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Power Quality Improvement Techniques for Renewable Energy Sources Integrated Power System

Srikanth D[1], Pagudala Bhargavi[2], Lankala Raman Reddy[3], Danish Ahmed[4] and Yeshala Vinay Kumar[5]
[1-5]Vignan Institute of Technology & Science/ Department of EEE, Hyderabad, India
Email: vits.eee.srikanth@gmail.com, bhargavipagudala07@gmail.com, ramanreddy939@gmail.com, mdanish24689@gmail.com, yeshalavina-ykumar1234@gmail.com

***Abstract*— We are using solar photovoltaic systems, wind turbines and hydroelectric power plants of-ten now. This is because people want to use energy that's good for the environment and lasts a long time. There are some problems with using these kinds of energy. They do not always work because they depend on the weather. Solar photovoltaic systems and wind turbines can cause problems for the power grid. They can make the voltage go up and down. They can also make the frequency of the power unstable. Sometimes they can even make the power a little distorted. To fix these problems we need devices that can store en-ergy. We also need inverters and advanced power electronic converters. These things help the power grid work better. They make sure the electricity gets to people's homes safely.**

So, to make sure that Renewable Energy Sources like solar photovoltaic systems and wind turbines work well with the power grid we have to follow the rules, for the grid closely. This is important for Renewable Energy Sources to work properly. This study presents a hybrid renewable setup combining solar and wind energy, supported by battery backup. The configuration employs MPPT controllers, voltage regulation units such as boost con-verters, inverter components, and synchronization mechanisms. Focusing on reducing harmonics, enhancing power quality, and minimizing deviations in voltage and frequency. Real-time control strategies are applied to ensure high efficiency. The study also explores how complying with grid codes can support stable renewable integration.

Ultimately, the objectives are to develop a scalable and effective framework for RES inte-gration that boosts power quality, maintains grid stability, and contributes to global clean energy goals.

***Keywords*— Renewable Energy Sources, THD, PWM, Grid Integration.**

I. INTRODUCTION

The shift to energy has sped up the addition of solar and wind power to regular power grids. This change is happening because we want to use kinds of energy, minimize carbon emissions, and promotes energy security. Nev-ertheless, the unpredictable nature of renewables introduces several grid-level concerns such as voltage variations, harmonic issues, and synchronization problems, which undermine system dependability [6][7][13].

By creating a MATLAB/Simulink model of a hybrid renewable grid-connected system, this work tackles these issues. To improve flexibility and dependability, the simulation integrates a battery storage system with solar and wind energy sources. Key components such as bidirectional converters for battery management [11][19], AC-DC-DC converters for wind integration [17][18], and boost converters for PV units [1][2] are part of the setup.

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An intelligent inverter controlled through pulse width modulation (PWM) performs DC-AC conversion while keeping grid frequency and voltage in sync. This coordination enables stable power injection during fluctuations [3][8][16]. By simulating PV arrays under varying irradiance and a wind turbine based on a Permanent Magnet Synchronous Generator (PMSG), the concept replicates genuine circumstances. This improves the simulation's accuracy.[12][14]. Synchronized operation of the converters and battery ensures effective load sharing and voltage regulation. The PWM-driven inverter aids in grid alignment, enhancing the overall power quality. Battery support also provides ener-gy buffering, ensuring smooth supply even during peak demands or low production [11][19][24]. Real-time monitor-ing tracks power quality indicators like RMS voltage/current, THD, and active/reactive power. These measurements help evaluate system performance and compliance [4][5][20][25]. Dynamic feedback allows the model to adjust operations proactively to maintain reliable grid interaction.

II. Literature Review

Numerous studies have been conducted on the modelling and integration of photovoltaic (PV) systems into mod-ern power networks. Several MPPT methods have been created to maximize solar array energy collection. Perturb and Observe (P&O), incremental conductance, fuzzy logic-based controllers, and control algorithms are some of the common approaches that offer adaptive performance under dynamic environmental conditions including tempera-ture and irradiance fluctuations [4][5]. In order to convert the DC output from PV systems into grid-synchronized AC electricity, the inverter is an essential interface that collaborates with MPPT. It is crucial for maintaining power quality and supporting grid stability in addition to ensuring voltage and frequency alignment [3][8]. Multiple contri-butions in the literature have advanced renewable energy integration technologies. For example, B. Singh et al. de-veloped a DSTATCOM interface to enhance solar integration while improving voltage regulation and overall power quality [6]. H. Patel's work focused on the significance of effective MPPT algorithms in increasing the efficiency of solar energy conversion [1]. Similarly, S. Jain highlighted the advantages of hybrid renewable systems, especially for delivering reliable electricity in remote and rural areas where grid access is limited [16]. Despite these advancements, few studies have successfully demonstrated a complete simulation environment that unifies solar and wind energy generation, battery storage, and comprehensive power quality analysis using tools like MATLAB/Simulink. This pro-ject addresses that limitation by offering a fully integrated simulation framework, enabling researchers to analyse renewable energy behaviour in a more holistic and application-driven context.

