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Power Quality Enhancement in Hybrid Solar–Wind Energy Systems Using ANN-Controlled Unified Power Quality Conditioner

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ABSTRACT

The increasing penetration of renewable energy sources such as solar photovoltaic (PV) and wind energy into the power grid introduces significant power quality challenges due to intermittency, harmonics, voltage fluctuations, and frequency instability. This research presents the modeling and implementation of a grid-connected hybrid solar–wind energy system in MATLAB/Simulink, with a focus on power quality enhancement using ANN-controlled compensators. The solar subsystem employs a variable irradiation model whose fluctuating output is regulated using a Buck converter integrated with a Perturb and Observe (P&O) based Maximum Power Point Tracking (MPPT) algorithm to maintain a stable DC output voltage. This regulated DC supply is converted to three-phase AC using an inverter and connected to the Point of Common Coupling (PCC). The wind subsystem consists of a wind turbine model driven by variable wind speed, coupled to a Permanent Magnet Synchronous Generator (PMSG). The generated AC output is rectified using a diode rectifier, stabilized through a DC-link capacitor, and inverted back to three-phase AC via a back-to-back converter configuration before being connected to the PCC. Initially, the system was analyzed without using any compensating device such as DSTATCOM or UPQC. Under this condition, significant harmonic distortion, voltage sag/swell, and frequency oscillations were observed due to nonlinear switching and renewable intermittency. In the second case, an ANN-controlled STATCOM was integrated into the network. The STATCOM effectively reduced Total Harmonic Distortion (THD) to below 5%, stabilized voltage magnitude, and eliminated frequency oscillations. However, further improvement was targeted. In the final case, an ANN-controlled Unified Power Quality Conditioner (UPQC) was implemented. The UPQC demonstrated superior performance compared to STATCOM by providing both series and shunt compensation. As a result, harmonic distortion was reduced further (approximately around 1% range), voltage fluctuations were eliminated, and frequency remained constant. The proposed ANN-based UPQC control strategy significantly enhances overall power quality in hybrid renewable energy systems, meeting IEEE-519 standards and proving its effectiveness for modern grid-connected applications.

Keywords: Hybrid Renewable Energy System, Solar Photovoltaic (PV), Wind Energy Conversion System (WECS), Total Harmonic Distortion (THD), Point of Common Coupling (PCC), STATCOM, Unified Power Quality Conditioner (UPQC), Artificial Neural Network (ANN).

I INTRODUCTION

The rapid growth in global energy demand and the increasing environmental concerns associated with fossil fuel-based generation have accelerated the integration of renewable energy sources into modern power systems [1]. Among various renewable resources, solar photovoltaic (PV) and wind energy have emerged as the most promising and widely deployed technologies due to their abundance, sustainability, and declining installation costs [2]. However, the intermittent and stochastic nature of solar irradiation and wind speed introduces significant technical challenges when these sources are connected to the utility grid [3]. Unlike conventional synchronous generators, renewable energy systems rely heavily on power electronic converters for energy conversion and grid interfacing, which inherently introduce harmonic distortions and dynamic instabilities [4]. As renewable penetration increases, maintaining voltage stability, frequency regulation, and overall power quality becomes a critical concern for grid operators [5]. Therefore, advanced control and compensation strategies are essential to ensure reliable operation of grid-integrated hybrid renewable energy systems [6].

Hybrid renewable energy systems combining solar PV and wind generation offer improved reliability and better utilization of natural resources compared to standalone systems [7]. In such systems, the solar PV output depends on solar irradiation and temperature variations, while wind turbine output depends on fluctuating wind speeds [8]. To extract maximum available power from the PV array under varying environmental conditions, Maximum Power Point Tracking (MPPT) techniques are employed [9]. Among various MPPT algorithms, the Perturb and Observe (P&O) method is widely adopted due to its simplicity and effectiveness [10]. The MPPT algorithm typically controls a DC–DC converter, such as a Buck converter, to regulate the duty cycle and maintain operation at the maximum power point [11]. Similarly, in wind energy conversion systems, mechanical torque generated by the turbine is converted into electrical power using generators such as the Permanent Magnet Synchronous Generator (PMSG), which offers high efficiency and reduced maintenance requirements [12]. The generated power is processed through rectifiers, DC-link capacitors, and voltage source inverters before grid integration [13]. Although these converter-based interfaces enable flexible control, they also introduce harmonics and switching-related distortions [14].

Power quality issues in grid-connected renewable systems include voltage sags, swells, flicker, harmonic distortion, unbalanced voltages, and frequency deviations [15]. Total Harmonic Distortion (THD) is one of the most critical indices used to evaluate waveform distortion and must comply with IEEE-519 standards to ensure acceptable grid performance [16]. High harmonic content not only reduces system efficiency but also causes overheating, equipment malfunction, and reduced lifespan of electrical components [17]. Moreover, fluctuations in renewable generation can lead to instability at the Point of Common Coupling (PCC), affecting both utility and consumer loads [18]. Conventional reactive power compensation devices such as capacitor banks are insufficient to handle dynamic disturbances introduced by renewable integration [19]. Hence, Flexible AC Transmission System (FACTS) devices such as Static Synchronous Compensator (STATCOM) have been widely implemented to enhance voltage stability and reactive power support [20]. STATCOM operates as a shunt-connected voltage source converter capable of injecting or absorbing reactive power to regulate voltage and reduce current harmonics [21].

