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Review

Optimal Placement and Operation of FACTS Technologies in a Cyber-Physical Power System: Critical Review and Future Outlook

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Abstract: With the current transitioning and increasing complexity of power systems owing to the continuous integration of distributed generators (DGs) and Flexible AC Transmission Systems (FACTS), power system quality and security studies have extended to incorporate the impacts of these technologies. This paper presents a review of the operation and reliability impacts of FACTS technologies in improving power quality and security in modern Cyber-Physical Power Systems (CPPS). While introducing DG to the power system helps to decentralize the network for easy accessibility and enhances clean energy system, it creates new challenges such as harmonics, voltage instability, and frequency distortion. These challenges can be tackled with FACTS devices which are flexible and dynamic smart electronic controllers used to stabilize power system parameters to improve power quality and reliability. This paper examines the current state-of-the-art optimization techniques and artificial intelligence and/or computational techniques for optimal placement and operation of FACTS devices. This review highlights the generational advancement of FACTS technologies and the different objectives of optimal placement and operation of these devices. Moreover, the concept of CPPS is discussed with the potential utilization of distribution-FACTS (D-FACTS) devices for network security. Furthermore, a bibliometric analysis was carried out to show research trend of FACTS utilization. The result presents future trajectories for power utility industries and researchers interested in power system optimization and the application of FACTS technologies in smart power system networks. Some of the significant findings leads to proposed demand-side management for placement of DGs and FACTS technologies as a more strategic optimal system sizing to minimize cost. It was also concluded that future design of FACTS/D-FACTS devices must consider and appreciate interactions with the automated systems of CPPS to enhance effective integration. To this end, design modification of the operational configuration of these devices with sensors for real-time synchronized control and interaction with other CPPS technologies is an area that requires more research attention in the future.

Keywords: optimization; FACTS technologies; distributed generators; renewable energy sources; power system; transient analysis; smart grid

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Citation: Okampo, E.J.; Nwulu, N.; Bokoro, P.N. Optimal Placement and Operation of FACTS Technologies in a Cyber-Physical Power System: Critical Review and Future Outlook. *Sustainability* **2022**, *14*, 7707. https://doi.org/10.3390/su14137707

Academic Editors: Boyu Qin, Ke Ma and Qianjun Zhang

Received: 19 April 2022
Accepted: 2 June 2022
Published: 24 June 2022

1. Introduction

Power System Quality and Reliability

Quality and reliable electricity is paramount to both the supply authority and the consumers [1]. The continual demand for electricity as the world's population continues to grow keeps the power system constantly transitioning into more complex interconnected networks. This increasing complexity is due to power system quality and reliability problems requiring advanced technologies to improve existing traditional networks. Power system challenges are vast in dimension, ranging from generation problems, such as access to energy sources, generator capacity, and ageing, to transmission problems such as, voltage losses, reactive power imbalances, and harmonics, and distribution problems, such as voltage surge, components faults, line sag, etc.

A quality power system is the delivery of power to the end-user as demanded. The consistent and uninterrupted supply of power defines its reliability [2,3]. Reliability concepts can be divided into system accuracy and system security [4]. According to Sinishaw et al. [4], system accuracy is the ability of the power system to deliver power to the end-user constantly as demanded within the system operating constraints. In contrast, system security is concerned with the ability of the system to withstand abrupt disturbance and respond quickly and adequately to dynamic changes in the network. The complex and interconnected nature of the power system involves many components operated within predetermined constraints, some of which limit the effective generation, transmission and distribution of power. However, the network system must be operated with the understanding and effective allowance for these constraints for efficient delivery of quality power. Furthermore, even when the system is operated within the acceptable limits, further consideration must be put in place for unforeseen circumstances, such as transient faults and natural causes of interruptions. Power system is perpetually open to changes that will enhance the quality and reliability of the systems to cope with their limitations and sudden disruptions. These perpetual required changes to the power system involve adjustment of exiting components, parameter modifications, and introduction of new technologies. Therefore, researchers and power system engineers are constantly proposing new ways of operating the system or new technologies to improve security. The challenge is that even the new technologies create new operating boundaries and introduce new disturbances in the system. For instance, the introduction of renewable energy sources (RES) as distributed generators (DGs) to decentralized power system networks and provide more environmentally friendly and sustainable energy comes with some degree of uncertainty owing to intermittency and uncontrolled characteristics [5–7]. Moreover, components ageing and failure contribute to power system reliability issues [8,9]. Power system components failure rate can be improved by proper planning (generator capacity, transmission, and distribution expansion planning), timely maintenance, and replacement of worn-out equipment [10–13]. Other power quality problems, such as voltage instability, reactive power imbalances, harmonics, and a host of others, can be attributed to the ageing of existing power system components and RES penetration as DGs. To tackle most of these power system challenges, several researchers and power system engineers have suggested that the FACTS technologies be integrated into the power system network, especially considering the cost of replacing existing old infrastructures [14–17]. The optimal location of DGs and FACTS devices in the power system network is of high economic importance. Therefore, several authors have proposed several optimization approaches for optimal placement of FACTS devices [1,18–22]. A survey of impact assessment and optimization approaches for optimal placement of FACTS and DG were presented in [23–25]. Most previous reviews in this area available in open literature considered impact assessment of FACTS devices for power system quality enhancement and optimization techniques used for optimal placement of FACTS and DGs in traditional centralized power system transmission networks. This paper presents an updated assessment review of the reliability impacts of FACTS technologies considering its operations in a cyber-physical power system (CPPS). CPPS involves the use of automated technologies, such as computer-aided technologies, information and communication technology (ICT), and technologies such as the internet of things (IOT) and the internet of energy (IOE). The remainder of this paper is such that Section 2 presents an overview of FACTS technologies, Section 3 details a survey of optimization approaches used for placement of FACTS devices with objectives of improving power system reliability, Section 4 presents impacts of FACTS in a deregulated CPPS and future outlook, Section 5 examine research trends and prospects, and Section 6 concludes the review with an outline of important findings and recommendation for future work.

2. Overview of FACTS Technologies

The advancements in power electronics have shown considerable improvement in satisfying the need for voltage stability and power quality improvement by introducing FACTS technology [26]. The main functions of these devices are reactive power compensation, voltage control, and power flow control to enhance better power quality in modern power systems [27]. The first generation of FACTS devices were mechanically controlled capacitors, inductors, and phase-shifting transformers with mechanical on-load tap changers [26]. The second generation was developed such that thyristor valves replace the mechanical switches. This gave a significant improvement in the speed of the devices. The third generation was designed using voltage source converter (VSC) based devices [26]. These devices provide multiple and total control of the power system parameters [28]. To further extend the application of FACTS devices to a distribution network, there are custom power (CP) devices similar to FACTS devices, except that they are used only in distribution networks. An example is the distributed synchronous static compensators D-STATCOM [24]. The modification of FACTS to CP to be used in distributed networks can be considered as the foundation for the fourth generation of FACTS technologies. This advancement expands the application of FACTS controllers from being used only in transmission networks to deregulated CPPS networks.

2.1. Benefits of FACTS Technology in Power System

FACTS devices are used in power systems for economic and technical benefits. Most existing power systems are old and operate under full capacity due, amongst other things, to infrastructure or components worn-out. Building a new power grid or replacing existing components will be an expensive venture; FACTS devices are, therefore, used to optimize the system performance capacity at a lower cost. Furthermore, in a deregulated power system network and competitive market, FACTS devices can be used to maximize consumers' social welfare and utility's profit in the face of imbalance cost due to RES uncertainty [18,19]. Moreover, when optimally placed, FACTS devices can reduce congestion, curtailment and price volatility [29,30].

Research has shown that FACTS technologies can be used to tackle many power system quality and reliability challenges such as: optimizing line power transfer capacity and loadability [31–33]; limiting short circuit currents [34]; enhancing power system transient stability state and system security [22,35,36]; compensate reactive power and load for optimal performance [37]; reducing sub-synchronous resonance and enhancing system damping [38,39]; and improving voltage stability and general power system quality [40,41].

2.2. Classification of FACTS Controllers

According to Rath et al. [29], FACTS controllers can be divided into four categories according to how they are connected: shunt controllers, series controllers, series-series controllers, and series-shunt controllers.

2.2.1. Series Controllers

Series Controllers inject voltage in series with the line. They are used to reduce the transfer reactance of a power line and hence increase transmission line capacity and improve system stability. Examples of series controllers are Thyristor Controlled Series Compensator (TCSC) and Static Synchronous Series Compensator (SSSC) [42]. Figure 1 shows the structure and form of TCSC designed with two-directional thyristors.

While the TCSC can be modelled as a series impedance, the SSSC is a series voltage source [42]. Figure 2 shows the Schematic diagram of SSSC designed based on solid-state voltage source converter and series connected to a transmission line through a transformer.

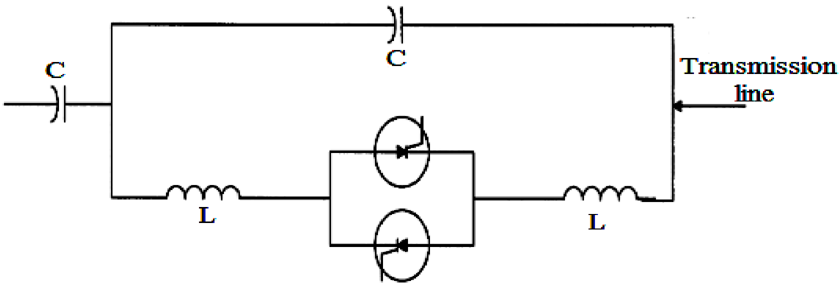


Figure 1. Schematic diagram of TCSC.

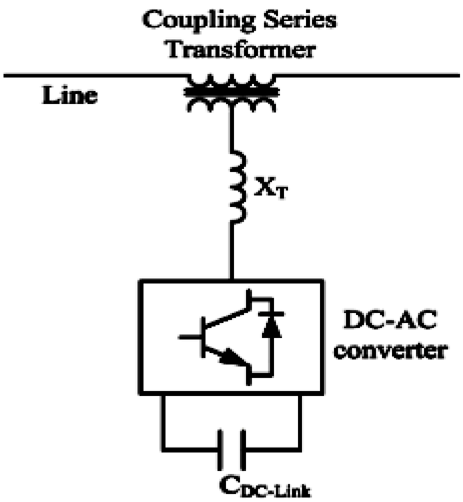


Figure 2. Schematic diagram of SSSC [43].

