Modeling, Control, and Simulation of a Grid-Connected Solar PV–Wind Hybrid Energy System with MPPT Techniques

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Abstract – The growing global demand for electrical energy, along with increasing environmental concerns and the depletion of fossil fuel resources, has accelerated the adoption of renewable energy technologies. Among various renewable sources, solar photovoltaic (PV) and wind energy systems have emerged as promising solutions due to their abundance and sustainability. However, the intermittent and uncertain nature of these energy sources limits their ability to provide reliable power when operated individually, thereby motivating the development of hybrid renewable energy systems.This paper presents the modeling, control, and simulation of a grid-connected solar PV–wind hybrid energy system designed to enhance power reliability and maximize renewable energy utilization. The proposed system integrates a solar PV array and a wind energy conversion system (WECS) through a common DC-link and interfaces with the utility grid using a grid-side inverter. Maximum Power Point Tracking (MPPT) techniques are employed to extract the maximum available power from both renewable sources. The solar PV subsystem utilizes a DC–DC converter with an MPPT control scheme, while the wind subsystem employs an optimal torque control–based MPPT strategy for efficient wind energy extraction.The complete hybrid system is modeled and simulated using the MATLAB/Simulink platform under varying solar irradiance and wind speed conditions. Simulation results demonstrate effective maximum power extraction, stable DC-link voltage regulation, and smooth power injection into the grid. The outcomes confirm that the proposed grid-connected PV–wind hybrid system provides an efficient, reliable, and sustainable solution for modern renewable power generation.

Keywords: Hybrid energy system; Solar photovoltaic; Wind energy conversion system; Maximum Power Point Tracking (MPPT); Doubly-Fed Induction Generator (DFIG); Grid-connected renewable energy.

I. INTRODUCTION

Electrical energy plays a crucial role in economic growth, industrial expansion, and overall societal development. Almost all modern infrastructure sectors, including manufacturing, transportation, communication, healthcare, and residential services, depend on a continuous and reliable supply of electricity [1]. Rapid industrialization, population growth, and technological advancements have significantly increased global energy demand, placing substantial stress on conventional power generation systems [2 – 3].

Conventional electricity generation is largely dependent on fossil fuels such as coal, oil, and natural gas. Although these sources have supported large-scale power generation for decades, they suffer from serious drawbacks. Fossil fuels are finite in nature and are being depleted at an accelerating rate. In addition, their combustion releases greenhouse gases and harmful pollutants, leading to climate change, global warming, and severe environmental degradation. These environmental and resource limitations have raised concerns about the long-term sustainability and economic viability of fossil fuel–based power generation [4].

In response to these challenges, renewable and sustainable energy sources have gained considerable attention. Renewable resources such as solar, wind, biomass, and hydro energy are environmentally friendly, naturally replenished, and capable of reducing carbon emissions. Among them, solar photovoltaic (PV) and wind energy technologies have experienced rapid development due to technological advancements, reduced costs, and wide availability. However, renewable energy sources are inherently intermittent and depend heavily on weather conditions, which can lead to fluctuations in power generation [5 – 6].

Standalone renewable energy systems that rely on a single energy source often face reliability issues and are unable to consistently meet load demand due to resource variability. These limitations can result in voltage instability, power shortages, and increased dependence on energy storage or backup systems [5]. To overcome these issues, hybrid renewable energy systems that integrate multiple energy sources have been developed.

Solar PV and wind energy systems exhibit complementary characteristics, making their hybridization highly effective. Solar energy is predominantly available during daylight hours, whereas wind energy is often stronger during nighttime or cloudy conditions. By combining these two sources, power availability is enhanced, fluctuations are reduced, and overall system reliability is improved. When integrated with the utility grid, PV–wind hybrid systems can further enhance energy utilization by injecting surplus power and supporting grid stability [6].

The objective of this work is to model, control, and simulate a grid-connected solar PV–wind hybrid energy system using maximum power point tracking (MPPT) techniques. The proposed system aims to achieve efficient power extraction from both solar and wind resources, maintain stable grid interaction, and demonstrate reliable performance under varying environmental conditions using the MATLAB/Simulink platform [7].

