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Review article

A comprehensive review of flexible alternating current transmission system (FACTS): Topologies,applications, optimal placement, and innovative models

Mehdrad Tarafdar Hagh [a], Mohammad Ali Jabbary Borhany [a], Kamran Taghizad-Tavana [a,*], Morteza Zare Oskouei [b]

[a] *Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran*
[b] *Faculty of Electrical Engineering, Sahand University of Technology, Tabriz, Iran*

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ABSTRACT

This paper is a comprehensive reference for researchers interested in flexible AC alternating current transmission systems (FACTS) technologies. This study investigates modified UPFC models. Besides UPFC, an overview of DPFC will be presented, and the critical differences between these advanced power flow control technologies will be discussed. In particular, we will do a comparative evaluation of three well-known DPFC models: Distributed Series Reactor (DSR), Distributed Static Series Compensator (DSSC), and Distributed Unified Power Flow Controller (DUPFC). This work also discusses the latest models of FACTS technology, such as Carbon Nanotubes (CNT), Multi-winding transformers (MWT), and Line-to-Line Compensators (LLC). Finally, this review paper introduces advanced optimization techniques for optimal placement and design of FACTS devices.

1. Introduction

The extension of cities and the ever-increasing need of today's societies to use energy to fulfill all kinds of daily needs has turned the electrical industry into one of the world's most significant and essential industries [1]. A mismatch between line power flow and capacity is one of the main problems that must be resolved. In the absence of a power flow control device in the system, power flow operation is done according to the impedance of lines. Therefore, lines with low impedance can withstand more power, which leads to increased line losses and system instability [2]. When there is a mismatch in power flow and line capacity, and when demand exceeds supply, it is not always possible to apply traditional methods of turning off appliances. Effective power flow control can offer a number of advanced approaches to balance supply and demand without shutting down devices. Power flow control systems can re-route electricity through alternate paths to avoid overloading certain lines. This involves the use of power electronics such as Flexible AC Transmission Systems, which can dynamically control the power flow by changing line impedances. This technology was created after the problems that arose in the 1980s with the construction of transmission lines, which act as a suitable alternative to traditional methods [3]. Table .1, analyzes the problems that led to the emergence of FACT devices and their impact on solving these problems. FACTS devices, such as Static VAR Compensators (SVCs), Static Synchronous Series Compensators (SSSCs), and Unified Power Flow

* Corresponding author.
E-mail addresses: tarafdar@tabrizu.ac.ir (M. Tarafdar Hagh), jabaryali.com@gmail.com (M.A. Jabbary Borhany), kamrantavana66@gmail.com (K. Taghizad-Tavana), m.zare@sut.ac.ir (M. Zare Oskouei).

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Controllers (UPFCs), can control voltage, current, and phase angle across transmission lines to optimize flow paths and prevent overload. Power flow control systems integrated with predictive analytics can forecast demand peaks and plan for capacity management in advance. By predicting where and when demand will spike, utilities can adjust power flow to preemptively manage mismatches. Artificial intelligence and machine learning methods help optimize power flow by adjusting real-time parameters based on historical and current data, effectively anticipating demand and generation shortfalls. Demand response programs are another way to power flow control. Instead of turning off devices, they help reduce the pressure on the system by shifting demand from peak hours to off-peak hours [4,5]. In addition, when demand exceeds supply, instead of cutting loads or turning off devices, energy storage systems can increase grid flexibility by charging during off-peak hours (low demand) and discharging during peak hours (high demand) [6]. Each technique allows grid operators to address mismatches without simply shutting down devices, thus enhancing system resilience and reliability. Together, they provide a framework for more innovative and more flexible grid management that can accommodate variations in load demand without compromising the stability or efficiency of the power system.

Among the mentioned techniques, in this review article, we will analyze the FACTS devices more deeply in order to optimal control of power flow. From 2024 to 2032, the FACTS Devices market is expected to experience steady and positive growth, suggesting a promising future for the industry. Critical factors drive this growth, including rising consumer demand, technological advancements, and evolving consumer preferences. In developing countries, feasibility studies on FACTS technologies have gained substantial attention, driven by the need to improve power system stability, enhance transmission efficiency, and support the growing energy demands. Fig. 1, depicts the leading regions in the FACTS devices market [7]. The Asia-Pacific region dominates the FACTS devices market due to rapid industrialization, urbanization, and infrastructure development. Also, countries such as China, India, Japan, and South Korea are leading the adoption of FACTS technologies to enhance grid stability and integration of renewable energy resources and respond to the growing demand for energy. Moreover, the region's market dominance is driven by supportive government policies, investments in grid modernization projects, and the growth of smart grid infrastructure. Although North America and Europe hold substantial market shares, the Asia-Pacific region's rapid growth trajectory positions it as the main driver of the global FACTS devices market [7]. We have analyzed several examples of practical projects using FACTS devices to clarify the issue and the importance of this technology in developing countries.

- China: While China is now classified as an upper-middle-income country, many large-scale projects are in rural and developing regions [8]. The Three Gorges Dam transmission project employed FACTS devices, including Static Synchronous Compensator (STATCOM) and SVC, to stabilize the long-distance transmission lines and reduce power losses. These systems improved power flow, particularly in remote regions.
- India: Voltage fluctuations and reactive power management challenge ed the Indian transmission grid. Hence, the Power Grid Corporation of India deployed STATCOM at many substations in states like Uttar Pradesh, West Bengal, and Tamil Nadu [9,10]. This helped improve voltage stability, increase reactive power support, and reduce losses, especially during peak hours.
- Brazil: The great extent of Brazil's hydro-based power system spans over large distances, which introduces several challenges regarding power quality and stability. To support voltage stability and power quality, SVCs were installed in several areas of the Brazilian grid, including the southern and northeastern regions. This setup has been particularly valuable for areas with high industrial loads, improving reliability and reducing outages.
- Pakistan: Pakistan's transmission grid experiences frequent voltage instability due to a high load-shedding frequency [11]. To maintain voltage levels, reduce reactive power issues, and improve grid reliability, SVCs were installed in regions such as Punjab and Sindh. These installations have been beneficial in stabilizing the grid during peak load periods.
- South Africa: Eskom, the utility of South Africa, has integrated FACTS devices, including STATCOMs and SVCs, for mitigating voltage stability in areas of high wind and solar generation [12,13].
- Bangladesh: Bangladesh commissioned UPFC to help address load and power quality management issues in the emergent city of Dhaka [14]. The device enhances voltage control and improves the capability of power transmission, thus helping in maintaining stability in the grid needed by the fast-expanding urban demand.

Table 1
Problems related to transmission lines, how they are addressed by FACTS devices and remaining challenges.

Problem	Description	Solution offered by FACTS devices	Present status & Challenges
Overloading	High demand leading to line overloads and reduced efficiency	This technology improves power flow & reduces overloads via balancing loads	Managing increasing demand without new infrastructure remains challenging
Voltage instability	Sag voltage	This technology enhances voltage stability via adjusting power dynamically	Complexity in integration with renewable resources
Losses of transmission capacity	Inadequate capacity leading to inefficient transmission	This technology improves line utilization & capacity without new lines	Capacity limitation in dense urban area
Long transmission distance	Long transmission distance has led to increased losses	This technology reduces transmission losses & makes long-distance power transfer feasible	Ensuring reliability over ultra-long distances
Environmental constraints	Challenges in building new transmission lines due to environmental restrictions	This technology reduces the need to build new lines	Limited scalability is a major challenge for sensitive areas

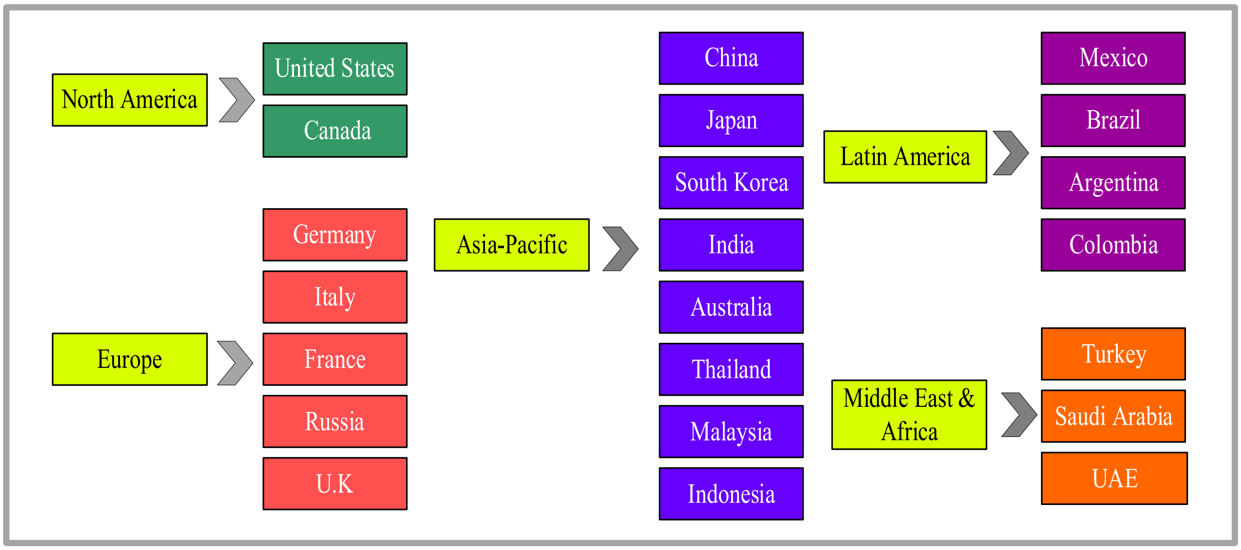

Fig. 1. Leading regions in FACTS devices market.

In addition, Fig. 2, shows the size of the global FACTS devices market. Global facts devices market size was USD 1350.5 million in 2020, and the market is projected to touch USD 2688.49 Million by 2032, exhibiting a compound annual growth rate (CAGR) of 5.9 % during the forecast period [15]. Table .2, provides a list of top FACTS device companies.

Unified Power Controller (UPFC) is a subset of FACTS controllers, which is more powerful compared to other FACTS controllers [16]. This type of controller has a complex structure, high initial capital expenditure and high operational and maintenance requirements [17,18]. Fig. 3, shows the applications of FACTS controllers in power grids. It is worth noting that DPFC has recently been created as a distributed control system utilizing small single-phase units. Also, unlike the UPFC type, this technology is economical and highly reliable because it does not require high voltage separation between phases [19].

Reference [20], examines various methods for finding the best spots to place FACTS controllers. It also discusses the main problems these controllers can help with, like keeping the power system stable, improving power quality, and reducing congestion. The reference also discusses different ways FACTS devices can be used. The optimal power flow in the presence of HVDC lines and the optimal placement of FACTS to improve the stability of the power system in different conditions are presented in Ref. [21]. In Ref. [22], the authors focused on the effect of UPFCs to improve the transfer capability of the transmission line. Reference [23], comprehensively reviews FACTS devices in modern power systems. In this research, dealing with power quality and sustainability with the influence of renewable energies has been one of the main goals of the authors. In Ref. [24], K. Sedraoui et al. have applied a new algorithm for compensating the harmonics created by electric arc furnaces according to UPFC. Reference [25], provides a comprehensive review of conventional optimization algorithms to enhance the performance of power systems by different controllers based on FACTS devices.

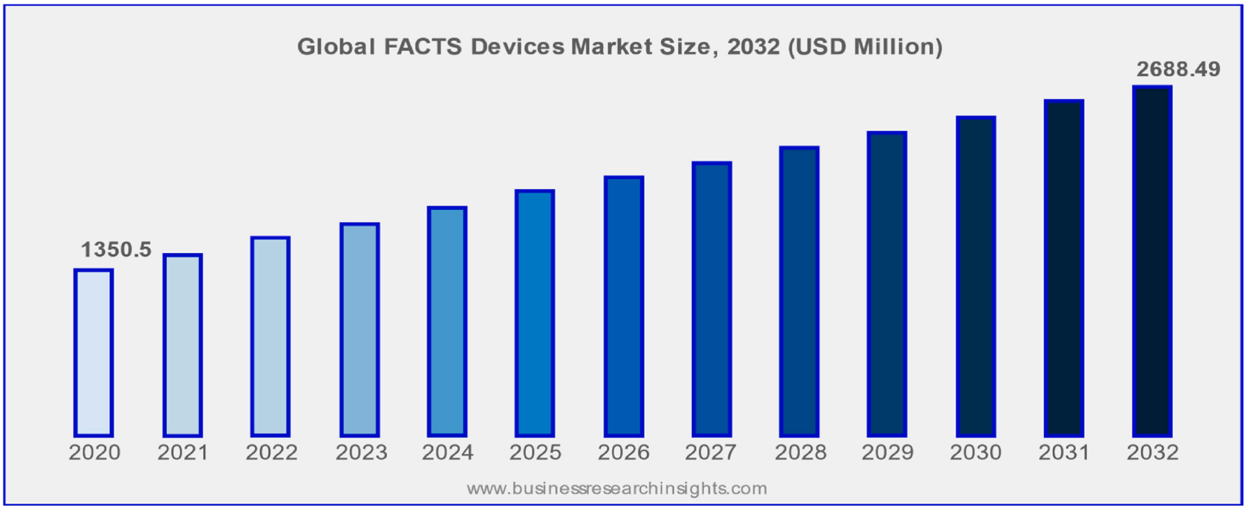

Fig. 2. Global FACTS devices market size.

