# Enhancing Power Quality in Solar, Wind, and Hybrid Systems Using Intelligent Converters: A Comprehensive Review

[1]Amresh Kumar, [2]Amit Kumar Asthana
[1]Research Scholar, Department of Mechanical Engineering, Truba Institute of Engineering & Information Technology Bhopal (M.P.) India
[2]Assistant Professor, Department of Mechanical Engineering, Truba Institute of Engineering & Information Technology Bhopal (M.P.) India
[1]kumar.amresh70@gmail.com, [2]asthana603@gmail.com

* Corresponding Author: Amresh Kumar

***Abstract:***

*The power quality issues that are involved in integrating renewable energy sources (RES) like solar photovoltaic (PV) and wind with present-day power systems cannot be overstated. In either a strong grid environment or in a weak grid system, the inherent variability and intermittency of RES, along with nonlinear loads and grid disturbances, can result in voltage sags, harmonics, flickers, and frequency deviations, hampering the grid stability and also inducing havoc to sensitive consumer equipment. This review provides a detailed discussion on some of the technologies and intelligent control schemes being developed to further enhance power quality in solar, wind, and hybrid renewable energy systems. Among its most notable topics is the manner in which advanced power electronic converters like synchronous machines with frequency control, or otherwise known as grid-following or grid-forming converters, can aid in addressing PQ problems. Furthermore, integration with smart control allows the use of innovative controllers, such as artificial neural networks, fuzzy logic, ANFIS, and model predictive controllers among others, to enhance power quality in real time. In this submission, the performance of hybrid systems is also assessed, demonstrating blockades in-demand to control voltage and frequency under fluctuating operating conditions, due to various amounts of renewables coupled with energy storage. Also looked up recently during this review will be the various ways suggested UPQCs, STATCOMs, and filtering and protection schemes for active and passive adjustment are being analyzed for optimization bases. Insinuations also extend over what we find are significant obstacles, that is, system scalability, computational complexity, interaction among multiple designs, and real-time performance limitations. This paper concludes by pointing out the gaps in research and setting forth prospective directions for the deployment of intelligent converters based on renewable systems to endure safe, stable, and high-quality power delivery.*

***Keywords:*** *Power Quality, Renewable Energy, Solar PV, Wind Energy, Hybrid Systems, Intelligent Converters, Unified Power Quality Conditioner.*

## I.INTRODUCTION

Renewable energy systems have come to occupy a central place in current power plan as most of the countries seek clean and affordable power. The growth in demand and commitments to mitigate global change, with dropping technology costs, are prompt solar, wind, and hybrid installations [1]. Renewable energies do not only contribute to emission mitigation, but also reduce supply diversification, enhance energy security, and promote creative innovation over grid and power electronics [2].

### Transition from Conventional Grids to Renewable-Dominated Systems

Traditional electric systems were built around big centralized power stations powered by fossil fuels that fed the generated electricity in a single, one-directional current to users. For all that, this model may have brought stability [3] however, it relegated systems to staunch, non-versatile mechanisms that had numerous points of failure and were ever-so-emitting loads of carbon. As renewable technologies have matured, new limitations of conventional grids have become more visible: the grid can flexibly integrate variable generation, suffer from high transmission losses over long distances, and is sensitive to price and fuel shocks [4]. Adopting a more dominant intermittently renewable system implicates numerous distributive, modular sources closer to load centres, propped up by intelligent converters and digital controls. Systems of this exhibit bidirectional power flow, enhanced point-of-common-coupling support in terms of voltage and frequency, and better resilience under disturbances [5]. All in all, the transition represents a flashy technological update simultaneously it is expected to be a systemic shift of the way power is being produced, managed, and consumed [4]-[5]. Figure 1. represents Conventional Grids to Renewable-Dominated Systems.

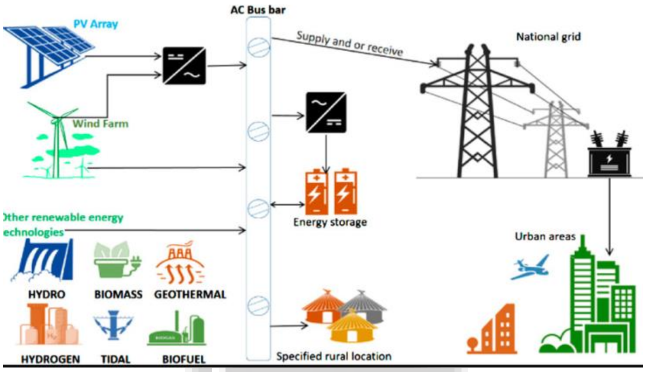


*Figure 1: Conventional Grids to Renewable-Dominated Systems [5]*

**Growing Role of Distributed Energy Resources (DERs)**

Distributed Energy Resources (DERs) (such as rooftop solar, small wind turbines, battery storage, electric vehicles and controlled loads) are remolding our modern distribution grids. Now, the grid systems are no longer designed wholly around a centralized plant [6]. In fact, many small, smart assets can be combined to satisfy energy demand, reduce overloads, and strengthen the grid. DERs decrease peak demand, exclude huge infrastructure upgrades, and improve grid reliability by decreasing energy flows from a gap. When smartly managed, DERs can offer voltage support, frequency control, and even black-start resources using smart inverters, advanced converters, and communication platforms [7]. DERs hand power back to the consumer, engaging them to become "prosumers" who play an active role in the energy and resilience markets [8]. With shaping policies, handy digitalization, and developing market mechanisms, the DERs contribution has grown more, becoming a fundamental imperative of sustainable grid systems.