II. HYBRID SYSTEM DESCRIPTION AND MODELING

This section describes the overall configuration and mathematical modeling of the proposed grid-connected solar PV–wind hybrid energy system. The system integrates two renewable energy sources—solar photovoltaic and wind energy—through power electronic interfaces to ensure efficient energy conversion, maximum power extraction, and reliable grid interaction [8].

2.1 Overview of the Grid-Connected PV–Wind Hybrid System

The proposed hybrid system consists of a solar photovoltaic (PV) array and a wind energy conversion system (WECS) connected to a common DC-link. The PV array generates direct current (DC) power, while the wind turbine drives a doubly-fed induction generator (DFIG) to produce electrical power from wind energy. Power electronic converters are employed to regulate and condition the generated power from both sources before it is supplied to the utility grid [2].

The common DC-link acts as an energy coupling and buffering stage, allowing coordinated control of power flow from the renewable sources. A grid-side inverter converts the DC-link voltage into three-phase alternating current (AC) synchronized with the grid. This configuration enables efficient utilization of renewable energy and allows excess generated power to be injected into the grid [3].

2.2 Solar Photovoltaic System Modeling

A. PV Cell Equivalent Circuit

The solar photovoltaic system is modeled using a single-diode equivalent circuit, which accurately represents the electrical behavior of a PV cell. The model consists of a current source representing the photo-generated current, a diode corresponding to the p–n junction, a series resistance accounting for internal losses, and a shunt resistance representing leakage currents. For simplicity and practical analysis, the shunt resistance is considered large and is often neglected, resulting in a simplified model [10].

This equivalent circuit captures the nonlinear current–voltage characteristics of the PV module and forms the basis for performance analysis and MPPT implementation.

B. Effect of Irradiance and Temperature

Solar irradiance and cell temperature significantly influence the output characteristics of a PV module. An increase in irradiance leads to a proportional increase in photo-generated current, resulting in higher output power. The open-circuit voltage also increases slightly with irradiance. Conversely, an increase in temperature causes a reduction in open-circuit voltage due to increased carrier recombination within the semiconductor material, leading to a decrease in overall efficiency [7].

These variations shift the maximum power point on the power–voltage (P–V) curve, making real-time MPPT essential to maintain optimal operation under changing environmental conditions.

2.3 Wind Energy Conversion System Modeling

A. Wind Turbine Power Characteristics

The mechanical power extracted from a wind turbine depends on wind speed, air density, rotor swept area, and turbine efficiency. Wind power is proportional to the cube of wind speed, which makes wind energy highly sensitive to variations in wind velocity. As a result, even small changes in wind speed can cause significant fluctuations in output power.

B. Tip Speed Ratio and Power Coefficient

The performance of a wind turbine is characterized by the power coefficient Cp, which represents the fraction of available wind power converted into mechanical power. The power coefficient is a function of the tip speed ratio (TSR) and blade pitch angle. The tip speed ratio is defined as the ratio of the blade tip speed to wind speed [8]. For a given turbine, there exists an optimal TSR at which Cp reaches its maximum value, corresponding to maximum power extraction.

C. DFIG-Based Wind Turbine Model

In the proposed hybrid system, a doubly-fed induction generator (DFIG) is employed for wind energy conversion. The DFIG enables variable-speed operation by controlling rotor currents through back-to-back power electronic converters. The stator of the DFIG is directly connected to the grid, while the rotor is interfaced through converters that handle only a fraction of the total generated power.

This configuration allows independent control of active and reactive power, improved energy capture efficiency, and smooth grid integration. The DFIG-based wind turbine model is therefore well suited for grid-connected hybrid renewable energy systems, providing stable and efficient operation under varying wind conditions [10].

III. POWER ELECTRONIC INTERFACE AND MPPT CONTROL

Power electronic converters form the core of energy conditioning and control in the proposed grid-connected PV–wind hybrid energy system. They enable efficient power conversion, facilitate maximum power extraction from renewable sources, and regulate energy flow between the sources and the grid [3]. This section describes the role of DC–DC converters and MPPT techniques employed for both the solar PV and wind energy subsystems.

