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A Review on Power Quality Enhancement in Solar-Wind System Using MATLAB

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Abstract: The growing demand of renewable energy sources (RES) such as solar photovoltaic (PV) and wind energy into power distribution networks has significantly increased the importance of power quality (PQ) enhancement due to issues like harmonics, voltage sags/swell and frequency fluctuations. Traditional power networks were not originally designed for such distributed, intermittent, and non-linear generation, and hence require advanced PQ mitigation techniques. Recent studies have presented a variety of solutions ranging from passive filters to intelligent control of active filters and custom power devices. It provide a comprehensive review of PQ enhancement methods, categorizing solutions into passive, active, and hybrid filters, along with custom devices like STATCOM and UPQC. Their work highlights critical research gaps, particularly the need for adaptive and intelligent controllers, hardware prototypes, and optimization-based filter tuning. Their simulation results demonstrate a significant reduction in total harmonic distortion (THD) and improved stability. The Multi-Converter Unified Power Quality Conditioner (MC- UPQC) for simultaneous PQ improvement across multiple feeders. Their study shows effective mitigation of sag, swell, and harmonic distortion, but also points to challenges in controller coordination, converter sizing, and integration with storage for practical applications. Taken together, the reviewed literature underscores that while UPQC, MC-UPQC are effective in theory and simulation, research gaps remain in practical implementation. These include adaptive and intelligent control under highly variable RES conditions.

I.INTRODUCTION:

The integration of renewable energy sources (RES) such as solar photovoltaic (PV) and wind into modern power systems has been rapidly increasing due to growing energy demand, depletion of fossil fuels, and the global drive toward carbon neutrality. While RES integration provides environmental and economic benefits, it also introduces significant challenges in maintaining power quality (PQ) in electrical networks. The inherently intermittent and stochastic nature of solar and wind resources leads to frequent voltage fluctuations, harmonics, unbalances, frequency deviations, and transient disturbances.

Furthermore, the widespread use of power electronic converters in RES interfacing, as well as in industrial and residential loads, introduces nonlinearities that exacerbate PQ issues. Over the last two decades, a variety of PQ enhancement techniques have been proposed. Traditional methods, such as passive filters, were effective for specific harmonic frequencies but suffer from problems of resonance and fixed compensation. To overcome these drawbacks, active power filters (APFs) were introduced, offering dynamic and adaptive compensation for harmonics and reactivepower. Later developments such as unified power quality conditioners (UPQC) and distribution static compensators (DSTATCOM) provided more comprehensive solutions by simultaneously mitigating voltage and current disturbances. Recent research has also focused on hybrid approaches that combine passive and active filtering for improved efficiency, and on multi-converter configurations like MC- UPQC, which extend PQ compensation to multiple feeders, making them suitable for interconnected distribution networks.

The objective of this review paper is to provide a comprehensive synthesis of recent PQ enhancement techniques for renewable-rich distribution systems. By critically analyzing conventional methods, custom power devices, filter topologies, and intelligent control strategies, this work identifies the strengths, limitations, and future directions in PQ improvement. The review draws from both theoretical contributions and practical case studies, thereby offering a consolidated perspective on how PQ enhancement can be achieved in modern grids with high RES penetration.

Despite these advancements, several research gaps remain.It emphasize, the majority of reported solutions are validated only in simulation environments, with limited experimental or hardware-based verification.

REASONS FOR DEGRADATION IN POWER QUALITY

As we've seen, the non-linear load introduced into the power source by electronics and drives can cause problems with power quality, which in turn can cause electrical devices used by end users to malfunction, fail, or simply stop working. Therefore, power quality degradation impacts sensitive equipment for a variety of reasons. The Techniques to improve the Power quality of a hybrid system are as shown in fig below.