**Concept of Power Quality in Modern Power Systems**

Power quality is the extent to which electric power is delivered smoothly and without interruption to the consumer's end, posing risks of problems like flicker, transients, and harmonic signals [9]. Thus, in the renewable-rich distribution networks of today, power quality is a significant issue to address. This is owing to the reason that manufactures and service providers are becoming more and more dependent on manufacturing computers and other delicate electronic products [10].Figure 2 represents Power Quality in Modern Power Systems

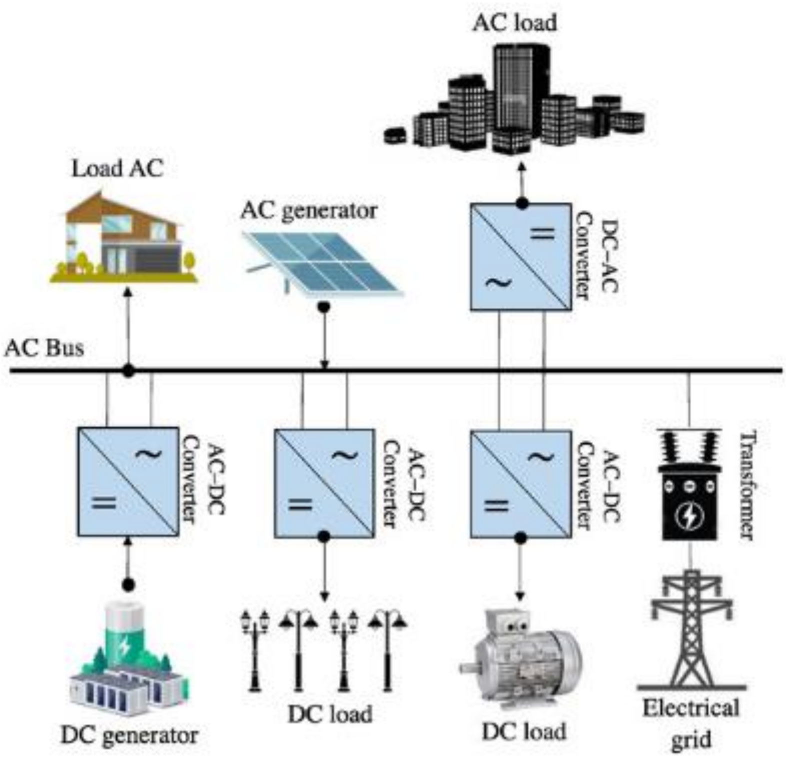


*Figure 3:Power Quality in Modern Power Systems [10]*

**Key Power Quality Parameters**

The quality of power is judged on the basis of certain quantifiable measures designed to describe the voltage, current, and frequency. The voltage magnitude cannot exceed a range of tolerance for fear of operating breakdown. Frequency deviation indicates a severe mismatch between the huge power generation from far-off places and emaciated demand [10]. Harmonics are caused by the nonlinear behavior of the loads and converters, wherein these stress the equipment through overheating and losses [7]. Voltage dips, swells, and other interruptions disturb the running of the industry and severely damage sensitive electrical equipment. Flicker causes visible light fluctuations and makes life uncomfortable for common people. Unbalance makes motors and transformers susceptive to damage, as this is when the phase voltages displaced from phase to phase differ [11]. Power factor shows how power is effectively utilized, low power factor increasing losses and current drawn. These parameters are used by power engineers for identifying the cause of disturbance, design mitigation strategies, and adhere to the grid codes and standards.

**Impact of Poor Power Quality on Consumers and Utilities**

Electricity dispatch may require extra care when a power-quality issue is detected in order to ensure that any such issue will not compromise grid reliability. Although under these conditions, consumers might benefit from their smart meter, a power trading platform could serve as an additional solution for environmental problems, such as intense climate-change concerns [10]-[11]. The possibility for a quick electric meter reading based on the amount of energy transferred, or any local network upgrade to incorporate the basic of energy trading (or compensate) should be considered and implemented accordingly [9].

**Overview of Solar Photovoltaic Systems**

Solar photovoltaics instead change solar energy directly into electricity through semiconductor devices. Photovoltaics have also seen wide adoption in both small-scale residential, big commercial projects, and utility projects thanks to increasingly reduced costs, modular design, and reduced operating costs [10]. If combined with intelligent converters and storage, PV significantly contributed to clean, decentralized power generation (PVP), which is considered to be kind of growth [11].