3.1 DC–DC Converter for Solar PV System

The solar photovoltaic array produces a low-level and variable DC voltage that depends on solar irradiance and temperature. To interface the PV array with the DC-link and ensure efficient power transfer, a DC–DC converter is employed. In this work, a boost-type DC–DC converter is used to step up the PV output voltage to the required DC-link level [4].

The DC–DC converter also serves as an impedance matching device between the PV array and the grid interface. By controlling the duty cycle of the converter switch, the operating point of the PV array can be adjusted dynamically. This capability is essential for implementing MPPT algorithms, which continuously modify the duty cycle to maintain PV operation at the maximum power point under varying environmental conditions [1].

3.2 MPPT Techniques for Solar PV

Due to the nonlinear voltage–current and power–voltage characteristics of the PV array, maximum power extraction cannot be achieved without dedicated control. MPPT techniques are therefore employed to track the optimal operating point corresponding to maximum power generation.

In the proposed system, MPPT is implemented by regulating the duty cycle of the DC–DC converter based on measured PV voltage and current. The control algorithm continuously evaluates the power variation and adjusts the operating voltage accordingly. This ensures that the PV array delivers maximum available power despite changes in irradiance and temperature, thereby improving overall system efficiency [7].

3.3 Optimal Torque Control–Based MPPT for Wind System

For the wind energy conversion system, an optimal torque control–based MPPT strategy is employed. The objective of this method is to maintain turbine operation at the optimal tip speed ratio, where the power coefficient reaches its maximum value. Instead of directly measuring wind speed, the control algorithm determines a reference electromagnetic torque as a function of rotor speed.

The optimal torque reference is defined by a quadratic relationship between torque and rotor speed. This reference torque is applied to the rotor-side controller of the DFIG, which regulates the generator currents to achieve the desired torque. By doing so, the wind turbine continuously operates along the maximum power curve for a wide range of wind speeds, ensuring efficient energy extraction [5].

3.4 Role of Power Electronic Converters in Energy Regulation

Power electronic converters play a vital role in regulating energy flow within the hybrid system. The DC–DC converter ensures optimal power extraction from the PV subsystem, while the rotor-side and grid-side converters associated with the DFIG enable flexible control of wind power generation and grid interaction.

These converters coordinate the power exchange between the renewable sources and the DC-link, stabilize system voltage, and facilitate smooth power injection into the grid. Through precise control of voltage, current, and power, power electronic interfaces ensure reliable operation, enhanced efficiency, and compliance with grid requirements in the proposed PV–wind hybrid energy system [4].

IV. GRID INTERFACE AND CONTROL STRATEGY

The grid interface and associated control strategy play a critical role in ensuring stable operation and efficient power transfer between the hybrid renewable energy system and the utility grid. The control scheme is designed to regulate the DC-link voltage, manage active and reactive power flow, achieve proper grid synchronization, and enable coordinated power sharing between the solar PV and wind energy subsystems [3].

4.1 DC-Link Voltage Regulation

The DC-link acts as a common coupling point between the renewable energy sources and the grid-side inverter. Maintaining a constant DC-link voltage is essential for reliable inverter operation and stable power injection into the grid. Variations in solar irradiance and wind speed can cause fluctuations in the power generated by the PV and wind subsystems, leading to disturbances in the DC-link voltage [8].

To mitigate these effects, a closed-loop DC-link voltage control strategy is implemented. The measured DC-link voltage is compared with a predefined reference value, and the resulting error is processed by a proportional–integral (PI) controller. The controller output adjusts the inverter current reference, ensuring that the power delivered to the grid balances the power generated by the renewable sources. This control approach effectively stabilizes the DC-link voltage under dynamic operating conditions [10].

4.2 Grid-Side Inverter Control

The grid-side inverter serves as the interface between the DC-link and the three-phase utility grid. Its primary function is to convert DC power into AC power with appropriate voltage magnitude, frequency, and phase alignment. The inverter is controlled using a current-controlled voltage source inverter (VSI) scheme to ensure precise regulation of output currents. By employing feedback control loops, the inverter maintains sinusoidal current waveforms and minimizes harmonic distortion. Output filters are used to suppress switching harmonics, thereby improving power quality and ensuring compliance with grid standards [9].

