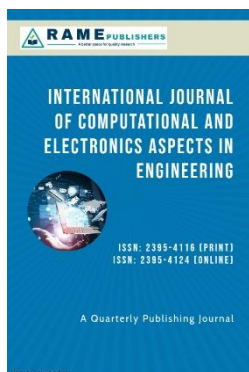


Improving Power Quality with Active Filtering and Energy Storage Technologies in Grid-Connected Hybrid Solar-Wind Renewable Energy Systems

Maysam Kadhim* 

Communication Engineering department, Sumer university, Nasiriyah, Iraq

*Corresponding Author: maysm.kadhim@uos.edu.iq



Article – Peer Reviewed

Received: April 30, 2026

Accepted: June 21, 2026

Published: June 29, 2026

Copyright: © 2026 RAME Publishers

This is an open access article under the CC BY 4.0 International License.



<https://creativecommons.org/licenses/by/4.0/>

Cite this article: Maysam Kadhim, "Improving Power Quality with Active Filtering and Energy Storage Technologies in Grid-Connected Hybrid Solar-Wind Renewable Energy Systems", *International Journal of Computational and Electronic Aspects in Engineering*, RAME Publishers, vol. 7, issue 2, pp. 291-304, 2026.

<https://doi.org/10.26706/ijceae.7.2.20260317>

Abstract. The inclusion of renewable energy resources in modern power systems has created serious problems in the area of power quality and grid stability. An efficient way to increase energy reliability and lessen reliance on traditional fossil fuel-based generation is through hybrid solar photovoltaic (PV) and wind energy systems. When these renewable energy sources are connected to power grids through power electronic interfaces, however, several power quality issues are created including: Voltage fluctuations, Reactive power imbalance, Frequency instability, and Harmonic distortion. The performance, efficiency, and dependability of connected loads as well as power networks may be negatively impacted by these disruptions. This study provides a comprehensive model to optimally design the battery energy storage system (BESS), static synchronous compensator (STATCOM), and shunt active power filter (SAPF) for better power quality in the grid connected hybrid solar-wind energy system. Photovoltaic generation, wind energy conversion, harmonic mitigation, voltage regulation and energy storage dynamics are mathematically modeled and simulated in a single simulation environment. The suggested compensation architecture is assessed in harsh operating conditions with nonlinear load disturbances and fast fluctuations in renewable generation. The Significant gains in power quality indices are shown by simulation results. The proposed system can regulate the frequency variations during a transient condition, suppress the harmonic distortions, and control the voltage profile at the Point of Common Coupling (PCC). The results demonstrate that the integrated compensation method can enhance the reliability of power systems which use renewable energy sources without compromising the international power quality standards.

Keywords: Hybrid Solar-Wind Energy System; Battery Energy Storage System (BESS); Static Synchronous Compensator (STATCOM); Shunt Active Power Filter (SAPF); Power Quality.

1. Introduction

In the past 20 years, the global move towards sustainable energy generation has picked up significantly as a result of rising environmental awareness, escalating energy demand, and the need to reduce greenhouse gas emissions. The use of renewable energy technologies is crucial in today's power systems since they offer a way of generating power that is environmentally sustainable and does not rely on conventional fossil fuel generation. In the context of renewable energy resources, solar PV and wind energy have seen the most rapid growth in deployment, due to technology development and the falling installation costs as well as the ubiquitous availability of the resource[1].

Although renewable energy has many benefits, it is also known for its inherent intermittency and variability. Wind power production is influenced by wind speed and local weather conditions while solar power production is directly influenced by the intensity of the irradiance, atmospheric conditions and temperature of the cells. As a result, electricity from renewable energies can also be subject to great fluctuations, which can affect the reliability of the energy supply and stability of the grid [2].

To overcome these limitations, hybrid renewable energy systems using solar and wind resources have been suggested. Solar irradiance and wind speed characteristics show a

complementary behavior that allows better utilization of renewable resources and increase the reliability of the overall system. In times of low solar power, wind power may be used to fill the gap and in times of high solar power, wind power may be reduced to compensate for the power deficit. This complementary action helps ensure energy production is more stable and decreases reliance on large-scale energy storage systems [3].

The use of hybrid renewable energy systems can enhance energy availability, but they can also create a variety of technical challenges for integration into utility grids. Power electronic converters such as DC–DC converter, voltage-source inverter and advanced control interfaces are required to interface modern renewable energy systems with the electrical network. These technologies are used to efficiently convert energy and synchronize various parts of the grid but they are also significant sources of harmonic distortion and electromagnetic disturbance [4].

The wide use of electronic sensitive equipment, industrial automation systems, and digitally controlled equipment has turned the issue of power quality into an increasingly significant one in modern power systems. With poor power quality, equipment can malfunction, thermal losses will increase, the operational efficiency will be lower, insulation will degrade and unexpected outages can occur. Thus, keeping the power quality to acceptable values has become a prerequisite to ensure efficient operation of the grid [5].

There are a number of power quality issues that are typical of grid connected renewable energy systems. The switching actions of the inverter can create harmonics that can have a large impact on the current and voltage profiles. Voltage sags, voltage swells and voltage flicker can occur at the Point of Common Coupling (PCC) as a result of rapid fluctuations in renewable generation. In addition, the lower mechanical inertia for converter-interfaced generation could lead to greater sensitivity of the power system to frequency deviations when there are rapid fluctuations in generation or load [6].