2.2.2. Shunt Controllers

Shunt controllers are mainly used in high voltage systems to improve voltage profiles by supplying reactive power as they inject current into the system at the point of connection. The shunt controller only provides or absorbs variable reactive power when the injected current is in the 900 phase with the line voltage. Any other phase relationship will also control real power as well. Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) are such controllers [44].

The SVC is designed with Thyristor Switched Capacitor (TSC) and Thyristor Controlled Reactor (TCR) or Thyristor Switched Reactor (TSR), as shown in Figure 3. The TSR is used to absorb reactive power, while the TSC is used to supply reactive power [45].

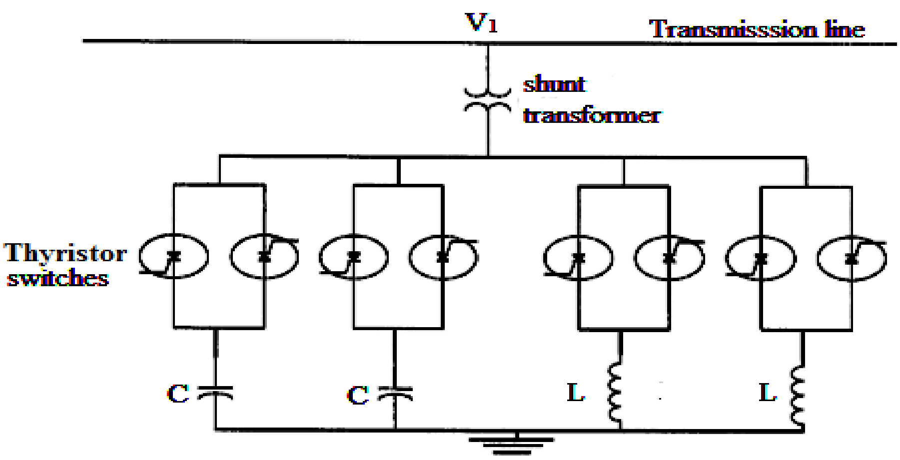


Figure 3. Static Var Compensator.

STATCOM is an advanced SVC designed with a VSC which has a Gate turn off thyristor and d.c capacitor linked with a transformer connected to a transmission line, as shown in Figure 4. The conversion of dc input voltage into ac outputs to compensate for the real and reactive power of the system is performed by STATCOM [45].

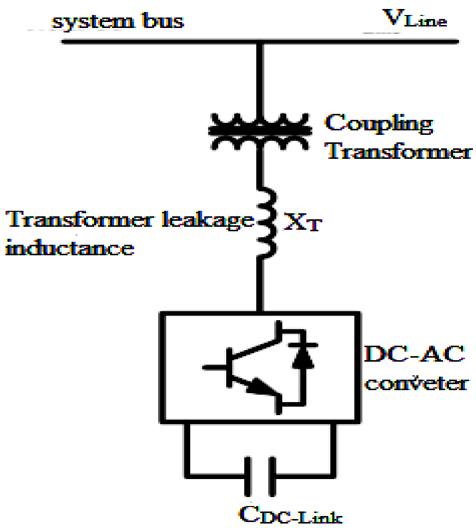


Figure 4. Schematic diagram of STATCOM [43].

2.2.3. Combined Series-Series Controllers

This is a combination of separate series controllers, which are coordinately controlled, in more than one transmission line system. It could also be a unified controller, in which series controllers provide independent series reactive compensation for each line and also transfer real power among the lines through the power link. Interline Power Flow Controller (IPFC) [44].

IPFC has two series converters connected to two different transmission lines, as shown in Figure 5. It provides a very good power flow control for more than one transmission line, with each of the two SSSC giving series power addition for its own transmission line. The two converters are joined through a DC capacitor and attached to the AC network through transformers directly connected. By this, it not only provides reactive power addition, but also any of the converters can be manipulated to inject real power to the dc joint from its own Transmission line.

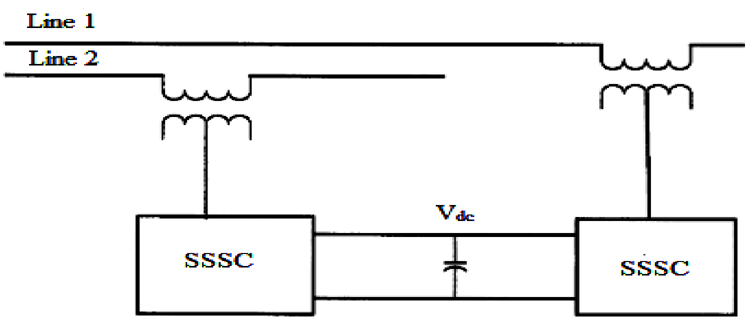


Figure 5. Schematic diagram of IPFC.

2.2.4. Combined Series-Shunt Controllers

These controllers have combined shunt and series controllers, which have sophisticated control. A real power exchange can occur through their shared DC link when the shunt and series controllers are jointly used. The Unified power flow controller (UPFC) is a series-shunt controller. It is considered one of the most versatile and powerful FACTS devices in the power system today [46]. It is primarily used for flexible control of powers for better voltage stability. It allows concurrent or independent control of these parameters with transfer from one control scheme to another in real-time. Figure 6 depicts the schematic diagram of UPFC.

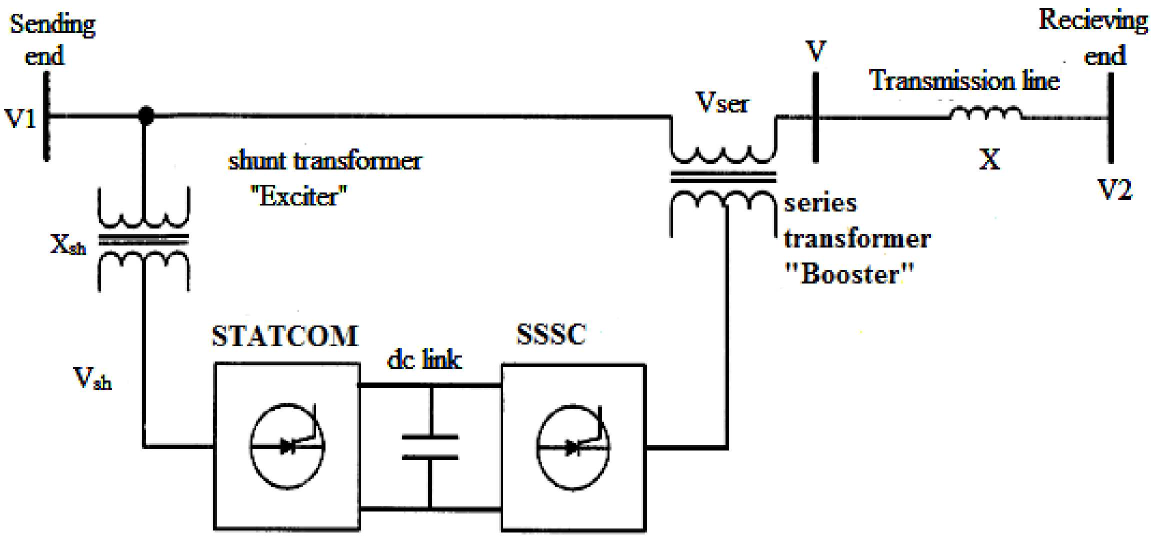


Figure 6. Schematic diagram of UPFC [47].

UPFC, as shown in Figure 6, is designed using STATCOM and SSSC linked together with a d.c. The converters are connected to the line with transformers. The unique combination of this device allows for flexibility of operation when connected to a power system network.

The dynamic flow controller (DFC) is a hybrid device combining a Phase Shifting Transformer (PST) and switched series compensator, such as TSC and TSR, as shown in Figure 7.

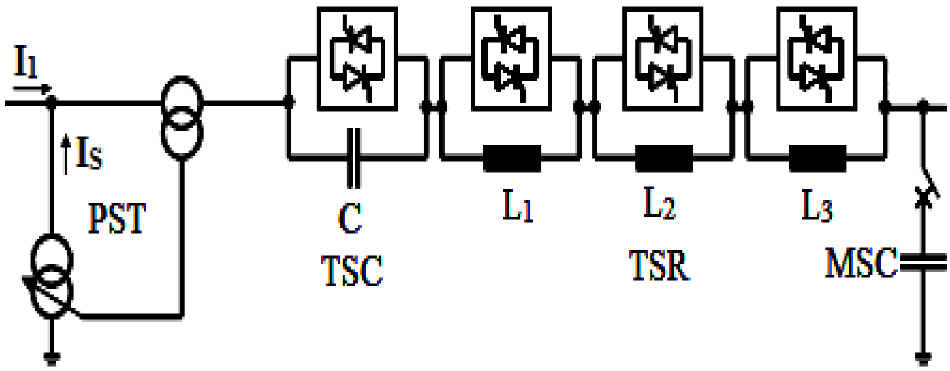


Figure 7. Schematic diagram of DFC [42].

2.2.5. The Merit of the Voltage Source Converter Based FACTS over Thyristor Controlled Devices

- They consist of voltage source converters designed with an insulated-gate bipolar transistor or integrated gate-commutated thyristor, making them capable of controlling their output voltage;
- With the voltage source converters, there is no risk of shunt or series resonant with the inductive line impedance that may initiate sub-synchronous oscillation;
- They can control their output voltage over the whole VA rating independent of the AC system parameters;
- They exchange controllable real power with AC system.

Figure 8 depicts an overview of major FACTS devices classified according to their connection and different generations.