4.3 Active and Reactive Power Control

Active and reactive power control is achieved through decoupled control of inverter current components in the synchronous reference frame. The direct-axis (d-axis) current component controls the active power injected into the grid, while the quadrature-axis (q-axis) current component governs the reactive power exchange.

This decoupled control strategy allows independent regulation of active and reactive power, enabling efficient delivery of renewable energy and support of grid voltage stability. The system can operate at unity power factor or provide reactive power compensation as required by grid conditions [4].

4.4 Grid Synchronization Using Phase-Locked Loop (PLL)

Accurate grid synchronization is essential for safe and stable grid-connected operation. A phase-locked loop (PLL) is employed to extract the grid voltage phase angle and frequency. The PLL continuously tracks grid voltage variations and provides synchronized reference signals to the inverter control system.

This ensures that the inverter output remains synchronized with the grid, minimizes transient disturbances during power injection, and prevents circulating currents. The PLL-based synchronization enhances system stability and facilitates smooth interaction with the utility grid [5 – 6].

4.5 Power Sharing Between Solar PV and Wind Subsystems

In the proposed hybrid system, the solar PV and wind subsystems operate independently with their respective MPPT controllers. Each subsystem extracts the maximum available power based on prevailing environmental conditions. The generated power from both sources is combined at the DC-link and transferred to the grid through the inverter.

Power sharing between the PV and wind subsystems occurs naturally according to resource availability. During high solar irradiance, the PV subsystem contributes more power, while during strong wind conditions, the wind subsystem becomes dominant. The coordinated control of the DC-link and inverter ensures smooth integration of power from both sources without interference, resulting in reliable and efficient hybrid system operation [9 – 10].

V. SIMULATION SETUP AND RESULTS

This work explains grid connected PV wind system in MATLAB Simulink. simulation of a hybrid PV wind system for three phase grid system. The simulation results for varying irradiance conditions and varying wind speed conditions are also explained.

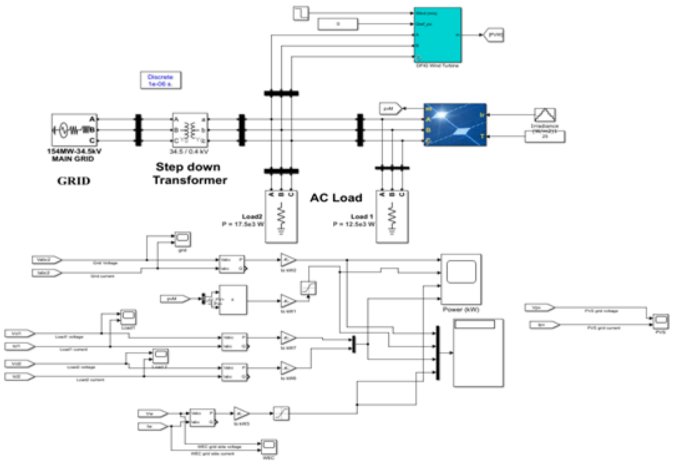

Figure 5.1. MATLAB/Simulink model of the three-phase grid-connected PV–wind hybrid energy system.

TABLE I: PV PARAMETERS

Parameters	Specifications
Scale Array, Multiplier for 100 kW	0.45
Nominal Grid Connection L-L Voltage, Vrms	400
Grid Frequency, Fnom [Hz]	50
Simulation Time Step, Ts [s]	1e-6
Controller Time Step, Ts_Control	1e-4

TABLE II: WIND PARAMETERS

This block implements a model of a variable speed pitch-controlled wind turbine using a doubly-fed induction generator (DFIG).

