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Artificial Neural Network Based Grid-Integrated Photovoltaic/Wind Hybrid Power Generation to Improve PCC Voltage and Power Factor

Abstract: - In response to growing energy demands and the imperative for sustainability, this paper introduces a three-phase Solar-Wind hybrid system for efficient grid integration. Building upon previous research in solar and wind power, our study addresses the intermittent nature of these sources by proposing a synergistic approach. The integration of solar and wind technologies aims to enhance overall system reliability and contribute to a more robust and environmentally friendly energy grid. By combining solar photovoltaic and wind power, the system optimizes performance at the grid connection. The integration uses MPPT techniques to enhance power output in varying weather. An ANN controller is developed for precise power point tracking of the photovoltaic array. This controller maintains stable grid voltage and unity power factor using Vector Control in a multilevel inverter. Simulation in MATLAB/SIMULINK validates the system's ability to optimize power utilization and stabilize the grid under changing conditions. In summary, the paper proposes a method to enhance Solar-Wind hybrid performance using MPPT and ANN control for accurate voltage regulation, resulting in significant improvements.

Keywords: Solar array, Wind Energy, PV, MPPT, PI Controller, ANN

I. INTRODUCTION

In light of the escalating global demand for sustainable energy solutions, the exploration of renewable alternatives, such as wind and photovoltaic (PV) power, has become paramount. However, existing literature and technologies exhibit certain gaps that necessitate further investigation. Notably, the reliance of solar and wind power on elements like sunlight and wind speed poses challenges to their reliability. The emerging trend of combining PV and wind into hybrids holds promise, but there remains a need for advancements in modeling, control systems, inverters, and sliding mode controls [1].

The existing literature highlights the common use of the Doubly Fed Induction Generator (DFIG) for wind energy extraction due to its simplicity and effectiveness. Despite this, there is still a gap in the comprehensive integration of a 1MW solar station and a 9MW wind facility through an AC-bus to enhance overall system performance. This research is motivated by the need to bridge these gaps, offering a more integrated and robust approach. Furthermore, while Maximum Power Point Tracking (MPPT) is acknowledged as crucial for optimizing power generation in changing conditions, there is a need for a more detailed exploration of its application to both solar and wind sources within a hybrid system. This study seeks to address these gaps by implementing MPPT for both sources, thereby maximizing power generation while maintaining a unity power factor and ensuring grid stability [2]. By delineating these specific research gaps, this study not only aims to contribute to the academic understanding of PV/wind hybrid systems but also offers practical insights that can inform advancements in renewable energy technologies, addressing the pressing concerns of intermittency and power reliability. In this study, we introduce a novel grid-connected hybrid power system that seamlessly integrates photovoltaic (PV) and wind assets, elucidated through a comprehensive Matlab/Simulink model. The PV component of the system incorporates an Artificial Neural Network (ANN)-based Maximum Power Point Tracking (MPPT) method, optimizing power capture. Concurrently, an enhanced MPPT method is employed for the wind farm, adeptly adapting to varying wind speeds. Both Proportional-Integral (PI) and ANN controllers effectively regulate the DC link voltage of the Voltage Source Inverter (VSI). Simulation results underscore the superior performance of the ANN controller compared to the conventional PI controller, particularly evident in the step response of the DC-link voltage.

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The control framework ensures a unity power factor and facilitates reactive power injection, thereby guaranteeing the stability of the Point of Common Coupling (PCC) bus voltage irrespective of external conditions or fluctuations in active power. The proposed control approach consistently upholds the performance, stability, and reliability of the hybrid energy system. Through the presentation of this advanced hybrid model and control strategy, this research not only addresses existing gaps in PV/wind hybrid systems but also contributes valuable insights for the optimization of grid-connected renewable energy solutions[6].