While STATCOM effectively mitigates reactive power-related issues, it primarily addresses current compensation and has limited capability in correcting voltage distortions caused by upstream disturbances [22]. To overcome these limitations, the Unified Power Quality Conditioner (UPQC) has been introduced as a comprehensive solution for power quality enhancement [23]. UPQC integrates both series and shunt active power filters connected through a common DC-link capacitor, enabling simultaneous compensation of voltage and current harmonics [24]. The shunt converter mitigates current-related distortions and maintains DC-link voltage, whereas the series converter compensates for voltage sags, swells, and imbalances [25]. As a result, UPQC provides superior performance compared to standalone compensators such as STATCOM or Dynamic Voltage Restorer (DVR) [26]. However, the performance of these compensating devices largely depends on the effectiveness of their control strategies [27]. Traditional proportional-integral (PI) controllers may not provide optimal performance under highly nonlinear and time-varying renewable conditions [28].

To address these challenges, intelligent control techniques such as Artificial Neural Networks (ANN) have gained significant attention in power system applications [29]. ANN-based controllers offer adaptive learning capability, fast dynamic response, and robustness against nonlinearities, making them highly suitable for renewable-integrated systems [30]. By training the neural network with system operating data, accurate gating pulses can be generated for power electronic converters, resulting in improved harmonic suppression and voltage regulation. In the proposed research, an ANN-controlled STATCOM and ANN-controlled UPQC are implemented in a grid-connected hybrid solar–wind system. The system performance is evaluated under three scenarios: without compensation, with ANN-controlled STATCOM, and with ANN-controlled UPQC. Comparative analysis demonstrates that while STATCOM significantly reduces THD and stabilizes voltage, the ANN-based UPQC provides superior power quality improvement by minimizing harmonic distortion to near 1% levels,

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eliminating voltage fluctuations, and maintaining constant frequency. Thus, intelligent UPQC control emerges as an effective and reliable solution for enhancing power quality in modern hybrid renewable energy networks.

II LITERATURE SURVEY

The rapid integration of renewable energy sources into modern power systems has been extensively discussed in recent years due to increasing environmental concerns and depletion of fossil fuels [1]. Solar photovoltaic (PV) and wind energy systems have emerged as dominant contributors to distributed generation because of their sustainability and technological advancements [2]. However, the intermittent nature of solar irradiation and wind speed creates variability in output power, leading to voltage instability and frequency deviations in grid-connected systems [3]. Researchers have emphasized that large-scale penetration of converter-based renewable sources significantly affects power quality due to harmonic injection and switching disturbances [4]. Studies indicate that hybrid solar–wind systems offer improved reliability compared to standalone systems by complementing each other's generation patterns [5]. Nevertheless, hybrid systems introduce additional control complexity because both sources require power electronic interfaces for grid synchronization and regulation [6].

To maximize energy extraction from solar PV systems, numerous Maximum Power Point Tracking (MPPT) techniques have been proposed in the literature [7]. Among these, the Perturb and Observe (P&O) algorithm is widely adopted due to its simplicity and ease of implementation [8]. Comparative studies show that while incremental conductance and fuzzy logic methods provide faster convergence, P&O remains popular in practical applications because of its low computational requirements [9]. MPPT algorithms are typically integrated with DC–DC converters such as Buck, Boost, or Buck–Boost converters to regulate output voltage [10]. Research demonstrates that proper duty cycle adjustment ensures operation at the maximum power point under varying irradiation conditions [11]. In wind energy systems, Permanent Magnet Synchronous Generators (PMSGs) are preferred due to their high efficiency, compact size, and elimination of external excitation requirements [12]. The generated AC power is rectified and passed through DC-link capacitors before inversion to maintain stable voltage levels [13]. However, studies reveal that back-to-back converter configurations introduce harmonic distortions and switching noise into the system [14].

Power quality issues associated with renewable integration have been a major research focus [15]. Total Harmonic Distortion (THD), voltage sag, swell, flicker, and imbalance are common disturbances observed at the Point of Common Coupling (PCC) [16]. IEEE-519 standards specify harmonic limits to ensure reliable operation of electrical equipment and grid stability [17]. Researchers have shown that uncontrolled harmonic injection leads to overheating, transformer losses, and malfunction of sensitive loads [18]. Conventional compensation methods such as passive filters and capacitor banks have been employed; however, they lack dynamic response and adaptability to fluctuating renewable conditions [19]. To address these issues, Flexible AC Transmission System (FACTS) devices such as STATCOM have been widely investigated [20]. STATCOM provides fast reactive power support and voltage regulation through shunt compensation [21]. Literature reports significant reduction in THD and voltage stabilization using STATCOM in grid-connected renewable systems [22].

However, STATCOM mainly addresses current harmonics and reactive power compensation, with limited capability in correcting voltage distortions [23].