**Operating Principles of PV Systems**

A PV cell, made from materials like silicon, is typically in a state of excitement. When sunlight finally reaches the cell, photons disrupt the electron arrangement, therefore generating a flow of electric current through the p–n junction, an action known as the photovoltaic effect [12]. Individual cells are linked together to form modules and arrays to give voltage and power levels. Having the DC–DC converter and maximum power point tracker (MPPT) under control, it goes for maximum energy extraction for varying irradiance and temperature. The DC output is then converted to AC via an inverter, working in sync to the grid or local loads. Protection, monitoring, and control systems provide for operating security and efficiency [13]-[14].

**Common Power Quality Challenges in PV Integration**

**Table 1: Power Quality Challenges in PV Integration [14]**

| Power Quality Issue | Main Cause | Effect on System | Typical Mitigation |
|---|---|---|---|
| Voltage fluctuations | Rapid changes in solar irradiance (clouds/shading) | Unstable voltage at feeder ends | Smart inverters, voltage regulators, storage |
| Harmonics | Power electronic inverters and nonlinear loads | Overheating, increased losses, equipment malfunction | Filter design, improved PWM, active filtering |
| Flicker | Frequent small voltage variations | Visible light flicker, user discomfort | Reactive power support, ramp-rate control |
| Voltage sag/swell | Sudden connection/disconnection of PV or loads | Nuisance tripping, process disruption | Ride-through capability, coordinated control |
| Frequency deviation | Imbalance between generation and demand | Instability in weak grids | Inverter frequency support, droop control |
| Unbalance | Uneven phase loading or single-phase PV systems | Motor heating, reduced efficiency | Phase balancing, three-phase interconnection |
| Islanding | PV continues supplying an isolated section | Safety hazards, improper protection | Anti-islanding detection and protection |
| Poor power factor | Reactive power exchange with grid | Higher currents, losses, penalties | Inverter-based VAR control, compensation |

**Overview of Wind Energy Conversion Systems**

Wind energy conversion systems soak up kinetic energy from the wind and then convert it into electricity using aerodynamic rotors, drive trains, generators, and control electronics. The interfaces of the electrical grids, forecasting, and supervisory control all get integrated to ensure the highest energy efficiency, reliability, and sustainability [15]. Figure 4 represents Wind Energy Conversion Systems

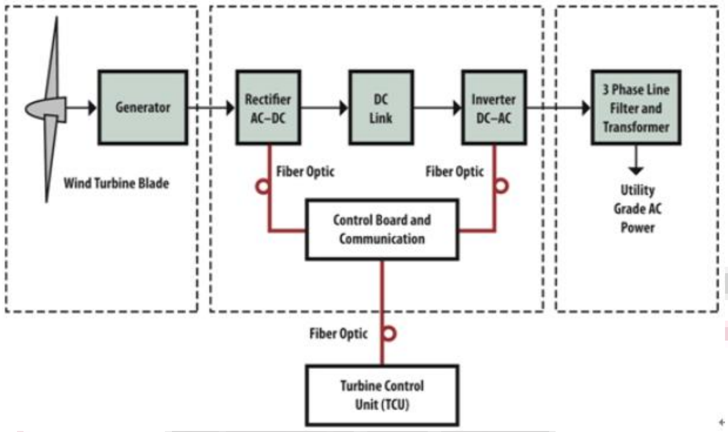


**Figure 5: Wind Energy Conversion Systems [16]**

**Wind Turbine Technologies and Operation**

Blades designed for extracting energy from wind using aerodynamics are fitted onto the rotor that eventually drives the low-speed shaft across the gearbox. While yaw and pitch systems orient the blades and nacelle for more efficient capture, the power electronics take care of voltage, frequency, and reactive power regulation [16]. Modern control strategies are used to counter the loads, stiffen operation against the fury of a storm, and manage the operation of a swarm of wind turbines within a farm. Availability and structural safety are managed throughout different wind-speed conditions with the employment of towers, foundations, and condition-monitoring via lifecycle-aware maintenance planning and performance optimization. It is through such a basis of data-enhanced mechanisms that the expenses and downtimes would be cut down [17].

## II. HYBRID RENEWABLE ENERGY SYSTEMS (HRES)

Hybrid Renewable Energy Systems (HRES) are systems combining two or more renewable sources, usually solar PV, wind, sometimes including storage or diesel backup, to provide an uninterrupted electric supply [19]. HRES optimize resource efficiency, reduce intermittency, and increase their resilience by sharing power conditioning, control, and grid interfaces. They are increasingly being rolled out in micro grids, remote communities, and grid-connected applications to lower lifecycle costs and emissions [20].Figure 6 represents hybrid renewable electric system (HRES)