In summary, this paper is structured to comprehensively address the optimal integration of power generation from photovoltaic (PV) and wind sources. Section II delves into the overarching theme of optimal integration for power generation from both PV and wind sources. Subsequently, Section III provides a systemic analysis of the photovoltaic power generation system, offering insights into its design and functionality. In Section IV, the focus shifts to the wind-to-power conversion system, exploring its components and operational considerations. Moving forward, Section V presents the simulation results, showcasing the performance and efficiency of the integrated PV and wind power generation system. Finally, Section VI encapsulates the key findings and conclusions drawn from this study, summarizing the implications and potential avenues for future research in the realm of renewable energy integration.

II. OPTIMAL POWER BLEND PV AND WIND INTEGRATION ANALYSIS

The hybrid PV/wind device combines a 100 kW solar station and a 9MW wind facility through a primary bus for better overall performance [7]. Solar modules in parallel use a DC/DC boost converter and consolidated DC/AC inverter. Incremental conductance MPPT extracts optimal PV energy under variable sunlight, linked to the PCC bus through a 260 V/25 kV Δ/Y transformer. The wind side has a DFIG with a huge wind turbine, integrating converters for voltage control and energy extraction using a power-based modified MPPT, it captures peak wind electricity, connecting to the PCC bus through a 575 V/25 kV Δ/Y transformer working at unity power factor, the hybrid device feeds the grid through 30 km lines and a 25 kV/120 kV Y/Δ transformer[8][9] This integration maximizes resources, enhances device performance, and provides sustainable energy throughout diverse climate[10][11].

Certainly, here's a step-by-step procedure for the described hybrid PV/wind system:

System Configuration: Start by configuring the hybrid system, combining a 100 kW solar station and a 9MW wind facility through a central bus.

Solar Module Setup: Arrange solar modules in parallel for efficient power generation. Employ a DC/DC boost converter to enhance the voltage for optimal energy conversion. Utilize a consolidated DC/AC inverter for synchronized power flow.

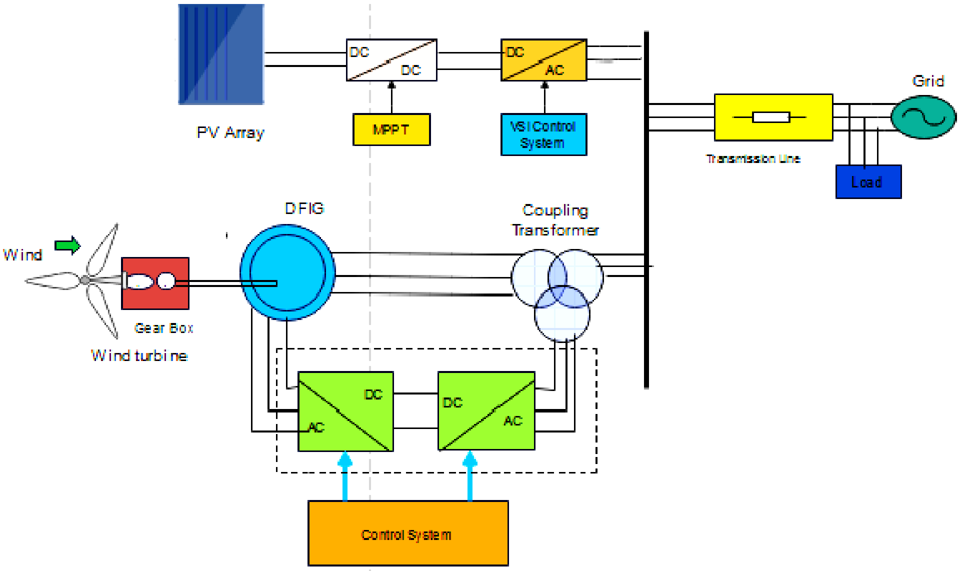

Fig. 1 Renewable Integration Designing Solar-Wind Hybrid Power Systems

PV Energy Optimization: Implement Incremental Conductance MPPT technology to continually track and extract optimal PV energy, adapting to variable sunlight conditions.