Table 2
List of top FACTS device companies.

Company	Country
Hitachi ABB Power Grids	Switzerland
Siemens	Germany
Mitsubishi Electric	Japan
Liaoning Rongxin Xingye Power Technology Co,Ltd	China
FGI	Finland
Toshiba	Japan
Taikai Power Electronic Co.,Ltd	China
Sieyuan Electric Co., Ltd	China
Hyosung	South Korea
NR Electric Co., Ltd	China
AMSC	U. S
GE	U. S

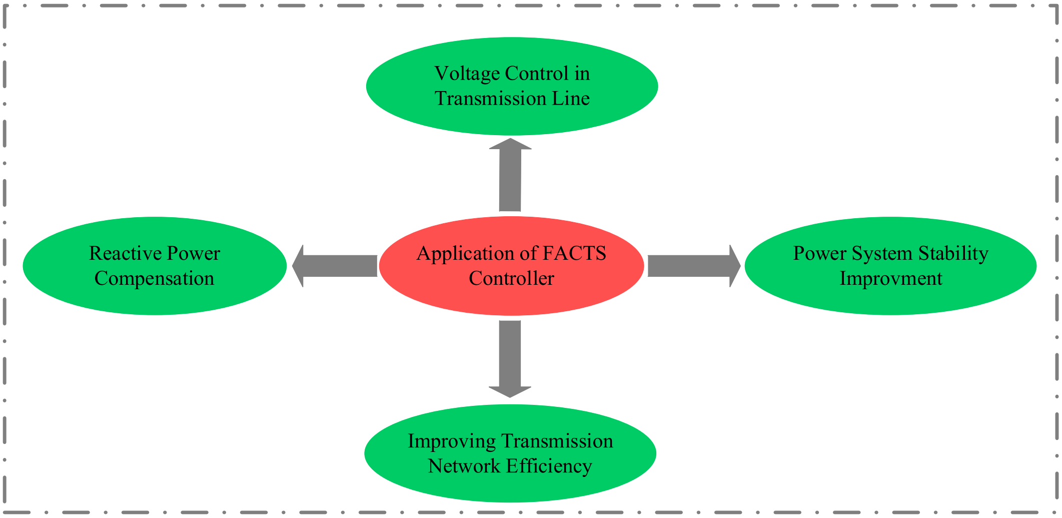

Fig. 3. FACTS controller's applications in power grids.

In Ref. [26], the authors do a detailed review of FACTS to enhance the stability and capability of power flow in the power system. The studies conducted in Ref. [27] show that using a STATCOM and a Series Capacitor (TCSC) can significantly improve the voltage profile. Furthermore, STATCOM is a critical FACTS component contributing considerably to reactive power management, voltage regulation, power factor correction, and enhanced power grid performance. Therefore, Youjie Ma et al. [28], extensively studied this equipment's background, application status, challenges, and development trends. The enhancement of voltage stability using FACTS devices under emergency conditions has been investigated in Ref. [29]. In Ref. [30], researchers investigate STATCOM control to raise the stability of the power grid by considering renewable energy sources. In Ref. [31], the authors focused on a hybrid power flow controller to improve power quality. Reference [32], presents the available literature on various techniques for optimizing FACTS devices. In addition, this study compares FACTS optimization methods and presents the advantages and disadvantages of each technique. Reference [33], examines FACTS devices for power quality in the smart grids in the presence of renewable energies. To increase dynamic stability, the authors of [34], proposed a hybrid algorithm that utilized the ideal placement and size of UPFCs. In Ref. [35], DFACTS is described as another technique for achieving economical energy flow regulation. In another study, the authors propose an optimal configuration method of DPFC intended to raise the loading of power systems [36]. Reference [37], compares the dynamic performance of FACTS devices such as STATCOM and SVC. In this research, using MILP, the optimization of system performance costs is considered. To locate the optimal UPFC to enhance the power grid's performance, the authors in Ref. [38], have used the grey wolf optimization algorithm. Reference [39],examines the effect of UPFC in reducing the intensity of overload in power grids. In addition to this discussion, transient stability in power systems is essential because power systems operate based on algorithms and automatic controls and should not be affected by unwanted changes. In order to increase the transient stability of power system, researchers suggested utilizing a static synchronous series compensator (SSSC) in Ref. [40]. Reference [41], studies effect of STATCOM on angle the stability and voltage of power systems. In Ref. [42], the main goal is to reduce transient energy as an indicator for power system damping. Therefore, the researchers used STATCOM and SSSC to achieve this goal, and the results confirm the ability of these FACTS-based devices to dampen power system fluctuations. In a different study, the authors integrate and arrange FACTS equipment optimally using a meta-heuristic algorithm to minimize losses and lower overall expenses [43]. In Ref. [44], the effect of combining super capacitors and FACTS devices is analyzed to regulate frequency deviations in restructured power systems. In Ref. [45], the authors conduct extensive studies on meta-heuristic optimization methods and evolutionary algorithms inspired by nature to optimize FACTS devices. Also, this research investigates the advantages and disadvantages of these methods. Comparison of intelligent algorithms with FACTS devices to minimize total power losses are presented in Ref. [46]. It should be mentioned, while losses in power systems are inevitable, but it is necessary to maintain a stable and reliable network. By understanding and effectively managing losses, system operators can ensure the efficient delivery of electricity to consumers [47,48]. Reference [49], proposes an adaptive D-FACTS to improve power quality in an isolated microgrid. Reference [50], presents a comprehensive techno-economic assessment for different FACTS devices used with wind farms. Another study extends the computational advantages and accuracy of the decoupled state estimation model, widely accepted and employed in operation centers around the world, for processing networks equipped with FACTS devices [51]. Another study simulates TCSC and SSSC to improve the power grid's stability and transmission capability [52]. A novel approach for optimal allocation of series FACTS devices for transmission line congestion management is presented in Ref. [53]. Also, the effect of shunt FACTS devices on voltage regulation in transmission lines has been investigated in Ref. [54]. Reactive power compensation during grid system convergence using FACTS devices is presented in Ref. [55]. Another valuable study examines strategies to enhance the integration of renewable energy sources in Nigeria using FACTS devices. It is worth mentioning that the optimal location for the FACTS device can be determined by using the reactive power sensitivity index through modal analysis [56]. Robust design and best control channel selection of FACTS-based wide-area damping controllers for improving modern power system stability using Grey Wolf Optimizer is presented in Ref. [57]. In another study, Mohammad Shahzad Nazir and colleagues examine FACTS technologies and their integration into renewable energy systems. The authors also aim to improve power quality by examining the current status of FACTS devices [58]. The authors' purpose in Ref. [59], is to investigate the role of advanced FACTS devices, specifically STATCOMs, in improving the stability and reliability of power systems with increasing penetration of non-programmable renewable energy sources. The study aims to benchmark the current state-of-the-art technologies, compare different options for system inertia improvement, and identify the most suitable solutions for various practical situations in the power system. Also, improvement of voltage stability in constant speed wind energy conversion system through STATCOM is presented in Ref. [60]. In addition, the authors in Ref. [61], have compared STATCOM, SVC, TCSC, and UPFC for voltage stability and reduction of power losses in the power system network. [62], aims to optimize a multi-area distribution grid with high levels of PV and electric vehicle charging stations by using D-FACTS devices (on-load tap changer transformers, step voltage regulators, shunt capacitors, and shunt reactors). The goal is to reduce power losses and voltage deviations and avoid overvoltage and voltage drop issues caused by PV power injection and electric vehicle charging. The research proposes a model based on distribution network load flow and optimizes it using a modified particle swarm optimization (PSO) algorithm. Reference [63], presents a comprehensive review of various conventional and adaptive algorithms that control D-FACTS devices to improve power quality in utility grids with penetration from renewable energy sources.

Despite the significant advancements in FACTS technology and its widespread application, comprehensive studies still need to be conducted to systematically evaluate various FACTS device topologies' long-term operational and economic performance under dynamic grid conditions. Such an analysis is crucial for optimizing the deployment and control strategies of FACTS devices to ensure the resilience and sustainability of modern power systems. This work reviewed numerous FACTS equipment modifications, including UPFC, STATCOM, and other cutting-edge models, and discussed each model's benefits, drawbacks, and engineering uses. The investigation presented in this paper will contribute to better comprehending the advancements in FACTS technologies and their potential applications in the power grid. As power systems evolve, utilizing FACTS devices will become increasingly vital in ensuring efficient and reliable power transmission and distribution. These devices offer effective voltage stability enhancement, reactive power control, power flow regulation, and oscillation-damping capability. This paper reviews the new and improved topologies studied in recent years due to the increasing need for this equipment. Therefore, this study of newly introduced technologies and power circuits can improve the gaps in this field and be used in future studies of researchers in this field.

In Section 2 of this work, the authors focus on modified UPFC models. In Section 3, studies have been conducted on DPFC devices. Also, Section 4 is dedicated to Modified power circuit topologies for STATCOM. In section 5, the authors focus on innovative models of FACTS controllers. In addition, Section 6 focuses on the optimal design of FACTS devices. Section 7 discusses the role of FACTS technology in reducing generation costs. Section 8 focuses on discussing the findings of this study and comparing them with other works. Finally, Section 9 is dedicated to conclusions, limitations and suggestions for future work.

2. Modified models of UPFC

2.1. A UPFC without transformer

A typical UPFC contains two inverters linked in series and parallel to the transmission line via a back-to-back DC link [64]. These inverters with high voltage and power must use these large transformers to attain the appropriate power and voltage level at the output [65]. The main disadvantages of these large transformers are.

- High losses
- Very high price
- Bulky (They account for 90 % of system's weight)

It should be mentioned that UPFCs based on zigzag transformers still need to be faster in dynamic response due to transformer saturation and magnetic flux. A fully transformer-less UPFC with a configuration based on cascading multilevel inverters (CMIs) is offered in Ref. [66] as a solution for this issue. The proposed device has new advantages over the previous conventional device, such as no transformer, high efficiency, very low Total Harmonic Distortion (THD) of output voltage (lower than 1 %), lightweight, low price, and fast dynamic response. Due to the fast dynamic response in this device, using quick and distributed power flow control, it is possible to reduce the congestion of transmission lines, and renewable energy sources can be integrated with power systems. Controlling lines' reactive and active power is an essential requirement in the power grid. If they are not controlled, the lines may be overloaded, affecting all the network lines, and the system capacity will be limited [67]. Also, with the advent of renewable energy

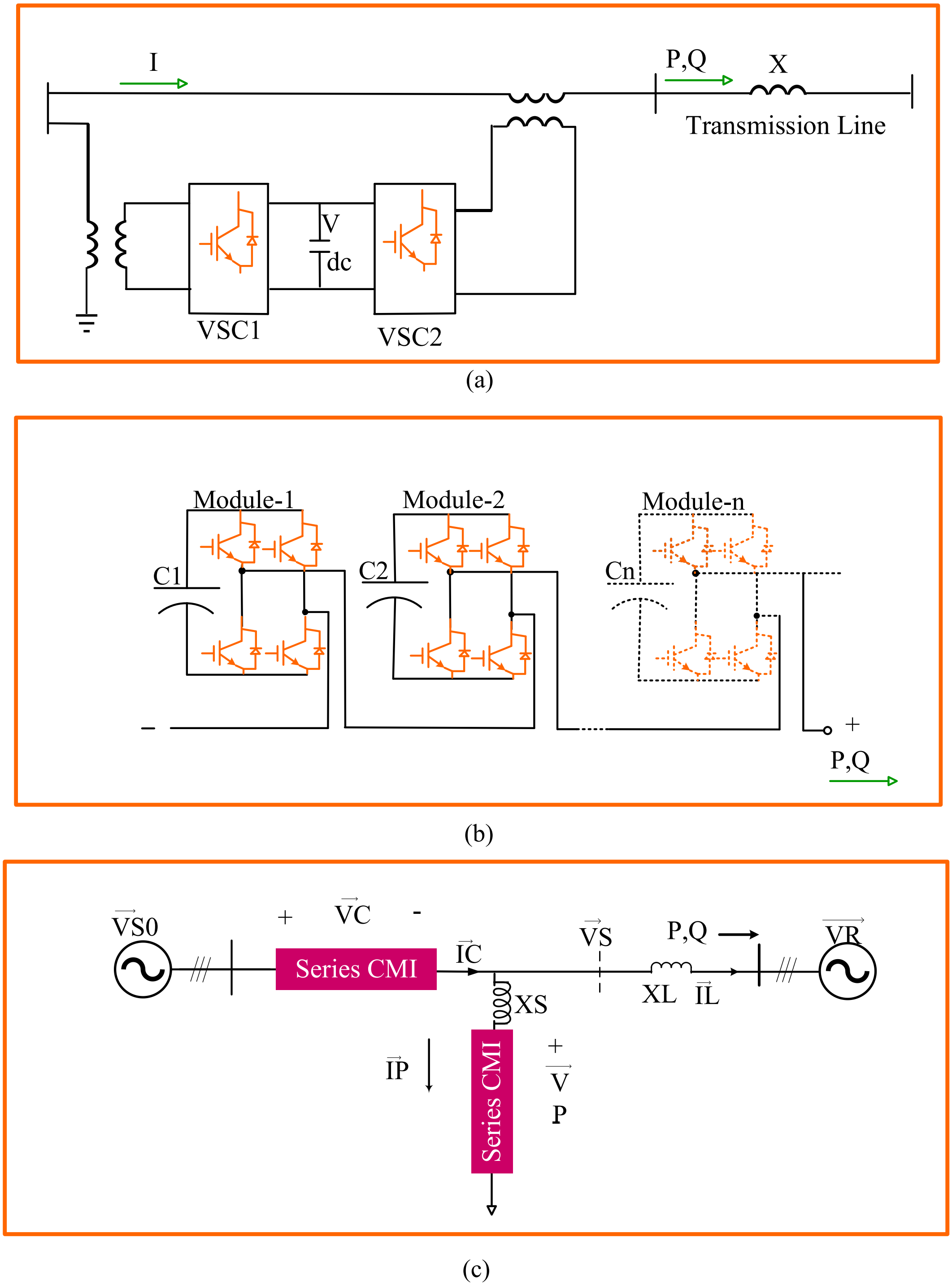

Fig. 4. **(a)** Conventional UPFC. **(b)** The CMI based on H-bridges. **(c)** UPFC system configuration without transformer.

