A Comprehensive Study of Power Quality Improvement Techniques in Smart Grids with Renewable Energy Systems

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Abstract The power quality problems are very important now-a-days in modern power electrification. As the transition to smart grids progresses in traditional electrical power grids, power quality issues are becoming increasingly significant. This paper presents a review of power quality improvement techniques often used in micro-grids. The most recent distributed flexible AC transmission system (D-FACTS) devices-based soft computing techniques are reviewed. The power quality issues that arise with the penetration of renewable energy sources are thoroughly analyzed, along with power quality (PQ) mitigation strategies including several D-FACTS devices and control algorithms such as artificially intelligence-based control algorithms and meta-heuristic optimization methods. For the benefit of engineers and academicians working in this field of study, 25 research publications have been carefully evaluated and organized for rapid reference.

Keywords FACTS technologies · Power quality · Renewable energy sources · Smart grid · Artificial intelligence techniques · Meta-heuristic optimization

1 Introduction

The load side harmonics produced by the power electronics devices perturb the supply current and cause it to wander from the fundamental signal. Large power quality (PQ) difficulties have been brought on by the large input of renewable sources into the power system and grid linked power electronics interfaces. The primary objectives of power quality improvement (PQI) devices are to stop harmonics from propagating to the grid, from being injected into a load, or from being compensated, mostly on the consumer side [1]. The majority of PQI equipment is multifunctional, meaning it can

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do many tasks simultaneously with the same hardware, increasing co-effectiveness in addition to being dependable and efficient. This category contains both active and passive power filters. The aforementioned problems may be greatly alleviated by IoT-inspired applications by enabling two-way communication protocols that help turn outdated power grids into contemporary smart grids (SG). The SG is made up of several power configurations, such as distributed generation (DG) or micro-grids (MG), which combine various energy sources with different demand characteristics [2]. The geographic location of the renewable energy production sites, which is typically in remote areas where surface conditions are favorable for solar and wind energy while the transmission systems are relatively weak, is another factor that restricts the integration of these energies. This poses new difficulties for controlling voltage and compensating reactive power. Power quality enhancement devices/techniques are divided into three categories [3]. First generation devices include passive filters, active filters, and hybrid filters. Second generation devices include static synchronous compensator (STATCOM), dynamic voltage restorer (DVR), static var compensator (SVC), and unified power quality conditioner (UPQC). Third generation devices include multifunctional distributed generation (MFDG), electrical springs (ES) and smart impedance, etc. The normal distribution of long PQ disturbances shows that disturbances lasting less than one second occur much more often than others [4].

Smart grids range from advanced AC/lighting systems to emergency appliances and connected devices with agile controllers. Power system operators often use custom power devices (CPDs) and retain some of their generation capacity as spinning reserve (SR) to maintain power levels [5]. These parameters include not only the physical layout of the unified power quality conditioner (UPQC), but also its control architecture and the characteristics of the supply chain to which it is connected. The battery energy storage system (BESS), transformer and inverter are connected to the DVR and installed in series with the load. These components balance active and reactive power requirements to reduce sags and surges. Flexibility that allows the distribution static synchronous compensator (DSTATCOM) network to improve power quality by changing the common point voltage. If it is planned to place the BESS in parallel with the DC bus capacitor, then DSTATCOM can exchange active and reactive power with the network [6].