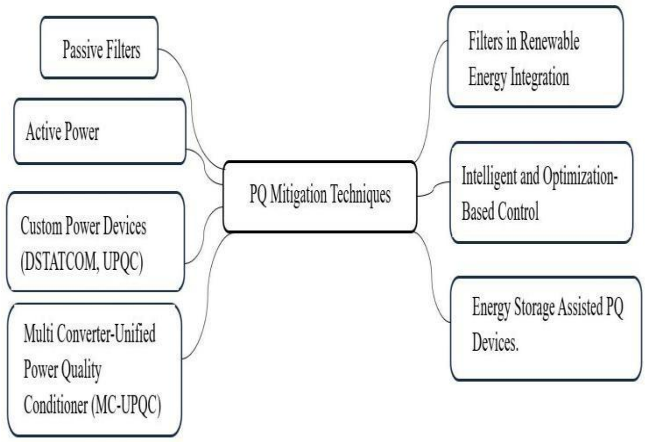


Fig1: PQ Mitigation Techniques

1. Conventional PQ Mitigation Techniques These are traditional hardware-based methods used to suppress harmonics, regulate voltage, and control reactive power.

Passive Filters:

These filters use combinations of resistors (R), inductors (L), and capacitors (C) to eliminate specific harmonic frequencies.

Advantage: Simple design and low cost. Limitation: Fixed compensation; not suitable for dynamic loads or variable renewable sources.

Active Power Filters (APF): APFs use power electronic converters to inject compensating currents dynamically, canceling harmonics and reactive power. Advantage: Real-time control, suitable for nonlinear and varying loads.

Example: Shunt and series active filters in MATLAB simulation models.

Custom Power Devices (DSTATCOM, UPQC):

DSTATCOM (Distribution Static Compensator):Improves voltage regulation and compensates reactive power.

UPQC (Unified Power Quality Conditioner): Combines series and shunt converters for both voltage and current compensation.

Advantage: Highly effective for PQ problems like sags, swells, flicker, and harmonics in hybrid renewable systems.

Multi-Converter–Unified Power Quality Conditioner(MC-UPQC):An advanced version of UPQC using multiple converters interconnected through a DC link.

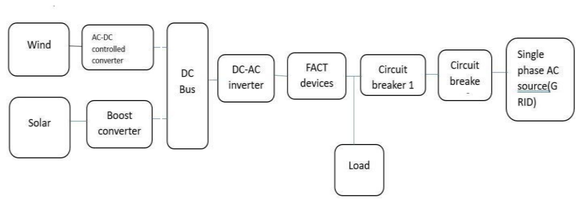
Advantage: Provides compensation across multiple feeders; ideal for solar–wind hybrid grids.

MATLAB/SIMULINK MODELLING

The proposed system integrates both solar and wind energy sources to enhance power generation reliability and efficiency while addressing power quality concerns. The system aims to improve power system performance through the utilization of a STATCOM (Static Synchronous Compensator) device and advanced control strategies. Given the variable nature of wind power generation, maintaining power quality becomes a challenge. To tackle this issue, the article suggests employing simulation and analysis techniques to optimize the filtering, rotation, and power enhancement capabilities of synchronous static amplifiers. These amplifiers, coupled with effective control strategies, can mitigate power fluctuations and improve overall system stability. The integration of solar and wind energy into the power system involves multiple steps, including power generation, transmission, and distribution. The main objectives of this work are to ensure the continuous supply of electricity to meet customer needs while maximizing the efficiency of power generation.

After going over the STATCOM's main operating idea, we can now understand how it working for which the proposed flow diagram is presented in figure 1. Source V1 in the diagram above is the voltage coming out of the STATCOM and electrical circuit of STATCOM is shown in figure 2. When the power system's reactive power demand goes up, STATCOM raises its output voltage V1 while keeping the phase difference between V1 and V2 the same (it shall be noted here that there will always exists small phase angle between V1 and V2 to cater for the leakage impedance drop in the interconnecting Transformer).

Because V1 is bigger than V2, STATCOM will send reactive power to the power grid. So, STATCOM gives out reactive power and acts as a generator of reactive power.



FLOWCHART

The flowchart depicts the methodology of enhancing power quality in solar-wind systems. It begins with data acquisition from the system, followed by signal processing, application of PQ improvement techniques, and simulation in MATLAB, concluding with performance analysis and results evaluation.

RESEARCH GAP

After looking at the research that has been done and is being done in the field of improving power quality and reducing harmonics, several research gaps have been found.