resources, challenges such as voltage and frequency control and transient stability are raised, which must be investigated [68,69]. The CMI series portion and the CMI parallel part of the UPFC structure are separated in this article. Each CMI consists of several modules as follows.

- H-bridge
- Half-bridge

Fig. 4 (a) Conventional UPFC, (b) CMI based on H-bridges, and (c) showing transformer less UPFC system configuration. One benefit of this configuration is that each part is modular, offering great flexibility in adding or removing H-bridge modules to achieve any desired voltage level. A parallel CMI can inject a current into the transmission line perpendicular to line voltage, resulting in no active power interchange between any of the CMIs, making the CMI possible for use in the suggested transformer less UPFC. In general, the control target for UPFC without transformers encompasses various functions, such as the adjustment of active power through the series part, compensation of reactive power through the parallel part, and regulation of DC balance for both the series and parallel parts. The special characteristics of this device can be summarized as follows.

- Due to the elimination of the transformer, the proposed UPFC has smaller physical dimensions, resulting in lower weight, high efficiency, fast dynamic response, lower cost, and higher reliability.
- The new UPFC uses modular CMIs, and by using this advantage, more flexibility in system design and higher reliability can be achieved. The device can continue to work when any part is defective by bypassing it.
- In device configuration, shunt CMI must be connected after series CMI. Each CMI is equipped with a DC capacitor that can be utilized to support voltage applied to the DC link so that all capacitors are variable.

In summary, according to the experimental results, UPFCs that do not have transformers can independently control active and reactive power in the transmission line in light and heavy load conditions. Furthermore, the DC link's voltage can be adjusted within a ±5 % reference value. The only technology that can practically be used to attain elevated voltage levels without any reliance on

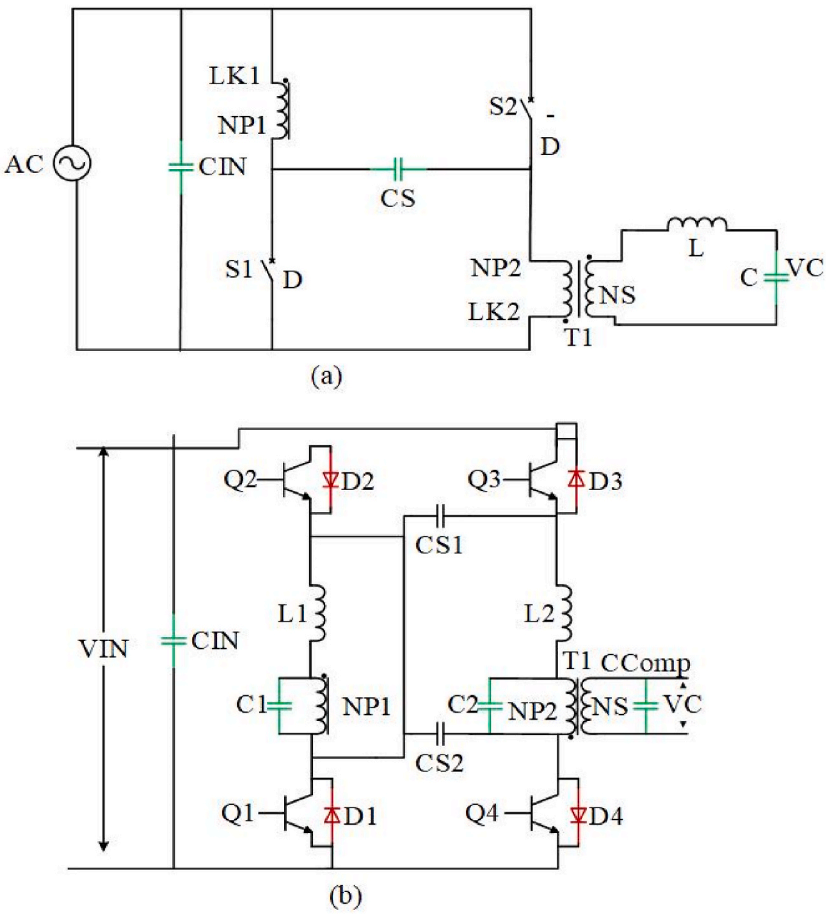

Fig. 5. Evolvement of PPCD circuit. **(a)** A simple push-pull ac-ac forward converter. **(b)** PPCD circuit's final design.

transformers is the cascaded multilevel inverter (CMI). However, because a conventional UPFC utilizes a pair of back-to-back inverters to facilitate active power exchange, the CMI inverter cannot be used directly in a traditional UPFC [70]. If we want to connect two grids with a significant phase difference, a large current will first pass through the transmission line, resulting in a damaged generator or equipment. Therefore, connecting two AC networks simultaneously with an additional device is possible. According to this issue, the research was conducted in this field [71]. If we want to connect two grids with a significant phase difference, a large current will first pass through the transmission line, resulting in a damaged generator or equipment. Therefore, connecting two AC networks simultaneously with an additional device is possible. According to this issue, research has been conducted in this field.

2.2. A UPFC without large electrolytic capacitors

The UPFC device in DC link to connect inverters back-to-back requires an electrolytic capacitor, which can have a short life [72]. Also, using this capacitor will cause system reliability problems due to energy storage. Instead of using significant energy storage elements, AC to AC converters can be used, but using this method requires many control switches, leading to an increase in cost and switching losses. Furthermore, the control strategy of these techniques is associated with difficulties that can affect system reliability [73]. Based on this, different types of this compensator model have been proposed [74]. To overcome these disadvantages, the DPFC device can be useful [75]. This converter may be used to adjust the power flow. Also, they are highly efficient and more economical [76]. The suggested PPCD circuit is adopted from a push-pull forward DC-DC converter. As seen in Fig. 5, part (a), the input and output voltages of the AC-AC push-pull converter are both AC, and the MOSFETs S1 and S2 have been replaced with two bidirectional switches. Transformer T1 is a three-winding transformer, with the number of turns of the secondary and primary windings indicated by NP1, NP2, and N2, respectively. Fig. 5, part (b) shows the completed PPCD circuit modified from the AC-AC forward push-pull structure circuit. As is evident, each bidirectional switch contains two IGBTs with reverse-parallel diodes. Therefore, the connected IGBTs Q2-Q3 and Q1-Q4 can be replaced by bridge-type IGBT modules that can be utilized in high-power applications with this configuration. Output LC filter is moved to both primary sides, NP1 and NP2, from the secondary side of the NS transformer in the final version. As a result, high-frequency harmonic components placed on NP1 and NP2 are removed. Therefore, the design of the transformer becomes easier. The pulse width modulation method is employed to produce switching signals for switches. The rationale behind generating the switching patterns is contingent upon the various polarities of input voltage. If input voltage, denoted as Vin, is positive during operation, Q1 and Q3 are subjected to high-frequency switching, while Q2 and Q4 remain in the on state. Conversely, When Vin is negative, the switching patterns are inverted. Lastly, MATLAB and Simulink have been used to simulate and validate the efficacy of the suggested device in terms of voltage compensation and the removal of excess harmonics. A prototype of the device has been made and tested. In addition to the adequate voltage compensation, the attenuation of high-frequency harmonics caused by the switching through the circuit's wire impedance accounts for the THD of the resultant voltage in experimental results, which is lower than in simulation. Its voltage control and compensation circuit are developed using SRF theory, which results in minimal power transmission losses.

2.3. UPFC has two shunt converters along with a large series capacitor

A typical UPFC combines a parallel converter and a series converter connected through a DC link [77–80]. The UPFC shunt converter adjusts the DC link voltage [81]. The series converter is responsible for adjusting reactive and active power flow in the line by injecting the controlled series voltage into the line, which can be controlled and changed in magnitude and phase angle [82]. Techniques like "zigzag transformer connections" and "multilevel converters" can solve this issue [83]. Zigzag arrangement has disadvantages such as high losses and occupying a large area. However, multilevel converters meet THD standards without incurring the costs of inter-level converters, which is a good contender for UPFC structure [84].

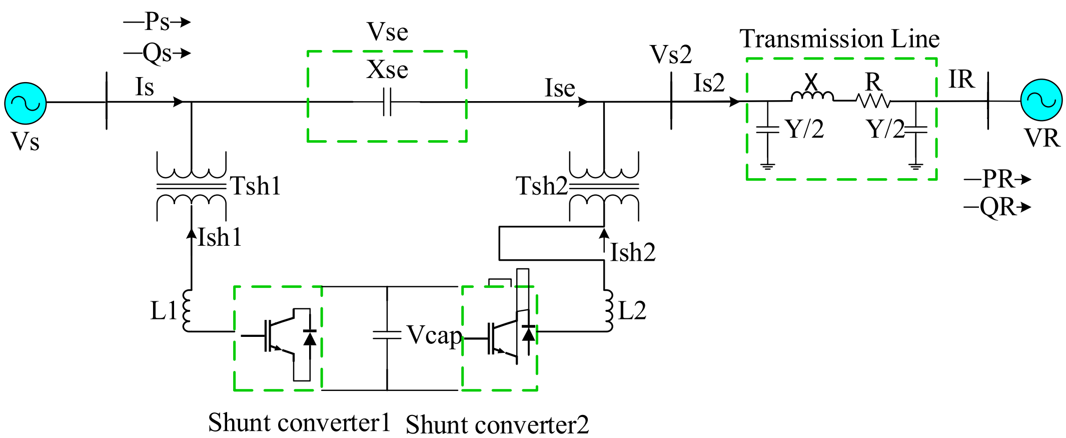

Fig. 6. Structure of the presented UPFC.

To solve the mentioned problems, a new configuration is proposed in Ref. [19]. In the new mode, as seen in Fig. 6, UPFC contains two three-phase two-level converters parallel to the transmission line, which are linked together via a DC connection and a series capacitor between these two shunts. The new mode can control active and reactive power like the conventional mode, but its main advantage is voltage injection with very low total harmonics. Converter number 1 provides or absorbs the necessary active power. Adjusts DC link capacitor voltage. It also exchanges reactive power for the sender side. Converter number 2, with the reference current, can control the current in the series capacitor and inject the required series voltage. Consequently, the current in the series capacitor is variable and is controlled by converter number 2. Thus, power flow in a series capacitor will be variable [19]. The control system, measurement instruments, isolation transformer, and shunt converter designs of shunt converter 1 and 2 are almost identical. Therefore, this device will require less design time and manufacturing expense than conventional UPFCs, which require two stages for series and parallel converters.

2.4. A UPFC with central node

Center-node UPFC (C-UPFC) comprises three voltage source inverters connected by a common DC link. It is worth mentioning that a converter is connected in series at both ends of the line. Also, two more converters are connected in parallel at the midpoint, where the line length is halved, and its power transmission capacity is doubled. The AC voltage value at the middle of the line and reactive and active power at either end can be independently controlled by C-UPFC. Through their DC link, the two series converters make the actual AC power rectified by one appear as reverse power [85]. In a two-machine system, it is impossible to simultaneously control both the reactive and active power of lines by conventional UPFC [86,87]. The suggested device can regulate the sending and receiving sides' reactive and active power intermediate point voltage, and DC link voltage values. The reactive and active power of sending and accepting sides can be controlled by adjusting the size and phase angle of the line current. Injecting VS and Vr series voltages allows the line current to be controlled. The midpoint bus voltage can be changed, and the shunt inverter can manage the DC link voltage. Similar to a STATCOM, a parallel converter operates [88]. DC link voltage varies and depends upon the series inverters' active power exchange with the system. The shunt inverter must provide the losses of three inverters and the active power of series inverters to regulate DC link voltage. The line current can be balanced, and its harmonics can be compensated for using the shunt converter. The general schematic of C-UPFC is displayed in Fig. 7.