Over the past decade, intelligence-based evolutionary algorithms have been developed for complex optimization problems, including genetic algorithms (GA), particle swarm optimization (PSO), differential evolution (DE), bacteria foraging (BF) and ant colony enhancement (ACO), artificial bee colonies (ABC), learning-based optimization, and recovery studies [7]. The aforementioned task is completed by utilizing the salp swarm optimization algorithm's (SSA) intelligence to determine the ideal combination of proportional plus integral (PI) controller parameters and the value of the dc-link side capacitance, which results in the least amount of settling time and overshoot under DG injection and load switching conditions. SSA is a more advanced approach for resolving various optimization issues when compared to genetic approach (GA) and particle swarm optimization (PSO) [8]. Singh et al. [9] implemented an 11-level cascaded multilevel inverter (CMLI)-based distribution static compensator (DSTATCOM) to mitigate the harmonic content of an induction furnace in a steel plant. In another attempt, the comparison of two CPDs, UPQC, and DSTATCOM for harmonic mitigation in an induction furnace has been performed [10]. Only a few researches were devoted to compiling and assessing the features of these new UPQC models, despite the literature being updated with new models and control methods. Therefore, this study will provide an in-depth analysis of the UPQC patterns and the impact of these different structural configurations on the functionality of the device and associated distribution system. The most significant contribution of this review is to provide a review of the literature on the models, control algorithms, and performance of the D-FACTS devices now in use.

2 Power Quality and Facts Devices in Power Networks

Voltage, current, and/or frequency variations caused by power quality issues may lead to device failure or malfunction. Electrical systems must also maintain sinusoidal voltage with consistent amplitude and frequency so that its users are never without the power they need. Unwanted behavior, power outages, and interference with surrounding communication cables may all be brought on by poor power quality. The issue of electrical system quality has become increasingly complicated in modern times. As a consequence, PQ concerns might get greater attention from energy providers and end customers. It might be difficult to maintain network quality within acceptable bounds. The detrimental effect on quality has been well explored [11]. In the Springer, IEEE and Science Direct databases, the quality enhanced AC flexible transmissions search turned up 14,532 scholarly papers from 2015 to April 2023. The quantity of publications published globally between 2015 and April 2023 is shown in Fig. 1. Figure 2 shows the most well-known researchers and research facilities throughout the globe together with the number of publications each has received.

3 Power Quality Enhancement in Renewable Energy Sources Using Artificial Intelligence Techniques

It is widely believed that renewable energy sources (RES) will shortly displace traditional fossil fuel power production, giving rise to a novel idea of power grids driven by DG systems. However, there are still certain challenges to be solved, such as sporadic power production. Because of this, efforts are being made to develop additional technologies, such as energy storage systems (ESS), dependable power electronic devices, processing systems, and low-latency communications [12].

An intelligent fuzzy controller-based AC-DC micro-grid system has been shown by Nafeh et al. [13] to potentially enhance voltage stability and system power quality. These regulators include fuzzy-PI (FPI), fuzzy-PID (FPID), and distributed static