Integration with Point of Common Coupling (PCC): Connect the solar output to the Point of Common Coupling (PCC) bus through a 260 V/25 kV Δ/Y transformer.

Wind Energy Harvesting: On the wind side, integrate a Doubly Fed Induction Generator (DFIG) with a substantial wind turbine for effective energy extraction. Implement converters designed for precise voltage control.

Wind MPPT System: Utilize a power-based modified MPPT approach for the wind system to capture peak wind electricity.

Integration with PCC for Wind: Connect the wind system to the PCC bus through a 575 V/25 kV Δ/Y transformer operating at a unity power factor.

Grid Connection: Feed the grid seamlessly by interconnecting the hybrid device through 30 km transmission lines. Ensure a reliable connection using a 25 kV/120 kV Y/Δ transformer.

Resource Maximization and Performance Enhancement: Evaluate the integration to ensure maximization of resources and enhancement of overall device performance.

Sustainability Assessment: Assess the system's sustainability across diverse climatic conditions, ensuring resilience and reliability [10][11].

This step-by-step procedure outlines the key stages of configuring, optimizing, and integrating the hybrid PV/wind system, emphasizing resource efficiency, performance enhancement, and sustainable energy production.

III. PHOTOVOLTAIC POWER GENERATION SYSTEMIC ANALYSIS

The PV conversion device significantly improves solar energy generation via efficient electrical modeling and characterization of photovoltaic arrays. These arrays, with interconnected modules, are optimized using a DC/DC boost converter and a major DC/AC inverter, making sure cost-effectiveness, performance, and stable DC-link voltage. Shockley diode modeling replicates PV behavior for environmental simulations [12]. Incremental conductance MPPT tracks maximum power point, while the DC/AC inverter controller manages energy flown. Accurate modeling is critical for peak energy extraction. Figure 2showcases array traits, adapting to solar modifications. MPPT and control techniques maximize PV energy, greatly boosting solar system efficiency [13].

A) Progressive Conductance Maximum Power Point Tracking Method

The Progressive Conductance Maximum Power Point Tracking (MPPT) algorithm is instrumental in enhancing the performance of photovoltaic (PV) systems [14]. It continuously adjusts the panel's voltage and current to ensure optimal operation at the maximum power point (MPP), adapting to changes in temperature and irradiance [15]. By assessing the ratio of power change to voltage change, the progressive conductance MPPT algorithm determines the MPP shift direction. This adaptive process aligns the panel's conductance with power changes, gradually fine-tuning the voltage towards the MPP. Distinguishing itself from other MPPT methods, the progressive conductance technique excels, especially in rapidly changing conditions, enabling efficient and swift MPP tracking for optimized energy generation. Its efficacy and cost-effectiveness have solidified the progressive conductance MPPT as a favored choice in PV systems, significantly enhancing panel efficiency and overall power output [16].

B). ANN MPPT

An artificial neural network (ANN), inspired by the human brain's structure and functioning, has the ability to enhance solar panel power output through maximum power point tracking (MPPT). Through ensuring operation at the panel's peak power point (MPP), an ANN MPPT device optimizes energy generation [19]. This technique includes training the neural network with input data such as solar irradiance, temperature, voltage, and corresponding energy output. The neural network learns these correlations to generate a control signal that adjusts the panel's operating point for correct MPP tracking. ANNs are adept at handling nonlinear relationships, adapting their accuracy as data evolves. However, implementing ANN MPPT requires substantial training data and computational resources, potentially raising system costs. Performance relies on input quality and neural network complexity, introducing challenges for efficiency optimization. In essence, ANNs hold potential for enhancing solar panel efficiency, though their implementation demands data, resources, and careful efficiency considerations [20].

