Enhancing Power Quality and Reactive Load Distribution in Solar-Wind Hybrid Systems Through Converter Controls: A Review

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Abstract: *The critical role that cutting-edge converter controls play in addressing the problems with reactive load distribution and power quality within solar-wind hybrid systems is examined in this review. These hybrid systems present an encouraging way forward as the world looks for more sustainable energy solutions. However, they deal with complicated grid integration problems and patchy generation, which can affect the stability of the power supply. This review covers the use of active power filters, grid-interactive inverters, and more sophisticated reactive power management techniques to get around these obstacles. Better voltage regulation, harmonics reduction, and balanced reactive power supply are all made possible by these control technologies. To improve system performance and reliability, we also look at the advantages of integrating energy storage systems. These innovations are becoming more and more important as technology develops for the seamless integration of solar-wind hybrid systems into modern power grids, ushering in a cleaner, more resilient, and sustainable energy landscape.*

Keywords: *Advanced converter control, Power quality, Reactive load distribution, Solar-wind hybrid systems, Grid-interactive inverters, Active power filters, Reactive power management,*

1. INTRODUCTION

In the field of power electronics, electronic circuits are used to convert and control the flow of electrical energy from one form to another, such as from alternating current (AC) to direct current (DC) (rectifier), from DC to AC (inverter), from DC to DC (dc-converter), or from AC to AC (ac-converter). It has many uses, including industrial automation, small- and large-scale storage systems, electric vehicles, and hybrid renewable energy sources. Figure 1 displays a block diagram of a power electronic system. In this case, a key element of any power electronic system that is essential to achieving high energy efficiency is the power processor unit. Due to the costs associated with wasting energy and the difficulties in effectively managing the heat produced as a result of energy dissipation, it is imperative to reduce power losses in this unit. This highlights the value of modeling power conditioning systems and taking into account their losses in the power industry. [1].

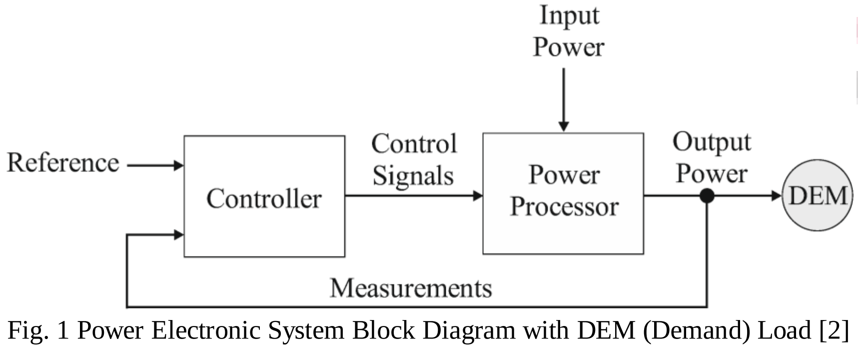

Fig. 1 Power Electronic System Block Diagram with DEM (Demand) Load [2]

Modern attempts to address climate change and make the shift to sustainable energy sources have made the integration of renewable energy sources, such solar and wind power, a pillar [3]. Hybrid solar-wind systems that combine the advantages of both energy sources have drawn a lot of interest as a way to generate electricity effectively. It is not without difficulties, though, for them to be seamlessly integrated into the current power networks [4]. Upholding power quality and efficiently spreading reactive loads rank among the most important concerns. Convertor control tactics play a crucial role in this situation, which cannot be understated. This article examines the topic of converter control in solar-wind hybrid systems, examining how these techniques help to improve power quality and optimize the distribution of reactive loads. It reveals the complexities of various control strategies, illuminating their importance in maintaining the dependable and long-term performance of hybrid renewable energy systems.

2. CHALLENGES IN SOLAR ENERGY'S POWER QUALITY

Concerns about power quality have become more prominent in the modern energy landscape, especially as renewable energy sources gain popularity. The importance of comprehending and resolving power quality issues has increased as the world moves toward cleaner and more sustainable forms of power generation. The complex power quality issues posed by renewable energy sources must be thoroughly understood by engineers, technicians, and system operators. These difficulties cover a wide range of topics, such as voltage stability, harmonic distortions, frequency changes, and reactive power imbalances. Additionally, elements like intermittent renewable energy production, unpredictable weather patterns, and complex integration of these sources into already-existing power grids add to the difficulty of ensuring consistent and dependable power quality. A comprehensive comprehension of this dynamic energy landscape a holistic understanding of power quality issues is essential to design, operate, and maintain renewable energy systems that meet the stringent demands of modern electricity grids while advancing the goals of sustainability and environmental responsibility.