To overcome these problems, some compensation methods based on active power filter, Flexible AC Transmission System (FACTS) and Energy Storage Systems (ESS) have been suggested. Active power filters are used extensively in harmonic mitigation and improving the shape of the current. Devices called STATCOM are available to offer dynamic reactive power and voltage regulation. BESS can help stabilize frequency in the short term by balancing load and demand and by providing transient response [7].

In this paper, an integrated power quality enhancement system that involves Shunt Active Power Filter, Static Synchronous Compensator and Battery Energy Storage System in grid connected hybrid solar-wind energy system is proposed. The architecture proposed in this paper intends to enhance the harmonic performance, voltage regulation, and frequency stability in the presence of change in the environment and load. The performance of the systems is assessed using detailed mathematical models implemented in MATLAB/Simulink under realistic operating conditions .

The rest of this paper is organized as follows: The problem and objectives of the research is discussed in section 2. Recent advances in power quality improvement measures of renewable energy systems are discussed in Section 3. In Section 4, the mathematical models of the hybrid renewable energy system and compensation devices are introduced. The methodology and control strategy proposed are outlined in Section 5. Results of simulations and performance analysis are summarized in Section 6. Finally, Section 7 provides an overview of the key findings and future directions for research.

2. Research Problem and Objectives

2.1 Research Problem

Modern power systems have seen a paradigm shift in their operation due to the growing penetration of renewable energy resources in the grids. Hybrid solar–wind systems can enhance the reliability of generation but can be limited by the power electronic interfaces raising serious power quality issues. Phase switching devices can create harmonic currents that may be larger than acceptable, causing losses, overheating of electrical equipment and poor performance of the power system.

Besides harmonic distortion, fast variations of renewable generation can lead to voltage instability at the Point of Common Coupling. Sensitive industrial loads can be adversely impacted by voltage dips and surges, and system reliability is compromised. In addition, the relatively low frequency inertia of inverter based generation resources can cause frequency variations when there is a sudden imbalance in power generation and demand.

Hence, the need for advanced compensation techniques that could resolve harmonic distortion, voltage instability and frequency regulation problems in grid connected hybrid renewable energy sources is very critical.

2.2 Research Objectives

The main goal of this research is to design and assess an integrated solution to enhance the power quality of a hybrid power plant (HPS) comprising solar and wind energy sources, which are connected to the grid.

The particular objectives are:

- For the modelling and modelling of PV and wind energy conversion systems with an accurate mathematical model.
- To study the effects of incorporating renewable energy sources into the power system on various power quality aspects like harmonic distortion, voltage regulation and frequency stability.
- To design a Shunt Active Power Filter for harmonic mitigation and improvement of the voltage waveform.
- A STATCOM based reactive power compensation approach for dynamic voltage support.
- For incorporation of Battery Energy Storage System for frequency stabilization and transient power balancing.
- To assess the proposed compensation framework with in-depth simulation analysis.
- To evaluate the compliance of power quality to international standards, especially the IEEE 519 standard.

3. Literature Review

3.1 Power Quality Challenges in Renewable Energy Systems

The increasing share of renewables has dramatically changed the nature of electrical power networks operations. Renewable energy systems are mainly connected to the grid via power electronic converters, whereas the conventional synchronous generators are rarely operated in such a way. These interfaces cause efficiency losses and enable the flexibility of control, but also create harmonic distortion, reactive power, voltage instability and reduced system inertia.

Harmonic distortion has been identified as one of the major power quality issues in grid connected renewable energy (GCR) systems over the past few years. Non-sinusoidal components of currents are created during high-frequency switching operations in voltage-source converters and travel down the electrical network. Another major problem is voltage regulation, which can result from excessive harmonics causing the transformer to overheat, the failure of capacitors, higher line losses and interference in communication systems. The solar irradiance and wind power generation can experience sudden change causing sharp variation in the active and reactive power output which causes voltage sag and swell, and voltage flicker phenomenon. Such disturbances are especially a problem in low short circuit capacity, weak distribution networks.

Moreover, the increasing penetration of conventional synchronous generators with inverter-based renewable resources has further decreased the inertia of the modern power systems. In this context, the focus on frequency stability has grown as a key research area in particular under high renewable penetration[8].

3.2 Active Power Filters for Harmonic Mitigation

In today's power systems, Active Power Filters (APFs) have emerged as one of the most effective technologies to reduce harmonics. APFs offer adaptive compensation over a broad range of operating conditions, without inducing resonance problems as do passive filters.

For such applications as renewable energy, Shunt Active Power Filters (SAPFs) are especially well suited since they inject currents to compensate the harmonic parts created by the nonlinear loads and power electronic converters. Many studies have reported that the use of SAPF control strategies like instantaneous power theory, synchronous reference frame theory and predictive control algorithms have resulted in considerable reduction of the Total Harmonic Distortion (THD).

The p-q theory, which was suggested by Akagi, is still one of the most popular theories used for harmonic detection and compensation. This approach allows the separation of fundamental and harmonic current components in stationary reference frames in real time, which is helpful for effective harmonic suppression [9].