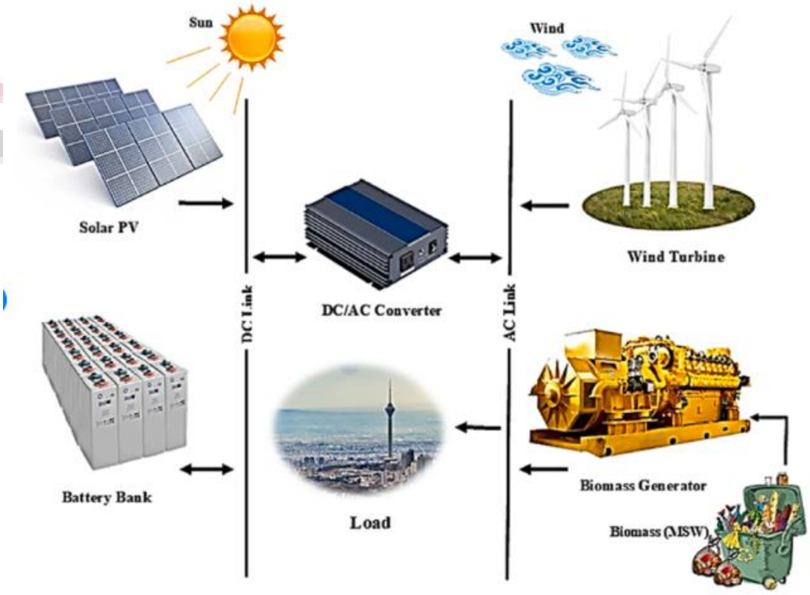


FIGURE 7: HYBRID RENEWABLE ELECTRIC SYSTEM (HRES) [21]

**Need for Hybridization**

Solar and wind resources exhibit natural temporal complementarity, because for every region where maximum wind power is expected, daily solar power yields are also the highest, each being subject to variability in itself. In each case, this situation may lead to either curtailment, the requirement for storage, or the injection of backup power [21]. A wind-solar hybrid sorts the combination, thereby smoothing out the net power profile, and increasing inverter and powerline usage, and thereby reducing fossil-derived hot reserves dependence. At the same time, hybrid wind-solar harness the electric power industry off-grid, and through the improvement of voltage and frequency support, take its reliability somehow to a higher level, and consequently reduce the levelized cost of energy (LCOE) [22]. Efficient sizing, forecasting and coordinated control, that save the complementarity from being all in vain, get the most of the solution.

**Challenges in Coordinating Multiple Renewable Sources**

Integrating hybrid systems necessitates a certain level of sophistication when it comes to energy management, be it for the balance struck between generation, storage, and loads, or compliance with grid codes. [21] Uncertain predictions over resources make dispatch decisions further complicated, and in a flash rapid fluctuations may spiral in to voltage, frequency, and ramping issues. Sharing converters and transformers introduces control interaction, harmonics, and protection coordination challenges [23]. Optimal sizing and placement must be added to accommodate variations in lifecycle costs in contrast with the rest of land constraints. Cyber-secure communications, inter-workable standards, and real-time monitoring are essential, especially for the microgrids operating in islanded and grid-connected modes. Finally, regulatory frameworks and tariffs should incorporate a regime for recognizing hybrid assets and ancillary-service capabilities [22]-[23].

## III.Intelligent Converters for PQ Enhancement

Renewable energy systems are endowed with an ample share of improving power quality PQ; this is where smart converters play a crucial role. These converters reduce issues such as harmonics, voltage sags, and flicker by dynamically controlling voltage, frequency, and reactive power. To commit a reliable laboratory experiment, with stability reach, it is destined ever to attain the best possible power delivery from any solar, wind or hybrid system.

**Overview of Power Electronic Converters: -**Complex grid problems might get activated upon switching-feedforward control mechanism with guns in energy production. Thus, grid-forming control can eradicate severe issues of frequency and prospective liability exploiting particularly-generation choices-indispensable-vacuum equation to plug into their control mechanisms to establish pseudo-inertia.Grid-former control provides a recent innovation to rightly stabilize and instantaneously establish an in-house system for renewable energy sources in order to safeguard every behavior capacity of some variable renewable-energy penetration and lessen the injection-point penetration by putting kilometer reach high with black-starting time. PDIF and PIDF are countries that have long since utilized grid-forming control with confirmed success in realizing stabilization estrogen sombre from converting velocity output systems.

**Role of Intelligent Controllers: -**Intelligent controllers enhance performance of a converter using resilient, predictive, and robust control. Fuzzy logic controllers manage non-linearities and uncertainties within renewable systems. ANFIS, which is a self-learning controller, combines neural networks and fuzzy logic for real-time optimization of PQ parameters. Neural networks predict disturbances in the system and bolster proactive control, while Model Predictive Control (MPC) optimizes power flow and voltage regulation over future time horizons. These controllers assist effectively in harmonic compensation, voltage stability, and reactive power management. Further, their integration with power electronics converters can enable autonomous, flexible, and resilient control of PQ enhancements, a requirement in solar, wind, and hybrid renewable energy systems.

**Active and Reactive Power Management Techniques: -**A proper management of both active and reactive power plays an indispensable role in the preservation of power quality in renewable generations. Active power control is responsible for regulating the power injected into the grid so as not to let the grid get disturbed by changes of demand due to renewable energies like solar and wind. A number of technologies such as droop control, MPPT, and pre-constructed active power provide help to ensure the optimum use of energy while sustaining the stability of the grid. Reactive power control helps in effecting voltage regulation and in the reduction of loss, normally done through STATCOMs, synchronous condensers, or other such methods of cure. A combined active-reactive power control brings an alleviation from voltage scarcity, fluttering, and harmonic distortion which later ends up boosting a great power quality in return. Such systems require significant integration of energy storage that can also provide substantial amounts of both active and reactive power when physical limits are at stake. Well contemplated monitoring, predictive algorithms, and intelligent control ensure that active and reactive power flows are optimized, so as in support of a stable, reliable, and top-quality power supply.