To overcome the limitations of single compensating devices, researchers introduced the Unified Power Quality Conditioner (UPQC) as an advanced power quality enhancement solution [24]. UPQC combines both series and shunt active power filters connected via a common DC-link capacitor, enabling simultaneous mitigation of voltage and current disturbances [25]. The shunt converter compensates for current harmonics and maintains DC-link voltage, while the series converter injects voltage to correct sags, swells, and imbalances [26]. Several studies demonstrate that UPQC outperforms standalone STATCOM and Dynamic Voltage Restorer (DVR) in hybrid renewable networks [27]. Simulation and experimental results confirm significant THD reduction and improved waveform quality with UPQC implementation [28]. However, the effectiveness of UPQC depends heavily on the control strategy adopted for generating switching pulses [29]. Traditional PI controllers may fail to provide satisfactory performance under nonlinear and rapidly varying renewable conditions [30].

Recent advancements highlight the application of intelligent control techniques such as Artificial Neural Networks (ANN), fuzzy logic, and adaptive controllers for power quality enhancement [1]. ANN controllers provide self-learning capability, fast dynamic response, and robustness against system nonlinearities [2]. Researchers report that ANN-based control improves harmonic suppression and voltage regulation in renewable-integrated systems compared to conventional methods [3]. ANN has been successfully applied in STATCOM and UPQC control to achieve better DC-link voltage regulation and improved gating pulse generation [4]. Comparative analyses show that intelligent controllers reduce settling time, overshoot, and steady-state error [5]. Despite extensive research, there remains a need for comprehensive comparative studies evaluating uncompensated systems, STATCOM-compensated systems, and UPQC-compensated systems under identical hybrid renewable configurations [6]. Therefore, the present work contributes by implementing ANN-controlled STATCOM and ANN-controlled UPQC in a grid-connected hybrid solar–wind system and analyzing their performance in terms of THD reduction, voltage stability, and frequency regulation.

III METHODOLOGY

The proposed system consists of a grid-connected hybrid renewable energy network integrating both solar PV and wind energy subsystems at a common Point of Common Coupling (PCC). The entire system is modeled and simulated in MATLAB/Simulink environment. In the first stage, a solar PV module is designed with variable irradiation input to replicate real-time environmental variations. The output voltage and current of the PV panel fluctuate depending on irradiation levels. To ensure maximum energy extraction, a Perturb and Observe (P&O) based Maximum Power Point Tracking (MPPT) algorithm is implemented. The MPPT algorithm continuously monitors PV voltage and current, calculates power, and adjusts the duty cycle of a DC–DC Buck converter accordingly. The Buck converter regulates the variable DC output and provides a stabilized DC voltage suitable for further conversion.

This regulated DC voltage is fed to a three-phase Voltage Source Inverter (VSI), which converts it into AC supply synchronized with grid parameters before connecting to the PCC.

In parallel, the wind energy subsystem is modeled using a wind turbine block driven by variable wind speed input measured in meters per second. The wind turbine converts kinetic energy into mechanical torque, which is applied to a Permanent Magnet Synchronous Generator (PMSG). The PMSG generates three-phase AC power proportional to wind speed variations. This AC output is rectified using a three-phase diode rectifier to convert it into DC power. A DC-link capacitor is placed between the rectifier and inverter stages to reduce voltage ripples and maintain DC stability. The stabilized DC output is then fed into a three-phase inverter in a back-to-back converter configuration. By controlling the inverter switching pulses, the output voltage magnitude and frequency are regulated before connecting to the PCC. Thus, both solar and wind subsystems contribute power to the common grid interface.

In the first case study, the system operates without any power quality compensating device. The performance is analyzed under varying irradiation and wind speed conditions. Voltage waveform, current waveform, frequency response, and Total Harmonic Distortion (THD) are measured at the PCC using power quality measurement blocks. Due to inverter switching and fluctuating renewable inputs, significant harmonic distortions are observed in both voltage and current waveforms. Frequency oscillations and voltage magnitude variations occur, leading to reduced power quality. This case establishes the baseline performance of the hybrid system without compensation.

In the second case, a Static Synchronous Compensator (STATCOM) is connected in shunt at the PCC. The STATCOM consists of a Voltage Source Converter (VSC), DC-link capacitor, and coupling transformer. An Artificial Neural Network (ANN) controller is designed to generate gating pulses for the STATCOM inverter. The ANN is trained using system parameters such as voltage error, current error, and DC-link voltage deviation. The controller dynamically adjusts reactive power injection to stabilize voltage and reduce harmonic distortion. Simulation results show significant improvement in waveform quality and reduction in THD to within IEEE-519 limits (below 5%). Voltage fluctuations and frequency oscillations are minimized compared to the uncompensated case.