2.1 Problems with Voltage Regulation

The management of distribution system voltages has been significantly hampered by the extensive adoption of distributed solar energy. Due to intrinsic mechanical restrictions, traditional voltage management techniques such as online load tap changing (OLTC) transformers, voltage regulators (VRs), and shunt capacitors are unable to quickly respond to sudden voltage variations. The result of this ineffective voltage management has been problems including spillage from solar power and, in rare circumstances, overall shutdowns of distributed solar farms [5]. These problems underscore the importance of addressing voltage regulation challenges in the context of solar energy integration.

2.2 Voltage Sag, Swell and Flicker

Many topics demand investigation in the larger field of power quality research. These include the direct computation of time-domain steady-state solutions for systems with nonlinear and electronically switched loads, error analysis of numerical integration techniques used in time-domain simulations, effective and precise state estimation techniques for power quality applications, nonlinear load modeling, and the design of grounding systems.

Existing power quality difficulties can be seen from two different angles when it comes to measuring harmonics, voltage sags, voltage swells, flicker, surges, energy usage, and changes in frequency. The first perspective looks at disturbances that originate on the utility side but harm customers, while the second investigates disturbances that are caused by customers but also have an effect on the utility side. While it is known that revenue meter locations serve as the boundary between customers and utilities, this may not be the most natural boundary for power quality considerations. Instances where fault clearance times result in voltage sags unacceptable to customers or where time-varying loads like arc furnaces or variable-speed drives introduce unwanted harmonics into the utility feeder exemplify such cases [6].

Poor power quality in both cases extends over the revenue metering point and into the territory of the opposing party. Results from system studies can be used to inform the creation of approaches for identifying concerns with consumer power quality, particularly if these problems are caused by utility system activities. Even when only one party is directly involved in the solution within their operational zone, there are specific circumstances in which collaboration between the utility and the consumer may be necessary to find the best solution, possibly involving cost-sharing for implementation.

Power quality issues can be brought on temporarily by a variety of sources, including failures, switching capacitor banks for power factor correction, large motor starting transients, or the usage of static var compensators. As a result of such events, these problems appear as voltage sags, voltage swells, flickers, surges, and interruptions.

Harmonics reduction, modeling of harmonic sources, and measuring voltage and current signal distortion at crucial system locations through harmonics studies are further areas of power quality study. Through the processing of measured or recorded signals, signal processing techniques play a critical role in assessing power quality.

Grid-connected photovoltaic (PV) systems rely on an essential operating tenet that is centered on the detection of voltage and current within the local grid, particularly from non-linear loads. The success of such systems depends on this fundamental idea, which acts as their key component. The grid's voltage and current parameters must be precisely measured in the first step. After obtaining these readings, the system continues by calculating a command current signal that includes not only the active power component intended for injection into the power grid but also additional components corresponding to harmonic and reactive load currents. When dealing with the harmonics and reactive power issues, the sophistication of these PV systems is brought to the fore. These systems are capable of managing and mitigating harmonic and reactive current components by continuously monitoring the actual compensation current generated in response to the command current. This means that the PV system simultaneously compensates for the active power component of the grid current, ensuring that it aligns with the intended injection, and offsetting any undesirable harmonic and reactive current components originating from the nearby non-linear loads. To put it simply, this technique enables grid-connected PV systems to contribute to the grid with improved power quality, decreased distortion, and increased efficiency, as described in reference [7].

2.3 Voltage Imbalance, Fast and Slow Voltage Variations

Voltage variations exhibit differences between the supplier's side and the user's side. The International Electrotechnical Commission (IEC) 038 standard distinguishes two voltage types in electrical networks and installations:

Supply Voltage: This refers to the line-to-line or line-to-neutral voltage at the point of common coupling, which is the primary supply point of an installation.

Utility Voltage: This represents the line-to-line or line-to-neutral voltage at the plug or terminal of an electrical device.

Voltage characteristics undergo evaluation based on the EN 50160 standard, which pertains to supply voltage, and the IEC 61000-2-2 standard, which addresses utility voltage.

