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Power Filter Control Strategies for Power Quality Enhancement in Renewable Energy-Fed Nonlinear Load Systems: A Comprehensive Review

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Abstract

The gradual assimilation of renewable energy systems including solar photovoltaic and wind energy systems into today's electrical grid system has brought serious power quality issues to light, especially for nonlinear loads. Harmonic distortion, reactive power requirements, voltage fluctuations, and current waveform distortions can negatively affect system effectiveness, dependability, and electrical equipment performance. Power filters can help overcome these major problems and improve overall power quality. The paper presents a comprehensive overview of various filtering techniques used in renewable energy systems and their performance assessment. Different filtering types such as passive filters, active power filters, hybrid filters, shunt active power filters and unified power quality conditioners are analyzed in terms of principles of operation, regulation strategies, harmonics compensation capabilities, response characteristics and degree of implementation complexity of the technologies. Classical regulation technologies including hysteresis control technology, synchronous frame control technology, instantaneous power theory application and PI controller-based technologies are compared with new advanced intelligent and adaptable technologies. The paper also discusses main obstacles coming from changing operating conditions, renewable intermittency, computing requirements and controller stability issues. Finally, new research trends are revealed.

Keywords: Renewable Energy, Power Quality, Nonlinear Load, Active Power Filter, Harmonic Mitigation, Filter Control.

I. Introduction

The fast incorporation of renewable energy sources (RES) namely solar photovoltaic (PV) and wind energy has changed the landscape of today's electricity by introducing much cleaner and environmentally friendly means of producing electricity than burning fossil fuels. The growth of renewable energy dissemination brings many challenges in the power quality area due to the fact that renewable generation equipment is connected to the electricity grid through power electronics converters and is often utilized to feed non-linear and dynamic loads. Non-linear loads, such as diode rectifiers, variable speed drives, switch mode power supplies, etc., consume distorted current and produce harmonics [1]. When the harmonics are combined with the impedance of the grid and RES conversion systems, it may lead to voltage distortions, increased losses in the system, electromagnetic interference, overheating and shortening the lifespan of the equipment.

Quality of power has emerged as an important concern in electrical systems powered by renewable energy sources. The main disturbances experienced in these systems consist of current and voltage harmonics, reactive power, voltage fluctuations, insufficient power factor, current unbalances, and fluctuations/disturbances of transient nature. The discontinuous character of renewable energy generation makes power quality control more difficult because solar radiation and wind speed are

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subject to variability depending on weather conditions. As a result, conventional methods for compensation of power quality will not always work well in rapidly changing conditions [2].

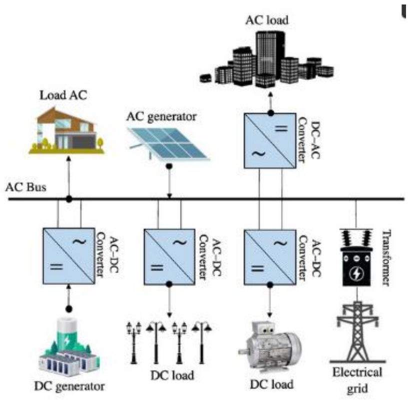

Figure 1: AC–DC Hybrid Power System Architecture [4]

The diagram shown in figure 1 describes how the sensors work with AC/DC generators, AC/DC loads, converters, transformers, and the electrical grid through a single AC bus. This is done to ensure that power is supplied in a coordinated manner. Power filters are commonly used to improve the quality of the electrical power supplied to nonlinear loads. Power filters can be categorized as passive filters, active filters (APFs), and hybrid filters based on their operation and configuration. Passive filters consist of inductors, capacitors, and resistors which allow for the low-impedance paths for given harmonic frequencies. However, even though these filters are easy and cheap to obtain, their performance can suffer due to several factors including parameter variations, resonance, and changes in the load conditions. Active filters are able to avoid many of these disadvantages and achieve significant improvements because they are based on power electronics converters and control techniques that make it possible to generate compensating currents or voltages. Shunt active power filters that are used in current harmonic suppression and reactive power compensation are an example of this type of power filter while series filters are commonly used for voltage disturbances [3].