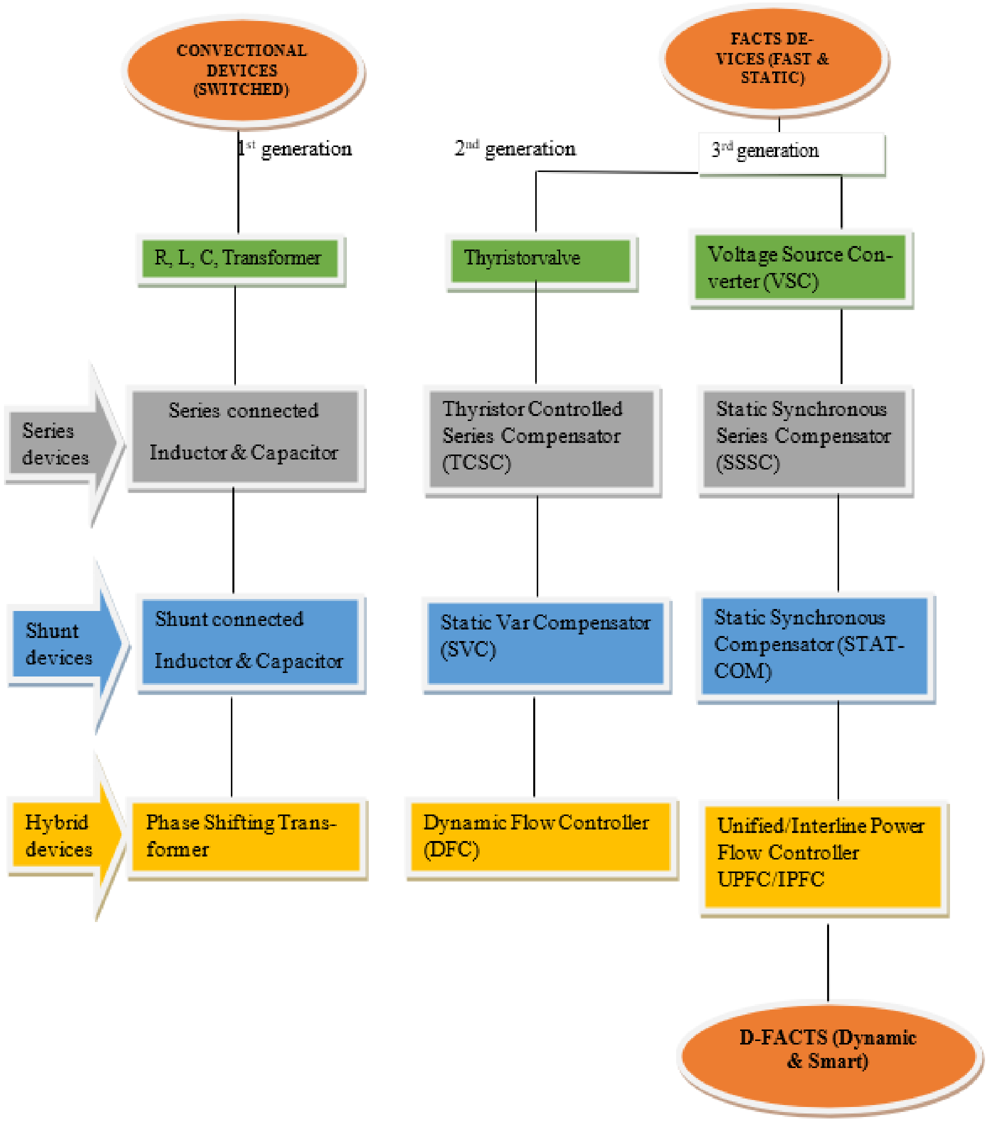


Figure 8. Overview of major FACTS devices.

2.2.6. Distribution-FACTS Controllers

D-FACTS technologies are advanced FACTS controllers mainly deployed in distribution networks. Due to the increasing introduction of DGs to the power grid, D-FACTS are becoming more promising than convectional FACTS devices, gaining more recent traction in power grid deployment [48]. D-FACTS devices are smaller and, hence, less complex and cheaper than traditional FACTS devices [49]. Beyond the merit of flexibility and cost-effectiveness, D-FACTS controllers are suitable for easy configuration with the sensing and communication system of the modern smart grid for advanced functionality. Therefore, D-FACTS devices are considered an alternative solution to the limitations of traditional FACTS devices.

The similarity of D-FACTS devices to other convection FACTS devices extends beyond functionality to technical configuration; hence, most D-FACTS devices assumed the name of the specific FACTS controller with a similar configuration. D- STATCOM, for instance, is designed to perform a similar function as STATCOM; therefore, the operational configuration and connection in the power grid are the same. Moreover, D-SSSC is the distribution version of the SSSC controller. Both are connected in series along power lines and provide dynamic control for power quality and security improvement.

Pinheiro et al. [48] demonstrates an application of series VSC in distribution network for effective power flow under variable load disturbances. The study results show VSC as active tool for independent control and transfer of real and reactive powers between distribution feeders. On the other hand, the biggest challenge of using series converter in an electrical power system is its ability to make smart decisions or otherwise be removed and protected in case of a short circuit or power outage [48]. An efficient coordination of voltage and reactive power in an automated distribution system using distribution SVC (D-SVC) alongside DGs was presented by Shaheen et al. [50]. This integrated configuration not only achieved optimum distribution system operation and control, but also minimized losses and reduce emissions [51]. D-FACTS can also be utilized to regulate the oscillatory stability of induction motors or synchronous generator [52].

3. A Survey on Optimization Methods

The optimal location, operation and control of FACTS controllers have been the focus of research in the area of FACTS installation and utilization in power systems. Due to the complexity of the power system network, successful installation and utilization of FACTS controllers are conducted, subject to certain constraints. Therefore, most optimal utilizations of FACTS devices are executed as constraint optimization with multi-objectives commonly geared towards general enhancement of power system quality, reliability, and security. Several optimization solution techniques have been utilized to solve the constraint-multi-objectives problem of FACTS placement, operation and control in the power system network. These optimization techniques are classified in Figure 9 as convectional mathematical methods and artificial intelligence techniques. The artificial intelligent techniques could be metaheuristic approach or hybrid metaheuristic approach.

Convectional mathematical optimization methods, such as Newton–Raphson, linear programming, non-linear programming, dynamic programming, eigen-value analysis, Lagrangian relaxation, sequential quadratic programming, index and sensitive methods, residue-based method, and many others, provide good convergence characteristic and strong accuracy performance but are usually drawback by limited global optima solution due to dependence on randomly selected initially values. Other drawbacks of these methods include long computational time and limitation in handling large non-linear multi-objective or multi-constraint optimization problems. These drawbacks can be minimized by modification of some of the existing methods. Bone et al. [53], for instance, presented a steady state model of FACTs devices using unaltered power-flow routines and concludes that the methods converges rapidly.

Heuristic and Metaheuristic techniques are dynamic nature-inspired algorithms that are capable of solving large and complex optimization problems and mostly have the potential of obtaining global optima solutions. These algorithms are based on the concept of evolution, animal intelligence, plant intelligence, and sometimes chemical and physical theories. Some of the commonly used Heuristic and Metaheuristic techniques are Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Bacterial Foraging Algorithm (BFA), Grey Wolf Optimizer (GWO), Fuzzy logic (FL), Ant Colony Optimization (ACO), Artificial Bee Colony (ABC), Bat Algorithm (BA), Firefly Optimization Algorithm (FOA), Cuckoo Search (CS), etc. Despite their superior fast computational advantage and ability to handle more complex optimization problem, metaheuristic methods have different drawbacks; hence, a continuous and sustained search by researchers for a better algorithm for optimal placement and sizing of FACTS devices [54]. The drawbacks of some of metaheuristic approach include undefined convergence by ACO; low convergence rate; parameter adjustment, as in the case of BA; and many more for each individual algorithm [54].

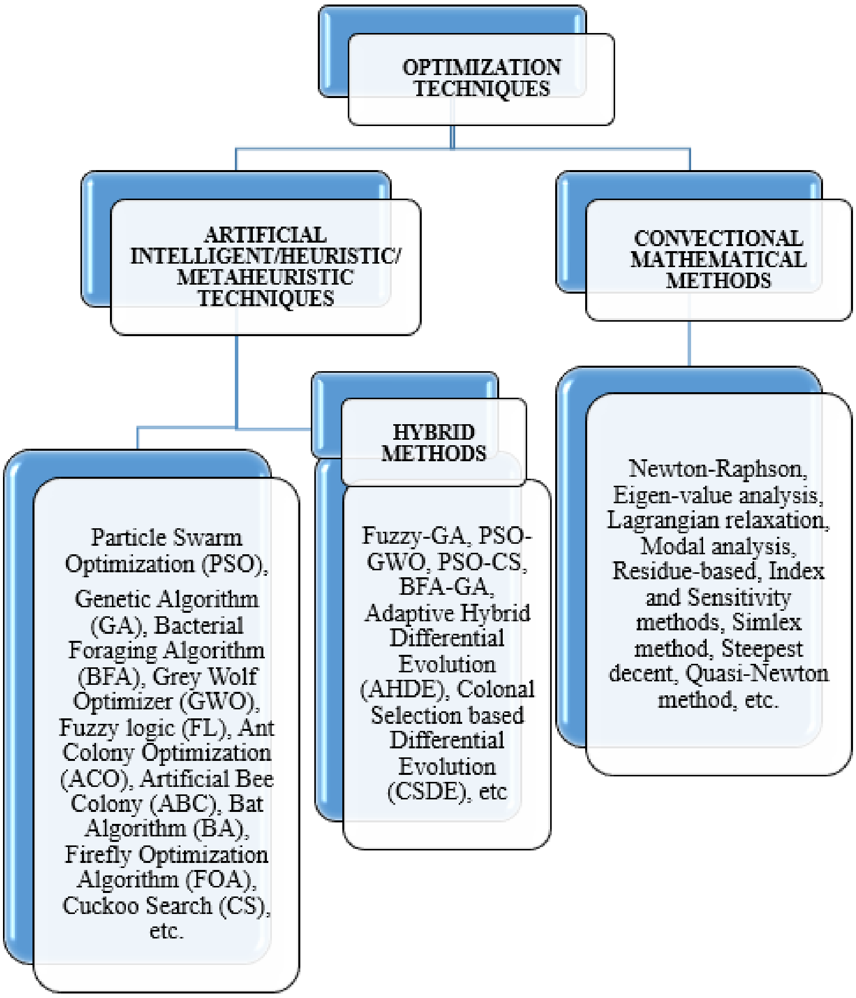


Figure 9. Classification of Optimization solution techniques.