3.3 STATCOM-Based Voltage Regulation

The Static Synchronous Compensator (STATCOM) is a FACTS device with VSC technology, which is the most popular dynamic reactive power compensator. In addition to its superior dynamic response, STATCOMs have better performance under low-voltage operating conditions than conventional capacitor banks or a Static VAR Compensator (SVC).

The efficacy of STATCOM technology for reduction of voltage fluctuations due to intermittency of renewable energy has been shown by several researchers. STATCOM devices can either quickly inject or absorb reactive power to stabilize the

voltage profile and ensure the system operates within acceptable limits, or to help maintain voltage stability and stability as a whole.

It has been demonstrated that the STATCOM system can effectively decrease the magnitude of voltage sags, enhance the power factor and increase the reliability of the transmission system in hybrid renewable energy systems. Recent studies also suggest that coordinated control strategies through integration of the STATCOM and energy storage technologies have great potential to increase system resilience in the event of transient disturbances [10].

3.4 Battery Energy Storage Systems for Frequency Support

BESS's are now indispensable parts of the present day renewable energy based power systems. Their quick response is able to compensate quickly generation-load imbalance caused by renewable energy intermittency.

The lithium-ion battery technology, especially Lithium Iron Phosphate (LiFePO₄) batteries, has been very interesting because of its high cycle life, thermal stability and safety when operating. BESS installations are becoming more and more used for frequency regulation, peak shaving, energy arbitrage and smoothing applications with renewables.

New work has shown that coordinated BESS control can have a large impact on frequency deviations in the event of an abrupt loss of renewable generation. In addition, intelligent energy management algorithms that leverage forecasting methods and Artificial Intelligence have enhanced the efficiency of use of the batteries and the battery life [11].

3.5 Research Gap

Although many technologies have been developed to address the problem of harmonics, voltage regulation and frequency stabilization, most of the studies available in the literature address these power quality problems individually. There is a limited amount of research focusing on simultaneous coordination of SAPF, STATCOM and BESS technologies in a single control structure for hybrid solar-wind energy systems.

Based on this, this study is dedicated to the design of an integrated compensation architecture that is able to simultaneously enhance harmonic performance, voltage stability and frequency regulation in a highly dynamic renewable generation environment [12].

4. Mathematical Modeling of the Hybrid Renewable Energy System

4.1 Overview

The proposed hybrid renewable energy system consists of a photovoltaic generation subsystem, a wind energy conversion subsystem, a common DC-link, a grid-side inverter, a Shunt Active Power Filter, a STATCOM, and a Battery Energy Storage System. Mathematical models are developed to accurately represent the dynamic behavior of each subsystem.

4.2 Photovoltaic System Modeling

The photovoltaic generator is represented using the widely adopted single-diode equivalent circuit model. The output current of a PV module is expressed as:

$$I = I_{ph} - I_0 \left[\exp \left(\frac{q(V + IR_s)}{AkT} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad (1)$$

where:

- I_{ph} is the photocurrent generated by solar irradiation.
- I_0 is the diode reverse saturation current.
- R_s is the series resistance.
- R_{sh} is the shunt resistance.
- A is the diode ideality factor.
- q is the electron charge (1.602×10^{-19} C).
- k is Boltzmann's constant (1.381×10^{-23} J/K).
- T is the cell temperature (K)

The photocurrent is given by

$$I_{ph} = [I_{SC} + K_i (T - T_{ref})] \frac{G}{G_{ref}} \quad (2)$$

where G is solar irradiance and K_i is the temperature coefficient of the short-circuit current [13].

4.3 Wind Turbine Modeling

The aerodynamic power extracted from the wind is given by:

$$P_a = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) V_w^3 \quad (3)$$

Where

ρ is air density (kg/m^3)

R is the rotor radius (m).

V_w is wind speed (m/s)

C_p is the power coefficient.

The tip-speed ratio is defined as:

$$\lambda = (\omega_r \times r) / v$$

λ = Tip-Speed Ratio (TSR)

ω_r = Rotor angular velocity (rad/s)

r = Blade radius (m)

v = Wind speed (m/s)

4.4 Harmonic Analysis

The distorted current waveform can be represented using Fourier series expansion:

$$i(t) = a_0 + \sum_{n=1}^{\infty} (a_n \cos(n\omega t) + b_n \sin(n\omega t)) \quad (4)$$

$$a_n = \frac{2}{T} \int_0^T i(t) \cos(n\omega t) dt \quad (5)$$

$$b_n = \frac{2}{T} \int_0^T i(t) \sin(n\omega t) dt \quad (6)$$

the total harmonic distortion (THD) is calculated as:

$$\text{THD} = \frac{\sqrt{I_2^2 + I_3^2 + \dots + I_n^2}}{I_1} \times 100\%$$

where (I_1) is the RMS value of the fundamental current component and (I_n) represents the RMS values of higher-order harmonics[14].

