# A Comprehensive Review on Intelligent Control of Hybrid Solar–Wind Energy Systems

[1]Dhanraj, [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
dhanrajy088@gmail.com, asthana603@gmail.com

* Corresponding Author: Dhanraj

***Abstract:***

*Worldwide shifts toward environmentally-friendly forms of energy have consequently led to an amplification of interest in hybrid renewable energy systems involving the solar and wind resources. These systems work in complementary operation, thereby increasing reliability and reducing environmental impact. Their intermittent and nonlinear natures, however, pose great challenges with regards to quality of power, grid stability, and energy conversion efficiency. This review paper offers an exhaustive assessment of major advancements in intelligent controller designs, giving a particular emphasis on Artificial Neural Network (ANN)-based optimization of hybrid solar–wind systems. The evolution of hybrid system architectures, major power quality problems encountered, grid synchronization issues, and control topologies—centralized, distributed, and hierarchical—are systematically analyzed. Using ANN frameworks, the study contrasts traditional control methods with AI-based control methods and presents enhanced flexibility, robustness, and prediction capabilities. The review further explores the hybridization of ANN with fuzzy logic, genetic algorithms, and fuzzy inference systems for further improvements in stability and convergence speed under sudden fluctuations in irradiance and wind speed. Key research gaps such as the availability of real-time datasets, standardization, and hardware-software co-design are brought up to point new directions of work. Overall, this review paper vividly brings out the importance of intelligent controllers in efficient grid integration and reliable operation of future-generation hybrid renewable systems.*

***Keywords:*** *Hybrid renewable systems, solar–wind integration, intelligent control, ANN optimization, power quality, grid synchronization, MPPT*

## I. INTRODUCTION

The present-day shifts and evolution rapidly shape the global energy terrain with the growing call for clean, reliable, and sustainable energy sources. Unabated industrialization with population and urban growth has tremendously pressured the existing fossil fuel-based generation infrastructure. Industrial and economic activities have for long depended on traditional energy sources, mainly coal, oil, and natural gas. Yet, being finite and subjected to fluctuating fuel price trends and ever-growing awareness of environmental degradation, these sources consequently alter the rate at which the alternative options should be considered [1]. Further, burning of fossil fuels mainly supplement all complaints for global warmings that, in turn, worsen climate change. Centralized power generation tends to be unreliable in electricity provision to remote and rural areas, stressing the importance of decentralized renewable-based generation [2].

With the increase in energy demand and the scarcity of conventional fuels, renewable energy resources have been favored as one of the principal options for new capacity generation. Being abundant, renewable, and with continually falling costs of generation, solar and wind power have gained immense popularity, both for large and small-scale applications. However, the variability of solar irradiance and wind speed imposes serious challenges on the system stability, energy reliability, and coordination at the grid [3]. To overcome such drawbacks, HRES were proposed to utilize particularly the solar PV and wind energy systems. These two resources are expected to be hybridized due to their complementary nature: solar energy being mostly available during daylight hours, whilst wind energy is mostly available at night or during cloudy conditions [4]. Thus, hybrid systems, by utilizing these complementary sources, provide smoother and more continuous power generation, improving reliability and ensuring that the burden is not placed on any particular resource.

Intelligent control for hybrid energy systems is the next evolutionary stage in the application of renewable energy technology. Intelligent control framework based on ANNs and other machine-learning algorithms can predict resource availability, optimize energy flow, and stabilize system operation under variable operating conditions [5]. These adaptive systems thus improve power efficiency and reliability, and they also, as a result, raise the integration possibilities into the grid, thus being considered the core of present smart-grid infrastructure [6].

### Evolution of Hybrid Renewable Systems

Intermittency and reliability issues faced by standalone wind and solar systems demanded advanced solutions with hybrid renewable systems. When solar and wind resource bases are considered together, these systems are expected to provide electricity from dawn to dusk and throughout seasons more consistently. The hybrid architecture seeks to make the best use of natural resources with improved conversion efficiency and resilience in modern decentralized power networks [7]. The principle behind hybridization is the complementarity of generation: when one source is weak, the other steps in, ensuring the power supply is stable. For example, PV modules generate power under high solar irradiance, while wind turbines yield good power output levels at night and in conditions of low solar irradiance. Hybrid solar-wind systems tend to maintain more constant energy output and are thus mostly suited for remote locations and microgrid applications [8].