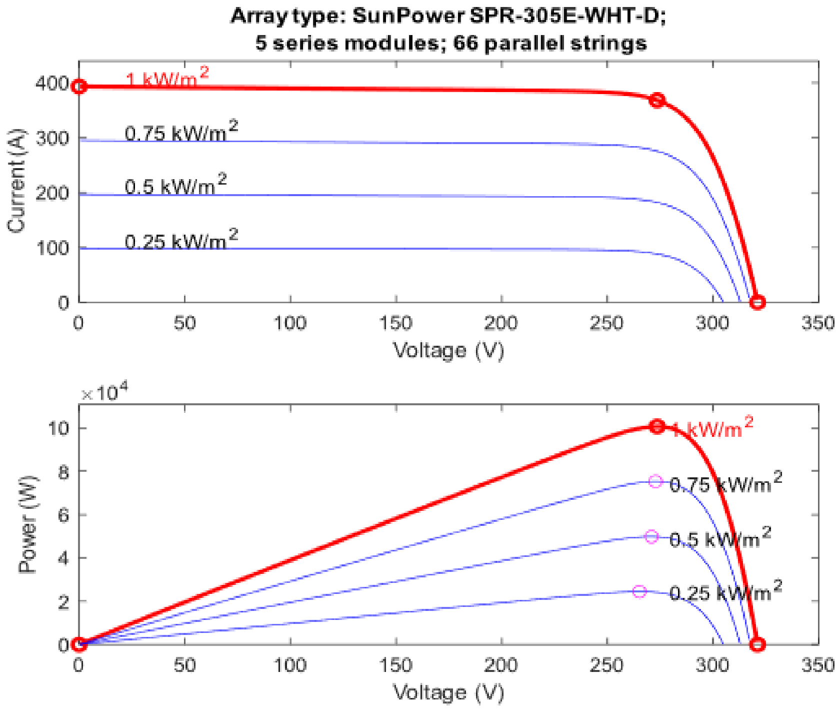

Figure 2. Performance Traits of PV Arrays across Changing Solar Irradiance

IV. WIND-TO-POWER CONVERSION SYSTEM

The wind turbine model employs mathematical representations to illustrate its behavior in different scenarios. It envisions the turbine as an aerodynamic force transmitting torque to a doubly-fed induction generator (DFIG)[3], as shown in Figure 3. This visualization captures the power characteristic curve of the wind turbines, elucidating the clear relationship between wind speed and the mechanical power generated by the turbine [17].

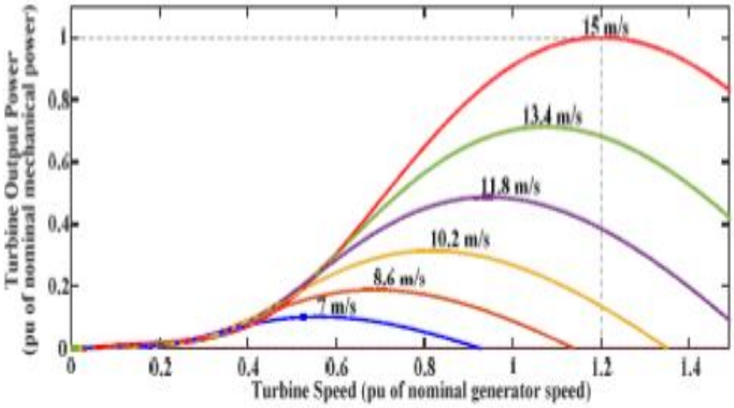

Figure 3. Wind Turbine Efficiency Profile.

Mathematically, the power produced by the wind turbine, labeled as P_m, can be expressed as:

$$P_m = 0.5\,\rho\,A\,C_p\,\lambda\,V^3$$

Inside the supplied equation, the symbols correspond to the subsequent quantities: ρ indicates air density, A indicates rotor swept region, C_p represents energy coefficient, λ stands for tip speed ratio (the ratio of blade tip speed to wind speed), and V represents wind speed.