III. System Design

In order to guarantee a smooth link with the electrical grid, this concept offers a hybrid energy architecture that combines wind-based generation and solar photovoltaic (PV) arrays. Delivering a reliable and environmentally re-sponsible power source while upholding strict power quality requirements is the key goal. For optimal power extrac-tion. The configuration includes solar panels, a PMSG-based wind turbine, and intelligent control algorithms to opti-mize power extraction. On the solar side, PV modules convert sunlight into DC electricity. An MPPT controller en-sures maximum power output across different environmental conditions. The voltage is raised by a boost converter to levels appropriate for the shared DC bus. For wind power, a PMSG converts mechanical input into AC electricity, which is then rectified to DC by a three-phase diode bridge. This output passes through a dedicated DC-DC convert-er to stabilize voltage before combining with the solar subsystem. To maintain equilibrium between energy genera-tion and consumption, the system includes a battery-based storage unit.

Lasty the grid interface is intended to facilitate the smooth flow of power in both directions between the utility grid and the hybrid energy system. Monitoring the vital parameters of voltage, current, and power characteristics in real time is of prime importance. The simulation results show that the suggested system has well-balanced sinusoidal waveforms and generates reduced harmonic content. To put it another way, this architecture facilitates the appropri-ate grid integration of renewable energy.

IV. Materials and Methods

The major renewable energy source for this project is the solar photovoltaic (PV) system. To achieve the desired voltage and current, there is an array of modules that are connected in parallel and series to meet the requirements.

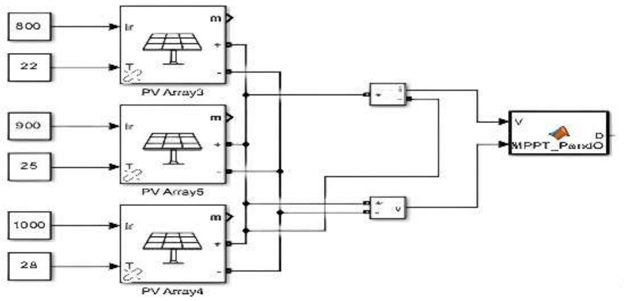

Fig 1: Solar PV Source

The model is intended to replicate the current and voltage characteristics of each module while accounting for variations in temperature, shade, and sunshine. To maximize energy output, the MPPT controller continuously modifies using Perturb and Observe. After that, the energy is transferred to a DC-DC Boost converter, which raises it to a voltage suitable for the shared DC connection.

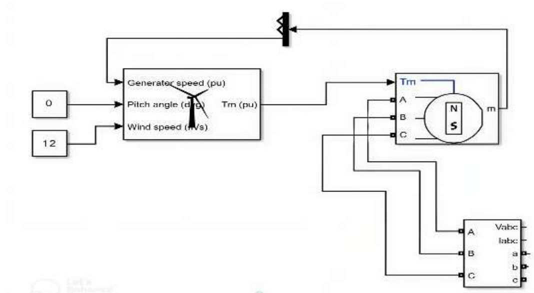

Fig 2: Wind Energy Source

The wind subsystem consists of a Permanent Magnet Synchronous Generator (PMSG). The PMSG transforms wind-generated mechanical torque into AC electricity when connected to a variable-speed wind turbine. This me-chanical input is subsequently converted into three-phase alternating current (AC) electrical power via the PMSG. To create a direct current (DC) signal, the AC output is then sent via a rectification stage that uses either an actively regulated rectifier or a diode bridge.
Voltage and current sensors continuously track electrical parameters, while key power quality indicators like RMS values, power factor, and THD assess performance. The simulation uses a discrete-time solver in MATLAB Simulink to realistically represent sampling behaviour and timing constraints, ensuring precise validation.