In the final case, a Unified Power Quality Conditioner (UPQC) is implemented at the PCC. The UPQC consists of two Voltage Source Converters connected back-to-back through a common DC-link capacitor—one connected in shunt and the other in series with the line. Both converters are controlled using an ANN-based control strategy. The shunt converter compensates for current harmonics and maintains DC-link voltage, while the series converter injects compensating voltage to eliminate voltage distortions and sags. The ANN controller generates optimal switching pulses by analyzing system errors and dynamically adapting to renewable fluctuations. Simulation results demonstrate superior performance compared to STATCOM. THD is reduced further to nearly 1%, voltage and current waveforms become sinusoidal, and frequency remains constant under varying operating conditions. The methodology concludes with comparative analysis of all three cases, confirming that ANN-controlled UPQC provides the best power quality enhancement for the proposed hybrid renewable energy system.

IV PROPOSED SYSTEM

The proposed research work focuses on the design and analysis of a grid-integrated hybrid renewable energy system consisting of solar and wind power generation units. In the solar subsystem, a photovoltaic (PV) panel is modeled with variable solar irradiation input to simulate real-time environmental changes. As solar irradiation varies, the PV output voltage and current fluctuate accordingly. To extract maximum power under varying conditions, a Perturb and Observe (P&O) based Maximum Power Point Tracking (MPPT) algorithm is implemented. The MPPT controls a DC-DC Buck converter, which regulates the duty cycle to ensure that the PV panel operates at its maximum power point. The Buck converter stabilizes the variable DC output voltage into a regulated DC level. This regulated DC supply is then fed into a three-phase inverter, which converts it into AC supply and delivers it to the Point of Common Coupling (PCC).

Simultaneously, the wind energy subsystem is modeled using a wind turbine driven by variable wind speed input (in meters per second). The wind turbine converts kinetic energy into mechanical torque, which is applied to a Permanent Magnet Synchronous Generator (PMSG). The PMSG generates three-phase AC power, which is first converted into DC using a diode rectifier. A DC-link capacitor is connected between the rectifier and inverter stages to stabilize the DC voltage by reducing ripples and maintaining constant voltage levels. The stabilized DC is then converted back into three-phase AC using a voltage source inverter in a back-to-back converter configuration. By properly setting inverter pulse signals, voltage magnitude and frequency are controlled. The wind subsystem output is also connected to the PCC, along with the solar output and the main grid supply.

In the first case study, no power quality compensation device was used. Although the system successfully delivered renewable power to the grid, significant power quality issues were observed. Due to inverter switching, nonlinear loads, and renewable intermittency, Total Harmonic Distortion (THD) levels were high. Voltage waveforms were distorted, current waveforms exhibited harmonic components, and frequency oscillations occurred at the PCC. Voltage sags and swells were also present under varying operating conditions. These disturbances affected overall grid stability and violated IEEE-519 harmonic standards, highlighting the necessity of compensation techniques.

To improve power quality, an ANN-controlled STATCOM was introduced in the second case. The STATCOM provides shunt compensation by injecting reactive power into the system. An Artificial Neural Network (ANN) controller was designed to regulate the switching pulses of the STATCOM inverter dynamically. With intelligent control, the STATCOM reduced harmonic distortion significantly, maintaining THD below 5%. Voltage magnitude was stabilized, and frequency oscillations were minimized. However, since STATCOM primarily compensates reactive power and current harmonics, it could not completely eliminate all power quality issues such as voltage distortions caused by upstream disturbances.

In the final stage of the research, an ANN-controlled Unified Power Quality Conditioner (UPQC) was implemented. The UPQC combines both series and shunt active power filters, enabling simultaneous compensation of voltage and current distortions. The ANN controller intelligently generates gating signals for both converters in the UPQC structure. As a result, the system achieved superior performance compared to STATCOM. Harmonic distortion was further reduced to nearly 1% range, voltage fluctuations were completely eliminated, and

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frequency remained constant under varying renewable inputs. Compared to the uncompensated case and the STATCOM case, the ANN-based UPQC provided the best power quality performance. Therefore, the research concludes that ANN-controlled UPQC is a highly effective solution for maintaining grid stability and improving power quality in hybrid solar–wind integrated power systems.