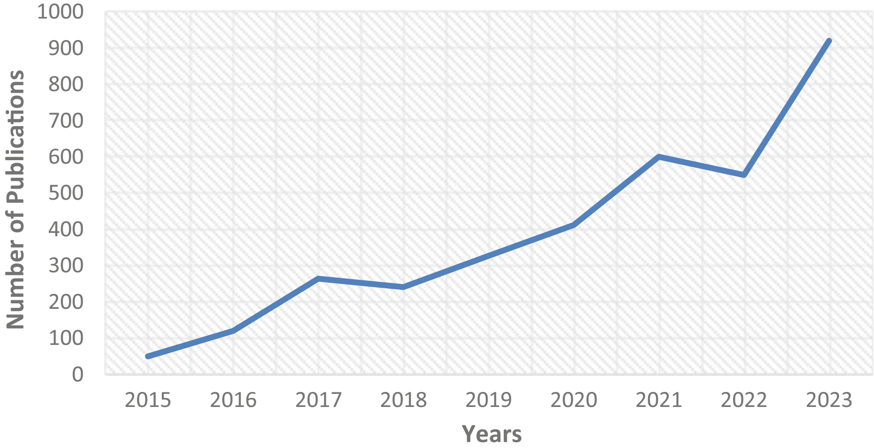

Fig. 1 Number of articles on FACTS devices from 2015 to 2023

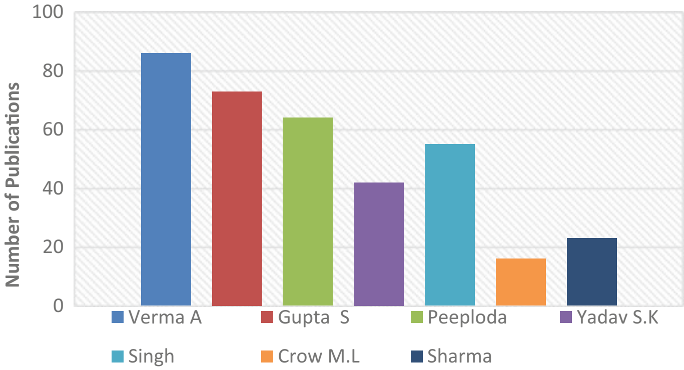

Fig. 2 Outstanding researcher in FACTS devices from 2015 to 2023

synchronous compensators (DSTATCOM) current regulators. Using the capabilities of the suggested system, two case studies simulate unforeseen interruptions and dynamic load changes in a hybrid AC-DC micro-grid including numerous renewable energy sources.

A grid-connected solar and wind photovoltaic system linked to an energy storage system (ESS) and an electric vehicle (EV) was reported by Sarita et al. [14]. Improvement methods include the unified power quality conditioner, generalized unified power flow controller (GUPFC), static var compensator (SVC), fuzzy logic controller unified power flow controller FLC-UPFC, and other AI-based strategies. FLC effectively regulates source-to-load and source-to-source power flow as well as peak and off-peak power usage.

Dheeban and Selvan [15] demonstrate how integrated solar UPQC in distribution systems might enhance power quality using an adaptive neuro-fuzzy inference system (ANFIS). Fuzzy model-based (FMB) controllers boost system performance and aid in generating reference currents by employing language principles to infer system characteristics. PV-UPQC operates well even under a variety of load circumstances. An adaptive neuro-fuzzy inference method reduces harmonic distortion overall by a certain amount.

Micro-grids may enhance power quality in linked electrical distribution networks, as shown by Renduchitala et al. [16]. Power quality problems at the sub-distribution level are resolved using unified power quality criteria. Harmonic currents and voltage imbalances are reduced. Additionally, a network-based adaptive fuzzy inference system that incorporates independent compensating devices in standard coupling stages offers a comprehensive solution for power control.

Grid integrated safety supervisory fuzzy controller (SSFC) was used by Kuchibhatla et al. [17] to build an adaptive approach for PQ analysis in renewable resources. Recurrent neural network (RNN) and cuttlefish algorithm (CFA) are both used in the adaptive approach. For SSFC devices, an adaptive approach is advised to regulate the switching of shunt capacitor banks on risky tuned arm filters. Specific suggested solutions improve demand management and energy efficiency operations for grid utilization. Here, effective power flow regulation with regard to network utilization is taken into account using a power injection model for SSFC.

4 Review Based on Optimization Algorithms

To improve the micro-grid's (MG) overall dynamic performance, Elmetwali et al. [18] provide a compensator with an adaptive switching filter (ASF) and a specially built proportional-integral (PID) controller. The grasshopper optimization algorithm (GOA) is used to establish the PID controller's optimal gain, allowing it to operate adaptively while the MG is running and adapt to changing operating conditions. Rajesh et al. [19] discuss the quality management strategy for RES in a micro-grid system. The recommended method is called the IBSMFO method because it combines an improved bat search (IBS) algorithm with a butterfly flame optimization methodology. In a manner similar to interbreeding, the mutation modifies the bats' dietary patterns. In this case, the moth flame optimization (MFO) algorithm has changed the improved bat search algorithm search procedure in an attempt to reduce the error function. Increasing the efficiency of the system's overall energy storage component is the recommended approach for improving performance.

A hybrid solar, photovoltaic, and wind micro-grid that uses STATCOM was constructed by Bakir et al. [20] to extend the system's stable operational range. The main contribution of this study is to use the genetic algorithm (GA) and bacteria set algorithm (BFA) to optimize the gain settings of the four PI controllers in the STATCOM loop, resulting in enhanced behavior and stability.