Usually, hybrid systems comprise converters, storage units, and regulators that facilitate power flow in between energy or from energy to load. The so-called intelligent-type converters ensure efficient conversion and balanced energy dispatching either towards the grid or local loads. When designed correctly, hybrid systems focus on improving energy continuity and system resilience while sharing common components, such as inverters and DC–DC converters, thereby optimizing land and infrastructure utilization [9].
Solar energy systems exploit sunlight to produce electrical energy using the photovoltaic conversion process [15]. Basically, solar energy installations consist of solar panels, converters, inverters, and controllers that, together, turn solar rays into usable electricity. It is a pollution-free, sustainable method of generating electricity that has become more and more economically viable through advances in PV materials and power electronics. [16] However, the big drawback with solar power is that it is totally dependent on environmental conditions like solar irradiance, temperature, and shading. Conversion and control techniques must be learned and applied in order to facilitate energy conversion at the DC–DC converter level while guaranteeing maximum power extraction and stability in the system [17]. Figure 1 describes Solar Energy System

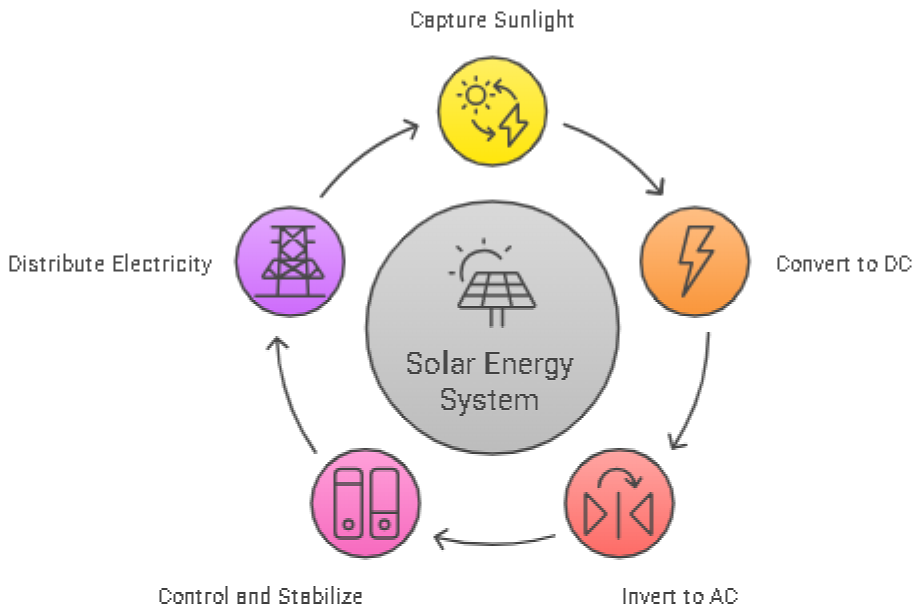


Figure 1: Solar Energy System

## II. GRID INTEGRATION OF HYBRID SYSTEMS

Grid integration of hybrid solar–wind systems enables an efficient utilization of renewable energy by considering distributed generation units that are installed to the main power grid. Continuous supply of energy, enhancement of reliability of the system, and support in voltage regulation are aspects of grid integration [18]. Proper coordination among converters, controllers, and synchronization mechanisms concerning grid stability and power quality is highly required.

### a. Role of grid-connected inverters

On the other hand, wind/solar conversion and hybrid renewable energy systems-interface depend on grid-connected inverters serving as a key interface. They convert DC produced by solar and wind subsystems to AC voltage and frequency compatible with the grid [19]. Inverters also perform voltage regulation, reactive power control, and power factor correction. Modern smart inverters are capable of grid-forming/grid-supporting functions including frequency regulation, harmonic mitigation, and fault ride-through. Thus, with their dynamic response capability, hybridity may stabilize the grid while maximizing efficiency of power transfer and meeting grid codes and safety standards [20]. Figure 2 describes Grid-connected inverters