The hybrid methods, which are either a combination of a convectional mathematical method with a metaheuristic method or a combination of two or more different metaheuristic methods, provide better performance in determining the optimal location, sizing and control of FACTS devices. This is because the dimensions of the optimization problems can be shared by each algorithm and the limitations of one can be complimented by the strength of another [55].

3.1. Optimal Sizing and Location/Placement of FACTS Controllers

To achieve the maximum benefits of FACTS utilization in a power system network, its location in the network is of paramount importance. Therefore, researchers have deployed different optimization techniques to determine the best possible location to place FACTS in a power system network to achieve an optimal solution. Yuvaraj et al. [56] used the Harmony Search algorithm (HSA) to size and locate D-STATCOM in a radial distribution system to minimize the system's total power losses. Taher and Amooshahi [57,58] employed hybrid immune algorithms such as immune particle swarm optimization (IPSO) and immune genetic algorithm (IGA) to optimally place UPFC to reduce the production cost of generators and installation cost of UPFC. At the same time, maximizing active and reactive power for system loadability, congestion management, and optimal power flow.

Similarly, in another study, Taher and Afsari [59] used an immune algorithm to determine the best size and location of D-STATCOM to minimize the system cost while improving the current and voltage profile of the system. Packiasudha et al. [60] used a cumulative gravitational search algorithm to optimally search for the best location of

FACTS device in a deregulated network with the objective of system loss minimization. The evolution algorithm was proposed by Alamelu et al. [61] for sizing and siting of UPFC in a power system network to minimize total system cost and enhance loadability. Inkollu and Kota [62] presented a hybrid method of particle swarm optimization (PSO) and gravitational search algorithm (GSA) for optimal setting of UPFC and IPFC to enhance voltage stability.

In recent years, due to high renewable energy penetration, the placement of FACTS devices with distributed energy has gain more consideration [63]. A model for optimal placement of FACTS controllers to curtail wind power cost in a highly wind power penetrated market environment was presented by Zhang et al. [64]. The stochastic mixed integer program bi-level model was also used to identify the investment decisions on series FACTS using a derived *shift factor* structure within a market environment under high wind power penetration. Furthermore, the proposed *shift factor* formulation is considered to outperform similar $B\theta$ formulation in area of computational speed as a result of its minimized model size but its limited application to DC power flow is a major setback in optimal power flow analysis. The co-optimization model was alternatively reformulated for transmission expansion planning with TCSC location by [65], wherein two mixed integer liner programs were proposed for better solution of the multi-optimization problem. An improved squirrel search algorithm was used to determine the optimal location of Generalized Unified Power Flow Controller (GUPFC) and IPFC integrated with wind farm and fuel cell [66]. The model was inspired by natural motion of flying squirrel from one tree to another using gliding positions. It was considered efficient for optimal location of the FACTS devices with objectives of enhancing voltage profile, reduce the operational cost and power losses of the system. Frolov et al. [67] implore sequence of quadratic programming to determine optimal location of FACTS devices for the control and management of uncertainty of renewable energy integration in a large transmission power system. The proposed multiple scenario-aware model shows strong efficiency. The associated uncertainty of wind power penetration in a deregulated network is considered with dynamic line rating by optimal allocation of SVCs and TCSCs using a probabilistic method in [68]. It was observed that the maximum loadability limit of dynamic line rating was better enhance with SVC than with TCSC or without any FACTS devices at all.

3.2. Optimal Operation and Control of FACTS Controllers

The optimal sizing and location of the FACTS devices are very important, especially for economic reasons [55]. The optimal operation and control of these devices for the technical enhancement of the entire power system is also very important [69]. Therefore, the optimal operation and control of FACTS devices to improve power system quality, reliability, and security have also been a further focus of research. Yavari et al. [70] utilized the combination of sliding mode control and instantaneous active and reactive power theories to design a non-linear controller for unified power quality conditioner (UPQC) that proved to be more effective in compensating current and voltage distortion than the conventional proportional-integral controller. Acharjee [71] presented a model with parameter setting of UPFC considering losses of both converters, losses of coupling transformers, and transmission losses in UPFC using a self-adaptive differential evolutionary algorithm. The use of UPFC improved power flow and minimized line losses simultaneously. Varma et al. [72] demonstrated the application of photovoltaic solar-based FACTs devices for stabilizing critical induction motor the first of its kind in Canada. Such stabilization of induction motors helps to minimize disturbance in a power system. It was observed the new PV-STATCOM is about 50 times less expensive than a normal STATCOM of similar sized.

The management of the power loop in the power system network is crucial to avoid losses and make the protection layer easy to set up [73,74]. Li et al. [75] proposed a sensitivity-based coordination model for the optimal setting of multiple UPFCs to determine the controllable range of active power settings to avoid active power loop flows.

The impact of high penetration of distributed renewable energy sources (DREs) in power systems requires sustained controllability. FACTS controllers can be utilized to curtail the high penetration of DREs [76,77]. Substation reconfiguration with voltage source converter of the UPFC to accommodate DREs for enhancing AC optimal power flow using sparse tableau formulation was considered in [76]. The impact and merits of UPFC to wind power integration in unit commitment is discussed in [77], where different dispatch strategies were considered. Elattar et al. [78] and Shaheen [79] formulated models for optimal power flow in hybrid AC-multiterminal DC grid with the integration of VSC for minimizing fuel cost, total environmental emission, and power losses. Similar objectives were also presented in [80,81].

Furthermore, flexibility and dynamic control provided by FACTS controllers in fault handling can be seen in the amplitude-based directional relaying scheme during single-pole tripping utilizing UPFC as detailed in [82]. A transient control scheme of the UPFC is designed to mitigate generator tripping of power systems by controlling the time derivative of Lyapunov function to be negative towards asymptotic stability [83]. The impact of this is that the system's attraction region is reshaped to align with the state point at fault clearing time for security.

Tables 1 and 2 highlights a summary survey of some literature focused on optimal placement and operation of FACTS and D-FACTS controller used in the power system network.

Table 1. Summary of optimal placement and operation of some FACTS/D-FACTS in power system network.

FACTS Devices	Optimization Approach	Power System Problem Solved as Objective Function	Outlook
TCSC & UPFC	Operational optimization model.	To maximize the social welfare for consumers and profit for utility while minimizing the effect of wind uncertainty.	TCSC and UPFC deployment successfully maximized social welfare in the face of imbalance due to wind intermittency [18,84,85].
SVC	Modified Newton-Raphson model, Adaptive differential search algorithm, ABC.	To minimize voltage, real, and reactive power losses. To minimize the cost of energy loss. To maximized hosting capacity of Photovoltaic.	SVC enhances voltage profile and improved overall power system performance [40,86–91].
STATCOM	Genetic algorithm (GA) and Bacteria foraging algorithm (BFA).	To minimize voltage fluctuation by compensating reactive power. Load margin enhancement.	Improvement of voltage stability [41,92–94].
TCSC	Sequential Quadratic problem SQP, Newton-Raphson model and Whale optimization algorithm (WOA), Catastrophe Theory.	To determine power system security margin. To increase transmission line capacity. To improve stability margin.	Bus voltage violation and losses can be reduce concurrently [20,95–98].
SSSC	Structure preserving energy function method, Multi-objective biogeography-based optimization (MOBBO), and WOA.	Transient stability and damping oscillation. To maximize system predictability while reducing system active power loss.	Improvement of system stability and reliability [99–101].
UPFC	Hybrid immune algorithm, Adaptive Grasshopper Optimization Algorithm.	To increase power system loadability and congestion management. To reduce power loss and enhance voltage profile.	The production cost of the generator and installation cost of UPFC was minimized [57,58,102,103].
IPFC	Firefly optimization algorithm.	To improve power system security while minimizing cost. Congestion management.	IPFC is effective in power system security improvement [104–106].

Table 2. Summary of optimal placement and operation of some D-FACTS in power system network.

D-STATCOM	Variation technique and stability index.	To minimize line losses and total harmonic distortion (THD).	Optimal placement of D-STATCOM can improve voltage profile and reduce THD [107–109].
UPQC	Variation technique.	To enhance voltage profile and reduce power loss. Cost minimization.	Unified power quality conditioner (UPQC) has both shunt and series controllers, therefore, have an advantage over other D-FACTS [110–112].
D-STATCOM	Direct load flow technique, Rooted tree optimization (RTO) and Lighting search algorithm (LSA).	Voltage profile improvement.	Maximum voltage profile improvement can be achieved when D-STATCOM is optimally placed alongside DG [113–115]
D-SSSC	Particle Swarm Optimization.	To enhance voltage profile and reduce line loss.	D-SSSC effectively improved power quality in a radial distribution system [116].
D-SVC & D-STATCOM	Variation technique	Economic feasibility	Wind farm stability improvement as D-STATCOM minimized the complexity of regulating the wind turbine-generators and improves the time response of reactive power compensation [117].

4. Cyber-Physical Power System and the Future Outlook of FACTS Integration

Yaacoub et al. [118] describe cyber-physical system (CPS) as interconnected systems with the ability to monitor and manipulate real objects and processes. The CPS and the IoT concepts are closely related except that the CPS deals with the interaction between physical networking and computational processes. It was further stated by Yaacoub et al. [118] that the integration of CPS and IoT birthed a new comprehensive concept, the internet of cyber-physical things (IoCPT). From these concepts, the idea of IOE and CPPS is derived. Hence, CPPS is a modern day smart grid power system with a network of traditional power system components, DGs, and computed aided automated devices, such as sensing and communicating technology [119]. "The strong interactions between systems in a CPPS introduce new challenges in maintaining high supply security, as new factors can affect the overall security of the power system. Such factors include cybersecurity, the behavior and constraints of neighboring energy systems, and the dynamics of interactions between the various systems" [120].