## IV. Power Quality Challenges in Converter-Dominated Renewable Grids

Grid-forming converters are important in renewable-dominated power systems because they mimic synchronous generators, which in turn contributes valuable distributed inertia and enhances system stability overall [1]. Control strategies for these converters must redress transient behavior and cooperate within weak grids, microgrids, or offshore systems. With all the advances made, challenges like interoperability, robustness, and extensive validation are considered indispensable. Consequently, it is worth considering that testing and coordinated cooperation among converters might become important. The possibility of frequency instability in low-inertia, converter-vigilant systems is still relevant [2]. There are degrees of investigation which should focus on virtual inertia, secondary-frequency regulation, and coordinated control, but still the challenge from communication delays, measurement uncertainty, and nonlinear converter behavior seems to be confronting. As for the hybrid inertia strategy, this theory should be exploited for innovations in system stability. Marketing mechanisms could also contribute to synchronized frequency restoration. Faulty converter tuning can generate oscillations, urging for coordinated distributed control and stability enhancement schemes. Tune-by-optimization has increased the ability to stabilize converter-modeled systems as well as to design for future grids. Operational reliability in large-disturbance stability-secured converter-dominated microgrids is susceptible to transients and islanding conditions from high magnitude sudden changes in either load or generation. Coordinated control, energy storage support, adaptable protection, and real-time stability-assessing tools are needed to support system stability. Robust protective designs should be included in this project. The research approaches to developing and studying the stability of systems under voltage source converters bear emphasis on the weak grid instability and the resonance and oscillations of utmost concern. Standardized frameworks for these issues are suggested to provide comparisons between different studies. It is observed that mutual interactions amongst the converters of the transmission level can cause oscillatory issues and result in a slack of the quality of power [6]. It is believed that multiple control loops set to work in overlay might lead to strange phenomena; of keen interest for operation are proper schemes for coordinated tuning to prevent any control input from simultaneously driving diverse converter nodes into conflicting actions. Penetration by intermittent renewable energy results in voltage fluctuations, frequency deviations, and increased reserve capacity requirements [7]. To help integration, improved forecast, energy storage, and demand-side flexibility are recommended, considering adherence to grid codes and due system planning as measures toward ensuring the stability of the system. A classification structure of asset power electronics is making utilities recognize possible staying risks operational benefits [8]. Through the functional categorization of the assets in the power-supply system, planning for the extension of converter use may be compared with other applications. Modern control strategies - such as FCS-MPC for active power filtering in cascaded H-bridge topology - uplift power quality by stringent harmonic elimination and fast dynamic reaction [9]. This application may be clearly restrictive in terms of computation needs, but it still offers a considerable amount of help for protecting system continuity. The design of any model and protracted information on converter-led systems endow with answers to the fields of transient stability, dynamic operation, and program setting [10]. Recognizably, a well-mentioned converter model is indispensable to ensuring accurate studying process plus a good network management. To improve reliability evaluations within converter-rich systems, a possibility is devised that utilizes variance-based sensitivity analysis to find out which critical parameters are being absorbed in the system [11]. Standardized metrics for inertia, stability, and fault-ride-through capability aim at comparability and interoperability [12]. If the ancillary service market design criteria are to be adapted to the increasing penetration of renewables at the distribution level [13], suitable solution mechanisms are required to contribute to a regulatory framework and a standardized form of participation structures expert at voltage and frequency support. Under weak-grid conditions [14], the coordination of robust Design of PLL and damping is needed for oscillation prevention within grid-synchronizing stability. Integration of offshore wind farms considers AC/DC transmission, choice of converters, reactive power management, and fault ride-through coordination [15]. In microgrids or weak grids, velocity, and variability, hybrid storage and multiple management systems contribute to stronger stability. Smart-transformer permitting a voltage allowance or flow control may introduce potential irregular service capacities in the two grid types via centralized and the additional decentralized and hierarchical arrangements [17]. The equivalent below models augmented with grid-forming converters provide a simplified approach to large-scale dynamics research, while still maintaining the core operating system behavior [18]. Single-input and Single-Output (SISO) impedance-based frameworks for small signal stability assessment can thus consider system-wise instability in the absence of full MIMO models in the best anticipation of oscillatory risk [19]. Because of the significance of power quality disturbances, minimization steps also focus on multi-frequency oscillations and voltage imbalances, which can be carried out as side controllers and unconventional grid support control measures, including filtering out impedances to improve grid stability with wideband harmonic attenuation ways [20].

The management of the DC-bus energy in converter-interfaced renewable systems with storage has been reported as a very crucial state to stabilizing power flow effectively [21]. These control strategies can provide a balanced DC-link when dealing with interactions between renewable nature and storage dynamics; to sum up, therefore enhanced transient response has been achieved with improved performances through the experimental studies of hybrid energy systems. Power conversion systems are identified for their nonlinear elements; through the implementation of modern control methodologies, all these subsystems with appropriate modifications for any nonlinear dynamics are specially adapted to a new environment in terms of work [22]. The predictive controllers, nonlinear controllers, and stiffening techniques that are embodied inside controllers are designed to ensure their reliability and applicability in renewable integration, drives, and DC grids. Additionally, the work underscores that practical application requires both robustness and adaptability to real-world conditions.