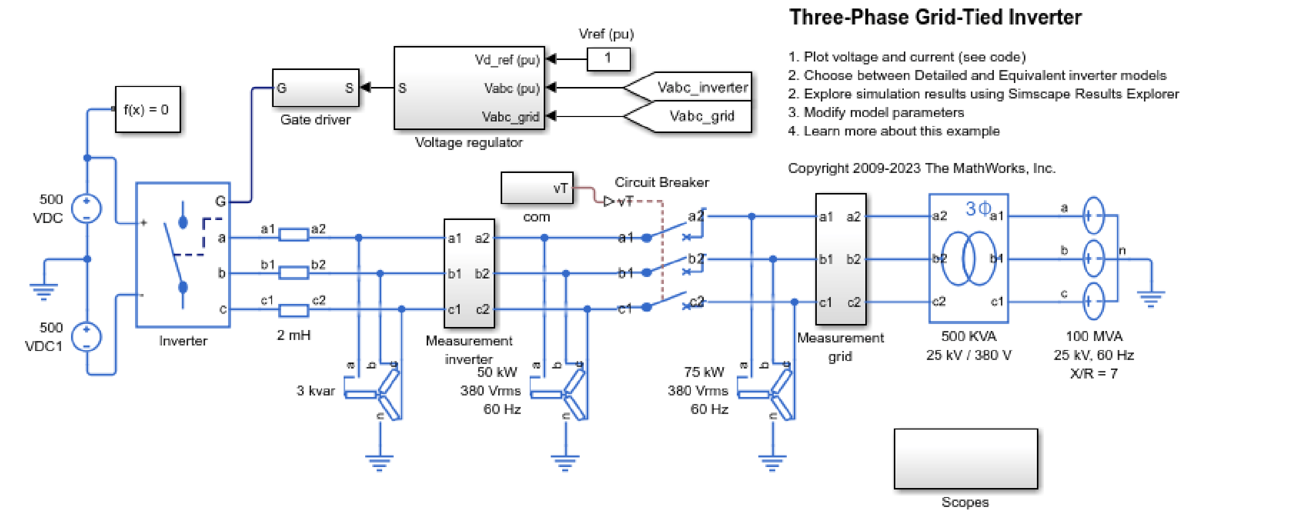


**Figure 2: Grid-connected inverters**

**b. Synchronization and interconnection standards**

Synchronization is the process of making sure the voltage, frequency, and phase of the hybrid systems' output are in agreement with those of the grid, prior to interconnection. Any improper synchronization may, thus, lead to circulating currents, sudden surges in power, or a situation of instability. Interconnection standards such as IEEE 1547, IEC 61727, and the grid codes of nations contain the technical requirements for safe and reliable interconnection [21], including voltage and frequency limits, protection schemes, anti-islanding measures, and power quality criteria. These standards guarantee that hybrid systems cooperate with the existing grid infrastructure, without causing any disturbances or faults. Compliance with Synchronous Standards will ensure that utilities continue to manage distributed energy resources effectively [22], while facilitating large-scale penetration of renewable energy sources into modern power networks.

**c. Issues in voltage, frequency, and reactive power control**

With respect to grid connecting hybrid renewable systems, one major challenge lies in maintaining voltage, frequency, and reactive power stability. Due to the intermittent nature of solar and wind, fluctuations could lead to voltage sags, frequency variations, and reactive power imbalances [23]. If inadequately controlled, power quality deteriorates to a highly unacceptable level, or worse, grids may force a disconnection from the hybrid system. Some of the advanced control schemes involve intelligent algorithms, adaptive inverter control, etc., so that the reactive power regulation and synchronization of the inverter can be maintained dynamically under ever-changing operating conditions [24]. Hence proper control of these parameters results in the enhancement of grid stability and its reliability so that higher penetration of renewable energy installations could be achieved without any compromise in the quality of power delivered.