The power coefficient,C_p, is a function reliant on tip speed ratio, λ, and can be articulated as follows:

$$C_p = 0.22(116/\lambda - 0.4\lambda - 5)\exp\left(-21/(116/\lambda - 5)\right)$$

The tip speed ratio, λ, is given by:

$$\lambda = \omega_r\,R/V$$

Inside the given equation, the variables correspond to the following values: ω_r signifies the rotational speed of the rotor, R indicates the radius of the rotor, and V represents the rate of the wind. The wind turbine model consists of mechanical losses, such as friction and drag that are encapsulated as a constant torque T_{loss}, subtracted from the aerodynamic input torque:

$$T_m = (P_m - T_{loss})/\omega_r$$

Here, T_m represents the wind turbines mechanical torque output.

The produced mechanical torque is inputted into the Doubly Fed Induction Generator (DFIG), where it undergoes conversion into electric power for seamless integration with the grid. The behavior of the DFIG can be appropriately represented the usage of principles from electric circuit idea. By using modeling the DFIG and the entire wind turbine system, it turns into feasible to employ control and optimization strategies for wind energy conversion systems. These models enable first-class-tuning of system performance and efficiency [18].

A) Enhanced Wind Power Generation through Modified MPPT

The improved MPPT method incorporates the measurement of mechanical power to precisely ascertain the best rotational velocity for a wind turbine, rendering wind speed measurements unnecessary [4]. This approach evaluates mechanical power to accurately pinpoint the ideal rotor rotation speed (w_{ref}) that corresponds with the wind farm's highest power output. Through the utilization of mechanical power calculations, this strategy presents a practical means to optimize power generation without relying on wind speed information [5].

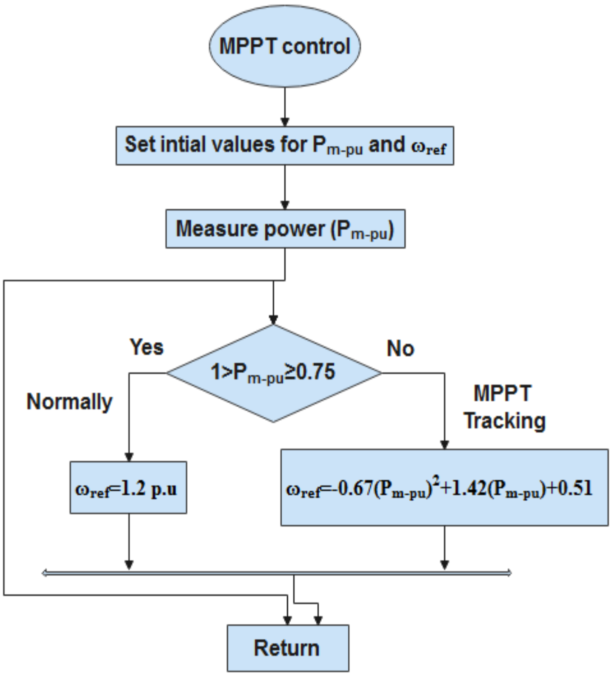

Figure 4. Improved MPPT Strategy Flowchart Incorporating Mechanical Power Analysis

The enhanced MPPT strategy's depiction is achievable through a flowchart. The sequence initiates by defining initial parameters: mechanical power (Pm-pu) and the satisfactory rotational speed (wref). Following this, the actual mechanical energy is computed should the computed energy surpass 0.75 p.u., the speed is customized to 1.2 p.u., in congruence with the 9 MW peak output. Conversely, if the energy stays below 0.75 p.u., the ideal speed is computed the use of the supplied equation. This process eliminates the need for wind speed measurements when evaluating the turbine's performance.

The tailored MPPT control method is designed to proficiently oversee and uphold the peak power generation of wind turbines, even within the presence of model inconsistencies or less precise wind speed sensors. Drawing upon the recorded mechanical electricity, this technique acts as a reliable indicator of the turbine's electricity technology, allowing precise calculation of the ideal rotor rotation speed by means of removing the requirement for wind velocity measurement, this adapted MPPT method simplifies the control mechanism, decreasing susceptibility to errors therefore, it complements the performance and overall performance of the wind power conversion device.