3. DPFC devices

DPFCs are also from the family of FACTS controllers, but with the difference that they have higher reliability and are more economical compared to UPFCs [3,89]. It is worth noting that, unlike UPFC, in DPFCs, the three-phase series converter is split up into many single-phase series dispersed converters throughout the line, and the customary interface between series and shunt converters is eliminated. Fig. 8, shows the conversion process from UPFC to DPFC mode [90]. Also, Table .3, compares the specifications between UPFC and DPFC.

The D-Facts concept improves the control and efficiency of power transmission grids. This method uses many low-ranking controllers instead of one high-ranking controller, which allows for easier synchronization and maintenance.

If one high-ranking controller fails, the system will not be fully functional, while the system will still be useable if several low-ranking controllers fail. Every D-FACTS module is powered by its own line, and it may be remotely controlled using wireless technology or a power line. In Fig. 9, the basic schematic of a D-FACTS device is shown [91]. A shunt converter can return current to the power grid at the harmonic frequency while absorbing the power grid's active power at the central frequency.

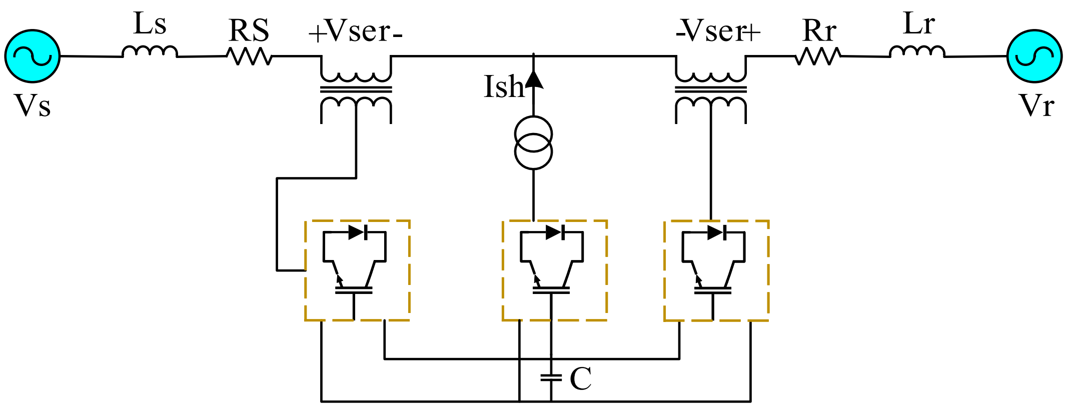

Fig. 7. General schematic of C-UPFC.

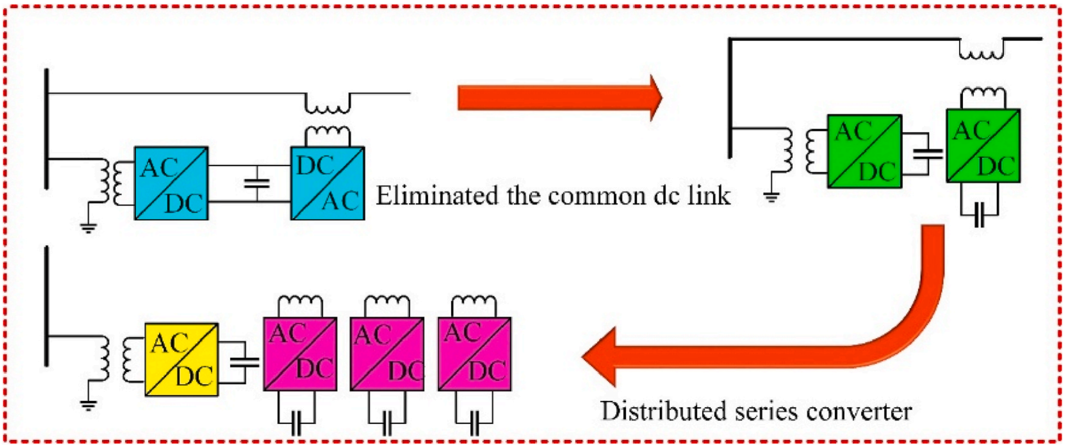

Fig. 8. Conversion from UPFC mode to DPFC mode.

Table 3
Comparison of specifications between UPFC and DPFC.

Specifications	UPFC	DPFC
Fault tolerance	50 %	65 %
Efficiency	Less (90 %–95 %)	High (95 %–98 %)
Transmission losses	20 %	25 %
Cost reducing in implementation	15 %	30 % (More cost-effective)
System stability improvement	75 %	70 %
Harmonic problem	Reduced	Effectively reduced
Dc link	Available	Not available
Reliability	Compared to the DPFC lower	Very high
Converter	✓ Two phases	✓ One single shunt
	✓ Three phases	✓ Multi independent series
Noise	High	Low

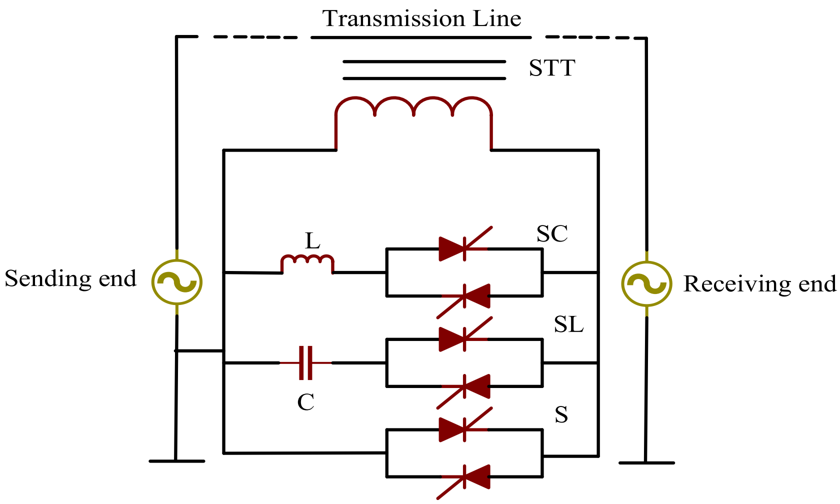

Fig. 9. Basic schematic of a D-FACTS device.

3.1. *Types of DPFC*

In this article, we review three essential categories of DPFCs as follows.

- DSR

- DSSC
- DUPFC

In Table .4, advantages, disadvantages and engineering applications of various types of DPFC devices have been introduced.

3.1.1. Analyses of DSR technology

Due to the ability to transmit enough power, this technology consists of several series units. This technology is generally available in two types: one that can be installed on masts and substations, and the other is lighter and can be installed on transmission lines. DSR technology, which includes a coupling transformer, power supply, composite switch, control unit, communication, etc., is depicted in Fig. 10. The coupling transformer's main component is a single rotating coil. Still, this transformer's secondary side features several revolving coils that may change the strong line current into a modest secondary side current. Also, an anti-parallel thyristor with a low capacity and a mechanical switch has been used to control whether the secondary circuit is on or off.

3.1.2. Analysis of DUPFC topology

In DUPFC topology, the third harmonic exchanges actuator power between parallel and series converters. Fig. 11, shows the DUPFC topology. The section related to parallel converters comprises two other converters connected by a standard capacitor. As shown in Fig. 11, the VSC1 converter is three-phase. It is related to AC power by a coupling transformer aiming to maintain capacitor voltage by absorbing active power. However, the VSC2 converter is unlike the single-phase converter. It is distributed along the line that passes through the neutral point. Finally, it absorbs the series portion of the widely distributed third harmonic current to stabilize the capacitor. Also, in the harmonic current, the third distributed topology in this topology causes additional losses, noise, and electromagnetic interference.

3.1.3. Analysis of DSSC topology

DSSC has been proposed for a cost-effective PF through the transmission line. According to Fig. 12, a DSSC is a low-power device that can be directly connected to the transmission line. DSSCs are suitable alternatives to FACTS controllers, which have advantages such as the need for less investment and better reliability. According to Fig. 12, single-phase transformers should be installed on the line with insulating clamps to support their weight. Also, the DC link capacitor of a single-phase inverter connects to another part of the single-phase transformer [92]. The injection voltage is 10–12V, which causes a slight change in line current.

There are two categories of wiring for isolated switches based on whether they are used to integrate DSSC.

- The DSSC device set has no interface and is linked to the line directly. In this case, maintenance is not considered.
- While power maintenance is being considered, the DSSC assembly is typically linked to the line through an isolation switch, as seen in Fig. 13.

The sine wave serves as the reference wave in one of the DSSC control schemes, and the switching mode of this converter is equal to the intersection of the triangle wave of the amplitude [93]. Finally, the reference sine wave is obtained. In addition, the excess power absorbed by the capacitor should be considered to get the voltage of the DC side of the regulation that can meet energy demand. Adjustment of the mentioned power and the modulation wave is required in real-time. In Fig. 14, the control diagram of the DSSC device is shown.

In the proposed arrangement, the amount of THD is lower than in the traditional models due to two-level shunt converters. It is also obtained from the simultaneous modulation adjustment, and the hook angle of the modulation wave pulse and the DC voltage balance control strategy is accepted according to Fig. 15. The control strategy in this module is based on adding a vector equivalent to the active power loss. If the amount of energy on the DC side is low, the active power will be absorbed significantly. On the other hand, if the amount of energy on the DC side is more than the limit, the added vector decreases the amount of active power absorption until it reaches the equilibrium point. Therefore, since this strategy simultaneously considers phase angle and amplitude, its response is fast and accurate.

Table 4
Introducing the specifications of DPFC devices.

Devise	Advantaged	Disadvantaged	Application in the electrical industry	Impact on transmission lines
DSR	Simple structure; Very low operating losses	There is no parallel compensator	Suitable for restraining the heavy load of the transmission line	Reduces transmission loss by managing line impedance, typically by a moderate percentage
DUPFC	It has robust performance, it will be able to quickly adjust flow of system, without needing extra space	It has larger operational losses compared to DSR	Increase transfer ability	A significant reduction in transmission losses provides increased controllability of voltage and reactive power
DSSC	It will be able to perform series and parallel compensation simultaneously and also balance the three-phase system structure	It has a complex structure	It can improve transmission capacity of system and also compensate asymmetry of system load and asymmetry of the line parameter	Moderate reduction in losses by injecting compensating voltage, enhancing power flow

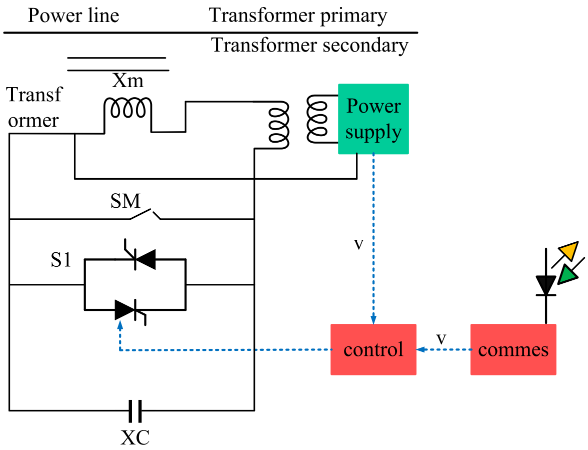

Fig. 10. Topology structure of DSR unit.

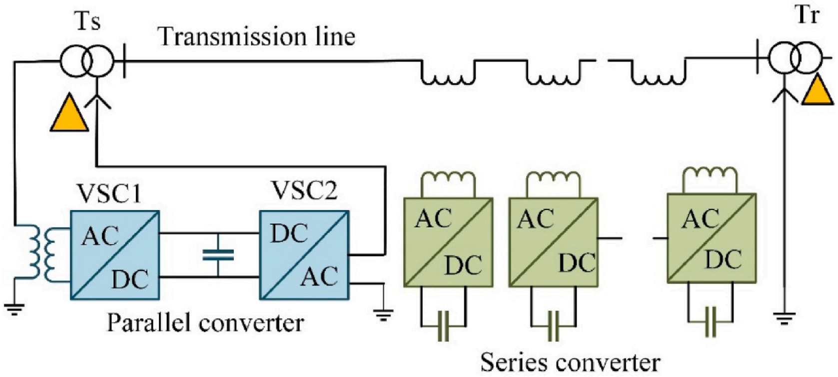

Fig. 11. DUPFC topology.