## III. POWER QUALITY CHALLENGES IN HYBRID SYSTEMS

Improving power quality in grid-connected hybrid solar–wind systems under various control and optimization scenarios has been addressed by a good number of recent researches [1]. A GA-ANFIS controller was proposed for a DPFC using model simulation, reducing the voltage THD significantly to nearly 0.03% under sag and swell cases [1]. Another study developed a probabilistic sizing approach and two-level control algorithm for smoothing the output of the hybrid system based on vanadium redox flow battery and supercapacitor, while emphasizing stability improvements over harmonic metric details [2]. Dynamic fault analysis of PV/wind farms showed that significant transient voltage deviations existed during grid fault simulations but did not conduct explicit PQ mitigation [3]. Wake-turbulence analysis in a wind farm was found to increase flicker severity (Pst) and voltage variability, and hence confirmed degradation in voltage quality in absence of any hybrid coupling or ANN mitigation [4]. Improved flickermeter algorithms also aimed at improving the accuracy of Pst/Plt for the grid-connected turbines but were not meant to be a control method [5]. Metaheuristic-tuned PID controllers with Grey Wolf–Sparrow Search hybridization brought voltage THD below 5% under microgrid simulation profiles but were limited to modeled profiles [6]. Flower Pollination-based intelligent controllers delivered 0.71% THD under hybrid conditions but did not scale to larger systems [7], while E-M optimizations delivered around 1.98% inverter THD under hybrid PV/wind/storage networks [8]. Experimental 12 kW solar-wind setups delivered 2.36% current THD but were still small-scale [9]. LC-filtered inverters reduced PV and wind voltage THD from above 30% down to under 5%, according to IEEE-519, but with prospects of resonance [10]. The integration of SVCs for reactive power control was not enough for active suppression of harmonics [11], whereas smart monitoring frameworks mostly tracked PQ indices without mitigation

[12]. ANN-based energy management with switched Z-source converters was reported to successfully reduce injected current harmonics of a prototype hybrid system [13], whereas DSTATCOM and UPQC configurations have always remained below 5% post-control THD accompanied by an improved voltage stability [14]–[15]. Further reviews pointed out that environmental variability increases flicker and voltage fluctuations, thus recommending adaptive ANN control [16]–[18]. Wake effect studies reinforced the demand for control strategies responsive to dynamic turbulence [19]. Comparisons of various mitigation devices concluded that hybrid combinations—such as DSTATCOM plus active filter or UPQC with storage—offer the best PQ performance, although most of the conclusions are simulation based with associated cost and implementation implications [20].

**Table 1: Power Quality Challenges in Hybrid Systems**

| Ref. | Technique / Approach | Results / Performance Metrics | Limitations |
|---|---|---|---|
| [1] | GA-ANFIS controller for DPFC in grid-connected solar–wind hybrid system | Load voltage THD reduced from 0.64%/0.60% to 0.03%; mitigated sag, swell, and harmonics | Simulation-only validation; limited fault/unbalance cases; no real-time feasibility study |
| [2] | Hybrid PV–wind with VRFB + SC two-tier hybrid storage and probabilistic sizing | Smoothed power output; improved stability; qualitative PQ discussion | No numeric THD values; simulation-only; focused on smoothing rather than PQ mitigation |
| [3] | Dynamic fault analysis on PV/wind hybrid system | Quantified voltage dips and recovery times under fault conditions | Focused on transient metrics; no harmonic/flicker data; no ANN-based controllers |
| [4] | Wake and turbulence modeling for wind farms using DIgSILENT | Quantified flicker (Pst) increases due to wake effects | Wind-only modeling; no solar coupling; lacks mitigation strategy |
| [5] | Enhanced flickermeter for wind turbine flicker estimation | Improved flicker accuracy and reduced measurement error | Diagnostic purpose only; lacks mitigation/control design |
| [6] | Grey Wolf + Sparrow Search optimized PID controller for microgrid PQ | Reduced THD to <5%; improved voltage regulation | Simulation-based; lacks real-time adaptability |
| [7] | Flower Pollination Algorithm–based intelligent controller | Achieved 0.71% voltage THD | Simulation only; untested scalability; limited transient fault handling |
| [8] | E–M/Controller for grid-connected solar–wind–storage hybrid inverter | THD ≈ 1.98%; improved harmonic control | Small synthetic dataset; no flicker/unbalance evaluation |
| [9] | Modeled 12 kW PV–wind hybrid converter system | Current THD ≈ 2.36% in experiments/simulations | Small-scale setup; limited operating conditions; no ANN PQ control |
| [10] | LC filter at inverter output of PV/wind systems | PV THD reduced 34.1%→4.85%; wind THD 42.5%→3.97% | Passive method only; ignores flicker/unbalance; potential filter resonance |
| [11] | SVC integration for reactive power support in hybrid grid | Improved voltage regulation and reduced dips | Effective for reactive PQ only; lacks active harmonic suppression |
| [12] | Smart PQ monitoring and measurement framework for PV–wind systems | Measured and aggregated Pst, Plt, and THD indices | Focused on measurement; no mitigation or control design |
| [13] | ANN control for Z-source converter in grid-tied PV–wind system | Reduced injected current harmonics; stable MPPT operation | Small-scale prototype; limited focus on flicker/unbalance |
| [14] | DSTATCOM-based PQ improvement in hybrid systems | THD <5%; improved voltage regulation | Depends on tuning/power rating; lacks transient buffering |
| [15] | UPQC/DVR control for hybrid microgrid PQ enhancement | THD reduced 25%→8–12%; mitigated voltage sag/swell | Simulation-based; costly and complex; DC-link management issue |
| [16] | Statistical PQ disturbance analysis in hybrid renewable systems | Quantified Pst; revealed increased flicker with irradiance variability | Analytical only; no control or mitigation proposed |
| [17] | Model predictive/fractional-order control for UPQC in hybrid systems | Reduced THD; faster voltage recovery during sag | Complex tuning; high computation load for real-time implementation |