In order to improve the voltage profile and reduce harmonic distortion utilizing specific compensating devices in low inertia systems, Sindi et al. [21] developed a multi-micro-grid connection. An adaptive power quality compensator (APQC), which comprises of series and parallel compensators, is one kind of compensating device. The use of a thyristor series controlled capacitor (TCSC) series compensator lowers the transient voltage and dynamic voltage profile. In order to accurately decrease voltage and current harmonic errors, Bharathi and Selvaperumal [22] proposed a modified UPQC PI controller based on the grey wolf optimization (GWO) technique that is incorporated into renewable energy sources like squirrel-cage induction wind turbines (SCIWT). Modified grey wolf optimization (MGWO) was also utilized by UPQC.

To address PQ issues in hybrid renewable energy sources (HRES) systems, Goud et al. [23] proposed atomic search optimization (ASO) with a unified power quality conditioner (UPQC). The main goals of the work are to lessen the PQ problem and balance the load demand in the HRES system. The UPQC system utility is beneficial for the PQ problem. Reddy et al. [24] developed a modified elephant herd optimization (EHO) technique and implemented using a distributed power flow controller (DPFC) to optimize power quality in smart grids. Nonlinear loads are delivered to the system through PQ. On the basis of the recurrent neural network (RNN) algorithm, the EHO method has been modified. Power parameters for PQ disturbances are then recovered after first estimating the projected power flow in the system using the multi-wavelet transform (MWT). Mishra et al. [25] presented a hybrid active power shunt filter (HAPSF) and fractional order low integral derivative controller optimized using grey wolf particle shower hybrid optimization to account for reactive power and harmonics under balanced and unbalanced load conditions.

5 Performance Evaluation

A total of 13 research papers were analyzed as part of this survey. Each research paper uses its own FACTS tool and a different verification algorithm. In this survey, the methods used and to what extent they appreciate the improvement in smart grid's power quality using FACTS devices is analyzed. In the analysis of current research articles presented in Table 1, some methods have low accuracy and computational complexity, and some methods do not effectively highlight areas of power quality improvement. FACTS use several power quality improvements for RES devices. However, the speed of artificial intelligence methods and meta-heuristic approaches needs some improvement.

Figure 3a depicts the review of grid integrated renewable energy sources in power quality improvement. Figure 3b shows the improvement of power quality utilizing FACTS devices like UPQC, STATCOM, and other devices. Figure 3c presents power

Table 1 Overall analysis of survey

Author's name	Renewable energy sources	FACTS devices	Algorithms	Objectives
Nafeh et al. [13]	Wind, PV, fuel cell, and battery	DSTATCOM	Fuzzy-PI (FPI) and fuzzy-PID (FPID)	To maintain unity power factor according to the control loops
Sarita et al. [14]	Wind and PV	UPFC and UPQC	Artificial neural network (ANN)	To facilitate quality upgrades and THD reduction
Dheeban and Selvan [15]	PV	UPQC	Adaptive neuro-fuzzy inference system (ANFIS)	To improve power quality issues
Renduchintala et al. [16]	Wind and PV	UPQC	Adaptive neuro-fuzzy inference system (ANFIS)	To restore the voltage and lessen peak voltage distortions
Kuchibhatlaet al. [17]	Wind and PV	SSFC	Recurrent neural network (RNN) algorithm	To improve power quality issues
Elmetwaly et al. [18]	Wind, PV, fuel cell, and battery	DSTATCOM	Grasshopper optimization algorithm (GOA)	To enhance the MGs' overall dynamic performance
Rajesh et al. [19]	PV, wind turbine, fuel cell, and battery	DPFC	Bat search algorithm and moth flame optimization	To improve power quality issues
Bakir et al. [20]	Solar-wind hybrid micro-grid	STATCOM	GA and BFA	To increase the reliability of operation
Sindi et al. [21]	Wind, PV, battery, and fuel cell	APQC and TCSC	Swarm intelligence-based puzzle optimization	To improve voltage profiles and reduce harmonic distortions
Bharathi and Selvaperumal [22]	Wind turbine	UPQC	Modified grey wolf optimization (GWO)	To eliminate the faults occurred during the transmission of power