Most energy distribution utilities currently control their network with a supervisory control and data acquisition (SCADA) system. It is a centralized system that monitors and controls the distribution network's behavior utilizing available data from the network system parameters. The current utilization of the SCADA in the distribution network limits response time, which can be improved upon by emerging advanced distribution system automation (DSA) [121]. Some of the new DSA devices employ sensing and intelligent system to provide fault prediction and enhance system protection. Figure 10 illustrates the integration of a cyber-system to a physical power grid.

The transition of power from the long exiting traditional network to CPPS involves a paradigm shift from the old model of a network structure of generation-transmission-distribution-utilization to a new approach of skipping transmission network by bringing generators to distribution centers [3]. This modernization of the traditional power system to a decentralized and sophisticated CPPS is accompanied by the increasing introduction of small DGs, RES, and different smart, automated devices [122]. These new technologies introduced associated power system reliability challenges that required modifications to the system operations, such as real-time power balance and control of bi-directional power flow. Apart from its convectional application to enhance voltage profile and maintain power system steady-state by dynamic control, D-FACTS technologies are finding new applications in the current CPPS environment. One such application is the controlling of "parallel flow" or "loop flow" [29]. Loop flow yields an involuntary cut down in transmission capacity that may belong to some other utility and hence foreclose beneficial transaction through that line [29]. Moreover, FACTS and D-FACTS have been considered to address economic and cyber-security threat of power system network concurrently as demonstrated by Liu et al. [123] using a newly develop interior-point solver for AC optimal power models. In the vine, Parastvand et al. [124] presented a novel topological perspective of location of FACTS devices considering the cyber-security of associated data exchange being critical for the controllability of wide area power system networks.

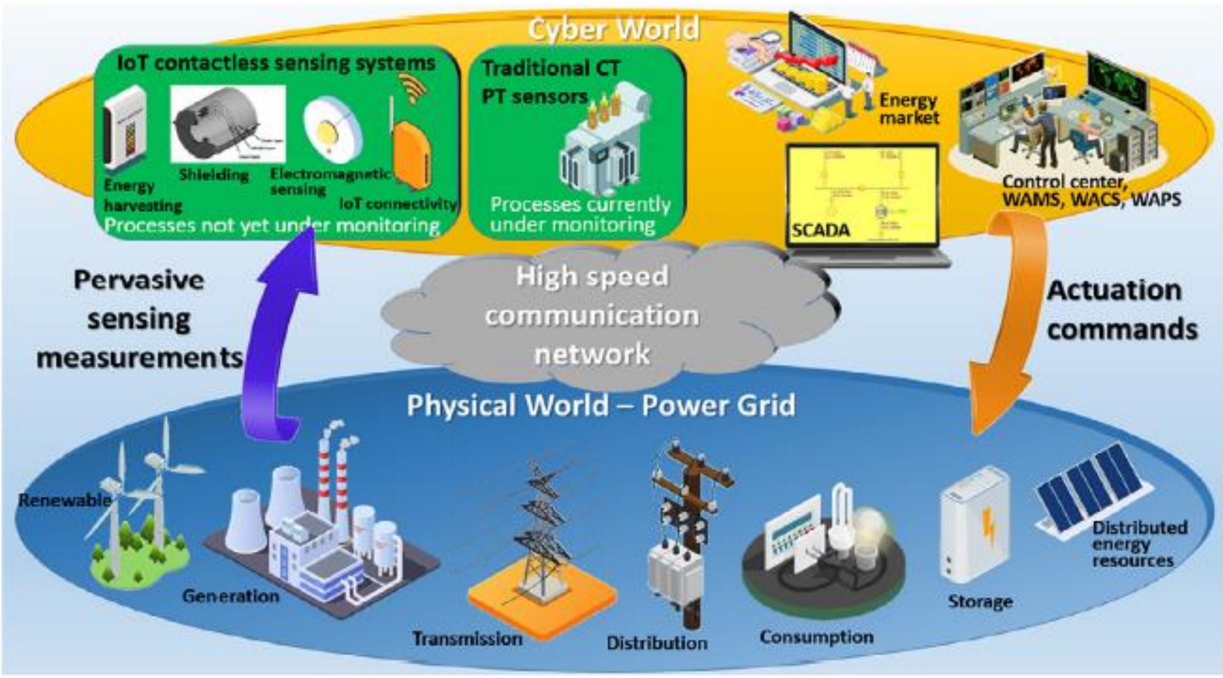
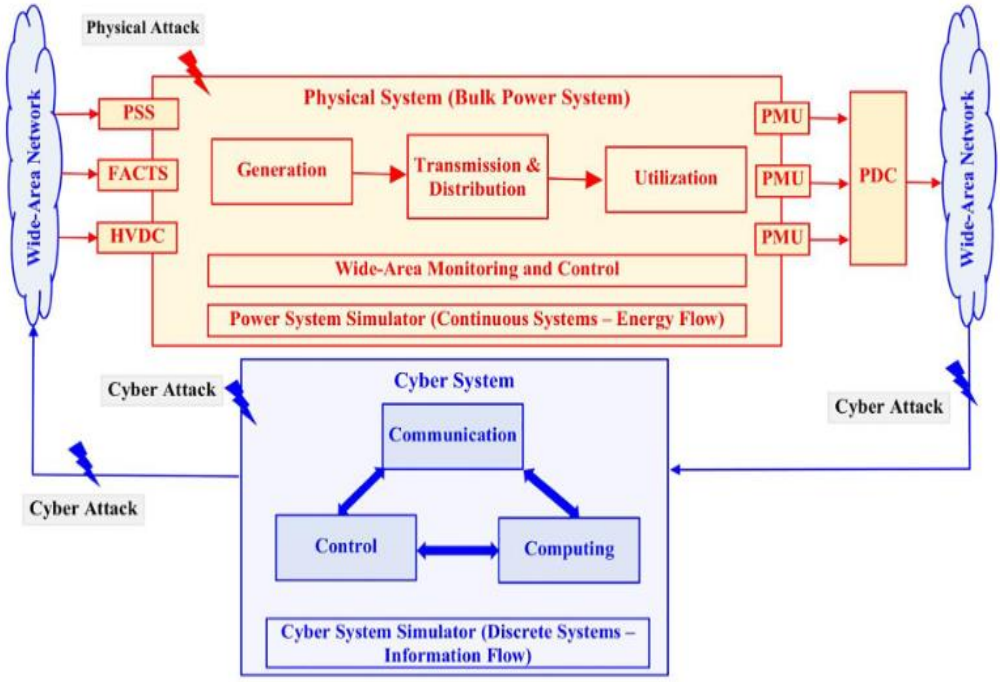
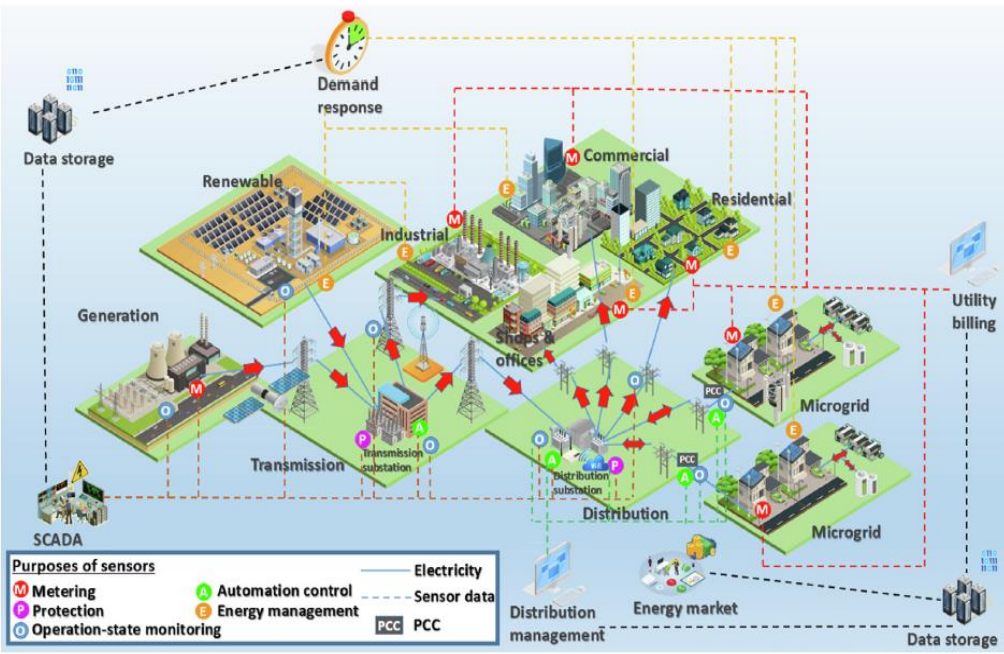


Figure 10. Integration of a cyber-system to physical power grid [122].

Padhy [125] proposed the modification of FACTS with an adaptive time delay compensation scheme that requires the signal modal information, such as frequency, amplitude, and damping. With this information, the latency can be compensated by predicting future trajectories of oscillatory response. According to Bibhu, this scheme can serve as a Wide-Area damping controller designed to address the issue of sampled-data control. Furthermore, D-FACTS has been considered for deployment in a CPPS for coordinated protection against false data injection cyberattacks (FDI) in a moving target defense (MTD) strategy [126–128]. The proposed defense strategy by Zhang et al. [126] works by actively perturbing the branch parameters needed to make up the false data injection attacks and thwart any further attack with optimally deployed D-FACTS device at each branch. The strategy protects the state estimation from being independently modified. The protection of state estimation against cyberattacks is very important, considering "its fundamental function of the energy management system, which calculates the optimal estimate of system's state variables with explicit model and sensor measurement collected by SCADA system" [126]. To further the effectiveness of MTD strategy, Liu and Wu [127] presented an expanded MTD-based AC optimal power flow model. The reactance of D-FACTS lines is considered as decision variables to find a trade-off between MTD effectiveness and the system losses. Then, a new algorithm for optimal placement of the D-FACTS devices was developed and utilized to maximize the composite matrix rank of the MTD strategy in detecting false data injection attacks. On the other hand, Li et al. [128] investigated the feasibility and limitation of using D-FACTS devices as a proactive false data detection strategy. The investigation was conducted considering three types of FDI attacks; single-bus FDI, uncoordinated multiple-bus FDI, and coordinated multiple-bus FDI attacks. It was concluded that the strategy is capable of detecting all three types of FDI attacks on buses or super-buses with degrees large than 1, if the D-FACTS controllers are placed to at appropriate branches but the strategy failed to detect FDI attacks targeted on buses or super-buses with degrees equaling 1. Figure 11a,b depicts a conceptual and sectional view of modern CCPS.