Parameters	Specifications
Number of wind turbines	1
Nom. power, L-L volt. and freq. [Pn (VA), Vs_nom (Vrms), Vr_nom (Vrms), fn (Hz)]	[45e3/.9 400 400 50]
Stator [Rs,Lls] (p.u.)	[0.023 0.18]
Rotor [Rr',Llr'] (p.u.)	[0.016 0.16]
Magnetizing inductance Lm (p.u.)	2.9
Inertia constant, friction factor, and pairs of poles [H(s) F(p.u.) p]	[0.685 0.01 3]
Initial conditions [s thiasibsicsphaseasphasebsphasecs]	[-0.2,0 0,0,0 0,0,0]

TABLE III: THREE PHASE SOURCE (GRID) PARAMETERS

Parameters	Specifications
Phase-to-phase voltage (Vrms)	(34.5e3)*1.00243
Phase angle of phase A (degrees)	0.071468
Frequency (Hz)	50
3-phase short-circuit level at base voltage(VA)	154e6
Base voltage (Vrmsph-ph)	34.5e3
Inertia constant, friction factor, and pairs of poles [H(s) F(p.u.) p]	[0.685 0.01 3]
Initial conditions [s thiasibsicsphaseasphasebsphasecs]	[-0.2,0 0,0,0 0,0,0]

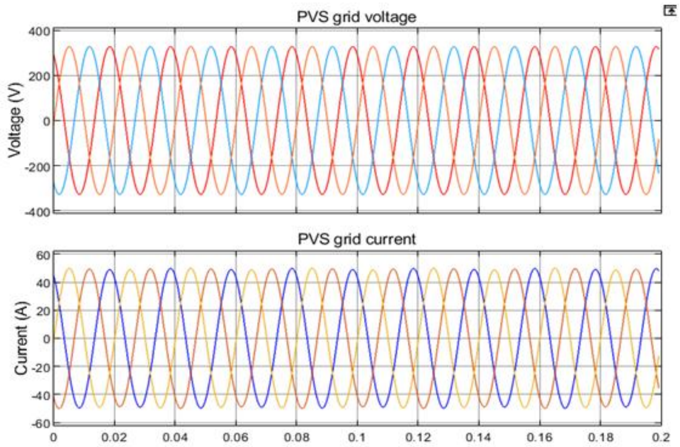

Figure 5.2.Grid-side voltage and current waveforms of the solar PV subsystem under steady-state operation.

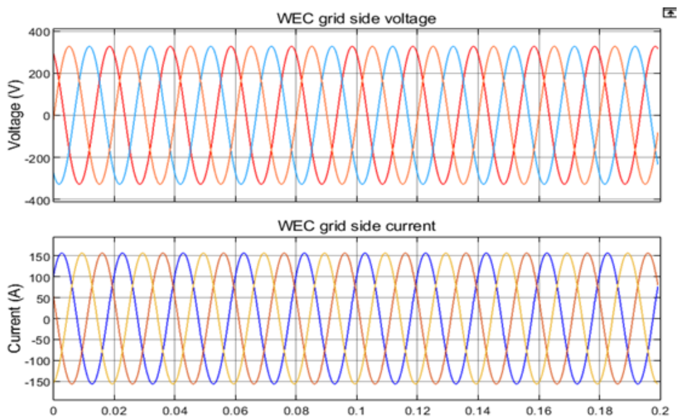

Figure 5.3. Grid-side voltage and current waveforms of the wind energy conversion system (DFIG-based WECS).

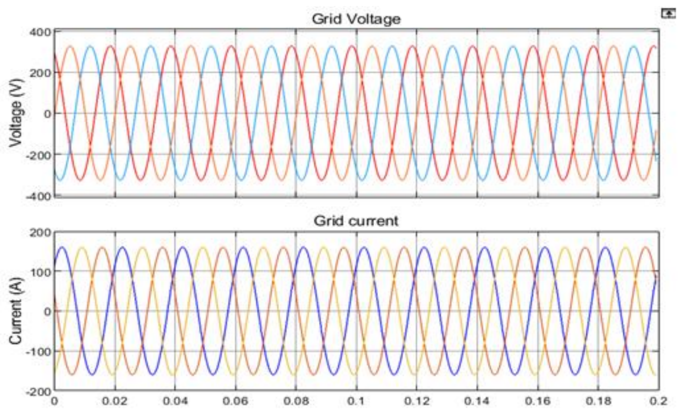

Figure 5.4. Three-phase grid voltage and current showing synchronized grid interaction.