| | | | |
|---|---|---|---|
| [18] | ANN/ANFIS hybrid with active/passive filters | THD <1–3%; improved PQ in simulation and hardware prototypes | Synthetic training data; limited scalability validation |
| [19] | Wind-farm wake modeling and flicker characterization | Quantified Pst increases for various layouts | Wind-only; lacks hybrid interaction or mitigation |
| [20] | Comparative analysis of DSTATCOM, UPQC, SVC, LC/active filters | THD <5%; improved voltage stability and PQ | Simulation-based; limited economic and practical validation |

## IV. CONTROL AND POWER-ELECTRONICS SOLUTIONS

Through various studies in the past few years, several MPPT enhancements and various inverter control schemes have been proposed for better extraction of energy, power quality, and grid stability of solar, wind, and hybrid systems [21]–[40]. Using a modified P&O algorithm that used variable step size and hysteresis criteria to make the decision, the steady-state oscillations were reduced by 26% and a tracking efficiency of 98.4% was achieved, albeit at the expense of algorithmic complexity and memory requirements [21]. A weighted P&O MPPT allowed a dynamic change in perturbation amplitude to maximize the stability and minimize power ripple at 30% power ripples; however, it required very fine tuning [22]. An adaptive incremental conductance method characterized by better tracking speeds of 72 ms and efficiency of 97.5% was found to be less robust under low irradiance [23]. The combination of modified model predictive control with adaptive P&O made MPPT 3.5% better while THD decreased from 3.8% to 2.6% and the power factor remained above 0.99 but was very expensive to compute [24]. A review of non-AI MPPT methods found that adaptive algorithms can achieve up to 98% tracking efficiency with convergence within 0.25 s, pointing towards incoherent testing standards [25]. The nonlinear fractional-order PI controller can reduce voltage overshoot and THD to as low as 2.1% while improving the transient response at the cost of complex tuning [26]. Adaptive PR control with frequency compensation had minimum steady-state error and THD of 1.8% and power factor of 0.998, but required online frequency detection [27]. The frequency-adaptive droop control increases power-sharing accuracy by 7.5%, but is not noise immune [28], whereas the reactive-power droop control enhances voltage stability and reactive-power sharing accuracy subject to precise local measurements [29]. The hierarchical droop–PI coordination shall restore grid voltage and frequency 30% faster than conventional approaches, however, it causes increased communication complexity [30]. Robust droop-based controllers achieved 98% accuracy with power sharing and ± 1.8% voltage deviation under 20% load variation, although they have only been confirmed through simulation [31]. The hybrid PI–droop–virtual-impedance control reduced the overshoot by 50% and steady-state error by more than 1%, with the sacrifice of quite complex tuning [32]. A voltage regulation coordination scheme utilizing on-load tap changer and switched capacitor shall reduce bus voltage deviation by 47% and network reactive losses by 12.4%; however, with a quick response from 420 ms, it relies on accurate feeder models [33]. The STATCOM control reduction method cuts transient THD from 4.7% down to 2.5% and manages to restore the 30%-sagged bus voltage in less than 150 ms, but it brings the downside of thermal stress and being costly [34]. Coordinated capacitor switching and dynamic var scheduling shall reduce voltage deviation by 35%, switching events by 28%, and improve power factor by 0.04. The engineered mechanisms may cause mechanical wear [35]. The rule-based EMS reduced diesel consumption by 18.7% and increased PV utilization by 12.1%, but the system had very little adaptability to tariff changes [36]. By using load timers, the demand-side management could shift 18% of the flexible load to during off-peak hours, and thus a 6.8% reduction of feeder peaks was achieved. But the downside is that large coordination is required [37]. State-of-charge-aware droop scheduling will improve power-sharing accuracy by ±2.5%, extend battery cycling interval by 20%, though this entirely depends on very accurate SoC estimation [38]. Seamless islanding detection must be capable of seamless transition within 210 ms and minimal transient overshoot (less than 3%) but suffer from nuisance tripping in the weak grid [39]. Economic rule-based dispatch in PV–diesel–battery systems achieved fuel savings of 21.3% and reduced generator running time by 24%; however, manual retuning was required for dynamic load or tariff variations [40].