(**a**)



(**b**)

Figure 11. (**a**) schematic representation of a Cyber-Physical Power System showing the integration of convectional power system with FACTS technology and cyber system to prevent cyber-attack and enhance over all power system security. (**b**) Showing the different element of a Cyber-Physical Power System [120,122].

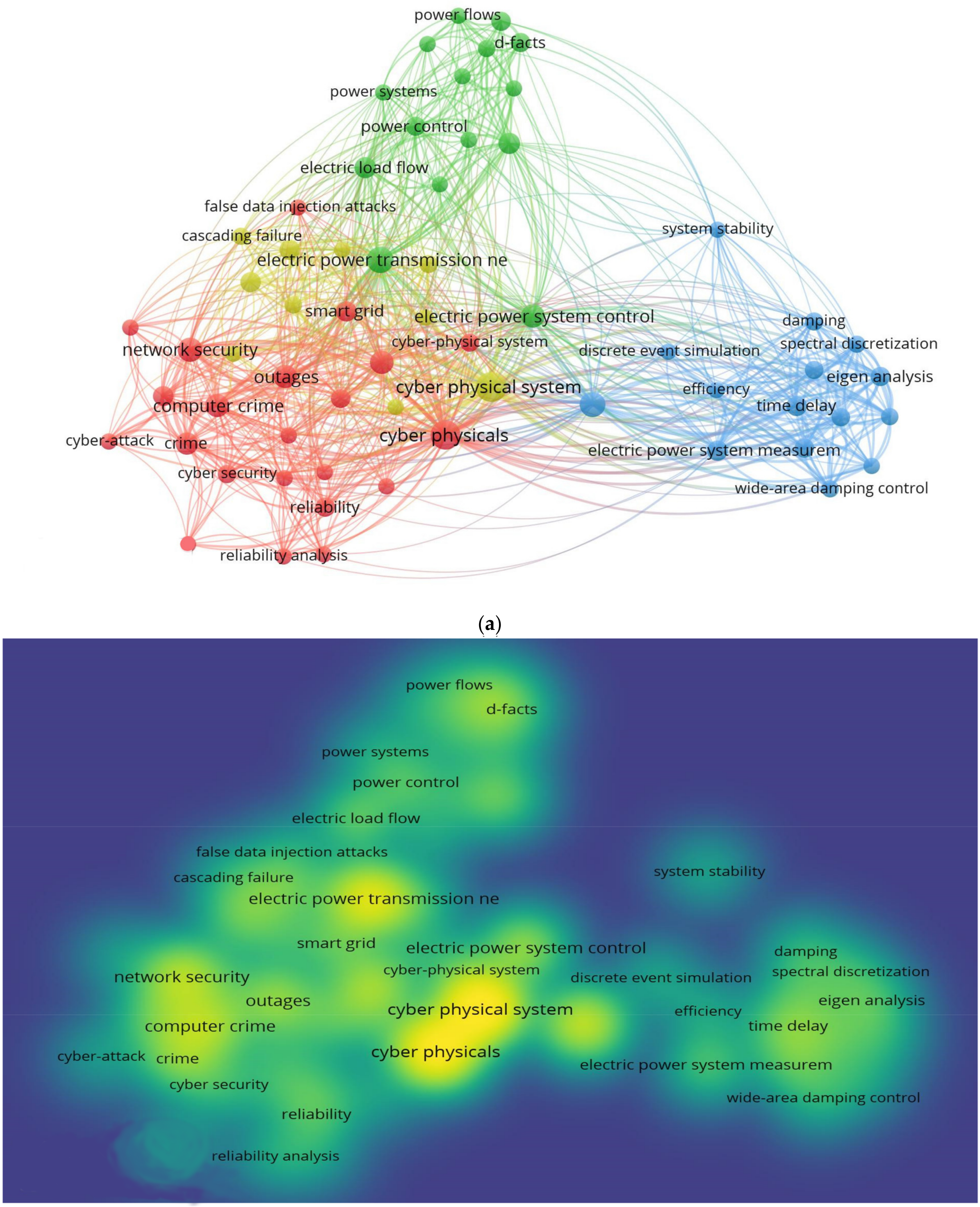
5. Research Trends and Future Prospect

Research output and trends in CPPS and integration of FACTS/D-FACTS were investigated with the VOSviewer software version 1.6.17 applied to data extracted from Scopus. The collection of data from Scopus was due to it being one of the largest databases with a focus on scientific research. It has searched indentation with some other science database. The data extraction was performed by searching the keywords "Flexible AC transmission system (FACTS)" OR "Distributed flexible AC transmission system (D-FACTS)" OR "Cyber-physical power system" in Scopus search space. The search was limited to only the engineering study area, a ten-year period of 2011–2021, considering only published journal articles and conference proceedings. This resulted in a total number of 1118 publications, but to further filter the available literature to specifics and sizeable number for easy analysis, a criterion was set to consider publication with five occurrences of keywords; 62 meet the threshold. Table 3 shows the details of the search output. The initial keywords generated further keywords co-occurring at least five times in the selected publications. The number of co-occurrence and times these words are linked are used to categorize the keywords into four clusters of relativity which by extension can be used to determine focus areas in the publications. Figure 12a represent a network visualization map that shows the links of the keywords, while Figure 12b represent a density visualization of the keywords for further clarity.

Furthermore, Figure 13a–e depicts overlay visualization of the keywords in the focus areas, which can be utilized to determine research trends within the period under consideration. From 2014 to 2015, the focus of research in the area of CPPS and FACTS/D-FACTS was on the network overlay of keywords with purple color in Figure 13a. The keywords network overlay with green color were the dominant focus of research between 2015 and 2018. From 2017 to 2019, the research focus shifted gradually towards the network overlay of keywords with yellow color. The purple color keywords are listed as cluster 2 in Table 3. Also, in Figure 13b, "power systems" is highlighted as a reference keyword to show the strongest links that determine the focus area of cluster 2. The strongest links of this cluster points to the integration of D-FACTS in power system for optimal power flow, power control, and power system stability. Similarly, "D-FACTS" was highlighted in Figure 13c, and the links show its application in the power system during the period (2014–2019) and, hence, the direction of future application. Figure 13d,e highlighted "electric power system control" and "cyber-physical power system", respectively; the outputs show a closely related network overlay of similar keywords the formed cluster 1, 3, and 4 of Table 3. These clusters are mainly green and yellow colors. The link between Figure 13d,e points towards the transition of research focus from convection electric power system control to electric power control in a cyber-physical power system. The network overlays of Figure 13c–e show that "electric power system control" (Figure 13d) is the common dominant factor between "D-FACTS" (Figure 13c) and "cyber-physical power system" (Figure 13e). However, there is a very weak link between "D-FACTS" and "cyber-physical power system". This weak link shows a research gap to be explored in the future.

Table 3. Summary of search output of keywords in relation to CPPS and FACTS/D-FACTS.

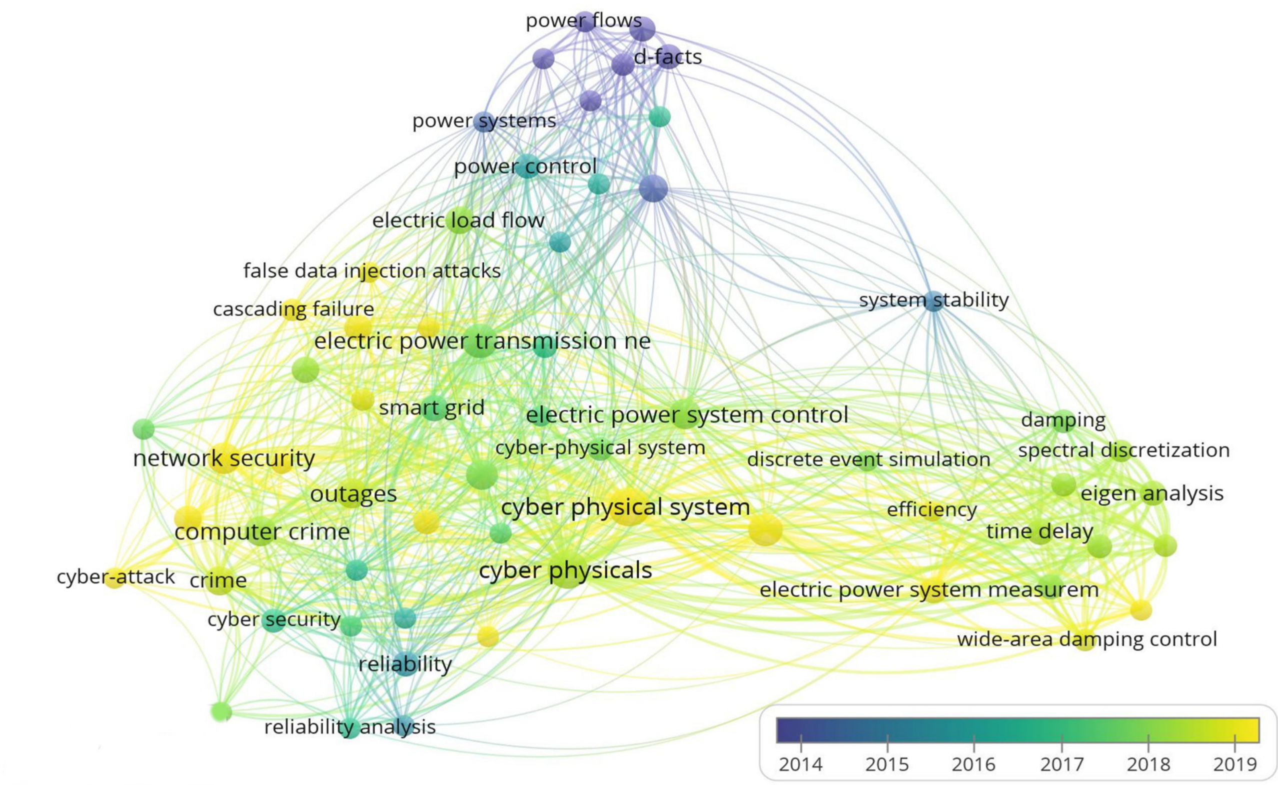
Network Cluster	Keyword	Occurrences	Total Link Strength
Cluster 1	Complex network	5	33
	Computer crime	22	144
	Cyber-physical power system	54	324
	Cyber-physical system	66	438
	Cyber security	9	49
	Cyber attacks	17	123
	Electric power system	6	33
	Embedded systems	22	120
	False data injection attack	6	23
	Monte Carlo methods	5	24
	Network security	25	150
	Outages	20	134
	Power system reliability	5	33
	Reliability	10	58
	Reliability analysis		
	Smart grid	12	58
	Smart power grids	11	74
Cluster 2	D-FACTS	10	48
	Distributed flexible AC transmission systems	7	41
	Electric load flow	14	92
	Electric power system control	21	155
	Electric power transmission	14	92
	Electric power transmission network	36	214
	Flexible AC transmission systems	5	33
	Flow control	5	36
	Optimization	5	37
	Power control	11	78
	Power electronics	10	38
	Power flows	6	34
	Power system operation	5	23
	Power systems	6	36
	Renewable energy resources	6	37
Cluster 3	Cyber-physical power system	54	324
	Damping	8	81
	Discrete event simulation	6	52
	Eigen analysis	21	236
	Eigenvalue and Eigen functions	8	84
	Electric power system measurement	12	118
	Small signal stability	7	90
	Spectral discretization	7	79
	System stability	6	44
	Time delay	13	125
	Wide-area damping control	13	153
	Wide-area measurement system	9	106
Cluster 4	Cascading failure	20	129
	Cyber-physical power system	54	324
	Dynamics	5	36
	Hybrid systems	5	19
	IEEE standards	5	33
	Physical power	8	45
	Real-time systems	5	24
	Topology	7	48