RESULTS AND DISCUSSION

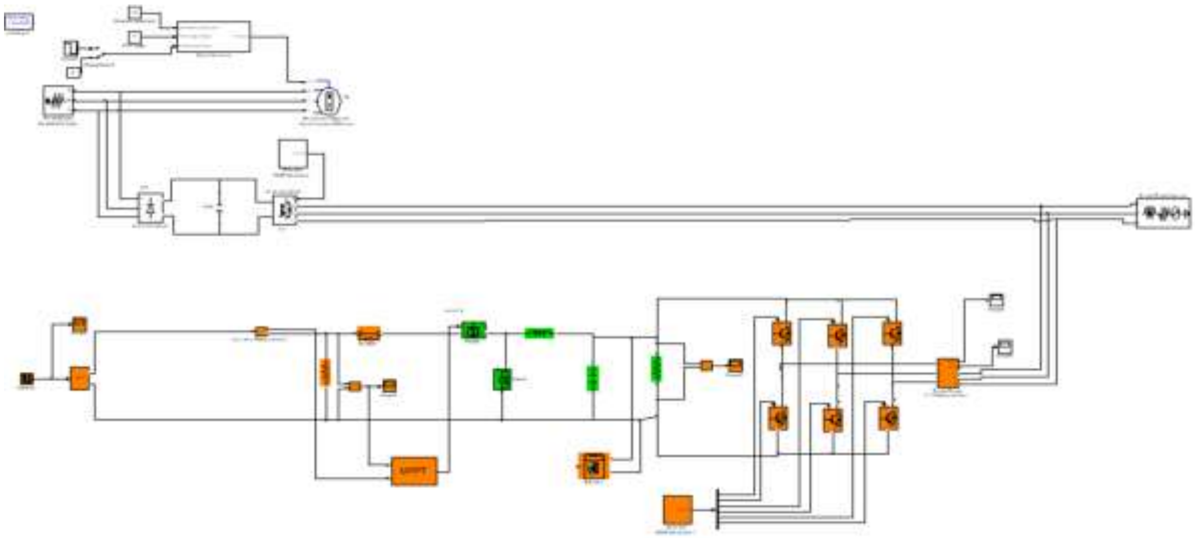


Figure 1: Grid-Connected Hybrid Solar–Wind Energy System

Figure 1 illustrates the overall configuration of the proposed grid-connected hybrid renewable energy system. The system integrates a solar photovoltaic (PV) array and a wind energy conversion system at a common Point of Common Coupling (PCC) along with the utility grid. The solar subsystem consists of a PV panel, MPPT-controlled Buck converter, and three-phase inverter. The wind subsystem includes a wind turbine, Permanent Magnet Synchronous Generator (PMSG), diode rectifier, DC-link capacitor, and inverter. Both renewable sources deliver regulated AC power to the grid. This configuration forms the base system used to analyze power quality performance under varying renewable input conditions.

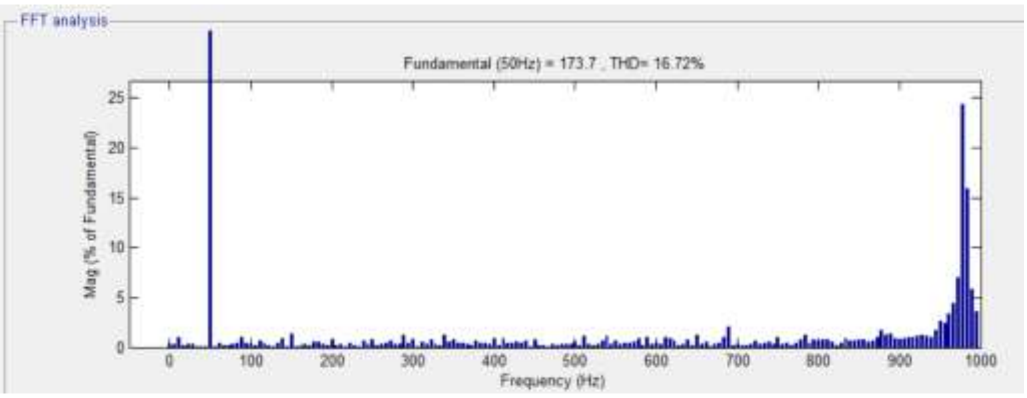


Figure 2: Voltage Harmonic Distortion of Hybrid System without Compensation

Figure 2 presents the voltage waveform and its corresponding harmonic distortion spectrum at the PCC when no compensation device is used. Due to fluctuating renewable inputs and inverter switching operations, the voltage waveform exhibits noticeable distortion from the ideal sinusoidal shape. The harmonic spectrum shows significant harmonic components across multiple frequency orders, indicating poor waveform quality. The distortion level is high and does not satisfy standard harmonic limits. This figure demonstrates the impact of integrating renewable sources into the grid without employing any power quality improvement device.

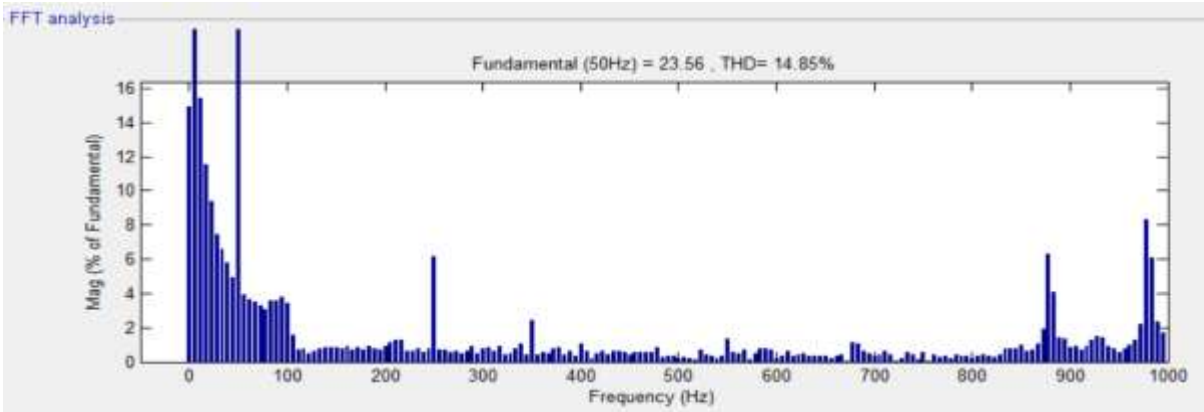


Figure 3: Current Harmonic Distortion of Hybrid System without Compensation

Figure 3 shows the current waveform and its harmonic distortion characteristics under uncompensated operating conditions. The current waveform is highly distorted due to nonlinear converter switching and fluctuating generation from solar and wind subsystems. The harmonic spectrum indicates the presence of dominant lower-order and higher-order harmonics, reflecting degraded power quality. The distortion level is high compared to acceptable standards, leading to reduced efficiency and potential stress on grid-connected equipment. This result highlights the necessity of incorporating compensation techniques for improving current waveform quality.