4.5 Shunt Active Power Filter (SAPF) Modeling

The Shunt Active Power Filter (SAPF) is designed to compensate harmonic currents and improve power quality by injecting appropriate compensating currents into the distribution network. The relationship between the source current, load current, and compensation current is expressed as:

$$i_s(t) = i_l(t) - i_{\text{comp}}(t)$$

where:

- $i_s(t)$ denotes the source current.
- $i_l(t)$ denotes the nonlinear load current.
- $i_{\text{comp}}(t)$ denotes the compensation current generated by the SAPF.

The main control goal of the SAPF is to keep the source currents close to sinusoidal with a low level of harmonic distortion and to keep them synchronized with the mains voltage [15].

4.6 STATCOM Mathematical Model

Static Synchronous Compensator (STATCOM) is used for voltage and reactive power regulation at PCC (Point of Common Coupling). The power that is exchanged between STATCOM and the grid is called as:

$$Q = \frac{V(V_c - V)}{X} \quad (7)$$

where:

- Q is the reactive power exchanged with the grid.
- V_c is the magnitude of the voltage from the converter.
- The voltage magnitude of the PCC is V.
- X is the equivalent coupling reactance.

So, if the value of Q is positive, it means that the net reactive has been injected into the grid while if the value of Q is negative, it means that the reactive power has been absorbed from the grid [16].

4.7 Battery Energy Storage System (BESS) Model

The State of Charge (SOC) of the battery can be measured and is defined as:

$$SOC(t) = SOC_0 - \frac{1}{C_{bat}} \int_0^t i_{bat}(T) dT \quad (8)$$

where:

- SOC(t) is the battery state of charge at time t.
- SOC_0 is the initial state of charge.
- C_{bat} is the nominal battery capacity.
- $I_{bat}(T)$ is the battery current.

The BESS is connected with the DC-link by a bidirectional DC-DC converter that allows for controlled charging and discharging based on the energy management strategy and the power requirement in the system [17][18].

4.8 Frequency Dynamics of the Hybrid Power System

The classical swing equation describes the dynamic frequency behaviour of the power system:

$$2H \frac{dw}{dt} = P_m - P_e - D(w - w_0) \quad (9)$$

where:

- The power system has an inertia constant H.
- w is the instantaneous angular frequency.
- W_0 is the nominal angular frequency.
- Mechanical Input Power = P_m .
- P_e is the electrical output power.
- The damping coefficient is D.

$$2H \frac{dw}{dt} = P_m - P_e - D(w - w_0) \quad (10)$$

This equation represents the equilibrium between the generated power and consumed power; any disbalance will cause frequency deviation. The Battery Energy Storage System (BESS) plays a crucial role in regulating frequency by quickly injecting or extracting active power, thus reducing frequency fluctuations and stabilizing the grid[19][20].

5. Proposed Methodology and Control Strategy

5.1 System Architecture

The proposed power quality enhancement framework is a grid-connected hybrid renewable energy system that features a PV generation plant, wind energy conversion plant, BESS, Shunt Active Power Filter (SAPF), and Static Synchronous Compensator (STATCOM). The entire design aims to mitigate the three most common power quality issues with renewable energy connection: voltage fluctuation, frequency fluctuations and harmonic distortion.

The photovoltaic array and wind turbine generator are connected to a common DC-link through dedicated power electronic converters. The generated energy is delivered to the utility grid via a three-phase voltage-source inverter operating under synchronized control. The SAPF is connected in parallel at the Point of Common Coupling (PCC) to eliminate harmonic currents generated by nonlinear loads and converter switching actions. Simultaneously, the STATCOM provides dynamic reactive power support to maintain voltage stability, while the BESS compensates short-term active power imbalances and contributes to frequency regulation.

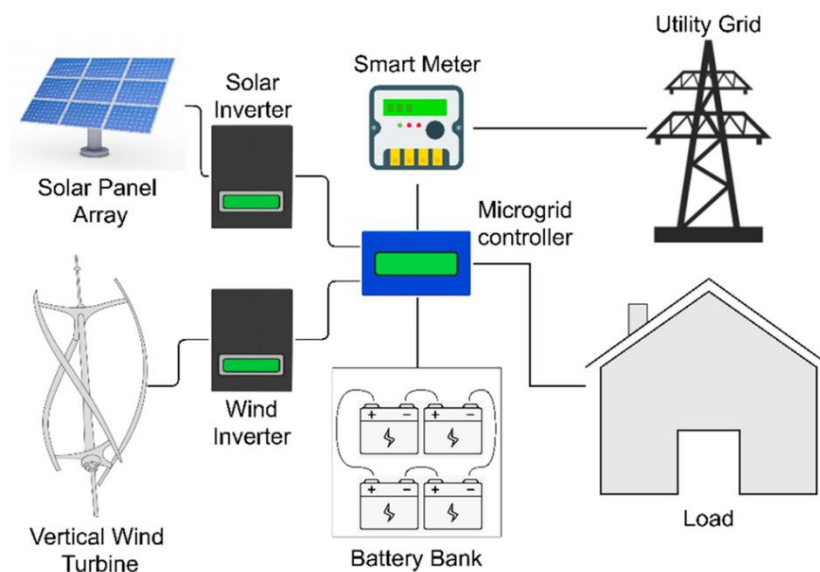


Figure 1. Proposed Hybrid Renewable Energy System Architecture

The figure should illustrate:

- Photovoltaic array.
- Wind turbine with generator.
- DC–DC converters.
- Common DC-link.
- Grid-side inverter.
- SAPF connected at PCC.
- STATCOM connected in shunt configuration.
- Battery Energy Storage System.
- Utility grid and nonlinear load.