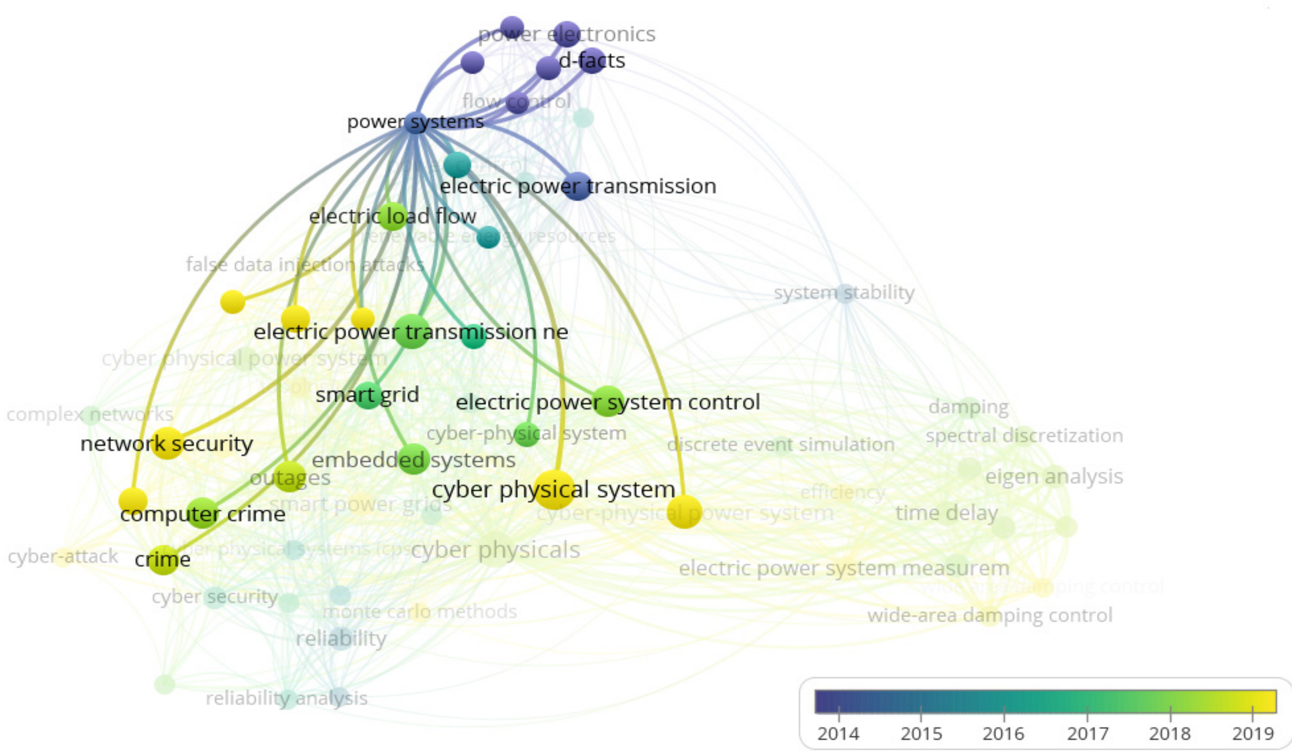
(**a**)

(**b**)

Figure 12. (**a**) Network visualization map and (**b**) density visualization map.

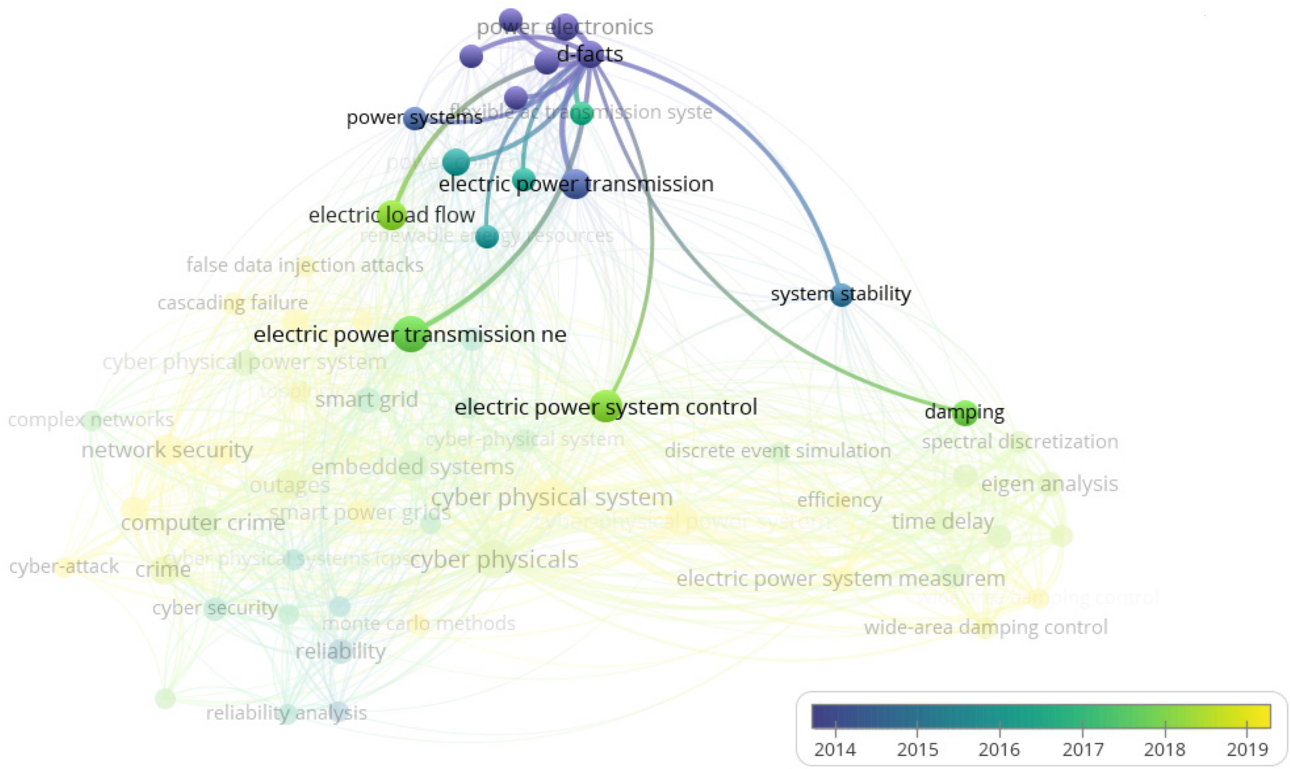


(**a**)