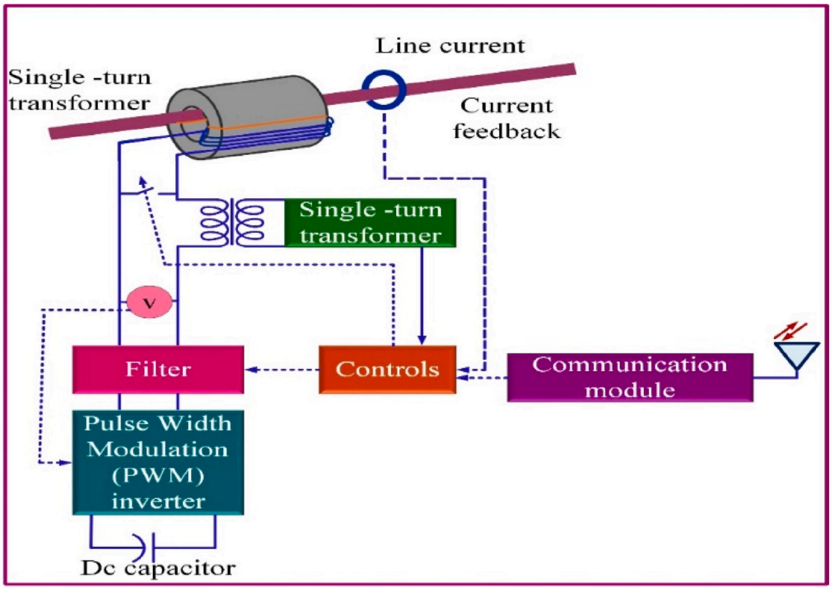

Fig. 12. Power circuit related to DCCS topology.

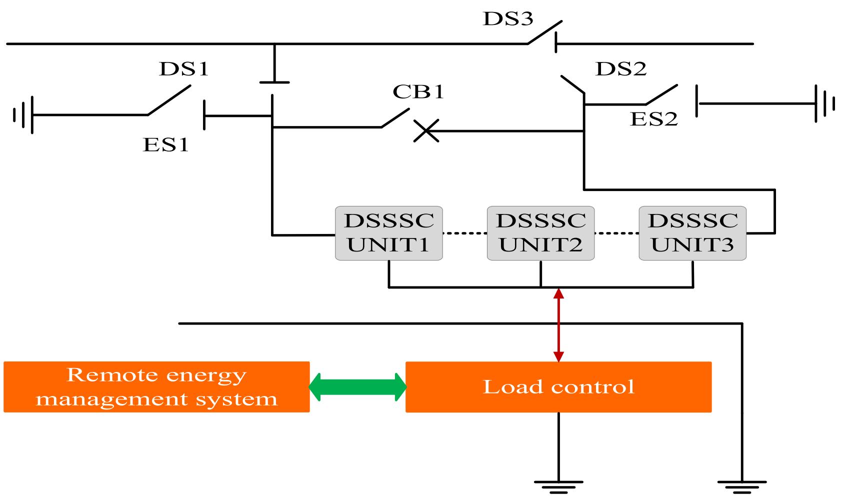

Fig. 13. DSSC device connection model.

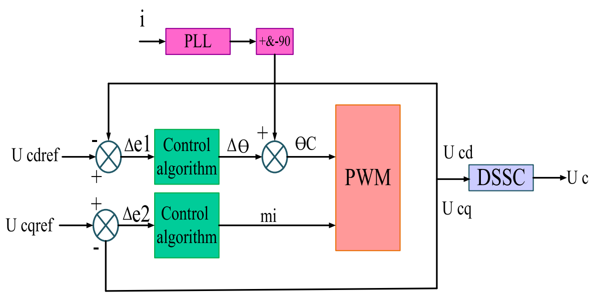

Fig. 14. DSSC control diagram.

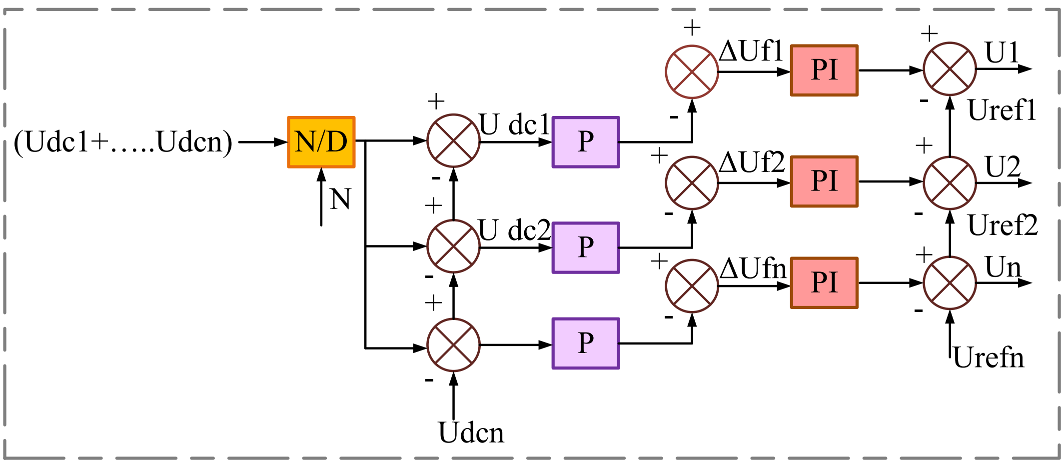

Fig. 15. H-bridge module control strategy.

4. Modified power circuit topologies for STATCOM

4.1. A LTC based STATCOM

- STATCOM acts as an independent voltage source that is able to adjust the voltage at the desired level [94,95].

STATCOM has some glaring flaws, including.

- In general, there is no method to determine the converter performance within the standard range;
- Switching losses are usually disregarded;
- The ohmic losses of the interface transformer, which is frequently a tap changer, are typically increased by internal ohmic losses of converter as well as magnetic effects of converter;

The optimal power flow solutions of the new STATCOM scheme introduced in Ref. [96] significantly reduce power system losses and converter internal power losses. In the optimal power flow proposed for this controller, the DC link is modeled as a PV-type bus with a constant DC voltage value and zero phase angle. The AC side voltage is adjusted by operating an OLTC transformer.

A series connection of an LTC transformer with a voltage source converter and a variable parallel impedance shows the new STATCOM model [97]. Fig. 16 (a) and (b) show the schematic of the VSC circuit and the VSC equivalent circuit, respectively. As seen in part (b), the voltage source converter is connected between the receiver side and the transmitter. The transmitter side is considered a DC bus, and the receiver side is viewed as an AC bus. To stabilize the voltage, a small capacitor bank is used on the DC side [98]. The DC side of a Newton-Raphson load distribution is a PV-type bus with a fixed voltage. Similarly, the highest and lowest values are set for the voltage value of VvR. Depending on the system, the dc circuit acts like a null in a steady state. Nullor is formed by combining the nullator and norator [99]. Nullators exhibit both short circuit and open circuit properties. It should be noted that converter, supplies voltage of capacitor but delays output voltage compared to AC system voltage. It should be stated that the dc capacitor itself is not used in absorbing or injecting reactive power [100]. Instead, this is done by PWM control in the voltage source converter. Physically, VSC is constructed as a two-level or multi-level inverter that uses self-commutated switches driven by PWM control.

It should be noted that PWM results in changing the shape of VSC waveforms [101].

VSC requires a phase angle to generate or absorb reactive power. VSC has no inertia and injects less harmonics [102]. It is also worth mentioning that its response is instantaneous and affects the impedance of the network very slightly.

Edc shows capacitor voltage on dc side, and Gsw offers resistance depending on switching losses. Therefore, as seen in Fig. 16, LTC transformer is the interface between ac and dc, and no reactive power passes through it. Only active power passes through it, which is dependent on the dc capacitor power because the generation and absorption of reactive power in VSC are done by the susceptance Beq connected to node 1.

m'_a is the size of the tap changer turn ratio of the LTC transformer, which corresponds to amplitude modulation factor of the VSC. Phase angle ϕ is phase angle of complex voltage V_1 with respect to system phase reference.

The series impedance linked to AC side of ideal transformer is X1 series reactance, which is the inductive property of the other elements of electric circuit seen in Fig. 16 part (b). Also, using R_1 series reactance, the ohmic loss is calculated, which is related to the square of the transmission line current.

4.2. Advanced STATCOM and SVC

Due to sensitive devices, voltage quality is one of the most important parts of power quality studies. Voltage disturbances mainly include voltage sag, swell, flicker, and harmonics. The term "Swell" is defined as the increase in the practical value of current or voltage, at the nominal frequency of the network, in about 110–180 percent of their rated value for some time of half a cycle up to 1 minute [103]. Voltage inflation can cause imbalanced current, which results in damages such as transformer failure, power switch failure, and disturbance in the operation of sensitive devices in power plants [104]. The following two FACTS controllers can significantly contribute to voltage quality as introduced [105].

A-SVC model includes a capacitor and TCR branch. The current TCR is an inductor connected in series with a thyristor and controlled by it. To use this model in a three-phase network, three single-phase TCRs are paralleled with a capacitor, which is connected as a delta connection. Under non-fault conditions, Harmonic currents with odd order, which have zero sequences, remain inside the delta connection and are not allowed to enter the network. Due to economic and technical constraints, the TCR voltage is limited to 50 kV or less, so this equipment cannot be used at high voltages. The primary function of this equipment is to absorb variable reactive

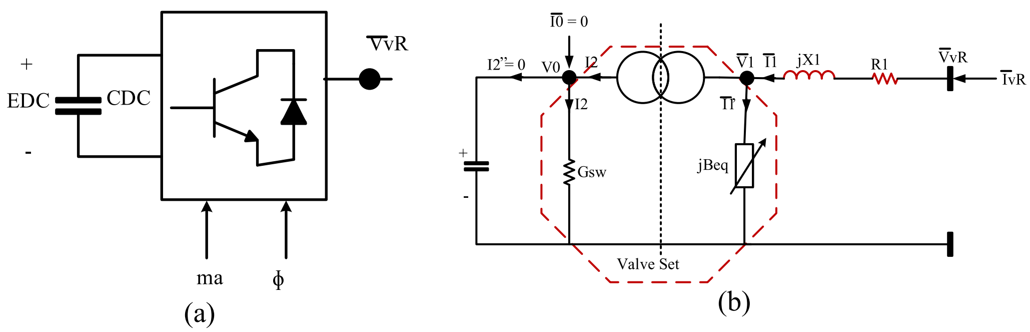

Fig. 16. (a) VSC circuit schematic. (b) Equivalent circuit of VSC.

power for any voltage increase. This equipment includes the following.

- Converter for voltage source
- A source of DC energy storage
- Coupling transformer

Since capacitor size plays a vital role in creating harmonic distortion, it aims to identify the most appropriate capacitor size for each voltage magnitude to minimize distortion in the waveform and keep excessive transients to a minimum. Fig. 17 (a) and (b) show the advanced SVC and STATCOM structures, respectively. DC voltage is converted into three-phase AC voltage through the voltage source converter and variable capacitor. Optimal control of botch reactive and active power distribution between equipment and network will be possible if the phase angle and output voltage of the STATCOM are controlled. In Table .5, STATCOM and SVC are compared.

5. Innovative models of FACTS controllers

5.1. Using CNT for dynamic control of transmission power

Due to the increase in energy demand and increasing penetration of renewable energy resources, FACTS can be used to control and increase transferable power [106]. Compared to conventional FACTS controllers, a new device called CNT is introduced in Ref. [107], which performs dynamic control of transmission power in transmission lines with a more straightforward solution and at a lower cost. A CNT attached to a transmission line is shown in Fig. 18. CNT has an AC converter consisting of two pairs of series switches, S1 and S2, between taps of the LTC transformer. In case of converter failure, using the "normal operation switch," the transformer can be returned to normal mode.

The CNT performs power control using Dual Virtual Quadruple Source (DVQS) method [72], in which both line voltage range and the phase angle can be changed. In this way, CNT can independently control reactive and active power in operating range.

The closed-loop controller produces a duty cycle for CNT switches by sampling the output current and voltage, calculating the reactive and active power of the line, and comparing those values to the corresponding reference values. The transmission line's dynamic power can be managed using this configuration. The controller evaluates the CNT device's operating range both without and with, taking line resistance into account. Since the reactance of the line is typically much higher than the line's resistance in a transmission system, the resistance of the transmission line is disregarded. However, line resistance is considered in the distribution system where the voltage is lower. The main feeder cable's resistance in the distribution system roughly equals the cable's reactance. This percentage is approximately 25 % for the lateral feeds [108]. A 720 V and 10 KVA prototype CNT have undergone some tests to verify the proposed controller.

The feasibility of using CNTs in dynamic transmission power control faces various challenges, which can be broadly analyzed regarding material limitations, manufacturing complexities, thermal management, integration issues, and economic constraints. Below we examine these challenges in more depth.