V. Results and Discussion

MATLAB Simulink was used to successfully simulate a hybrid energy model. System performance was evaluated based on voltage waveform quality, active and reactive power flow, and power factor behaviour. Enabling smooth renewable energy integration into the grid while concurrently monitoring and improving important power quality parameters.

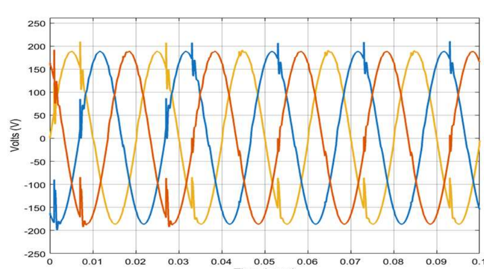

Fig 3: Output voltage

Small waveform distortions were visible at the start of the simulation, mostly as a result of converter switching activities and transient effects. These oscillations decreased as the system stabilized, and the voltage pro-files changed to clear, sinusoidal forms. The inverter's capacity to generate a balanced output was confirmed by the three waveforms' constant 120-degree phase displacement. This result shows how well the inverter and filter combi-nation work together to produce grid-compliant AC voltage with the least amount of distortion.

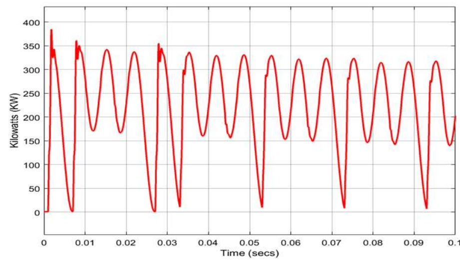

Fig 4: Active Power

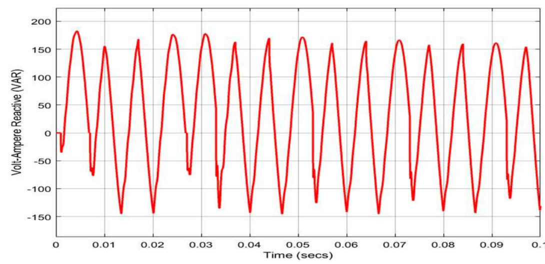

Fig5: Reactive Power

At first, there are obvious fluctuations in the active power output, which are probably caused by startup transients before the system stabilizes. As time progresses, these variations decrease and the power output converges toward a steady value, indicating effective transmission of usable energy from the renewable subsystems to the grid.

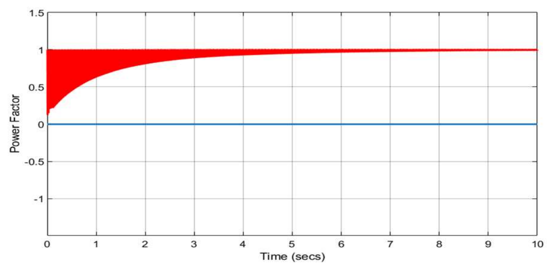

Fig 6: Power Factor

The power factor variation graph shows how well the system can sustain economical energy use over time. In or-der to demonstrate efficient real power delivery, the real component (seen by the red trace) first climbs quickly be-fore stabilizing near one. Simultaneously, the imaginary component (shown in blue) remains close to zero, suggesting minimal reactive power flow.

VI. MATHEMATICAL MODELLING

This section specifies in mathematical terms the behaviour of the suggested system of renewable energy and the behaviour of its characteristics. In reference to the simulated values, the analysis in this section highlights some of the parameters that are significant in the connection to the grid. The model is developed under the assumption of ideal operating scenarios, featuring a symmetrical three-phase sinusoidal output and near-unity power factor—aligned with the observed simulation performance.

A. Phase Voltage Equation

The output line voltage per phase is modelled as a sinusoidal waveform:
$v(t) = V_m \cdot \sin(\omega t + \varphi)$
V_{rms} = RMS voltage ≈ 230 V (from scope)
f = 50 Hz (grid frequency)
Calculations:
$V_m = \sqrt{2} \cdot 230 \approx 325.27$ V
$\omega = 2\pi f = 314.16$ rad/s
Therefore:
$v(t) = 325.27 \cdot \sin(314.16t)$