To control converters, approved despatch strategies exploit several layers like primary, secondary, and tertiary control. Comunication (and coordination) requirements are of primary consideration [23]. Feature requirements like plug-and-play operation, cyber-security, and bridging in new technology converter formats will still be very challenging. Whereas for new trend features, one would expect some emphasis toward artificial intelligence and adaptive control schemes for the autonomous resilience of a microgrid operation.The next line of control strategies in modern automatic generation control systems will need to be investigated in regard to integration with renewable systems [24]. Hybrid-despatch control schemes involving embedded PI controllers within discretized ordinary structures, in place with intelligent optimization techniques, enhance system response to disturbances . Control topologies are further enhanced with the introduction of power grids damping giant characteristics and, consequently, a more lucrative domain of AGC attraction to convert-rich systems.The fractional-order control in power electronic converters provides more flexibility and robustness in tuning than for the traditional integer-order counterparts. The aforementioned converters have been implemented in applications which include integration with renewable power sources, industrial drives, and grid-support. Comparative studies show better transient response while there is still quite a challenge ahead in industrial deployment and standardization.For efficient modeling and control application, particularly focused on dual-active-bridge (DAB) DC–DC converters, prolific studies have been carried out. The analysis of modes and switches reveals optimization trade-off between efficiency and transient response, with factors for enhancing system robustness including soft-switching techniques and multi-port configurations. Cooperative control strategies are desirable in future hybrid renewable usage.Examples of mechanisms of power electronics are the enablers for analog converters, advanced control systems, and safety mechanisms for grid integration of renewable energies [27]. Peculiarities regarding harmonics, weak-grid issues, and stability are dealt with, while potential solutions to boost system flexibility and resilience are shown in depth via case studies. Digitalization and coordinated control of converters are the two focal areas of future development.State-of-the-art control-methodologies for switch reluctance motors emphasize current regulation, torque control, and vibration interference suppression [28]. Comparative analysis of different controllers elucidates strengths and weaknesses, pointing to more intelligent and sensorless control as future trends to increase efficiency and performances.Converter topologies for connecting PV installations into the power grid and associated control strategies and design challenges have been predominantly examined in the reviewed literature. Additionally, a variety of different methods for centralizing and parallel inverter configurations used in "grid following" have been discussed [12]. Iterator topologies then followed design control strategies for both global energy management and safe design operations. types of power control and grid integration to reduce downtime and customs at ports._SYLLABUS METHOD developed GDS logic and MPC based noise currents residual conventional valley currents generation during GRID operation_FREE methodologies developed for centralizing generator swapping technique for PV inverter arrays. This article focuses more on hybrid technology approaches and optimized control solutions that could benefit the world environmentally and economically.Microgrid charging systems for electric vehicles demand interfaces and control strategies coordination between converters [30]. They go hand-in-hand with the essential discussion of centralized, distributed, and hybrid converter architectures favorable for grid support, harmonic mitigation, and demand-side management. Ongoing areas of study involve better integration of fast charging into the system secured from renewable energy sources to maintain efficiency and reliability.

**Table 2: Review of Converter-Dominated and Renewable Energy Systems**

| Ref | Main Focus | Methods | Key Power-Quality or Stability Issues | Major Findings | Identified Gap |
|---|---|---|---|---|---|
| [1] | Grid-forming converters in RES-dominated grids | Review of control strategies, stability analysis, and applications | Frequency/voltage stability, low inertia, black-start challenges | Grid-forming converters enhance stability, provide virtual inertia, support black-start | Lack of standardized testing and validation frameworks for large-scale systems |
| [2] | Frequency stability in converter-dominated grids | Analytical study and review of frequency response | Low inertia, poor damping, converter interactions | Emphasizes need for synthetic inertia and advanced control | Limited validation in large multi-converter systems |
| [3] | Reliable operation | Dynamic | Oscillations, control | Coordinated control | Implementation |

| | | | | | |
|---|---|---|---|---|---|
| | of converter-dominated power systems | modeling, optimization, coordinated control | conflicts, voltage deviations | frameworks improve reliability | challenges in real-world grids |
| [4] | Large-disturbance stability in microgrids | Review of disturbance behavior, hybrid control strategies | Islanding, voltage collapse, recovery issues | Hybrid control enhances fault-ride-through capability | Experimental validation needed for complex networks |
| [5] | Modeling and stability of VSC-dominated systems | Small-signal and nonlinear stability analysis | Resonance, harmonics, instability | Provides unified modeling framework for VSC systems | Needs integration with protection and control |
| [6] | Converter control interactions in transmission grids | Simulation-based interaction analysis | Converter–converter interaction, oscillations | Highlights interaction-induced oscillations | Requires robust coordination mechanisms |
| [7] | Impact of intermittent renewable penetration | Literature review of system-level effects | Voltage fluctuations, power imbalance, grid stress | Intermittency increases operational stress | Need for mixed-resource coordination and advanced control |
| [8] | Classification of power-electronic assets in grids | Framework for converter categorization | Mismanagement of assets, inconsistent grid support | Enables systematic planning of converter-dominated grids | Framework needs broader validation in diverse grids |
| [9] | Multi-level APF control for power quality | FCS-MPC (Model Predictive Control) for active power filters | Harmonics, current distortion | THD significantly reduced, improved PQ | Controller complexity and computational burden |
| [10] | Modeling & simulation of converter-dominated systems | PowerFactory-based modeling and simulation | Modeling inaccuracy, dynamic instability | Provides practical modeling guidance | Limited to simulation scenarios; real-world validation lacking |
| [11] | Reliability assessment of converter-dominated grids | Variance-based global sensitivity analysis | Uncertainty, reliability risks | Identifies dominant reliability drivers | Integration with economic/operational metrics missing |
| [12] | Testing grid-forming converter behavior | Specification & behavior testing framework | Inconsistent testing standards | Proposes standardized test methodology | Only part-I; full guidelines needed |