**Table 2: CONTROL AND POWER-ELECTRONICS SOLUTIONS**

| Ref. | Technique / Focus | Key Results / Performance Metrics | Limitations |
|---|---|---|---|
| [21] | Modified P&O with variable step-size and hysteresis | Tracking efficiency 98.4%, settling time 0.18 s, oscillations ↓26% vs. classical P&O | High implementation complexity, high memory use; unsuitable for low-cost MCUs |
| [22] | Weighted P&O with dynamic perturbation | MPPT efficiency ↑2.9%, power ripple ↓30%, tracking ≈97.8% | Requires precise weighting tuning; performance drops in fast irradiance change |
| [23] | Adaptive Incremental Conductance (IncCond) | Tracking time 72 ms vs 84 ms, power oscillation ↓1.66 W→2.01 W, efficiency = 97.5% | Sensitive at low irradiance; temperature-dependent |
| [24] | MFCS-MPC + adaptive P&O MPPT | MPPT ↑3.5%, grid current THD ↓3.8→2.6%, PF > 0.99 | High computational cost, parameter-tuning intensive |

| | | | |
|---|---|---|---|
| [25] | Review of non-AI MPPT (P&O, IncCond, HC, RCM) | Adaptive methods: efficiency 95–98%, convergence < 0.25 s | Lack of standardization, few hardware tests |
| [26] | Fractional-order PI (FOPI) control for inverter | Overshoot ↓15%, settling ↓22%, THD = 2.1% vs 3.5% (PI) | Complex tuning, higher computational burden |
| [27] | Adaptive PR controller with frequency compensation | THD ↓3.1→1.8%, PF = 0.998 under nonlinear loads | Needs real-time frequency detection; complex tuning |
| [28] | Optimized droop-gain tuning | Power-sharing accuracy ↑7.5%, transient Δf ↓0.08 Hz | Sensitive gain selection, poor noise resilience |
| [29] | Modified reactive-power droop | Voltage deviation ↓5%, reactive accuracy ↑10%, Δf < 0.03 Hz | Needs perfect local measurement; ignores delay effects |
| [30] | Hierarchical droop–PI coordination | Voltage/frequency restoration 1.2 s (30% faster), ΔV < ±1.5%, Δf < 0.05 Hz | High communication overhead, control complexity |
| [31] | Robust droop-based controller for islanded microgrids | Real-power sharing = 98%, ΔV < ±1.8% | Only simulated; no hardware validation |
| [32] | PI–droop–virtual impedance hybrid | Overshoot ↓6.4→3.2%, steady-state error ↓1.9→0.8% | Needs precise virtual impedance; many tuning variables |
| [33] | Voltage–reactive control (VRC) with OLTC + capacitors | Bus voltage deviation ↓47%, reactive losses ↓12.4%, response = 420 ms | Needs accurate feeder model; communication latency issues |
| [34] | STATCOM PI + adaptive gain scheduling | Bus voltage restored ±2% in 150 ms, THD ↓4.7→2.5% | Thermal stress, costly retrofit, sensor demands |
| [35] | Hysteresis-timed capacitor scheduling | Voltage deviation ↓35%, switching ↓28%, PF +0.04 avg | Mechanical wear; noise-triggered false operations |
| [36] | Rule-based energy management system (EMS) with SoC and tariff dispatch | Fuel ↓18.7%, PV use ↑12.1%, peak ↓9.5% | Rigid to tariff changes; requires manual retuning |
| [37] | Demand-side management (DSM) using timers and price signals | Demand shift 18%, feeder peak ↓6.8%, latency < 1 s | Scalability issues; privacy concerns; rebound effects |
| [38] | State-of-charge (SoC)-aware droop control | Battery cycling ↓14%, usable life ↑20%, sharing ±2.5% | SoC estimate errors; accuracy vs. longevity trade-off |
| [39] | Active frequency-shift + phase-jump islanding detection | Detection 80–120 ms, seamless transfer 210 ms, overshoot < 3% | Threshold tuning critical; weak-grid risk |