V. REULTS AND DISCUSSION

Through the utilization of the advised MPPT method and manage methods, the simulation effects underscore the effectiveness of the advocated MPPT method in correctly tracking the peak energy point for photovoltaic (PV) stations and wind farms. Moreover, these manage strategies assure a regular voltage on the point of common coupling (PCC) with the grid. The hybrid device proposition achieves a unity power factor and removes the injection of reactive energy, even if faced with fluctuations in active power due to environmental changes. These findings emphasize the feasibility and accomplishment of the proposed MPPT method and manage methodologies in the context of the solar-wind hybrid device.

A). Solar Irradiance-Driven PV System Performance with PI Controller

Within this phase, we compare the effectiveness of the MPPT algorithm across a range of solar irradiation stages, extending from 1000 W/m² to 250 W/m², as illustrated in figure 5(a). As showcased in figure 5(b), variations in solar irradiation effect the photovoltaic current (I_{pv}), main to a discount in the output current of the PV array. Likewise, Figure 5(c) showcases the capability of the MPPT controller to adapt the photovoltaic voltage (V_{pv}) in reaction to changing irradiance conditions.

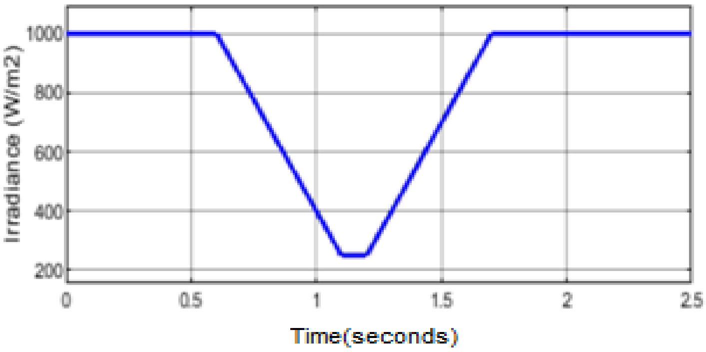

Figure 5(a) Solar Irradiance Variations

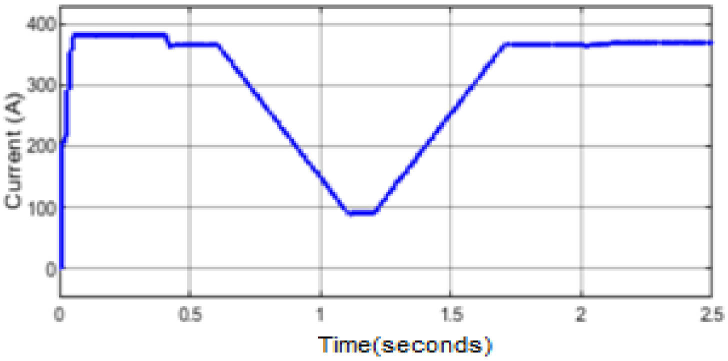

Figure 5(b) Changes in PV Array Current

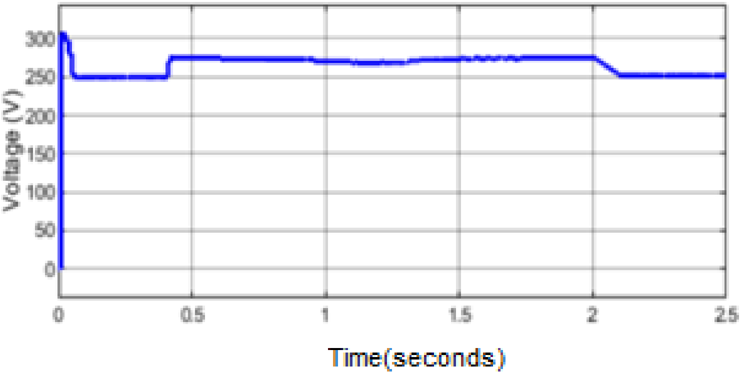

Figure 5(c) Voltage Variation in PV Array

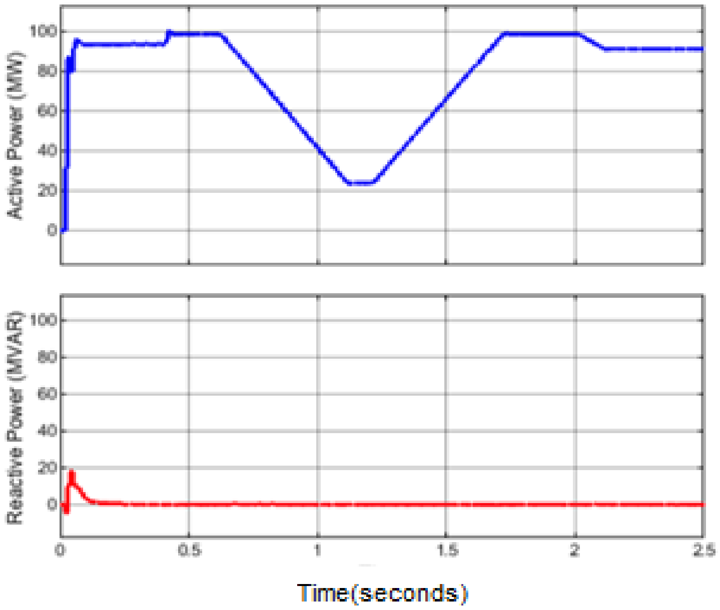

Figure 5(d) Injected Active and Reactive Grid Power

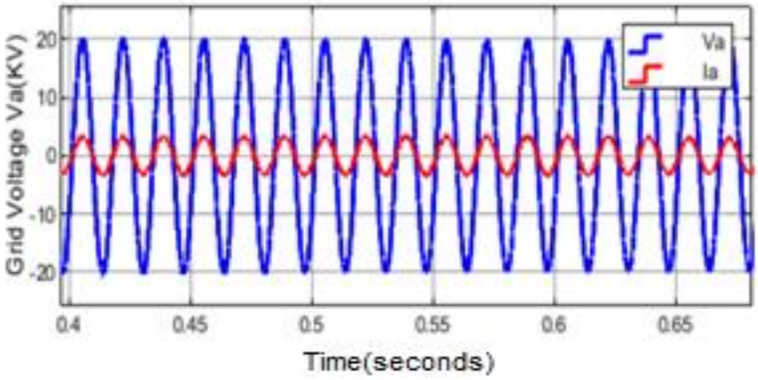

Figure 5(e). Three-Phase Current and Voltage Waveforms Controlled by PI Controller