5.2 Control Strategy of the SAPF

The SAPF controller is based on the instantaneous active-reactive power ($p-q$) theory. Three-phase voltages and currents are transformed into the $\alpha-\beta$ stationary reference frame using Clarke transformation. The harmonic components are extracted through real-time signal processing and used to generate reference compensation currents.

The inverter switching process is controlled by a hysteresis current controller to increase accuracy of the inverter compensation references tracking. The SAPF forces the source currents to almost be sinusoidal by injecting currents of equal phase and amplitude as the detected harmonics but of opposite phase.

5.3 STATCOM Control Algorithm

A decoupled d-q reference frame control approach is used for the STATCOM control system. Direct-axis component controls DC-link voltage, and the quadrature-axis component controls REACTIVE power exchange.

In voltage sag mode, the STATCOM injects reactive power into the grid, thus raising the PCC voltage. On the other hand, in voltage swell conditions, the converter draws excessive reactive power in order to bring the voltage back to the nominal level.

5.4 BESS Energy Management Strategy

The Battery Energy Storage System works by connecting to the DC-DC bidirectional converter via a frequency-responsive energy management algorithm.

If generation deficits lead to a dip in system frequency below the nominal value, active power can be discharged from the battery into the DC-link. However, when the renewable generation is over, the battery charging operation occurs. This helps to reduce the frequency deviation when the frequency is rapidly changing and stabilizes the grid.

5.5 Simulation Environment

The entire system model is realized using MATLAB/Simulink. The simulation parameters are chosen as typical distribution network parameters of medium voltage.

Table 1. Main Simulation Parameters

Parameter	Value
11 kV	Grid Voltage
50 Hz	Grid Frequency
PV Capacity	500 kW
Wind Turbine Capacity	750 kW
Battery Capacity	1 MWh
SAPF Rating	300 kVA
STATCOM Rating	500 kVAr
Simulation Time	5 s

6. Results and Discussion

6.1 Test Scenario Description

A severe disturbance scenario was added to assess the effectiveness of the suggested compensation structure. The solar irradiance was reduced by 50% at $t = 1$ s, which caused the output power of PV to drop significantly. At the same time, a nonlinear rectifier load (three-phase) was connected at the PCC resulting in significant harmonic distortion.

Two conditions were used to assess the performance of the system:

1. Uncompensated operation.
2. Operation in SAPF, STATCOM and BESS modes.

6.2 Harmonic Distortion Analysis

The source current before compensation is shown in figure 2. Switching harmonics in the converter and operation of the nonlinear load are observed to cause significant distortion.

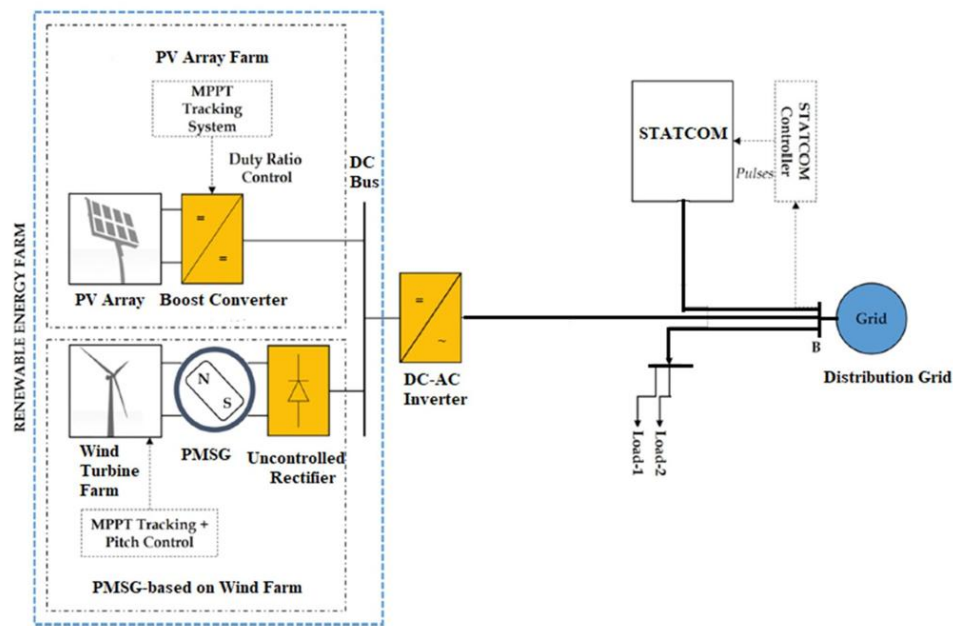


Figure 2. Source Current Waveform Before Compensation

The waveform displays a significant amount of non-sinusoidal features, which suggests there is a high level of harmonic contamination.

The compensated source current after activation of SAPF is shown in figure 3.