- **Material limitations:** CNTs have very good electrical and thermal conductivity [109], but variations in their chirality (It is worth mentioning that the arrangement of carbon atoms in the hexagonal lattice of CNTs, known as chirality, significantly impacts their electrical properties [110]. Metallic CNTs exhibit high conductivity, while semiconducting CNTs have lower conductivity), structure (Imperfections in the structure of CNTs, such as vacancies or dislocations, can disrupt the flow of electrons and reduce their overall conductivity), and length (The length of CNTs affects their electrical resistance. Longer CNTs generally offer lower

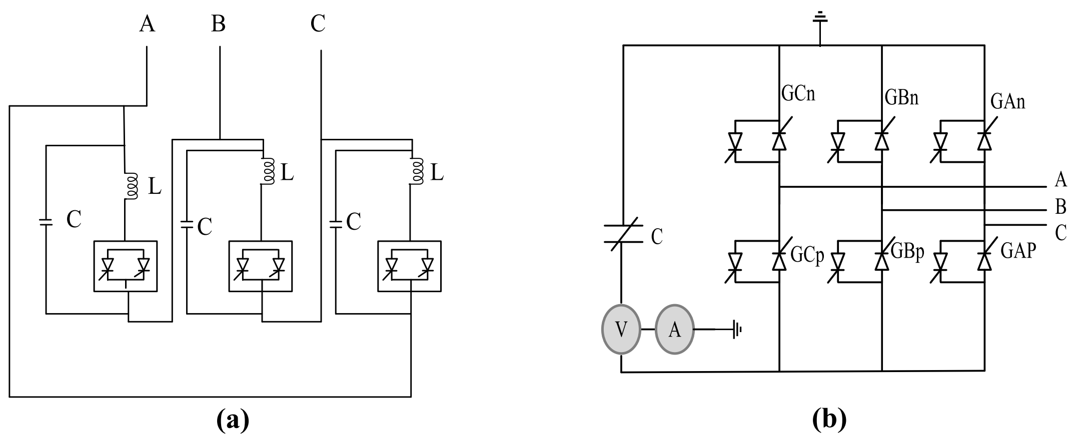

Fig. 17. (a) Structure of advanced SVC. **(b)** Structure of advanced STATCOM.

Table 5
Evaluation of STATCOM and SVC technical specifications.

Assessment	SVC	STATCOM
Main component	Thyristor	IGBT
Operation principle	Controlled shunt impedance	Voltage source control
Losses	Lover; around 1–2%	Higher; around 3–4%
Efficiency	97 %	98 %
Response time	1–2 ms	Faster than SVC for 30 ms
Reactive power range	Limited range, typically ±60–70 % of rated capacity	±100 % of rated capacity
Power factor correction	Capable, but less effective at low voltages	Can maintain near unity power factor
Control flexibility	Less flexibility	High flexibility with dynamic voltage control
Foot print	High	20–50 % SVC
Packaging model	Open	Continuer mode
The amount of space required	60*85m2	59*45
Harmonics	Very high	Good
Cost per Kvar	It varies between 40$ to 60 $	It varies between 55$ to 70$
Effect of voltage level on reactive power at connection point	Quadratic	Liner
Compensation accuracy	Good	Excellent
The amount of reactive power generation in three-phase short circuit mode	Little	Normal
Maintenance services	Very high	Little
Dynamic stability	Normal	Normal

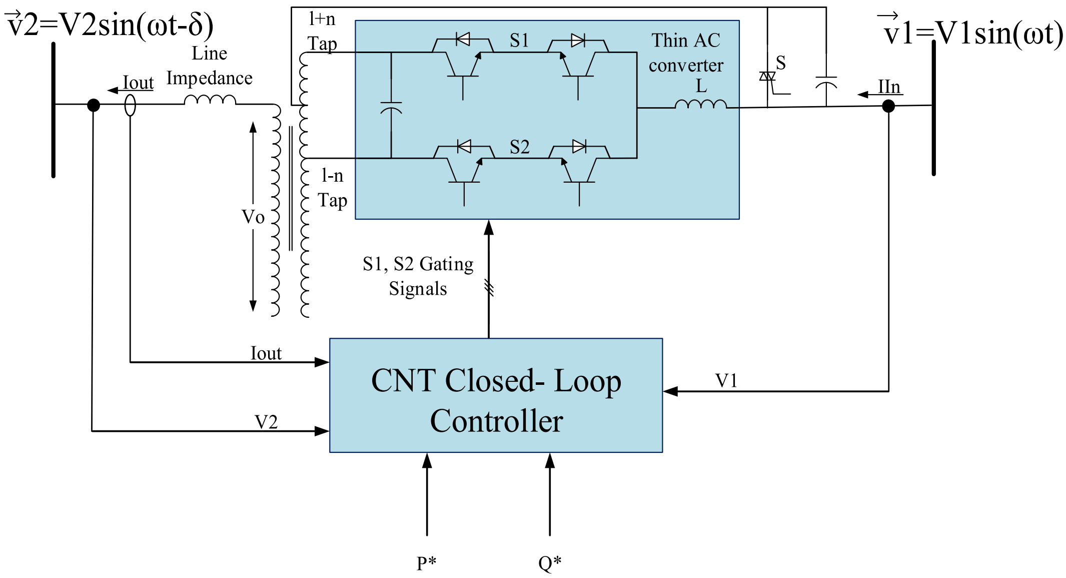

Fig. 18. Schematic of CNT with closed loop controller.

resistance, but controlling their growth to a precise length is challenging) can lead to inconsistent performance and affect the precision required for effective power transmission control.

- **Long-Term Stability and Reliability:** For dynamic transmission power control, the long-term stability of CNTs under varying loads and environmental conditions is crucial [111]. However, CNTs can experience degradation when exposed to factors such as oxidation, which may reduce their lifespan in practical applications.
- **Thermal Management:** Power control circuits often generate significant heat, which CNTs theoretically dissipate well due to their high thermal conductivity [112]. The reason for this is the strong covalent bonds between carbon atoms in their hexagonal lattice. Their thermal conductivity can be several orders of magnitude higher than traditional materials like copper or aluminum. However, CNT-based devices can suffer from local overheating and degradation under high currents and variable power loads, especially as scaling requirements make thermal dissipation even more challenging [113].
- **Manufacturing Complexities:** Large-scale production of CNTs is very challenging [114]. Maintaining high purity levels during CNT synthesis is crucial tomaintaining their exceptional electric al and mechanical properties. Impurities can significantly reduce performance [115]. Also, it is necessary to control the alignment of CNTs to optimize their properties [110]. Improper CNTs can lead to inconsistent performance and reduced efficiency in devices. Chemical vapor deposition is the most common method for

commercially producing CNTs. The critical difference between it and other methods is that CNTs are obtained by decomposing carbon-containing compounds. In contrast, in prior methods, CNTs were produced by the sublimation of graphite [116].

- **Economic constraints:** The high production costs of CNTs are a significant concern [117]. So, there are two ways:

✓ Reduce production costs

✓ Making the performance benefits more justifiable to justify the investor

- **Integration with Existing Systems:** Incorporating CNTs into existing semiconductor and power transmission systems requires compatibility with silicon-based technology [118]. CNTs' unique properties can lead to mismatch issues, affecting reliability and performance [109]. Developing reliable CNT-based interconnects and interfaces for dynamic power control applications remains an area requiring extensive research and development.

Overall, while CNTs offer promising attributes, these challenges collectively impact their feasibility for dynamic transmission power control applications. Addressing these challenges would require advancements in CNT manufacturing, material processing, and system integration to harness their full potential reliably and economically.

5.2. Hybrid power flow controller (HPFC)

The flexible UPFC can independently control a variety of system variables. However, a significant barrier to widespread use of this technology in power systems is FACTS controller's capital cost. As a result [119,120], introduces an affordable VSC-based FACTS controller. This item has been examined and put through testing. Based on a voltage source converter, this FACTS controller offers the

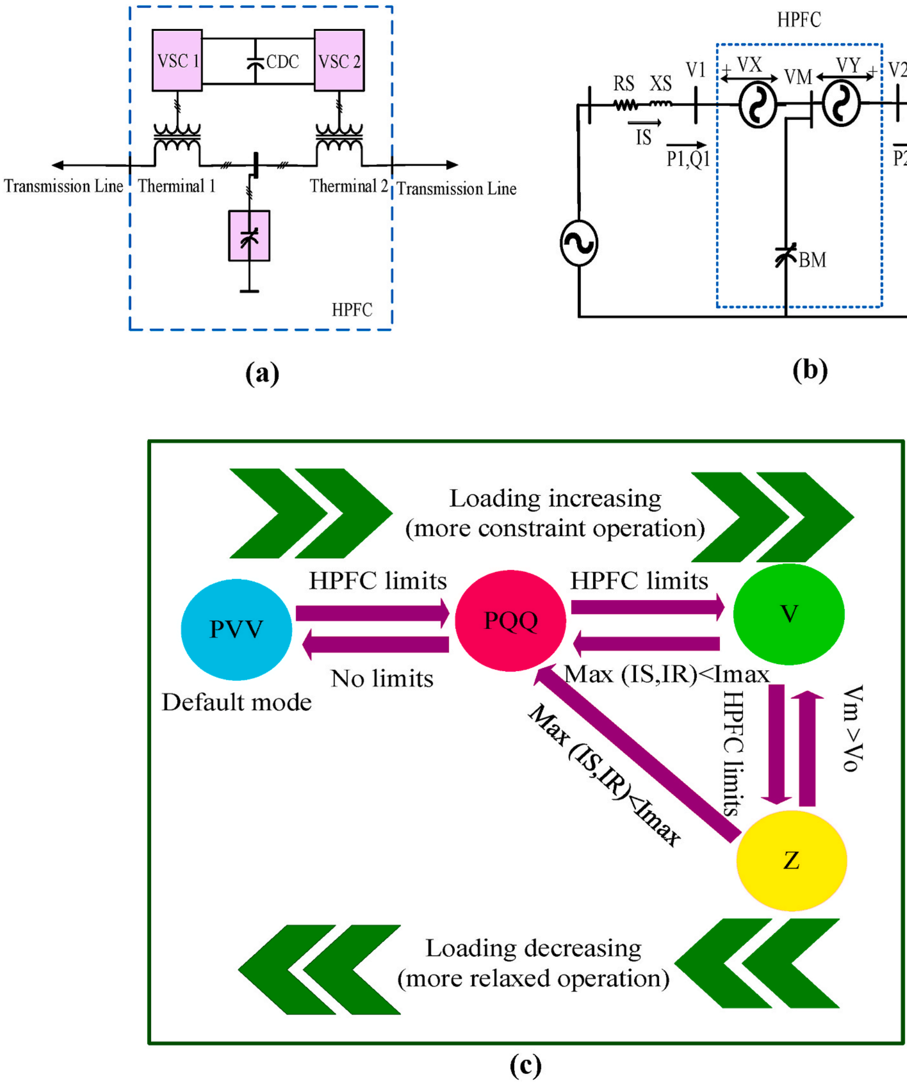

Fig. 19. (a) Schematic of HPFC. **(b)** HPFC equivalent circuit in a system. **(c)** Transition between the four control modes of the HPFC.

same operational properties as UPFC while costing less money. This device, consisting of converters and passive components (including capacitor banks), is known as a HPFC [121,122]. Fig. 19 (a), depicts a typical HPFC schematic. The shunt impedance in this configuration can be either a passive (switchable) capacitor bank or an SVC. Converters exchange active power via a shared DC link. The net exchange of active power with the system is zero if the device's internal active power losses are not considered. The converter's outputs and the parallel susceptance modify how power is distributed along the transmission line. An equivalent circuit for a single-line HPFC is depicted in Fig. 19 (b). The main parts of the controller are represented by a variable shunt with two voltage sources connected in series. The "Thevenin" equivalent circuit means the grid, and the voltage phasors V1 and V2 display the terminal voltage of controllers 1 and 2, which are connected to the power grid. The equal impedances of Thevenin include leakage reactances of controller series transformers. Also, Fig. 19 (c), shows four HPFC control modes. In PVV mode, the controller tries to maintain the IS, IR, Vx, and VY values within the allowed range defined for each by adjusting P, V1, and V2 parameters. If one of these variables reaches its limit and the parameter cannot be returned to the initial state with PVV mode, the controller switches to PQQ mode. In this case, the controller tries to maintain the main quantities in their allowed range by adjusting the P, Q1, and Q2 parameters. The controller continues to work in PQQ mode, and if it cannot correct the violation of the constraints in this control mode, it switches to V mode. The powers cannot be adjusted in V mode due to reaching the controller limits, and the controller becomes a shunt voltage regulator bypassing two series voltage sources. The voltage setting point is obtained in V mode by changing the variable shunt susceptance. There may come a point at which the shunt susceptance reaches its maximum value in terms of power transmission. As a result, the controller is viewed by the network at that point as a constant admittance, or what is referred to as the Z mode.

5.3. Unified power quality conditioner (UPQC)

A UPQC is a device that is similar in construction to a UPFC [123]. Fig. 20, describes the general configuration of UPQC, which is comprised of two essential parts [124,125].

- Power circuit;
- Control system;

The power circuit of this device consists of a common DC link, shunt, series converters, passive filters, and shunt and series transformers for connecting UPQC to the power grid. Below are some applications of shunt converters [126,127].