The simulation results presented in Figures 5.1–5.7 validate the effective operation of the proposed grid-connected PV–wind hybrid energy system. The DC-link voltage remains stable under varying solar irradiance and wind speed conditions, while the grid-side inverter injects balanced and sinusoidal currents into the utility grid. The active power profiles confirm proper power sharing between the solar PV and wind subsystems according to resource availability. Load voltage and current waveforms demonstrate reliable supply with acceptable power quality, confirming the robustness and stability of the proposed control strategy.

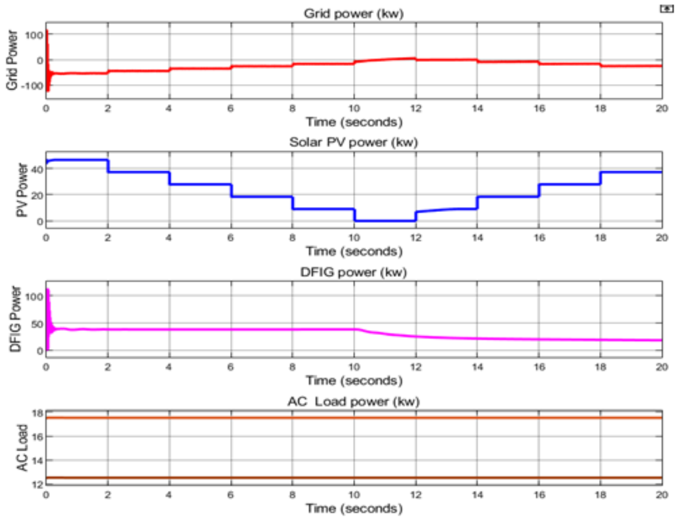

Figure 5.5. Active power profiles of solar PV, wind (DFIG), grid, and AC load.

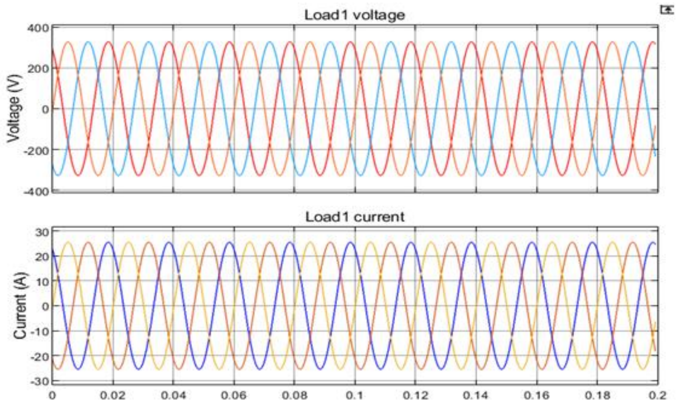

Figure 5.6. Voltage and current waveforms of Load 1.

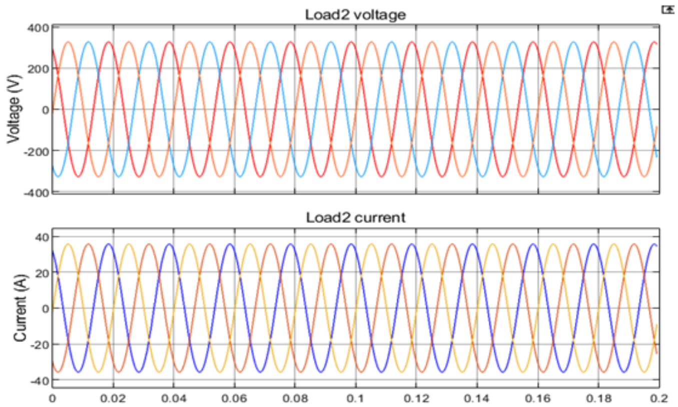

Figure 5.7. Voltage and current waveforms of Load 2.

CONCLUSION

This paper presented the modeling, control, and simulation of a grid-connected solar PV–wind hybrid energy system aimed at enhancing renewable energy utilization and system reliability. Detailed mathematical models of the solar photovoltaic subsystem and the wind energy conversion system were developed, incorporating the effects of environmental variations such as solar irradiance, temperature, and wind speed. The integration of both energy sources through a common DC-link and power electronic interfaces enabled coordinated operation and efficient power transfer to the utility grid.