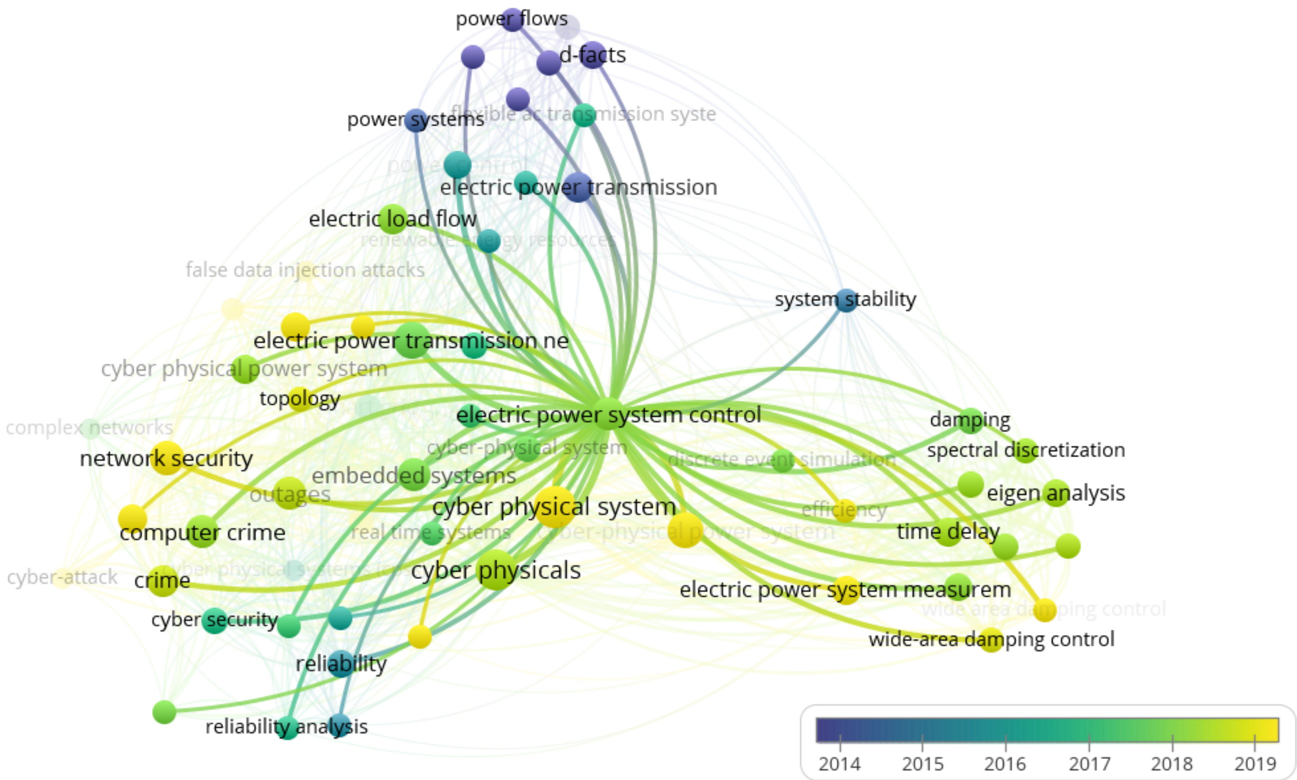


(**b**)

Figure 13. *Cont*.

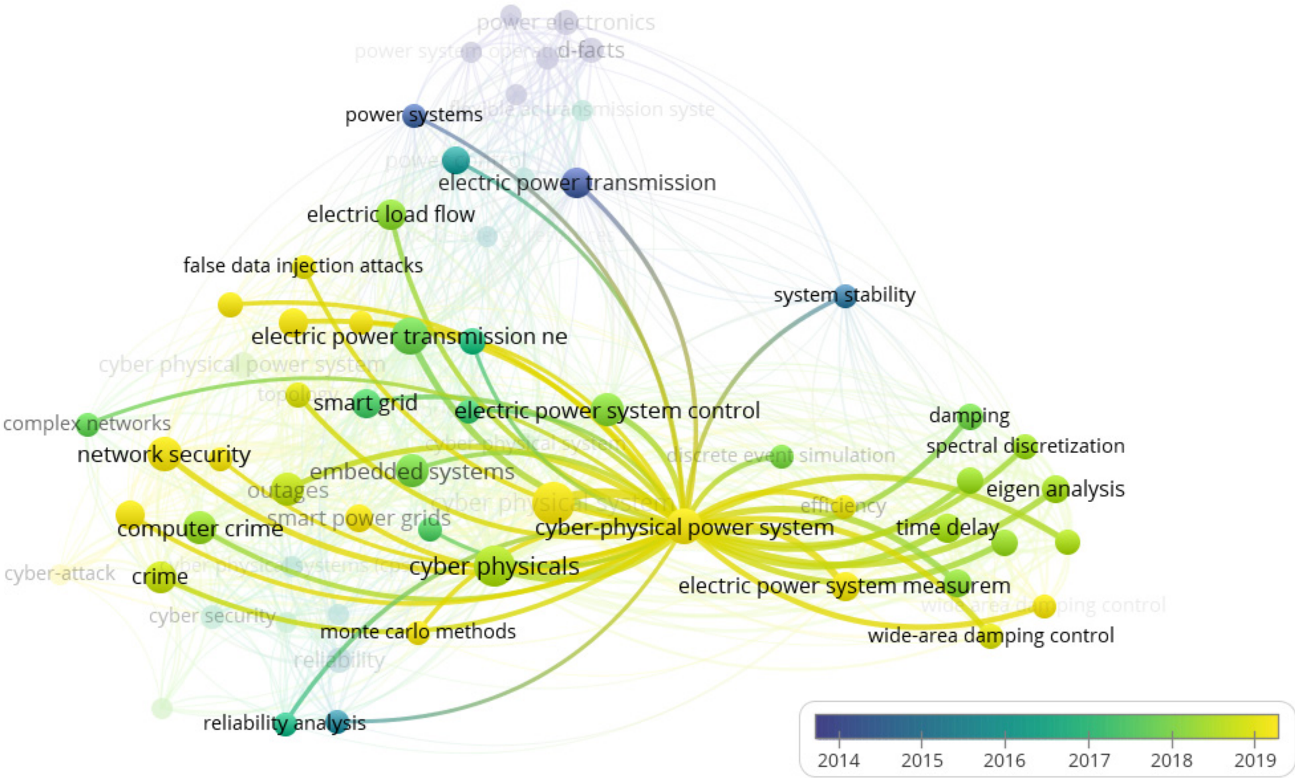


(**c**)



(**d**)

Figure 13. *Cont.*



(**e**)

Figure 13. (**a**) Overlay visualization showing research trend; (**b**) overlay visualization with "power systems" as reference keyword; (**c**) overlay visualization with "D-FACTS" as reference keyword; (**d**) overlay visualization with "electric power system control" as reference keyword; and (**e**) overlay visualization with "cyber-physical power system" as reference keyword.

6. Conclusions

This study presents a review of optimal placement and operation of FACTS/D-FACTS in a CPPS. The review covers a brief overview of the generational transition of FACTS devices to their placement and operation in power systems. Furthermore, the concept of CPPS was highlighted, and the relevance of its integration with D-FACTS technology was brought to light. A bibliometric analysis was carried out using VOSviewer software and data extracted from the Scopus database on research output considering FACTS/D-FACTS and CPPS. The important findings of this review, as well as the recommendations for future work, are summarized below:

1. It is predicted that going into the future, say 2050, a very large amount of energy will be generated by RES, while there will be a drastic reduction in fossil fuel power generation [129]. This implies that there will be more DGs penetration in power systems, bringing generation closer to distribution centers; hence, D-FACTS will be more required than convectional FACTS devices. This is also considering the minimized advantage of D-FACTS devices over FACTS devices;
2. CPPS of the future will be built with automated systems to include sensors, smart meters and communication systems to enable attributes, such as self-control, self-optimizing, and self-healing to guarantee autonomous power systems. Therefore, the future design of FACTS/D-FACTS devices must consider and appreciate interactions with the automated systems of CPPS to enhance effective integration. To this end, design modification of the operational configuration of FACTS/D-FACTS with sensors for real-time synchronized control and interaction with other CPPS technologies is an area that requires more research attention in the future;

3. Cyberattack has been identified as the common most feared challenge of future CPPS as it has the potential of causing a total system breakdown and a worldwide blackout. Therefore, the new trend of research toward the use of D-FACTS in an MTD strategy against FDI must be expanded to improve power system security;
4. In future, the advancement of optimal control capacity of FACT/D-FACT devices can be explored using cloud computing technology of the CPPS to store adequate data necessary to train the controllers with artificial intelligence required for dynamic control and protection of the system;
5. Research and discussion about FACTS/D-FACTS have been extensive and stretch over a long time, but the main focus remained on their optimal location and operation. Extensive research on the actual cost of installing and operating FACTS/D-FACTS devices is limited in the literature. This area requires more detailed research to determine the exact economic implication of the use of FACTS/D-FACTS technologies. This has the potential to enhance proper power system planning in the future;
6. Moreover, the real implementation or utilization of the FACTS/D-FACTS device is still very limited in several regions around the world. Countries that have them installed have only very few in their power grid. This low usage, especially in regions like Africa, is yet to be investigated. Few studies point towards limited production of these devices globally, but extensive research to ascertain the root cause leave room for further research;
7. Since CPPS is consumer-centered, it will be interesting for demand-side management to be considered along with optimal placement and operation of DGs and D-FACTS devices in such a deregulated system. This will possibly enhance consumers' participation in microgrid planning and decision-making regarding power system infrastructure, especially considering economic implications.

Author Contributions: Conceptualization, E.J.O., N.N. and P.N.B.; methodology E.J.O., N.N. and P.N.B.; software E.J.O., N.N. and P.N.B.; validation, E.J.O., N.N. and P.N.B.; formal analysis, E.J.O., N.N. and P.N.B.; investigation, E.J.O., N.N. and P.N.B.; resources, E.J.O., N.N. and P.N.B.; data curation E.J.O., N.N. and P.N.B.; writing—original draft preparation, E.J.O.; writing—review and editing, E.J.O., N.N. and P.N.B.; visualization, E.J.O., N.N. and P.N.B.; supervision, N.N. and P.N.B.; funding acquisition, N.N. and P.N.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

CP	Custom power
CPPS	Cyber-physical power system
DG	Distributed generator
DSA	Distribution system automation
D-SSSC	Distributed Static Synchronous Series Compensator
D-STATCOM	Distributed synchronous static compensators
D-FACTS	Distributed Flexible ac transmission system
FACTS	Flexible ac transmission system
GUPFC	Generalized Unified Power Flow Controller
ICT	Information and communication technology
IOT	Internet of things
IOE	Internet of energy
IoCPT	Internet of cyber-physical things

IPFC	Interline Power Flow Controller
PMU	Phasor Measurement Unit
PSS	Power System Stabilizer
PST	Phase Shifting Transformer
RES	Renewable energy sources
SCADA	Supervisory control and data acquisition
SSSC	Static Synchronous Series Compensator
SVC	Static Var Compensator
STATCOM	Synchronous static compensators
TCSC	Thyristor Controlled Series Compensator
TCR	Thyristor Controlled Reactor
TSC	Thyristor Switched Capacitor
TSR	Thyristor Switched Reactor
VSC	Voltage source converter
UPFC	The Unified power flow controller

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