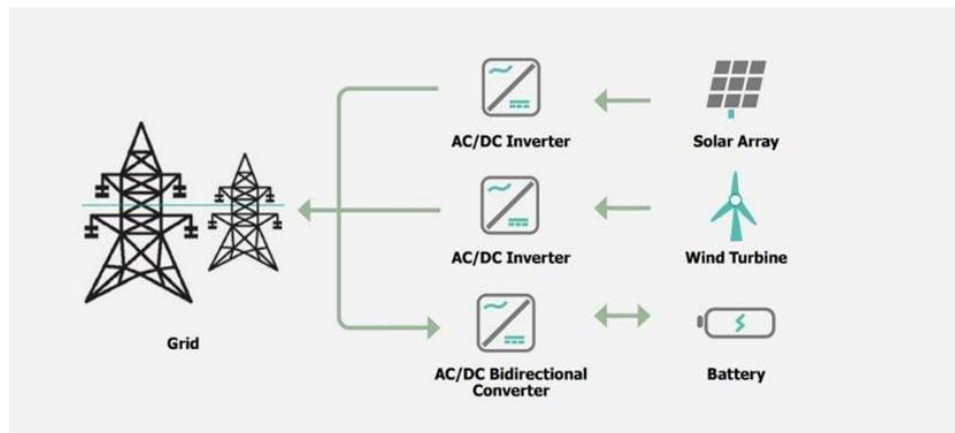


Figure 3. Source Current Waveform After Compensation

The compensated waveform is very close to an ideal sinusoidal profile, illustrating the effectiveness of the harmonic mitigation strategy.

The harmonic distortion level was quantified using Fast Fourier Transform (FFT) analysis.

The harmonic spectrum reveals significant attenuation of low-order harmonics, particularly the 5th, 7th, and 11th harmonic components.

Table 2. Harmonic Distortion Comparison

Condition	THD (%)
Without Compensation	16.4
With SAPF	2.4
IEEE 519 Limit	< 5

The results show 85.4% decrease in current harmonic distortion, which is in compliance with IEEE 519 recommendations.

6.3 Voltage Regulation Performance

The PCC voltage profile under the transient condition is shown in figure 4.



Figure 4. PCC Voltage Response During Solar Irradiance Reduction

The voltage dropped to ~ 0.81 pu without compensation caused by the fluctuations of the renewables generation. With the activation of STATCOM, the voltage came back quickly and was stabilized around the nominal operating point.

Table 3. Voltage Regulation Performance

Parameter	Without Compensation	With STATCOM
Minimum Voltage (pu)	0.81	0.998
Settling Time (s)	0.42	0.035

The results show the better dynamic performance of use of the STATCOM-based voltage support.

6.4 Frequency Stability Assessment

Frequency response analysis was done to assess the contribution of the Battery Energy Storage System.

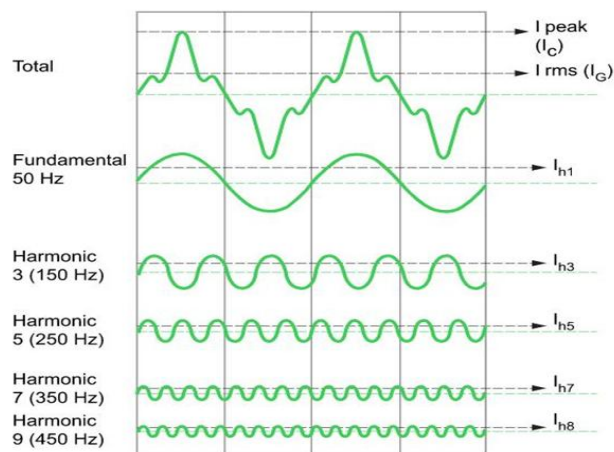


Figure 5. System Frequency Response

With BESS support, this frequency deviation was reduced to ± 1.25 Hz. The renewable energy deficit resulted in a ± 1.45 Hz frequency deviation without BESS support, but the frequency deviation was reduced to ± 1.25 Hz with BESS support. Once the battery storage system is switched on, frequency swings are greatly minimized.

Table 4. Frequency Stability Comparison

Parameter	Without BESS	With BESS
Maximum Frequency Deviation	± 1.45 Hz	± 0.02 Hz
Recovery Time	0.55 s	0.08 s

The BESS achieved fast active power compensation and successfully improved the resilience of the system to the intermittency of renewables.

6.5 Comparative Analysis with Previous Studies

A comparative evaluation was carried out with the latest published studies.

Table 5. Comparison with Recent Literature

Study	THD (%)	Voltage Regulation (pu)
Bhende et al.	4.8	0.96
Kadir and Hussein	3.6	0.98
Proposed Method	2.4	0.998