| | | | | | |
|---|---|---|---|---|---|
| [13] | Ancillary services market in distribution grids | Market design review & barriers analysis | Lack of incentives, integration barriers | Economic and technical barriers identified | Need for new market structures to enable DER participation |
| [14] | Grid-synchronization stability of converter-based resources | PLL-based stability overview | Synchronization loss, oscillations | PLL control impacts stability; alternatives needed | Limited large-scale validation |
| [15] | Offshore wind farm-grid integration | Review of infrastructure, challenges, and solutions | HVDC faults, coordination, stability | Comprehensive solutions for offshore integration | Real-sea validation limited; further testing needed |
| [16] | Microgrid & weak-grid stability with high VRE | Simulation & control analysis | Weak-grid instability, voltage sag | Advanced stabilizing controls enhance reliability | Real-world feasibility remains uncertain |
| [17] | Smart transformer operation in hybrid grids | Control scheme comparison & evaluation | Power flow, voltage regulation | Smart transformers improve flexibility and resilience | High cost and complexity; limited deployment experience |
| [18] | Equivalent active distribution networks | GFM-based equivalent modeling | Representation accuracy, grid response | Simplified modeling approach validated | Needs testing with varied network topologies |
| [19] | System-level small-signal stability assessment | SISO impedance-based analysis | Small-signal instability, resonance | Provides analytical tool for stability evaluation | Requires extension to multi-converter/multi-terminal systems |
| [20] | Power quality in large-scale wind integration | Multi-frequency oscillation mitigation & control | Voltage dips, harmonics, oscillations | Demonstrates improved PQ using advanced controllers | Limited diversity in test scenarios; needs broader validation |

## V. CONCLUSION AND FUTURE WORK

In this review, various techniques and strategies for enhancing power quality, stability, and control in renewable energy-integrated power systems have been examined. Grid-forming and grid-following converters emerge as fundamental elements for ensuring reliable operation, providing distributed inertia, and supporting weak-grid stability.Power electronics control strategies are common interview questions for power electronics and thermal engineers. Power quality problems are addressed using various power electronics, e.g., active or passive filters, active power compensators, and interfacing tools with energy storage, and so on. This is known as power electronics compensation. The different compensation strategies make use of some or other power electronics, with control strategies like quick hate loop, cascade hysteresis, neural networks, ANFIS, and fuzzy logic. Energy storage integration and DC-bus management were identified as essential enablers for balancing power flows and ensuring microgrid stability. Hierarchical and hybrid control architectures also help to ensure system resilience against varying operating conditions, while ancillary services and grid-synchronization mechanisms are enabling factors for weak-grid and offshore-grid connection. Market-based strategies, cooperative controls, and enhanced modeling framework underpinning enable to ensure system reliability, efficiency, and interoperability in converter-dominated system.

Nevetheless, various issues arose in the form of computational complexity, standardized modeling, and deploying intelligent controllers to a large-scale, mixed network. Future research is envisaged to entail autonomous, adaptive and AI-powered control solutions in addition to integrated energy management strategies to cover hybrid solar-wind-storage systems. Collectively, the literature emphasizes that efficient integration of renewable energy sources to the grid requires coordinated converter operation, robust control design, and intelligent power electronic strategies.

## REFERENCES


[1] Zhang, Haobo, et al. "Grid forming converters in renewable energy sources dominated power grid: Control strategy, stability, application, and challenges." *Journal of modern power systems and clean energy* 9.6 (2021): 1239-1256.

[2] Shrestha, Ashish, and Francisco Gonzalez-Longatt. "Frequency stability issues and research opportunities in converter dominated power system." *Energies* 14.14 (2021): 4184.

[3] Markovic, Uros. *Towards reliable operation of converter-dominated power systems: Dynamics, optimization and control*. Diss. ETH Zurich, 2020.

[4] San, Guocheng, et al. "Large-disturbance stability for power-converter-dominated microgrid: A review." *Renewable and Sustainable Energy Reviews* 127 (2020): 109859.

[5] Xiong, Liansong, et al. "Modeling and stability issues of voltage-source converter-dominated power systems: A review." *CSEE Journal of Power and Energy Systems* 8.6 (2020): 1530-1549.