3. Methods for Increasing Power Quality and Voltage Stability in Solar and Wind Hybrid Power Systems

The two main issues with wind and solar hybrid power systems are power quality and voltage stability. Since both sources are renewable, their respective output is reliant on their natural surroundings. The amount of sunlight varies throughout the day, and the wind's speed is not constant. The solar energy system will not function during the rainy season. As a result, voltage will fluctuate and power quality will decline. Various controllers are employed in this to maintain stability and improve power quality. The UPFC, D-STATCOM, IPFC, SVC, SSSC, and fuzzy logic controllers are used to enhance power quality and stability. The voltage stability of the power system is reduced as a result of harmonics and voltage swell, sag, which are produced within the system. The FACTS devices are attached to the inverter's output terminal prior to powering the load. These FACTS devices aid in enhancing power quality by reducing harmonics in the current waveform. The STATCOM used is a Static Synchronous Compensator, which is used as a shunt compensating device to reduce reactive power compensation, improve the steady state of the system, and also improve transient stability. Reactive and active power compensation are both done with it [8].

4. EMERGING TRENDS – RELATED WORK

The demand for power on a global scale has greatly increased recently. Renewable energy sources have taken on a crucial role in order to satisfy this expanding demand and emphasize environmentally responsible alternatives. Among these, eco-friendly choices like solar and wind power systems stand out. However, the stability of the system may be impacted by their reliance on shifting atmospheric conditions. Power quality issues, particularly harmonics and voltage instability, are a major barrier to the production of solar and wind energy. Through the use of FACTs devices as controllers, Sunny Vig and Harvinder Singh [9] addresses these issues by introducing a simulation model for solar and wind power systems. ETAP software is used to run the simulations.

Small-scale power generation from renewable resources is effective and environmentally friendly, however integration problems arise because of source variability. Mohammad Nurul Absar et al. [10] suggests improving the power quality in a grid-integrated renewable hybrid system, specifically for the Rohingya Refugee camp, by using wind and sun sources. In order to meet the demands for reactive power, it offers a Static VAR Compensator (SVC), a shunt-type FACTS device. The performance of the system was assessed using load flow analysis utilizing the ETAP software and taking into account different source availability. As a result of SVC integration, bus voltage increased by 2.9–3.3%, branch losses decreased by 2.–2.4%, and power transfer capacity increased by 7.5–9.0 units.

Reactive power control (RPC) of AC photovoltaic (AC PV) modules was the goal of D. Sutanto et al. [11], which is to suggest a straightforward structure. By absorbing or supplying reactive power, the proposed structure enables the adoption of a microcontroller at a reasonable cost to achieve an effective control of reactive power and maintain the grid voltage within reasonable limits. In order to improve the current control's dynamic response and lower the current harmonic distortion, the sliding mode control (SMC) is used. To illustrate the control strategy, a thorough PSIM simulation of an AC PV module connected to the grid in various operating modes is used. The simulation's findings demonstrate that the suggested solution can effectively control the reactive power of AC PV modules.

Y. Bae et al. examined an important facet of the changing energy landscape in their paper [12], focusing on the construction of sizable grid-connected power plants in response to the rising use of renewable energy sources. The possibility of grid instability increases as renewable energy sources take a bigger share of the market for electricity generation. This is especially true if these power plants are unable to sustain grid stability. Grid stabilization assumes an even more crucial role because of how different grid systems operate in different nations. This role has been supported by a variety of grid codes and regulations that are tailored to the unique requirements of each region. In order to demonstrate this, the German Association of Energy and Water Industries (BDEW) established strict guidelines for connecting power plants to the grid sthrough the introduction of a medium-voltage grid code. These grid codes, such as VDE-AR-N 4105 for photovoltaic (PV) systems connecting to low-voltage grids, serve as essential frameworks to guarantee grid stability and dependability. With a focus on managing both active and reactive powers, Y. Bae et al.'s research advances control strategies for these generating systems. Their study illustrates the efficacy of the suggested control strategy using a combination of simulation and experimental data analysis, drawing on practical experiences with a 100-kW PV inverter. In doing so, they offer insightful information about the necessity of grid stability in the context of increasing renewable energy integration, emphasizing the significance of robust control strategies in supporting a sustainable and resilient energy future.

As photovoltaic (PV) system development and installation continue to advance at an incredibly fast rate, relevant grid integration policies will subsequently change to accommodate more PV systems in the grid, according to Y. Yang et al. [13]. Similar to how conventional power plants participate in grid regulation today, the next generation of PV systems will take a more active role in it. In some nations, requirements for ancillary services, such as Low-Voltage Ride-Through (LVRT) connected to reactive current injection and voltage support through reactive power control, have been successful. These cutting-edge features can be offered by next-generation PV systems, and they will be improved in the future to guarantee an even more effective and reliable use of PV systems. Reactive Power Injection (RPI) techniques for single-phase PV systems are investigated in their research in light of this. The following are the RPI options: a) constant average active power control; b) constant active current control; c) constant peak current control; and d) thermally optimum control approach. Although they all have different goals, these solutions all adhere to the grid codes that are now in effect. Simulations are used to show the thermal optimal control technique for a 3 kW single-phase PV system. On a 1 kW singly-phase system operating in LVRT mode, the other three RPI techniques are empirically validated. These findings demonstrate the viability and efficacy of the suggested solutions for reactive power regulation in LVRT operation. Additionally, the design and execution factors for the characterized techniques are covered.