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The controller must ensure stability and at the same time achieve minimal distortion and a high power factor. Therefore, when selecting the type of filter and control method, it is necessary to take into account the shape of the system, load parameters, including the issue of renewable resource variability.

This work analyzes various power filtering techniques and their control methods in terms of improving power quality in systems with renewable energy sources that supply non-linear loads. It also provides an insight into the origins of power quality issues, discusses how to classify and operate filtering systems, as well as different control methods, and compares their performance [4].

II. Power Quality Issues in Renewable Energy-Fed Nonlinear Load Systems

The growing incorporation of renewable energy sources (RES), especially solar photovoltaic (PV) and wind energy, into modern power networks has come with many challenges in regard to power quality (PQ). The systems utilizing renewable energy are usually interfaced with the power grid using power electronic converters but nonlinear loads such as variable-speed drives, rectifiers, EV chargers, (Switched Mode Power Supplies) SMPS, and electronic devices draw distorted current. The presence of converter-based renewable power generation and nonlinear loads in the network causes significant deteriorations in the electrical power quality to consumers. In contrast with traditional synchronous generators, RES have variable and unpredictable generation characteristics, which can result in even greater voltage and frequency fluctuations in weak distribution networks.

One of the main PQ issues is harmonic distortion. Even when the supply voltage is sinusoidal, nonlinear loads are responsible for consuming non-sinusoidal currents. The power electronic converters that are used in wind and PV systems are able to introduce switching harmonic components to the grid current too; these components create conductor and transformer losses, leading to additional heating and decreased efficiency of the system, as well as interference with delicate electrical equipment. Another significant aspect of consideration is a poor power factor. Nonlinear loads tend to take both active and reactive power and create distorted currents which result in a low true power factor. Low power factors increase the current which is necessary for power taken in terms of active power and thus increase losses associated with transmission while decreasing the efficiency of the equipment used for distribution processes. It is worth mentioning the reactive-power compensation provided by the renewable energy converters which can be intended for regenerative power process; nevertheless, wrong control techniques can lead to the emergence of reactive-power oscillations and unstable operation. It is also essential to mention the voltage fluctuations and voltage variations in renewable energy systems. The output of solar panels is dependent on solar irradiance, cloud movements, and temperature changes whereas the production of wind power is affected by the wind speed. Such rapid processes connected with renewable energy production can trigger voltage variations [5]. There are some causes behind voltage sag, voltage swell, or interruption which include faults, switching operations, abrupt changes in load, or variations in renewables generation. Voltage sag describes the decrease of RMS voltage but voltage swell the increase. These disturbances can lead to wrong operation or failure of delicate electrical devices and equipment. For that reason, renewable energy converters must react to disturbances very quickly while keeping stable DC-link voltage and proper grid current injection. Reactive power unbalance and current unbalance is also the issue in addition to the ones mentioned above particularly for distribution networks serving single-phase and three-phase nonlinear loads.

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The unequal load can produce negative sequence currents, extra losses occurring, and overheating the rotating machines and transformers. Additionally, switching of converters can produce high-frequency components and electromagnetic interference. The interaction of renewable generation, converters, nonlinear loads, and grid impedance can lead to resonance phenomena. Resonance can increase some specific harmonic component causing distortions in voltage or current. Therefore, sometimes it is not enough to apply passive filtering to cope with rapid operating conditions. Therefore, maintaining acceptable power quality in renewable-energy-fed nonlinear-load systems requires coordinated control of renewable converters, loads, energy-storage units, and filtering devices. Advanced control techniques based on instantaneous power theory, synchronous reference frames, predictive control, adaptive control, and intelligent algorithms can improve dynamic compensation. Effective PQ management not only improves voltage and current waveforms but also enhances system efficiency, reliability, stability, and the capability of distribution networks to accommodate higher levels of renewable-energy penetration.