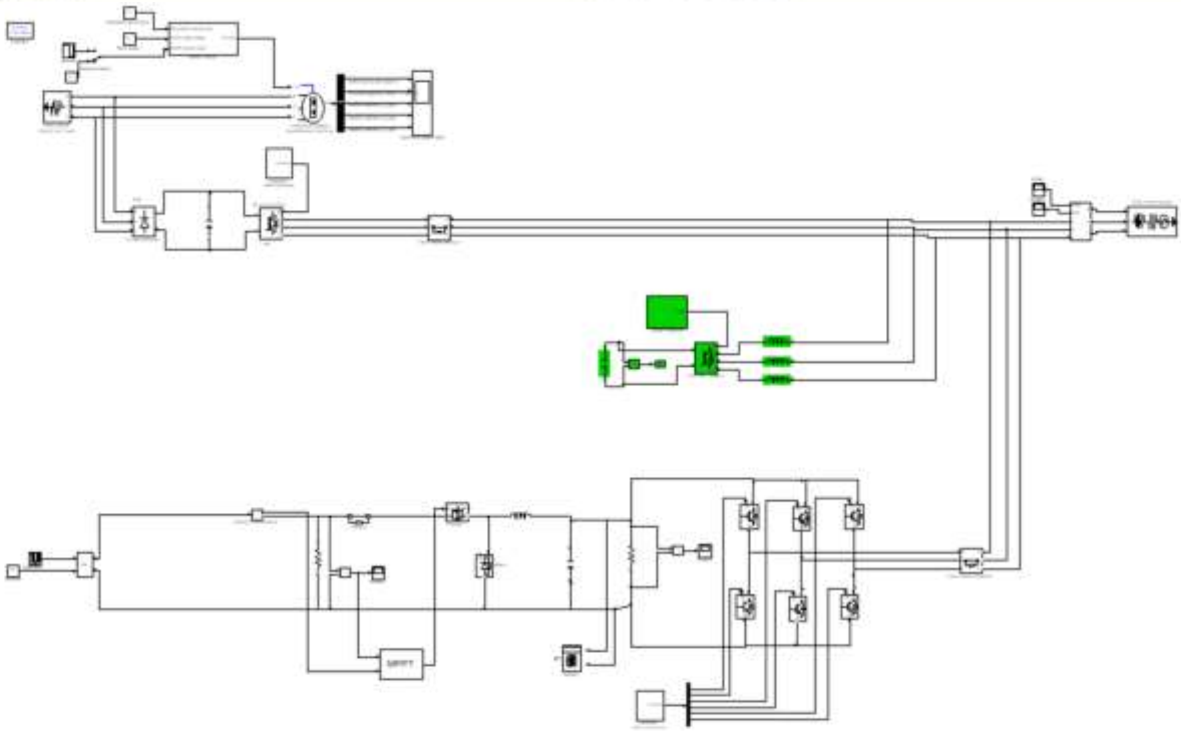
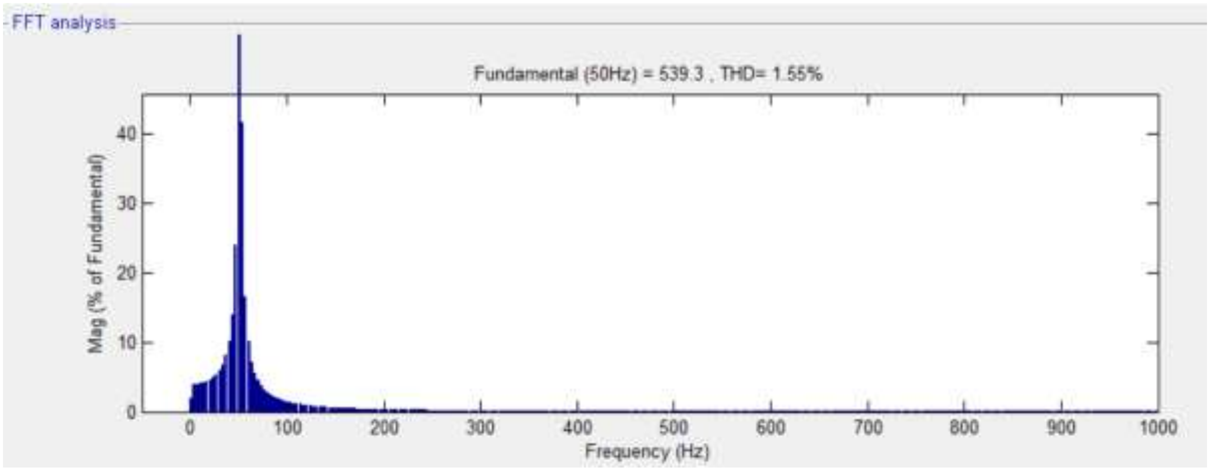