Maximum Power Point Tracking (MPPT) techniques were effectively employed to extract the maximum available power from both renewable sources. The solar PV subsystem utilized a DC–DC converter-based MPPT scheme to continuously track the optimal operating point under varying irradiance and temperature conditions. For the wind energy subsystem, an optimal torque control–based MPPT strategy was implemented, ensuring maximum wind power extraction across a wide range of wind speeds without the need for direct wind speed measurement. The applied MPPT techniques significantly improved the overall energy conversion efficiency of the hybrid system.

Simulation results obtained using the MATLAB/Simulink platform demonstrated stable DC-link voltage regulation, smooth grid synchronization, and effective active power injection into the grid. The coordinated control strategy enabled reliable power sharing between the solar PV and wind subsystems while maintaining acceptable voltage and current quality at the grid interface.

Overall, the proposed grid-connected PV–wind hybrid energy system provides an efficient, reliable, and environmentally sustainable solution for modern power generation. The work contributes to the effective integration of renewable energy sources into the utility grid and supports the transition toward clean and sustainable energy systems.

References

[1] Md. Wazedur Rahman; Karthikeyan Velmurugan; Md. Sultan Mahmud; Abdullah Al Mamun; Prasanth Ravindran "Modeling of a stand-alone Wind-PV Hybrid Generation System Using (MATLAB/SIMULINK)" IEEE 2021 International Conference on Computing, Communication, and Intelligent Systems (ICCCIS), 10.1109/ICCCIS51004.2021.9397194.

[2] Hayat Elaissaoui; Mohammed Zerouali; Abdelghani El Ougli; BelkassemTidhaf "MPPT Algorithm Based on Fuzzy Logic and Artificial Neural Network (ANN) for a Hybrid Solar/Wind Power Generation System" IEEE 2020 Fourth International Conference On Intelligent Computing in Data Sciences (ICDS), 10.1109/ICDS50568.2020.9268747.

[3] Divyanshi Srivastava; Rahul Kumar Rai; S.K. Srivastava "Performance Analysis of Single MPPT Technique using RBFN for PV and Wind Hybrid System" IEEE 2019 2nd International Conference on Power Energy, Environment and Intelligent Control (PEEIC), 10.1109/PEEIC47157.2019.8976692.

[4] Aquib Jahangir; Sukumar Mishra "Autonomous Battery Storage Energy System Control of PV-Wind Based DC Microgrid" IEEE 2018 2nd International Conference on Power, Energy and Environment: Towards Smart Technology (ICEPE), 10.1109/EPETSG.2018.8658550.

[5] R. Alik and A. Jusoh, "Modified perturb and observe (p&o) with checking algorithm under various solar irradiation," Solar Energy, vol. 148, pp. 128–139, 2017.

[6] O. Khan and W. Xiao, "Integration of start–stop mechanism to improve maximum power point tracking performance in steady state," IEEE Transactions on Industrial Electronics, vol. 63, no. 10, pp. 6126–6135, 2016.

[7] G. J. G. Jothi and N. Geetha, "An enhanced mppt technique for high gain dc-dc converter for photovoltaic applications," in Circuit, Power and Computing Technologies (ICCPCT), 2016 International Conference on. IEEE, 2016, pp. 1–9.

[8] G. Cipriani, V. D. Dio, F. Genduso, R. Miceli and D. L. Cascia, "A new modified Inc-Cond MPPT technique and its testing in a whole PV simulator under PSC," in Proc. of

the 2015 IEEE Applied Power Electronics Conference and Exposition (APEC), Charlotte, NC, pp. 3060- 3066.

[9] S. K. Ji, H. Y. Kim, S. S. Hong, Y. W. Kim and S. K. Han, "Nonoscillation Maximum Power Point Tracking algorithm for Photovoltaic applications," in Proc. of the 2014 Power Electronics and ECCE Asia (ICPE & ECCE), Jeju, pp. 380-385.

[10] Yi-Hsun Chiu, Yu-Shan Cheng, Yi-Hua Liu, Shun-Chung Wang and ZongZhen Yang, "A novel asymmetrical FLC-based MPPT technique for photovoltaic generation system," in Proc. of the 2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA), Hiroshima,pp. 3778-3783.