III. Fundamentals and Classification of Power Filters

Power filters are vital devices that enhance the quality of power by eliminating harmonics, compensating for reactive power, minimizing current distortion, and improving the quality of voltage in the electrical systems that utilize renewable energy sources and nonlinear loads. Nonlinear loads such as diode rectifiers, variable-frequency drives, switched-mode power supplies, and electric vehicle chargers cause the current to be distorted because the currents produced do not follow the sinusoidal voltage wave. The power filters generate compensating currents or voltages which eliminate harmonic disruptions and allow the current to obtain a sinusoidal wave form. Specifically, in the case of renewable energy systems, the power filters play a critical role because the power electronic interfaces used in conjunction with photovoltaic energy systems and wind systems can introduce even more switching harmonics into the system. Power filters can be divided into three general groups: passive power filters, active power filters, and hybrid power filters. Passive filters consist of some inductors, capacitors, and resistors arranged in different configurations. Passive filters can be classified into single-tuned, double-tuned, high-pass, and C-type depending on their behavior at certain frequencies. The single-tuned filter is designed to be able to have lower [6]-[7]. Active power filters are devices that employ power electronic converters to create compensating currents and voltages. In this regard, APFs are divided into three main types, which are the shunt APF, a series APF, and the unified power quality conditioner. In terms of the shunt APF, it works by being connected in parallel to the nonlinear load. As a result, the shunt APF injects compensating current to eliminate current harmonics and reactive powers. Inasmuch as the series APF is concerned, it connects in series with the supply, allowing it to compensate for voltage disturbances. Finally, the unified power quality conditioner is a device that integrates both shunt and series compensations.

Moreover, filters can be classified based on their connectivity arrangement. That means it's possible to distinguish shunt, series and combined filters. However, the choice relies upon the nature of a power quality problem, voltage level, load parameters, penetration of renewables into the system and speed of compensation. For the systems based on renewable energy and nonlinear loads, active and hybrid filters are becoming more common since they can change according to changing loads. Thus, it has to be pointed out that the appropriate topology of a filter and an efficient control system play a key role in effective THD reduction and improvement of power factor and stable operation of the grid.

IV. Conventional Power Filter Control Strategies

The control strategy used for an active power filter plays a major role in its performance as the controller decides on the reference compensating current or voltage and also generates the required switching signals for the converter. Some conventional methods employed for controlling the active power filter are instantaneous power theory, synchronous reference frame theory, hysteresis current control, and proportional-integral (PI) control. All the mentioned methods have turned out to be popular since they are quite simple and fast in their response [8]. Harmonics and reactive power components are removed, and the reference compensating currents to be generated are based on them; the method is considered very effective, particularly when dealing with nonlinear loads, but its efficiency may depend on the quality of supply voltages. The control strategy used for an active power filter plays a major role in its performance as the controller decides on the reference compensating current or voltage and also generates the required switching signals for the converter. Some conventional methods employed for controlling the active power filter are instantaneous power theory, synchronous reference frame theory, hysteresis current control, and proportional-integral (PI) control. All the mentioned methods have turned out to be popular since they are quite simple and fast in their response.

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Although conventional strategies are computationally simple and effective under steady operating conditions, their performance can deteriorate under rapidly changing renewable generation, grid disturbances, parameter variations, and highly nonlinear loads. These limitations have encouraged the development of adaptive, predictive, fuzzy, neural-network, and optimization-based control techniques for advanced power-filter applications.

V. Advanced and Intelligent Control Techniques For Power Filters

The growing adoption of renewable energy sources and power-related non-linear loads has resulted in a demand for the new control methods. Traditional control techniques like proportional-integral control, synchronous reference frame control, and hysteresis current control produce good results whenever working conditions are fixed, and the load, compensation capacities, and grid conditions remain the same. However, to get around the limitations imposed by the conventional methods, advanced and intelligent control systems apply predictions, adaptation, learning, optimization, and non-linear decisions. Model predictive control (MPC) is an important advanced method of active power filtering. This type of control evaluates how the filter currents are going to behave in the future and determines the switching states. The capability of MPC allows obtaining a rapid response, accurate current measurement, and direct control of all converter parameters. MPC suited for smart renewable plants where the photovoltaic generation and consumption vary rapidly, but this method is tightly complicated and costly. [10] Adaptive control varies the parameters of the controller based on fluctuations in the working conditions of the system. Unlike constant-gain controllers, the adaptive controllers are able to react against changes in the load current and grid impedance, renewable energy production, and disturbances of the system. This enables the adaptive control to achieve better performance in compensation in dynamic conditions. Continuous estimation of harmonics and making the corresponding references can be performed by means of adaptive filtering techniques as well. Fuzzy logic control (FLC) is another smart technique which does not need an accurate physical model of the power system. Instead, this approach uses linguistic rules and membership functions to take actions that are required based on input parameters such as the current error and its change rate. This technique is considered to be very effective under varying parameters [11].