B. Phase Current Equation

Assuming a balanced current waveform in steady state:
$i(t) = I_m \cdot \sin(\omega t)$
Where:
$I_{rms} \approx 7.5$ A (from RMS graph)
$I_m = \sqrt{2} \cdot I_{rms} \approx 10.61$ A
Hence:
$i(t) = 10.61 \cdot \sin(314.16t)$

C. Active Power (P)

Three-phase real power:
$P = \sqrt{3} \times VL \times IL \times \cos(\varphi)$
$VL = 400$ V
$IL = 7.5$ A
$\cos(\varphi) \approx 1$ (from power factor graph)
Thus:
$P = \sqrt{3} \cdot 400 \cdot 7.5 = 5196.15$ W

D. Reactive Power (Q)

Reactive power is calculated as:
$Q = \sqrt{3} \times VL \times IL \times \sin(\varphi)$
If $\varphi = 0°$, then $\sin(\varphi) = 0$;$Q = 0$ VAR
However, if reactive power from simulation is ≈ 250 VAR:
$\varphi = \tan^{-1}(Q / P) \approx \tan^{-1}(250 / 5196.15) \approx 2.75°$

E. Power Factor (PF)

If purely real power:
$PF = P / S = 5196.15 / 5196.15 = 1.00$
If reactive power exists:
$PF = \cos(\tan^{-1}(Q / P))$

F. Total Harmonic Distortion (THD)

From simulation: THD = 3.5%
General formula:
$THD = \sqrt{(I_2^2 + I_3^2 + \ldots + In^2)} / I_1 \times 100\%$
Low THD confirms waveform quality and proper inverter filtering.

G. RMS Values

Voltage:
$V_{rms} = V_m / \sqrt{2} = 325.27 / \sqrt{2} = 230$ V
Current:
$I_{rms} = I_m / \sqrt{2} = 10.61 / \sqrt{2} = 7.5$ A

VII. CONCLUSION

The simulation outcomes demonstrate that the system maintains efficient performance during steady-state operation. All major components—ranging from the photovoltaic array and wind generator to MPPT controllers, energy storage units, DC-DC converters, and inverter—collectively support the system's reliability and stability. Grid syn-chronization methods are also included to guarantee steady and seamless power delivery to the utility interface.

Key power quality parameters—such as harmonic content, RMS measurements, system power factor, and re-al/reactive power flow—were thoroughly evaluated during simulation. The total harmonic distortion (THD) remained low, around 3.5%, indicating that the inverter and filtering components effectively minimized waveform distortion. Additionally, the system maintained a power factor close to unity, reflecting efficient operation with minimal reac-tive power exchange. Active power output was stable throughout the analysis, confirming the dependable perfor-mance of the integrated renewable energy sources under standard operating conditions.

Overall, the hybrid model effectively integrates several renewable energy sources and demonstrates key features needed for grid-connected applications, such as voltage regulation, power quality assurance, and synchronization. This study confirms the practicality of using hybrid systems to improve power reliability, support grid stabil-ity, and increase renewable energy use in modern power systems. Future work could involve modeling under dy-namic load changes, fault conditions, and implementing real time control using hardware in the loop techniques.

FUTURE SCOPE

There are many potential for continued innovation and research when multi-source renewable energy systems, in-cluding hybrid storage, are connected, traditional power grid. Although this project successfully demonstrates that a PV-wind-battery configuration can achieve grid compatibility and operational stability, further advancements are possible in both the control architecture and hardware design. In particular, the development of intelligent control mechanisms capable of responding dynamically to changes in environmental inputs and varying load demands could significantly enhance system performance and reliability.
Integrating artificial intelligence (AI) and machine learning (ML) for predictive management and intelligent load scheduling is an emerging area. AI and ML can analyse historical data to forecast trends in solar irradiance, wind speeds, and consumption, enhancing MPPT performance, system reliability, and predictive maintenance. By analyz-ing historical operational data, AI and ML models can anticipate future trends in solar irradiance, wind velocity, and consumption patterns. Incorporating such intelligent systems also paves the way for improved fault diagnosis, adap-tive system recovery, and predictive maintenance in the grids.
Expanding the system's functionality to incorporate electric vehicle (EV) charging and demand-side management opens up new possibilities for smarter energy utilization. By doing so, the hybrid renewable setup evolves into a more integrated framework capable of meeting contemporary energy demands while promoting grid adaptability and lower carbon emissions. These planned improvements are meant to support the continuous shift toward cleaner, smarter, and more resilient energy infrastructures in addition to increasing the system's technical efficiency.

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