & editing, Visualization, Validation, Supervision, Investigation, Conceptualization. **Tomonobu Senjyu:** Visualization, Validation, Supervision, Investigation, Funding acquisition. **Mahmood Swadi:** Writing – original draft, Validation, Investigation, Data curation. **Mohamed Salem:** Writing – original draft, Supervision, Resources, Investigation, Conceptualization. **Ban H. Alajrash:** Writing – original draft, Visualization, Resources, Methodology, Conceptualization. **Saad Motahhir:** Writing – review & editing, Validation, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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