(continued)

Table 1 (continued)

Author's name	Renewable energy sources	FACTS devices	Algorithms	Objectives
Goud and Rao [23]	PV, wind and battery energy storage system	UPQC	Atom search optimization (ASO)	To mitigate power quality issues and compensate load demand in HRES system
Reddy et al. [24]	Wind, PV	DPFC	EHO algorithm	To improve the power quality issues
Mishra et al. [25]	–	Hybrid shunt active power filter (HSAPF)	PSO-GWO	To decrease the dc-link voltage deviation

quality improvement in a micro-grid using FACTS devices based on different optimization algorithms. It is clear from Fig. 3c that the most commonly used are the meta-heuristic optimization techniques.

6 Conclusion

Power electronic converters are becoming more and more crucial for integrating vital technologies into smart grids, including electric rail systems, electric mobility, and renewable energy sources (RES). As a result, power quality becomes more important when creating the latest power electronics solutions to maintain power quality and solve problems. In this paper, power quality improvement techniques usually implemented in micro-grids has been reviewed. Various FACTS devices and optimization techniques used for improving power quality are critical analyzed.

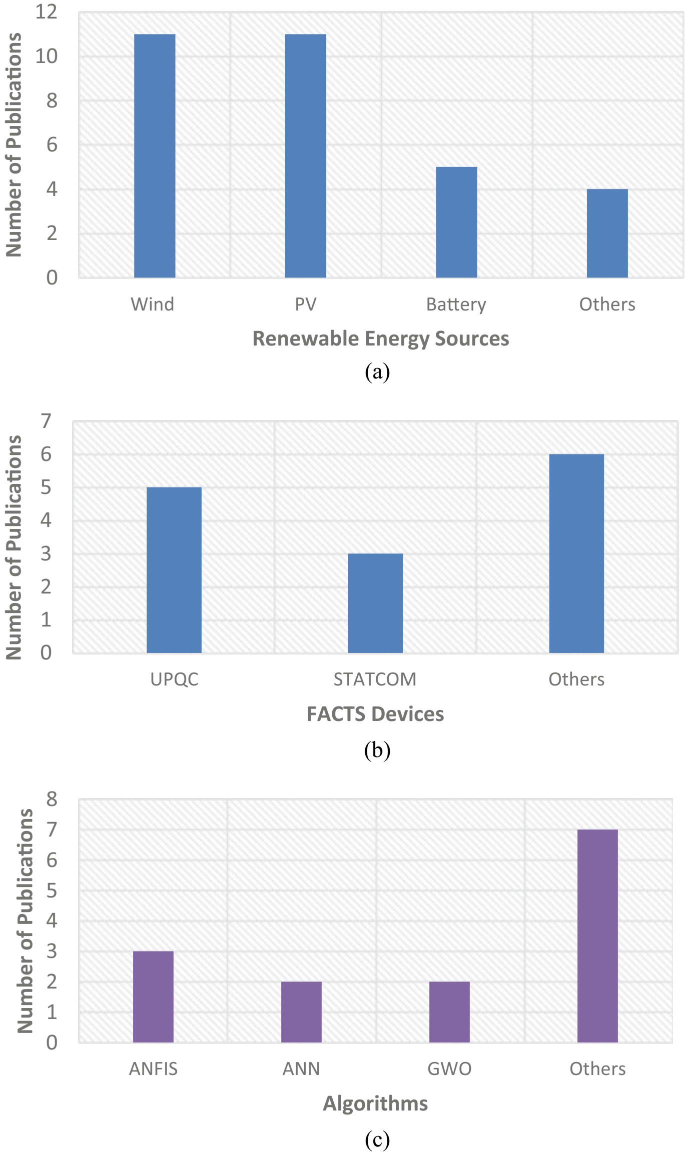

Fig. 3 Review based on **a** renewable energy sources, **b** FACTS devices, and **c** algorithms

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