Figure 4: Hybrid Solar–Wind System with ANN-Controlled STATCOM

Figure 4 illustrates the modified hybrid renewable energy system after integrating an ANN-controlled STATCOM at the PCC. The STATCOM is connected in shunt configuration to provide dynamic reactive power support and harmonic compensation. The ANN controller generates optimized gating pulses for the STATCOM inverter, improving voltage regulation and reducing harmonic distortion. Compared to the uncompensated system, waveform quality is improved, and system stability is enhanced. The network configuration demonstrates the role of STATCOM in mitigating power quality disturbances within IEEE harmonic standards.



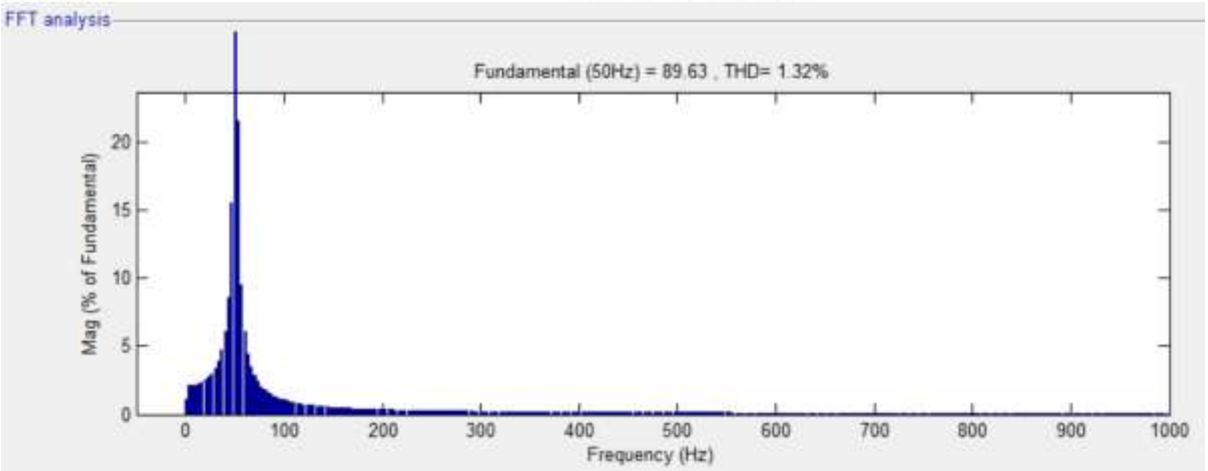


Figure 5: Voltage and Current Harmonic Distortion with STATCOM

Figure 5 presents the voltage and current waveforms along with their harmonic distortion plots after implementing the ANN-controlled STATCOM. The waveforms appear more sinusoidal compared to the uncompensated case. The harmonic distortion is reduced significantly and falls within IEEE-519 standard limits. Voltage fluctuations are minimized, and current harmonics are effectively suppressed. Although harmonic content is reduced compared to the base case, minor distortions still remain. This figure confirms that STATCOM improves power quality but does not provide complete elimination of voltage-related disturbances.