- Compensation for the negative effects of harmonics and other load flow disturbances;
- Active power absorption to maintain a constant DC link voltage;
- Reactive load current compensation;
- Correcting power factor;

Below are some applications of series converters [128].

- Flicker compensation;
- Compensation of voltage sags/swells;
- Creating resistance against resonant currents between load and grid;
- Improving the stability and damping of fluctuations in distribution systems;

In addition, two passive filters are placed at the output of the shunt and series converter to eliminate high-frequency fluctuations

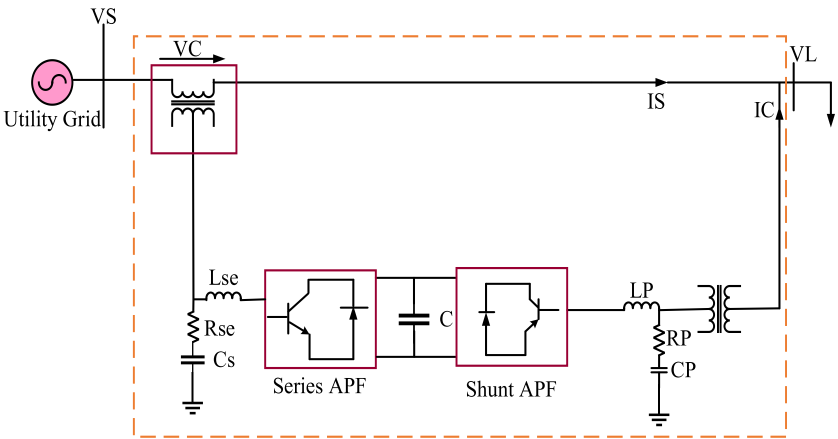

Fig. 20. UPQC schematic.

caused by the switching phenomenon. Two series and shunt transformers have been used at the output of the series and shunt converters to connect these two converters to the power grid and maintain the isolation between the power grid and UPQC, respectively.

The UPQC monitors the voltage and current waveforms at the point of common coupling (PCC) between the utility grid and the load. If any power quality disturbances are detected, the UPQC injects corrective signals to mitigate these issues. Fig. 21, presents the classification of UPQC devices [129].

The UPQC will be very effective in semiconductor-manufacturing industries, pharmaceuticals, and sensitive equipment that is highly susceptible to malfunction due to poor power quality. In addition, this device provides reliable power quality in areas where voltage fluctuations and harmonics are expected, which is essential for smart city infrastructure. It is also worth mentioning that the UPQC is suitable in systems with high penetration of wind turbines and solar cells, where fluctuations in the source can cause voltage sags/swells and affect the stability of the network. Future research and development efforts will be targeted toward cost reduction in UPQC systems, improvement of their control algorithms, and enhancement of their reliability. Further interest has been developed in developing modular UPQC systems which are easy to scale up or down depending on the application.

5.4. New device for adjusting the transmission line voltage, based on variable inductors

A new device to control injection voltage of compensator is presented in Ref. [71]. The proposed device includes a capacitor, a tap changer, variable inductors, and a series and parallel connection transformer. Similar to UPFC, it can adjust voltage at one point of transmission line [130]. UPFC must convert the AC voltage to direct DC voltage and then convert direct voltage to the desired AC voltage entering the line, which may reduce the conversion efficiency. This device converts the AC voltage directly to the desired AC voltage, which may be more efficient than the UPFC. Also, direct voltage adjustment, phase angle adjustment, and independent control of reactive and active power flow are other capabilities of this device. The configuration of this device is seen in Fig. 22 (Us) and (Vs) are the transmitter and receiver voltage phasors, respectively. IL is the line current phasor. Transmission line model is shown in the simplest possible form with only one (IL) inductor. Primary voltage of the transformer (T1) is equal to the bus voltage (US). (Vs) Parameter is considered as the compensation voltage, and this parameter is divided into and *Vcq* vectors, which are parallel and perpendicular to transmission line current (IL), respectively. Also, the parameter (Us) is the transmitter voltage and is divided into (Ucd) and (Ucq) vectors, which are parallel and perpendicular to the transmission line current (IL), respectively. In short, control is done so that if *Vcd* is in phase with (Uc), their result is more significant than zero, and the K key will be in position 1. If (Vcd) is not in phase with *Uc*, their result will be less than zero, and the KS key will be in position 2. If the result of these two vectors has a zero value, then the KS key is in position 3, and at this moment, the (K) key will also be closed, and only (Uc2) will remain in the circuit. Compensating voltage requires to be controlled at three different levels as well. To achieve the desired inductance, low-level inductance controllers adjust the inductance of variable inductors (LB) and (LC). Mid-level controls create the matching inductance required for supplying the compensating voltage. High-level controls are in charge of compensating voltage. As a result, the ability of the suggested device to continuously and independently modify both the phase and amplitude angle of the input voltage compensator it provides allows for the necessary voltage compensation.

5.5. Multi-winding transformer (MWT) based UPFC

In this section, the authors have focused on a modified version of the power flow controller to meet the specific requirements based on the multi-winding transformer (MWT) [131]. In electrical networks, sometimes the load is overloaded, which causes the current to increase in the circuit. This situation causes an increase in unexpected costs for repairs and other problems. Therefore, MWTs have

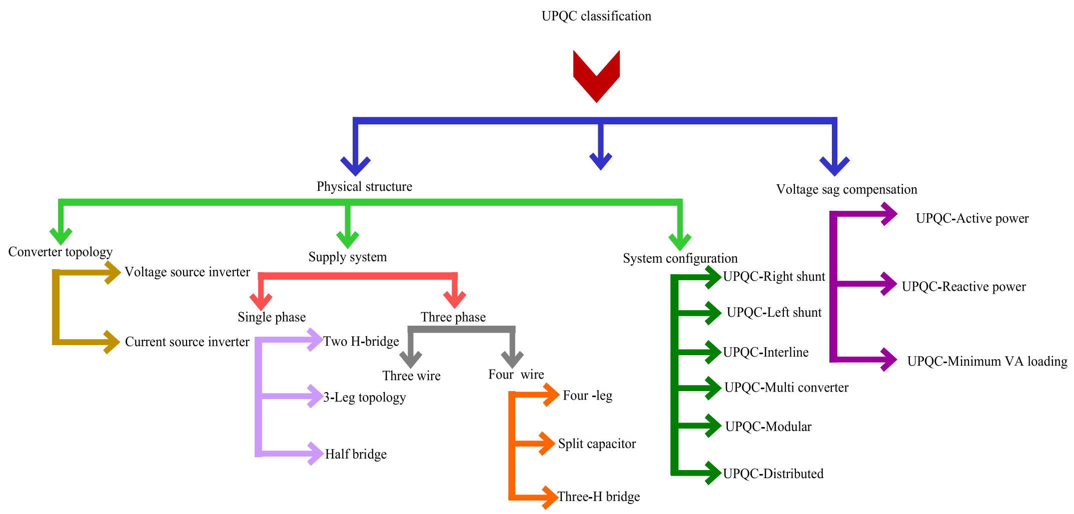

Fig. 21. UPQC classifications.

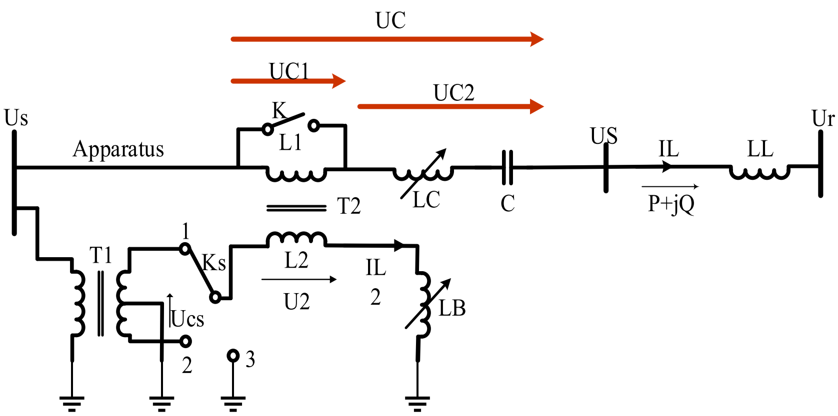

Fig. 22. System circuit schematic.

been introduced to reduce overload and increase power flow. MWT uses the ratio of variable voltage in the coils of the tap changer based on MWTs to power flow in the transmission lines. This new model dramatically increases compensating points using less copper and iron volume with higher flexibility. The switching logic for selecting the closest voltage vector is based on the asymmetric hexagonal decomposition algorithm to obtain the nearest compensation point in the hexagonal control region according to the power flow analysis.

Fig. 23, shows the location of each of the 9 switches on the transformer winding and the possible voltage vectors to control power flow. 19 voltage vectors are placed in a hexagon with sides equal to 10 V. This circuit is related to one of the phases of the system, and there is a similar circuit in the winding of other phases. If we increase the number of keys to 24, the number of voltage vectors available to control the power supply will reach 61. Although the number of switches increases, this does not increase losses during conduction because the switches have mechanical contact and little resistance during conduction and are in a steady state. Using a Sen Transformer, the line's reactive and active power flow can be independently controlled like a UPFC [132]. On the other hand, compared to the ST, the UPFC offers more precise compensation and a quicker dynamic response. On the other hand, UPFC has more excellent installation and operating costs, and switching losses cause higher losses in UPFC. Sen transformer technology has thus been extensively documented in the literature [133–135] for various applications, including load enhancement, available transmission capability (ATC) enhancement, and congestion management. With this developed MWT approach, the problem of less flexibility in the seen transformer (ST) and the higher cost of UPFC can be solved. By decreasing the copper and corresponding core volume, compensating points' resolution has been markedly improved compared to the power flow controller based on transformers.

5.6. Line-to-line compensator (LLC)

This topology falls under a new classification called LLC, which, unlike other controller models, does not have a series or parallel part. Fig. 24, shows this structure requires a three-phase transformer with a delta-delta, delta-star, or star-delta connection. A single-phase inverter is placed between each winding, and these inverters inject an increasing compensation voltage between each of the two phases of a three-phase transmission line. It is worth mentioning that LLC is a device based on a voltage source converter, which controls the line voltage's value by injecting and collecting a compensating voltage with the voltage between two phases. Therefore, the LLC voltage of the three-phase system must be available to provide this voltage through a delta connection [136,137]. LLC can be installed on a transformer with at least one delta winding installed on the primary or secondary side of the electrical system. However, if at least one triangle winding is not present on the primary or secondary side of the electrical system, a three-phase bank with at least one triangle side is placed in the LLC location. This structure can be extended to the level of distribution. Due to the delta winding and using the PWM converter, the third harmonics of the current are not injected [138]. If the LLC uses flexible energy sources such as fuel cells, it can exchange active power with the grid. FACTS controllers have a very flexible capability that can adjust active power in transmission lines, and LLC devices can also adjust active power in transmission lines [35].

6. Optimal design of FACTS devices

The optimal design of FACTS devices is crucial in enhancing modern power system performance, particularly in terms of stability, reliability, and efficiency [139]. FACTS devices can be expensive to install and maintain. Optimizing the design involves minimizing installation, operation, and maintenance costs while ensuring performance. The bacteria foraging algorithm is a bio-inspired optimization method that mimics the foraging behavior of *E. coli* bacteria. In the context of the optimal design of FACTS devices, the bacteria foraging optimization algorithm can be highly effective due to its ability to handle complex, non-linear, and multi-modal optimization problems common in power systems.

When using this algorithm for the optimal design of FACTS devices, the goal is to find the best settings (such as location, size, and parameters) for these devices to control power flow efficiently and improve the stability of the power system. It is worth noting that

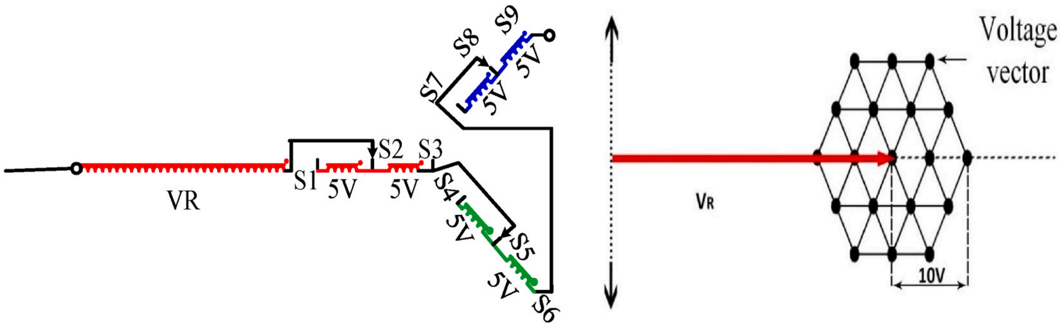

Fig. 23. One-way connection of tap changer transformer and 19 voltage vectors.