Artificial neural network (ANN)-based control uses learning capabilities to identify nonlinear relationships between system variables and required compensation signals. Neural networks can be trained using measured voltage, current, harmonic, and load information to estimate reference compensating currents rapidly. Once trained, an ANN can provide fast decision-making and can adapt effectively to complex operating conditions. Deep-learning models can further improve feature extraction and disturbance recognition when sufficient training data are available. Optimization-based techniques, including genetic algorithms, particle swarm optimization, and other evolutionary approaches, can be used to optimize controller parameters, filter sizing, switching strategies, and compensation performance. These methods can minimize harmonic distortion, switching losses, reactive-power requirements, or a combination of several objectives [12]. In recent times, hybrid intelligent control strategies have gotten a great deal of attention. These methods combine various forms of conventional control systems with fuzzy logic, neural networks, adaptive algorithms, predictive control, or optimization methods. Such combinations are capable of yielding better precision, increased speed of dynamic reaction, robustness, and adaptability than any single approach. In the case of non-linear load systems fed with renewable energy, intelligent controllers are especially advantageous since they can respond efficiently to the variable generation process, fluctuating loads, changes in the harmonic structure, as well as grid disturbances. Thus, intelligent control development is an important aspect of advanced active and hybrid power filter creation, which makes it possible to provide high-power quality in changing conditions.

In Table 1, we can find a comparison of the latest research that is related to the control techniques of the power filter. Several approaches used in the control include predictive control, adaptive control, control based on the use of neural networks, algorithms used for control, and hybrids, etc. The results obtained as a result of the research show that various parameters of the power filter improve, thoroughly harmonic mitigation, reactive power compensation, current control, and transient stability. Nevertheless, difficulties do persist, i.e., the complexity of calculation processes, parameter sensitivity, controller tuning, and not enough experimental proof of the effectiveness of the developed technology. The bottom line of the works analyzed is that there is a demand for the development of technology used for the power filter that would ensure the high quality of the power provided under conditions of the impact of the nonlinear load and renewable sources of energy.

Table 1 Comparative Analysis, Challenges, And Emerging Trends

Ref.	Power Filter / System	Control Technique	Main Objective	Key Findings / Contribution	Limitation / Research Gap
[8]	PV-interfaced multilevel inverter shunt APF	Predictive Direct Power Control	Improve PQ in grid-connected PV systems	Predictive direct-power control effectively reduces harmonic distortion and improves the dynamic response of the shunt APF.	Predictive control involves higher computational requirements and controller complexity.
[9]	Coal-fired power generation system	Extended-State Kalman Filter + Model Predictive Control	Improve system control and energy efficiency	Integration of state estimation with predictive control improves dynamic regulation and energy-saving performance.	Application is mainly focused on conventional generation rather than renewable-fed nonlinear loads.
[10]	Hydrogen–PV sustainable energy system	Robust hybrid control	Improve operational performance of integrated renewable systems	Hybrid control improves robustness and coordination between hydrogen and PV subsystems under changing operating conditions.	Does not specifically address comprehensive harmonic compensation using APFs.
[11]	PV-UPQC for electrical railway	AI-based hybrid control + Lyapunov optimization	Improve railway power quality	Intelligent control and optimization provide improved compensation and dynamic PQ performance in a PV-UPQC system.	Computational complexity and practical implementation remain important considerations.
[12]	PMSM drive system	SMO with improved prefilter and position-error compensation	Improve sensorless motor control	Improved observer and prefilter design enhances position estimation and control performance under varying operating conditions.	Primarily designed for motor drives rather than renewable-energy-fed APF applications.
[13]	Grid-forming converter	Virtual oscillator control + robust current control	Improve transient stability	Robust inner current control improves converter response	Focuses on grid-forming operation rather