Limited Integration of Multiple PQ Techniques:

Most existing studies focus on individual PQ improvement methods such as DSTATCOM, UPQC, or passive filters. There is still a lack of integrated hybrid approaches(e.g., combining MC-UPQC with intelligent control) that can address all PQ issues simultaneously in hybrid renewable systems.

Insufficient Modeling of Hybrid Solar–Wind Systems in MATLAB/Simulink: Many studies analyze PQ for either solar

PV or wind systems individually. Comprehensive MATLAB-based simulation models that consider dynamic interaction, intermittency, and synchronization of both sources are limited.

Underexplored Intelligent Control Strategies: While conventional controllers (like PI or PID) are commonly used, the application of AI-driven control techniques (fuzzy logic, neural networks, adaptive optimization algorithms) for real-time PQ enhancement is still in early stages and needs further validation Lack of Real-Time Implementation and Hardware Validation: Most research remains simulation-based. There is a significant gap in hardware-in-the- loop (HIL) or prototype validation to confirm MATLAB simulation results under real operating conditions.

Neglect of Energy Storage Integration in PQ Studies:

Energy storage systems (battery, super capacitor, flywheel) are rarely integrated with PQ devices. Research is needed to evaluate how energy storage- assisted PQ conditioners can stabilize voltage and frequency fluctuations in hybrid setups.

II.LITERATURE REVIEW

The integration of solar and wind energy sources into hybrid systems has gained significant attention due to their complementary nature and potential to enhance grid stability. However, this integration often introduces power quality (PQ) challenges such as voltage sags, harmonics, and frequency fluctuations. To address these issues, various mitigation techniques have been explored.

Power Quality Challenges in Hybrid Systems

Hybrid renewable energy systems (HRES) are susceptible to PQ disturbances due to the intermittent nature of solar and wind power. These disturbances can lead to voltage instability and increased total harmonic distortion (THD) The use of power electronic converters, while essential for integrating renewable sources, can exacerbate these issues if not properly managed.

III.CONCLUSION AND FUTURE WORK/SCOPE

The current global power supply is inadequate and cannot keep up with the ever-increasing demand for electricity. Furthermore, complexity at the load end is becoming more of an issue as electronic gadgets become increasingly commonplace. The poor quality of the electricity also causes power equipment to malfunction or the power system to fail.

It is crucial for customers to take preventative measures to overcome these issues and avoid financial losses due to PQ issues. This paper presents several contributors to power quality deterioration, as well as recent studies aimed at improving power quality, the research gaps revealed by this analysis, and the existing state of the art in this research domain, which includes many issues that have yet to be adequately addressed. To simulate the impact of a STATCOM (Static Synchronous Compensator)on power quality and system stability, you can use software like MATLAB/Simulink . First,model the power system including wind turbines, solar panels,transmission lines, and loads. initial conditions including wind speed profiles, solar irradiance, then run the simulation to observe the system's behavior under various disturbances. Analyze key metrics like voltage stability, power quality, and reactive power flow to assess the STATCOM's effectiveness, and fine-tune its control parameters for optimal performance.

III.RESULTS

Recent studies on power quality enhancement in solar-wind hybrid systems demonstrate significant improvements in voltage stability, harmonic reduction, and overall system performance. Techniques such as Unified Power Quality Conditioners (UPQC), Flexible AC Transmission Systems (FACTS) devices, and active filters have been widely employed to mitigate voltage sags, swells, and harmonics. Simulation results reported in the literature show that THD (Total Harmonic Distortion) can be reduced substantially—for example, UPQC has been observed to decrease voltage THD from 45% to around 26% and current THD from 8% to below 3%. In addition, the integration of power factor correction converters and advanced control strategies, including fuzzy logic, PID, and AI-based approaches, has improved voltage profiles, enhanced energy efficiency, and ensured near-unity power factor in hybrid systems. MATLAB/Simulink modeling has been extensively used to analyze these mitigation strategies, confirming their effectiveness under varying load and environmental conditions. Overall, these findings highlight that combining multiple PQ enhancement techniques with intelligent control strategies can significantly improve the reliability and efficiency of solar-wind hybrid energy systems.

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