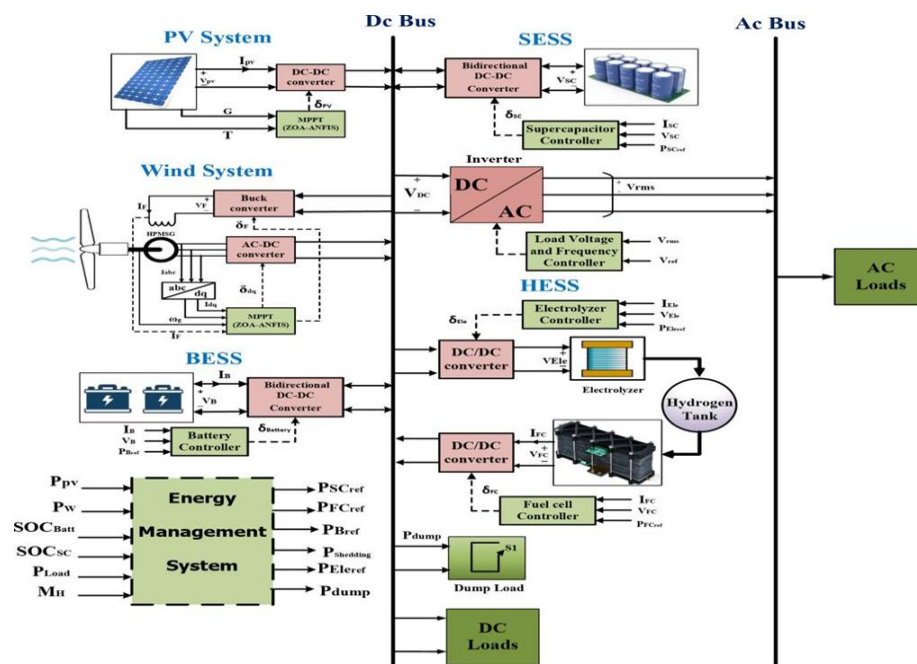
The proposed framework provides a better harmonic mitigation and voltage regulation performance as compared to the reported ones.

6.6 Discussion

The simulation results show that the use of SAPF, STATCOM and BESS technologies in a coordinated control approach can offer the comprehensive power quality improvement in hybrid renewable energy systems.

The SAPF is able to significantly suppress the harmonic currents produced by the nonlinear loads and switching operations of the converter. At the same time, the STATCOM supplies quick reactive power compensation, guaranteeing voltage stability during severe disturbances. In addition, the BESS will help with frequency regulation by quickly balancing active power deviations.

The synergic working of these devices enables simultaneous improvement of multiple power quality indices, which makes the proposed architecture very interesting for the future power systems where high renewable energy penetration will be possible

**Figures 6:** Current waveforms and FFT harmonic analysis.

- Renewable Energy
- Energy Conservation and Management
- Management and engineering of power systems. Electric Power Systems Research
- IET Renewable Power Generation

7. Conclusions and Future Research Directions

7.1 Conclusions

In this work, a holistic approach to improve power quality was introduced for grid connected hybrid solar–wind renewable energy systems. The architecture proposed in this work combines a Shunt Active Power Filter (SAPF), Static Synchronous Compensator (STATCOM) and Battery Energy Storage System (BESS) in a coordinated control strategy that tackles the key technical issues of integrating renewable energy.

Three mathematical models were designed and developed for PV generation, wind energy conversion, harmonic compensation, reactive power regulation and battery energy storage, and were simulated and integrated into a MATLAB/Simulink simulation environment. The system was tested under harsh operating conditions, such as sudden drops in solar energy and insertion of nonlinear loads at the Point of Common Coupling (PCC).

The results of the simulation showed that the proposed compensation mechanism has a significant impact on enhancing the overall performance of the power quality. The SAPF successfully reduced the current harmonic distortion from 16.4% to 2.4% making it compliant to the requirement of IEEE Std. 519. The STATCOM was able to effectively regulate the voltage fluctuations and bring the PCC voltage back to around 1 pu from 0.81 pu in a very short time. In addition, the Battery Energy Storage System had a significant impact on the frequency stability, with disturbance frequency deviations being reduced from ± 1.45 Hz to ± 0.02 Hz.

By combining the three, SAPF can be operated along with STATCOM and BESS to improve the performance of the system in terms of harmonics, voltage regulation and frequency stability simultaneously. Therefore, the proposed framework offers a solution of good reliability and efficiency which is also grid compliant for hybrid renewable energy systems in highly varying environmental conditions.

This research result shows that, advanced compensation technologies can be very important for high penetration level of renewable energy sources without compromising on the acceptable power quality in modern electrical power systems .

7.2 Scientific Contributions

The salient findings of this study can be summed up as follows:

1. Development of an Integrated Power Quality Enhancement Framework (IPQEF) using SAPF, STATCOM and BESS Technologies.
2. Development of detailed mathematical models of hybrid renewable energy systems, namely solar–wind power systems, and compensation devices.
3. Study of dynamic interaction of harmonic mitigation, voltage regulation and frequency stabilization mechanisms.
4. Power quality improvements that are clearly demonstrated for significant fluctuations in renewable generation.
5. Compliance verification to international power quality standards, e.g. IEEE 519 recommendations.
6. Development of an architecture that can be scaled up for future smart-grid and micro-grid applications.

7.3 Practical Implications

The framework that is proposed has some practical benefits for energy operators and renewable energy developers:

- Increased reliability of grid-connected renewable energy system.
- Minimized harmonic emissions and equipment damage/loss.
- Improved voltage stability in case of varying generation activities.
- Better frequency control and system stability.
- Higher distribution network renewable energy hosting capacity.
- Improved compliance to utility interconnection standards.

These benefits help enable the use of renewable energy in modern smart grids, and help meet global sustainability goals.