				and transient stability during disturbances.	than direct harmonic filtering.
[14]	Wind-power-integrated grid	Kalman filtering + Deep Residual Learning + BiLSTM	Improve wind-power forecasting and grid stability	Hybrid forecasting improves prediction capability, supporting better grid operation under variable wind generation.	Forecasting improvement does not directly provide real-time harmonic compensation.
[15]	Split-source inverter-based shunt APF	Adaptive control	Improve power quality	Adaptive control with split-source inverter topology provides effective harmonic compensation and improves power-quality performance.	Adaptive controller design and parameter tuning can increase implementation complexity.
[16]	Three-phase active power filter	Compound PI controllers	Improve current and voltage control	Parallel current and voltage control with compound PI controllers enhances APF dynamic performance and tracking capability.	PI-based control may require retuning when operating conditions change significantly.
[17]	PV-connected single-phase shunt APF	Nonlinear multi-loop control	Compensate nonlinear-load harmonics and reactive power	The nonlinear controller simultaneously addresses harmonic current, reactive power, PV voltage, and DC-bus regulation in a PV-fed APF system.	Multi-loop nonlinear control increases design and implementation complexity.
[18]	Shunt hybrid active power filter	EFLN-based nonlinear adaptive filtering	Reduce source-current harmonics and reactive-power burden	The nonlinear adaptive filter improves fundamental-current extraction, harmonic mitigation, and unity-power-factor operation; simulation	Algorithm complexity and real-time computational requirements may increase with system scale.

				was also supported by real-time hardware implementation.	
[19]	Shunt active power filter	Adaptive ANN/ADALINE + PI control	Improve PQ under nonlinear and dynamic loads	The adaptive neural-network controller improves fundamental-component extraction and SAPF switching performance under changing loads; laboratory implementation was reported.	ANN training and controller implementation require suitable computational resources and training conditions.
[20]	Three-level NPC shunt APF	Predictive direct power control + PLL + SVM	Improve harmonic compensation and converter control	Predictive direct-power control combined with PLL and SVM provides fast and accurate control of the three-level SAPF.	Predictive switching control requires accurate system information and significant computational processing.
[21]	Active, passive and hybrid APF systems	Comparative control strategies	Review APF control and compensation techniques	The study systematically compares reference-current generation, current-control methods, passive/active/hybrid filters, and APF applications in distributed-generation systems.	Review identifies the need for more adaptive, economical, and real-time intelligent control methods.
[22]	Three-level HAPF with PV, wind and EV loads	FOPID + Jaya Grey Wolf optimization	Improve PQ under renewable and EV-load variations	The optimized controller improves DC-link stabilization, harmonic mitigation, power factor, and performance under different EV, nonlinear-load, and solar-irradiation	Optimization increases computational burden and requires appropriate parameter selection.

				conditions.	
[23]	PV-based shunt APF	Optimal Operating Point Tracking + Harmonic Identification	Simultaneously supply load, mitigate harmonics and inject power into grid	The proposed PV-SAPF control coordinates PV operation and harmonic compensation; reported simulations achieved grid-current THD below 1% during surplus PV generation.	Further experimental validation under highly dynamic grid and nonlinear-load conditions is required.

VI.Conclusion

Different types of power filter technologies and strategies have been considered for the improvement of power quality in renewable energy-based non-linear load systems. Based on the performed analysis, it was concluded that harmonic distortion, reactive power, voltage fluctuation, low power factor, and current imbalances are still one of the main problems caused by nonlinear loads, power electronic converters, and intermittent renewable generation. Passive filtering is a simple way to address these issues but does not provide advanced dynamic performance. Traditional controls such as hysteresis, PI, synchronous reference frame, and instantaneous power theory have been proven to be effective, while high-tech solutions based on fuzzy logic, neural networks, predictive control, adaptive and optimization approaches show better results. Further research needs to focus on self-adapting filter controllers which can deal with renewable intermittency and dynamic nature of non-linear loads.

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