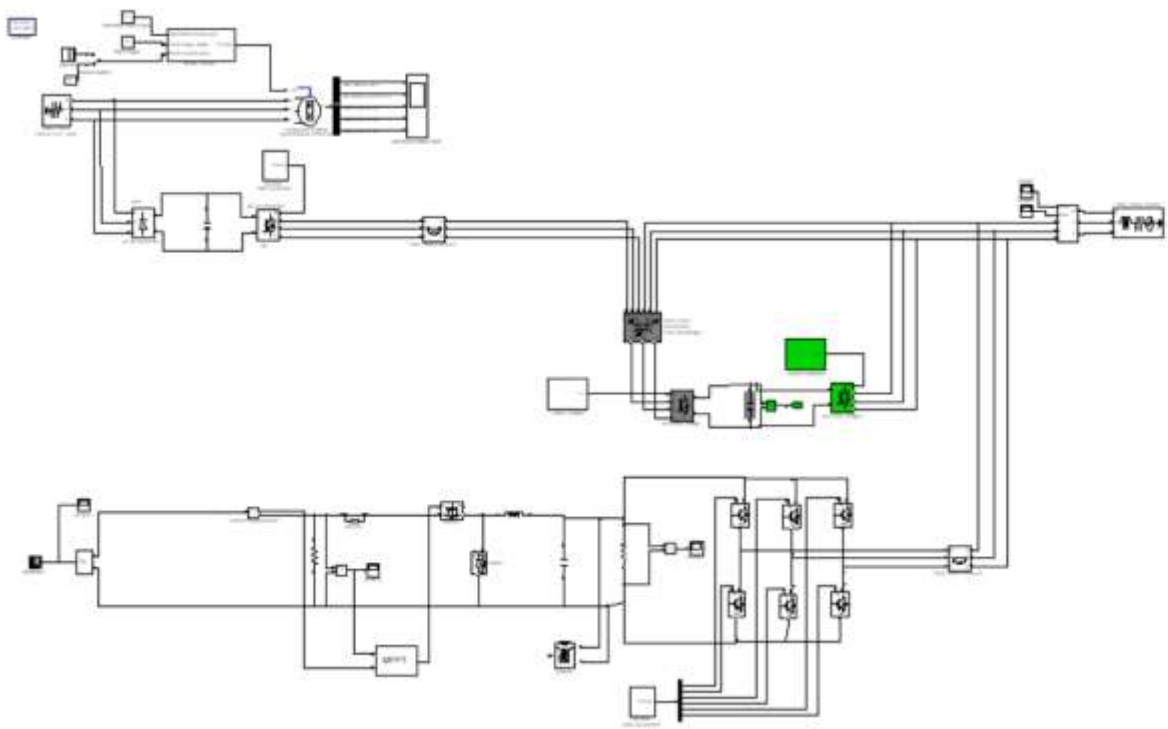


Figure 6: Hybrid System with ANN-Controlled UPQC

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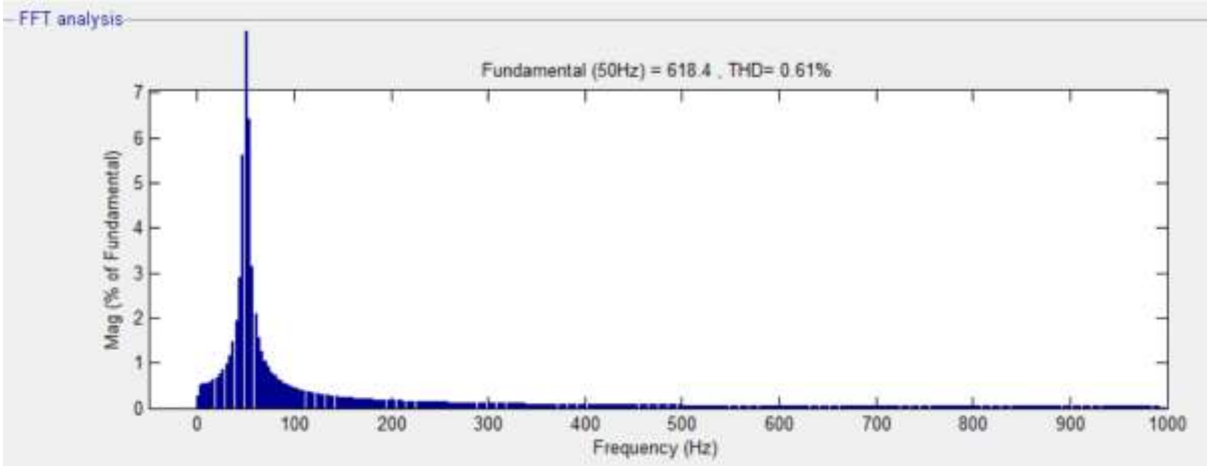

Figure 7: Hybrid System with ANN-Controlled UPQC voltage Harmonic Performance

Figure 6 and Figure 7 shows the hybrid renewable energy system integrated with an ANN-controlled Unified Power Quality Conditioner (UPQC) and its corresponding voltage and current harmonic distortion results. The UPQC, consisting of both series and shunt converters, provides simultaneous compensation of voltage and current distortions. The resulting waveforms are nearly sinusoidal with the lowest harmonic distortion among all cases. Compared to both the uncompensated system and the STATCOM-based system, the UPQC achieves superior harmonic mitigation and improved voltage stability. This figure demonstrates the comparative enhancement in overall power quality using intelligent UPQC control.

CONCLUSION

This research presented the modeling and analysis of a grid-integrated hybrid solar–wind energy system with a focus on power quality enhancement using intelligent compensation techniques. The solar subsystem employed a Perturb and Observe (P&O) based MPPT algorithm with a Buck converter to regulate variable irradiation-induced voltage fluctuations, while the wind subsystem utilized a Permanent Magnet Synchronous Generator (PMSG) with back-to-back converter configuration for stable grid interfacing. Initially, the system was evaluated without any compensating device, where significant harmonic distortion, voltage fluctuations, and frequency oscillations were observed at the Point of Common Coupling (PCC). To improve performance, an ANN-controlled STATCOM was implemented, which effectively reduced Total Harmonic Distortion (THD) to within IEEE-519 limits and improved voltage stability. However, further enhancement was achieved using an ANN-controlled Unified Power Quality Conditioner (UPQC). The UPQC provided simultaneous series and shunt compensation, reducing THD to nearly 1%, eliminating voltage sags and swells, and maintaining constant frequency under varying renewable inputs. Comparative analysis confirmed that ANN-based UPQC outperforms STATCOM in hybrid renewable networks. Therefore, intelligent UPQC control is a highly effective solution for ensuring superior power quality and grid stability in modern renewable-integrated power systems.

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