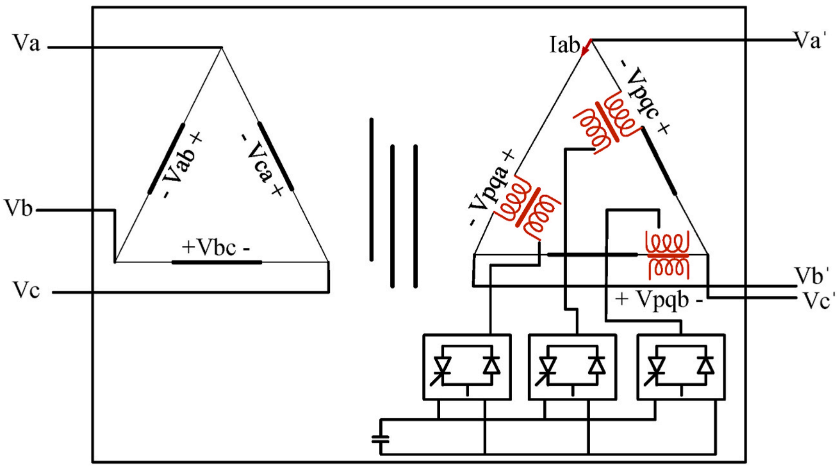

Fig. 24. Proposed power circuit topology for LLC.

this technique was first introduced in Ref. [140], to optimize the design of FACTS devices. The bacteria foraging optimization algorithm iterative search allows for finding an optimal solution to minimize system losses, enhance voltage stability, and manage reactive power flow. In addition, this technique can be combined with other methods, such as genetic algorithms or particle swarm optimization, to increase convergence and accuracy. A genetic algorithm is a widely used optimization technique for designing FACTS devices due to its robustness in dealing with nonlinear and multi-objective problems [141]. This algorithm optimizes the location and parameters of FACTS devices by simulating an evolutionary process that mimics natural selection. The genetic algorithm iteratively evolves solutions to enhance system performance through selection, crossover, and mutation, making it particularly suitable for complex power systems where multiple conflicting objectives and constraints are involved. Also, "differential evolution" is a population-based optimization technique suitable for FACTS devices' optimal design [142]. It is worth mentioning that in this technique, the optimization process starts with a population of randomly generated candidate solutions. Each "person" represents a possible configuration or setting for FACTS devices, including parameters such as device location, type, and control settings (for instance, consider voltage or impedance settings for devices such as STATCOM or SVC). Hence, the goal is to find the optimal configuration that improves system stability, increases power transfer capacity, and minimizes losses while meeting system constraints. In addition to the introduced techniques, particle swarm optimization can effectively help find the best solution for controlling power flow in electrical grids, resulting in the optimal design of FACTS devices.

Optimal placement of FACTS devices is critical to maximize their benefits; below are some of the primary objectives of optimal location [23].

- Enhancement of power system stability
- Maximizing social welfare
- Power losses reduction
- Minimizing Power generation cost
- Increase of system load ability

The strategic placement of FACTS devices is essential to increasing their advantages. Various techniques play a vital role in finding the strategic placement of FACTS devices. It can be effective in optimizing some special objectives, such as reducing losses and improving voltage stability. Meta-heuristic algorithms are a powerful and efficient approach to place FACTS devices. Traditionally, FACTS devices can be located using techniques, but their application is limited to simpler problems and may need to be more effective and practical in handling complex nonlinear constraints. Consequently, hybrid approaches benefit from the strengths of meta-heuristics and conventional techniques in overcoming their respective weaknesses. It should be noted that this problem can be solved by combining meta-heuristic global discovery capabilities with the local optimization efficiency of traditional methods. Fig. 25, summarizes the optimization techniques used for optimal placement [143].

7. The role of FACTS technology in reducing generation costs

Using FACTS devices to minimize the cost of power generation includes optimization of power flow, enhancing system stability, and maximizing use of the transmission network. FACTS technologies are systems based on power electronics, hence enhancing controllability and increasing power transfer capability [144]. Below, we have discussed in more detail how utilizing FACTS devices minimizes generation costs.

- **Enhanced power flow control**

FACTS devices such as SVC, Thyristor-Controlled Series Capacitors, and UPFC enable dynamic control over the power flow in transmission lines [145]. The flexibility will shift the power through less congested lines and reduce the requirement of high-cost, fast start generation units to meet the demand in crowded areas. By controlling voltage, phase angle, and impedance in various network sections, FACTS devices can prevent overloads in certain lines and distribute the load more evenly. This redistribution enables the system to work in a more economical way, where lower-cost locally controllable generators can supply power without network limitations.

- **Renewable energy integration**

FACTS devices support the grid integration of renewable energy resources by stabilizing voltage and managing reactive power [146]. By facilitating the integration of renewable energy resources, which often have lower marginal generation costs, FACTS devices help reduce dependency on conventional, higher-cost generation. For instance, STATCOMs or SVCs can provide reactive power compensation near wind power plants, ensuring stable voltage levels and allowing more renewable energy to flow into the grid.

- **Reducing transmission losses**

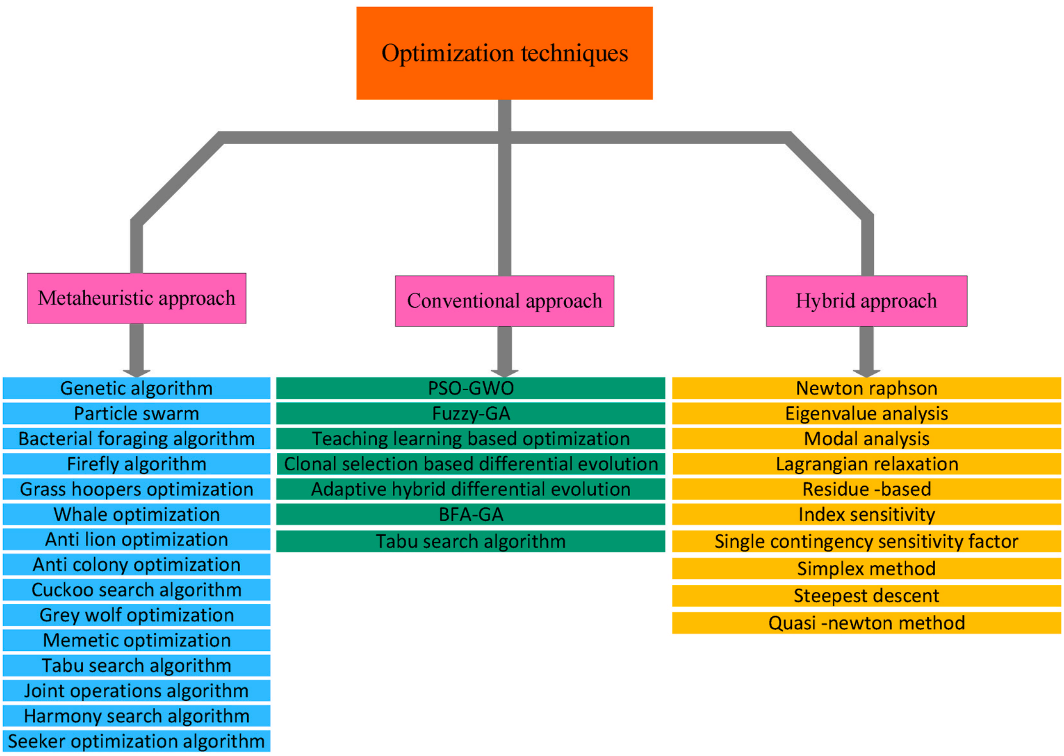

Fig. 25. Optimal placement of FACTS devices based on optimization techniques.

FACTS devices help optimize reactive power flow, reducing transmission losses [147]. Lower losses mean more of the generated power reaches the demand centers, potentially reducing the required generation. For instance, a STATCOM can inject or absorb reactive power at critical points, minimizing voltage fluctuations and losses. Lower losses reduce the total electricity generation needed to meet load demand, leading to fuel and operational expense savings.

- **Improved stability and reliability**

By stabilizing the voltage and frequency, FACTS devices help maintain grid reliability, reducing the risk of outages and costly corrective actions [148]. A UPFC, for instance, can stabilize the system following disturbances by adjusting the phase angle and voltage in real time. This stabilizing effect reduces the need for reserve capacity (which is usually more expensive to keep on standby) and avoids surplus generation to handle instability-related issues.

- **Increasing the system capability utilization**

By maximizing the capacity of existing lines, FACTS devices reduce the need to dispatch additional generating units to reduce economic costs. Thyristor-controlled series capacitor devices can help control the power flow on busy roads by adjusting line impedance dynamics [149].

- **Minimizing fuel consumption**

FACTS devices indirectly help lower overall fuel consumption by reducing the need for high-cost generation and optimizing power flows to take advantage of lower-cost units. Efficient power flow management means that low-cost, base-load generators (like coal or hydro) can operate more consistently, reducing reliance on fuel-intensive units. Therefore, this directly lowers fuel costs, which is an important factor in electricity production costs.

- **Economic Dispatch**

FACTS technologies allow network operators to implement economic dispatch more effectively and optimally by overcoming transmission constraints [150]. In economic dispatch models, FACTS devices are incorporated as control variables that adjust transmission capabilities to minimize the total generation cost. FACTS devices can reduce system constraints, allowing the economic dispatch to select the lowest-cost generation options without requiring costly adjustments to maintain power balance.

8. Discussion

This study evaluated various FACTS devices and their potential improvements, particularly on modified UPFC models. Our findings reveal several advantages of the transformer-less and capacitor-less UPFC variants, notably improved efficiency, lower THD, and reduced costs. This section compares our results with those of previous studies to provide a more comprehensive view of advancements and identify areas of differentiation. The resultsof this study are in agreement with various findings from the literature on the positive contribution of FACTS devices, such as the UPFC, DPFC, and STATCOM, to power flow control and stability. On the other hand, Sedraoui et al. [24] applied UPFC for the compensation of harmonics in electric arc furnaces, showing its possibilities for reactive power and voltage control. Similarly, other works, such as that by Ma et al. [28], highlight the role of STATCOM in reactive power management. Our research showed that modified UPFC models, in particular transformer-less configurations, not only match these benefits but also further improve them with faster dynamic response and lower operating costs by eliminating bulky components. The DPFC and DUPFC models have come up as reliable models for implementation with the capability of controlling cost-effective power flow across distributed networks [19,35].

Traditional DPFC configurations, for example, often yield effective voltage regulation and loss minimization at the cost of multiple numbers of distributed converters, thereby increasing the implementation complexity. The analysis in this paper demonstrates that modified UPFCs, with simple modular configurations, can also yield the same reliability and efficiency as such complex converter arrangements, and are thus becoming attractive options for high-reliability applications, possibly at a lower cost. The important contribution of our study is the demonstration of cost-efficiency benefits with modified UPFCs.

Most conventional studies, like Nazir et al. [58], have focused on the optimization of FACTS devices for the reduction of generation costs and transmission losses. Our work reinforces these goals by demonstrating that transformer-less UPFCs attain capital and operational cost reductions of 15–20 %, which is comparable to other cost-effective solutions such as DPFCs and STATCOMs. With fewer physical components, our study provides higher reliability and faster response times. The need for efficient FACTS devices has grown with the increasing integration of renewable energy sources that demand robust voltage and frequency control.

Various studies, including those by Ma et al. [28], have established that devices such as STATCOM and D-FACTS will be required to maintain stability in renewable-heavy networks. The obtained results indicate that the modified UPFC models presented in this article are able to be considered a valid alternative to traditional FACTS solutions, mainly for applications where efficiency, cost, and reliability are of major interest.

9. Conclusion

Rapid advancements in power electronics technology have resulted in constant enhancements to FACTS devices. These devices are used in power systems to increase transmission in the transmission line and improve the transmission network's voltage stability, transient stability, reliability, and thermal limitations. The authors have made this review a helpful article for researchers working on FACTS devices. In this paper, the authors investigate UPFCs without large electrolytic capacitors, without transformers, and with a central node. This paper also discusses power circuits and some key features of DSR, DUPFC, and DSSC technologies. We have also done a comparative analysis of SVC and STATCOM devices. The findings show:

✓ The losses in a STATCOM are typically about 3–4%, while in an SVC, they are generally around 1–2%;
✓ The response time in STATCOM is 30 ms faster than SVC;
✓ The STATCOM device supports a full reactive power range of ±100 % of its rated capacity, offering greater operational flexibility. In contrast, SVC provides a more limited range, typically around ±60–70 % of rated capacity;

Finally, this study examines advanced optimization techniques to determine the optimal location of FACTS devices to maximize their efficiency and effectiveness. In addition, the role of FACTS devices in reducing production costs and supporting the integration of renewable energy has been one of our other goals in this review article.

CRediT authorship contribution statement

Mehrdad Tarafdar Hagh: Supervision. **Mohammad Ali Jabbary Borhany:** Writing – original draft. **Kamran Taghizad-Tavana:** Writing – review & editing. **Morteza Zare Oskouei:** Supervision, Resources, Conceptualization.

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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