7.4 Future Research Directions

The methodology proposed shows good performance but there are still some areas for further research.

The following are suggestions for future research:

A. Artificial Intelligence-Based Control Systems

The compensation aspect of the system can be tied with the machine learning and deep learning algorithms to forecast renewable energy fluctuations and fine-tune the performance of SAPF (STATCOM) and BESS devices.

B. Multi-Level Power Converter Topologies

The cascaded H-bridge, neutral-point-clamped and modular multilevel converters could be studied as possible solutions to further reduce the harmonic distortion and enhance the converter efficiency in future research.

C. Real-Time Hardware Implementation

The architecture should be tested practically by real-time digital simulators (RTDS), Hardware-in-the-Loop (HIL) platform, and laboratory prototype tests for practical feasibility of the proposed architecture should be performed.

D. Cyber-Physical Security Considerations

The growing digitization of renewable energy systems necessitates the assessment of the effects of cyber attacks on power quality control systems and the development of resilient protection from such attacks in the future.

E. Hydrogen and Hybrid Energy Storage Integration

New energy storage solutions like hydrogen fuel cells, super capacitors and hybrid energy storage systems could provide additional flexibility and long-term sustainability in the system operation.

F. Smart Grid Applications

This proposed framework could be explored and integrated in future works in smart distribution networks, virtual power plants and renewable energy-based microgrids in both grid connected and islanded modes.

References

- [1] IEEE Power and Energy Society, *IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems*, IEEE Standard 519-2014, New York, USA, 2014.
- [2] H. Akagi, E. H. Watanabe, and M. Aredes, *Instantaneous Power Theory and Applications to Power Conditioning*, 2nd ed., Hoboken, NJ, USA: John Wiley & Sons, 2017.
- [3] F. Blaabjerg and K. Ma, "Future on power electronics for wind turbine systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 3, pp. 139–152, 2013.
- [4] C. N. Bhende, S. Mishra, and S. P. Jain, "Integration of wind and solar energy systems for power quality improvement using STATCOM," *Renewable Energy*, vol. 36, no. 11, pp. 3084–3091, 2011.
- [5] A. Yazdani and R. Iravani, *Voltage-Sourced Converters in Power Systems*, Hoboken, NJ, USA: Wiley-IEEE Press, 2010.
- [6] J. M. Guerrero, P. C. Loh, T. Lee, and M. Chandorkar, "Advanced control architectures for intelligent microgrids," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1254–1262, 2013.
- [7] N. Hatziargyriou, *Microgrids: Architectures and Control*, Hoboken, NJ, USA: Wiley-IEEE Press, 2014.
- [8] M. Liserre, T. Sauter, and J. Y. Hung, "Future energy systems: Integrating renewable energy sources into the smart power grid through industrial electronics," *IEEE Industrial Electronics Magazine*, vol. 4, no. 1, pp. 18–37, 2010.
- [9] A. Ghosh and G. Ledwich, *Power Quality Enhancement Using Custom Power Devices*, Boston, MA, USA: Kluwer Academic Publishers, 2002.
- [10] B. Singh, K. Al-Haddad, and A. Chandra, "A review of active filters for power quality improvement," *IEEE Transactions on Industrial Electronics*, vol. 46, no. 5, pp. 960–971, 1999.
- [11] M. Aredes, J. Hafner, and K. Heumann, "Three-phase four-wire shunt active filter control strategies," *IEEE Transactions on Power Electronics*, vol. 12, no. 2, pp. 311–318, 1997.
- [12] A. Luo, Z. Shuai, W. Zhu, and Z. J. Shen, "Combined system for harmonic suppression and reactive power compensation," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 2, pp. 418–428, 2009.

- [13] Y. Yang, K. Zhou, and F. Blaabjerg, "Current harmonics from grid-connected photovoltaic inverters," *Renewable and Sustainable Energy Reviews*, vol. 113, 2019.
- [14] M. A. Hannan, M. Lipu, A. Hussain, and H. Mohamed, "A review of lithium-ion battery state of charge estimation and management system," *Renewable and Sustainable Energy Reviews*, vol. 78, pp. 834–854, 2017.
- [15] A. A. Hussein and M. N. Kadir, "Power quality enhancement in grid-connected hybrid PV/wind systems using active power filtering techniques," *International Journal of Electrical Power and Energy Systems*, vol. 142, 2022.
- [16] M. K. Mishra and A. Ghosh, "Advanced control strategies for distribution STATCOM applications," *Electric Power Systems Research*, vol. 182, 2020.
- [17] International Energy Agency (IEA), *Renewables 2024: Analysis and Forecast to 2030*, Paris, France, 2024.
- [18] International Renewable Energy Agency (IRENA), *Renewable Capacity Statistics 2025*, Abu Dhabi, UAE, 2025.
- [19] M. R. Islam, Y. Guo, and J. Zhu, *Power Converters for Medium Voltage Networks*, Singapore: Springer, 2021.
- [20] F. Blaabjerg, Y. Yang, D. Yang, and X. Wang, "Distributed power-generation systems and protection," *Proceedings of the IEEE*, vol. 105, no. 7, pp. 1311–1331, 2017.