[6] Quester, Matthias. *Investigating converter control interactions in the transmission grid*. Diss. Dissertation, Rheinisch-WestfälischeTechnische Hochschule Aachen, 2021, 2021.

[7] Mlilo, Njabulo, Jason Brown, and Tony Ahfock. "Impact of intermittent renewable energy generation penetration on the power system networks–A review." *Technology and Economics of Smart Grids and Sustainable Energy* 6.1 (2021): 25.

[8] Vahle, Daniel, and Volker Staudt. "Contribution to the classification of power electronic assets in converter-dominated grids." *2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*. IEEE, 2020.

[9] Li, Hong, Yang Liu, and Jianfeng Yang. "A novel FCS-MPC method of multi-level APF is proposed to improve the power quality in renewable energy generation connected to the grid." *Sustainability* 13.8 (2021): 4094.

[10] Gonzalez-Longatt, Francisco M., and José Luis Rueda Torres, eds. *Modelling and simulation of power electronic converter dominated power systems in PowerFactory*. Springer Nature, 2020.

[11] Zhang, Bowen, Mengqi Wang, and Wencong Su. "Reliability assessment of converter-dominated power systems using variance-based global sensitivity analysis." *IEEE Open Access Journal of Power and Energy* 8 (2021): 248-257.

[12] Kersic, Manuel, et al. "Testing characteristics of grid forming converters part i: specification and definition of behaviour." *19th Wind Integration Workshop*. Vol. 20. 2020.

[13] Oureilidis, Konstantinos, et al. "Ancillary services market design in distribution networks: Review and identification of barriers." *Energies* 13.4 (2020): 917.

[14] Wang, Xiongfei, et al. "Grid-synchronization stability of converter-based resources—An overview." *IEEE Open Journal of Industry Applications* 1 (2020): 115-134.

[15] Ali, Syed Wajahat, et al. "Offshore wind farm-grid integration: A review on infrastructure, challenges, and grid solutions." *Ieee Access* 9 (2021): 102811-102827.

[16] Susanto, Julius. *Stability of microgrids and weak grids with high penetration of variable renewable energy*. Diss. Murdoch University, 2020.

[17] Zhu, Rongwu, et al. "Operation and control of the smart transformer in meshed and hybrid grids: Choosing the appropriate smart transformer control and operation scheme." *IEEE Industrial Electronics Magazine* 15.1 (2020): 43-57.

[18] Ungerland, Jakob, et al. "Equivalent active distribution networks considering grid forming converters." *2021 IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*. IEEE, 2021.

[19] Yang, Dongsheng, and Yin Sun. "SISO impedance-based stability analysis for system-level small-signal stability assessment of large-scale power electronics-dominated power systems." *IEEE Transactions on Sustainable Energy* 13.1 (2021): 537-550.

[20] Madhav, Ramtenki, and Mr M. Vijay Kumar. "POWER QUALITY IMPROVEMENT FOR WIND LARGE SCALE INTEGRATION WITH MULTI FREQUENCY OSCILLATIONS WITH MEASURED." *INFORMATION TECHNOLOGY IN INDUSTRY* 9.3 (2021): 901-909.

[21] Matas-Díaz, Francisco Jesús, et al. "DC-bus energy management of a converter-interfaced renewable energy source comprising an energy storage system." *2021 IEEE Madrid PowerTech*. IEEE, 2021.

[22] Luo, Wensheng, et al. *Advanced Control Methodologies For Power Converter Systems*. Vol. 413. Springer, 2022.

[23] Hu, Jiefeng, et al. "Overview of power converter control in microgrids—Challenges, advances, and future trends." *IEEE Transactions on Power Electronics* 37.8 (2022): 9907-9922.

[24] Ullah, Kaleem, et al. "Automatic generation control strategies in conventional and modern power systems: A comprehensive overview." *Energies* 14.9 (2021): 2376.
[25] Warrier, Preeti, and Pritesh Shah. "Fractional order control of power electronic converters in industrial drives and renewable energy systems: a review." *IEEE Access* 9 (2021): 58982-59009.
[26] Shao, Shuai, et al. "Modeling and advanced control of dual-active-bridge DC–DC converters: A review." *IEEE Transactions on Power Electronics* 37.2 (2021): 1524-1547.
[27] Tang, Zhongting, Yongheng Yang, and Frede Blaabjerg. "Power electronics: The enabling technology for renewable energy integration." *CSEE Journal of Power and Energy Systems* 8.1 (2021): 39-52.
[28] Fang, Gaoliang, et al. "Advanced control of switched reluctance motors (SRMs): A review on current regulation, torque control and vibration suppression." *IEEE Open Journal of the Industrial Electronics Society* 2 (2021): 280-301.
[29] Nguyen, Hoang Phuong, et al. "The electric propulsion system as a green solution for management strategy of CO2 emission in ocean shipping: A comprehensive review." *International Transactions on electrical energy systems* 31.11 (2021): e12580.
[30] Savio Abraham, Dominic, et al. "Electric vehicles charging stations' architectures, criteria, power converters, and control strategies in microgrids." *Electronics* 10.16 (2021): 1895.