The demands placed on the grid for the integration of PV systems are anticipated to change as a result of the surge in single-phase photovoltaic (PV) system installations. Therefore, in the future, PV systems should be increasingly capable of supporting the grid and providing low-voltage ride through functionality. The creation of suitable reference signals to address ride-through grid faults is the responsibility of the control methods, in conjunction with grid synchronization techniques, according to F. Blaabjerg et al. [14]. The behavior of grid synchronization techniques and control options in single-phase systems must therefore be assessed in the presence of grid faults. The purpose of this research is to give a benchmarking of grid fault modes that could appear in upcoming single-phase PV systems. The pertinent synchronization and control strategies are discussed in order to map out potential problems. Experimental research on a few faulty modes is done, and these results are reported at the end of this study. It is determined that under grid failures, single-phase PV systems have a wide range of control options. Due to its quick adaptive-filtering capabilities and ability to meet future requirements, the second-order-general-integral-based phase-locked-loop approach may be the most attractive alternative for future single-phase PV systems.

A significant change in the primary goal of photovoltaic (PV) system design is highlighted in the insightful study by E. Romero-Cadaval et al. [15]. In the past, the main objective was to maximize the amount of power that could be extracted from the PV array and then transferred to the AC grid. Maximizing conversion efficiency and perfecting maximum power point tracking (MPPT) algorithms for PV arrays operating under uniform illumination were the main focuses of efforts to achieve this goal. An expanded set of factors, however, emerges as PV plants are integrated into the grid infrastructure.

Now, designers must prioritize the system's dependability, the caliber of the power it delivers to the grid, the inclusion of protective mechanisms, and grid synchronization features in addition to power optimization. Getting the best possible energy output is, in essence, the core of the modern paradigm for PV power plants. This calls for the use of sophisticated control strategies that can successfully address the problems posed by partial shading occurrences and the different PV module orientations in response to shifting solar positions.

Furthermore, the creation of appropriate system topologies and control algorithms has been mandated by the shifting policy landscape, particularly with regard to the addition of reactive power to the grid. These factors are essential for ensuring that PV plants generate energy effectively, comply with legal requirements, and maintain grid stability. This all-encompassing strategy for designing PV systems highlights the complex interplay between increasing power output and taking care of important issues like grid integration, power quality, and compliance with changing industry standards and regulations.

A broad overview of practical PV energy system applications is provided. They discussed a number of significant topics, such as the MPPT function, which is especially important in distributed applications, and the most trustworthy simulation models that are helpful in the design of control systems. With an emphasis on synchronization, protections, and integration, the main topologies used in the PV power processing system are discussed, followed by grid connection issues.

5. CURRENT CHALLENGES

While promising for producing clean energy, solar-wind hybrid systems have significant problems with reactive load distribution and power quality. Grid stability is impacted by problems like harmonic distortion, voltage fluctuations, and uneven reactive power generation. Advanced converter controls, on the other hand, provide answers by allowing grid-interactive inverters to control voltage and synchronization, active power filters to lessen harmonics, and sophisticated reactive power management techniques. Energy storage system integration can also offer buffering capabilities to even out power output. These developments are essential for the smooth integration of hybrid solar-wind power systems into contemporary power grids, ensuring reliable and sustainable energy production.

6. CONCLUSION

This review underlines the crucial importance of advanced converter controls in resolving issues with power quality and reactive load distribution in solar-wind hybrid systems. The need for reliable and effective hybrid systems is growing as we move closer to a future with more sustainable energy sources. To combat voltage fluctuations, harmonic distortions, and imbalances in the generation of reactive power, converter controls, which include grid-interactive inverters, active power filters, and advanced reactive power management techniques, offer practical solutions. Additionally, the addition of energy storage systems expands the functionality of these controls. The seamless integration of solar-wind hybrid systems into modern power grids will be made possible by these innovations as technology advances, advancing us toward a cleaner, more resilient, and sustainable energy landscape.

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