| [40] | Rule-based economic dispatch for PV–diesel–battery systems | Fuel ↓21.3%, generator run ↓24%, outage-free operation | Requires manual tuning; less effective under variable tariffs |

## V. Power Quality Concerns

Power quality is one important factor to be considered in the integration of the hybrid solar–wind system, since variations in renewable generation may cause disturbances and hence instability to occur at the voltage and current level within the grid [14]. Highly advanced control, filtering, and standards are required to circumvent disturbances and provide for the stable operation of the grid so that power can be delivered consistently and with good quality.

Harmonics, flicker, and imbalance issues [15]

The hybrid renewable systems and power electronic converters introduce harmonics, flicker, and phase imbalance into the grid. Harmonics are produced through nonlinear switching operations in the inverter and converters, and they distort voltage and current waveforms. Flicker translates into rapid voltage variations causing visible intensity fluctuations in lights, whereas imbalance originates when power is flowing unequally across phases. These disturbances degrade power quality and life-span of equipment and affect sensitive loads. Mitigation could form the use of filters, advanced modulation techniques, and intelligent controller systems to maintain sinusoidal currents and balanced power distribution. It is evident that prevention of harmonic disturbances must be practiced in achieving grid integration that is both reliable and efficient..

## VI. CONCLUSION AND FUTURE WORK

This review analyzes control techniques for hybrid renewable energy systems, focusing on intelligent control, power quality improvement, and MPPT. Advanced control techniques that include modified-P&O, Incremental Conductance, and MPC-based control alongside the hybrid droop-control scheme confirm improvements in voltage stability, tracking efficiency, and harmonic reduction. Adaptive and predictive controllers under the ANN-, ANFIS-, and MFCS-MPC-based framework show enhanced system resilience in terms of dynamic irradiance, temperature, and load conditions with faster convergence and reduced THD. These intelligent methods provide the best utilization of solar–wind resources to keep the grid synchronization steady and conversion efficiency high. The review also stresses how important it is to coordinate converters, communication-based control layers, and DSM to make energy sharing and integration with the grid practically usable. Although some progress was achieved, the majority of studies are simulation studies, lacking instrumentation that can be realized on a large scale and capable of real-time validation. Computability issues, sensitive parametric considerations, and the lack of standardized performance assessment benchmarks continue to prevail as the major challenges. The future research domain should focus on the development of adaptive, self-learning controllers aided by artificial intelligence that can expedite operations by managing uncertainties in hybrid systems. Real-time HIL testing, standardized PQ evaluation structures, and cyber-secured, IoT-enabled lattices can add refinements to reliability. Hybrid storage coordination, data-driven forecasting, and scalable grid-interfacing designs will be paramount in attaining a manufacturing-infrastructure for efficient, intelligent, and sustainable hybrid renewable power installations.

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