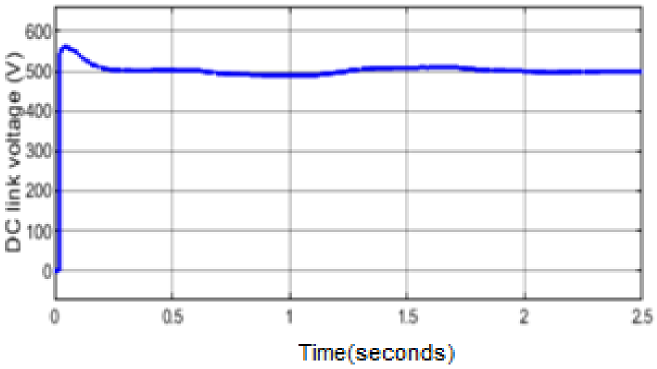

Figure 5(f). DC Link Voltage Regulation with PI Controller

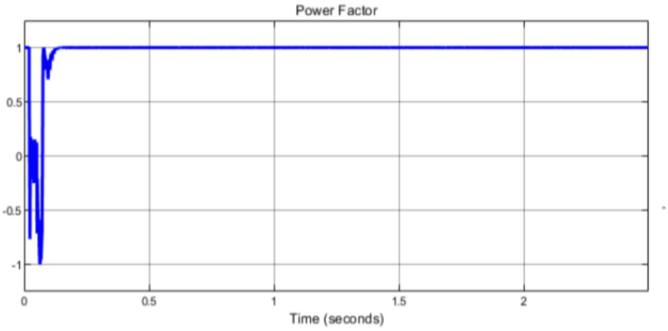

Figure 5(g). Power Factor Control of the Inverter Using PI Controller

Figure 5 illustrates simulation effects for the PV station across varying solar irradiance situations. In figure 5(a), the evaluation of the MPPT algorithm is provided, spanning from 1000 W/m² to 250 W/m². The impact of irradiance modifications on photovoltaic current (Ipv) is depicted in figure 5(b), where a decrease is evident similarly, figure 5(c) shows the modifications of photovoltaic voltage (Vpv) via the MPPT controller. The active and reactive electricity injection of the PV station is proven in figure 5(d), active electricity varies with irradiation modifications, while reactive strength remains constant at 0. Sinusoidal 3-section waveforms represent grid voltage and current in figure 5(e). The evaluation among DC-bus voltage control by the PI controller and ANN is demonstrated in figure 5(f), indicating slightly enhanced settling with the PI controller in the end, figure 5(g) exhibits the inverter strength element as measured by the PI controller.

B). Enhancing Photovoltaic Performance under Changing Solar Irradiance with ANN Controller

In Figure 6(a), the integration of grid voltage and power using the ANN controller is depicted. The swift stabilization of DC-bus voltage with the ANN controller is highlighted in Figure 6(b). Inverter power factor under varying solar irradiance conditions is showcased in Figures 6(c) and 6(d), providing a clear representation of the ANN controller's effectiveness in regulating the performance of the PV station.

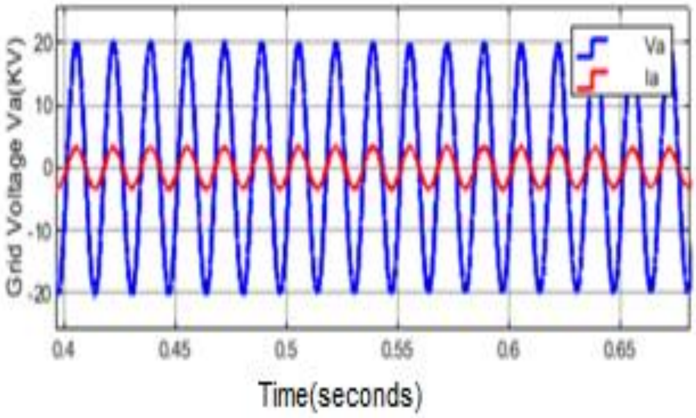

Figure 6(a). Three-Phase Current and Voltage Waveforms Utilizing ANN

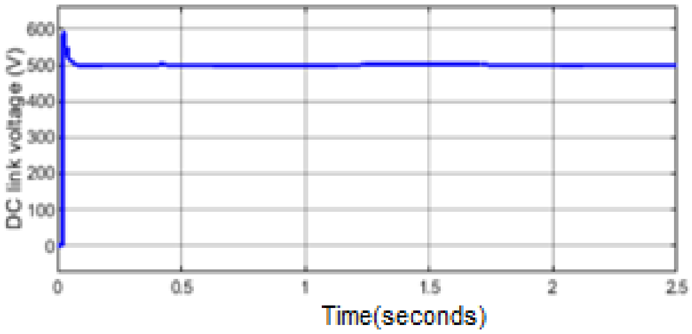

Figure 6(b). DC Link Voltage Management with ANN Controller

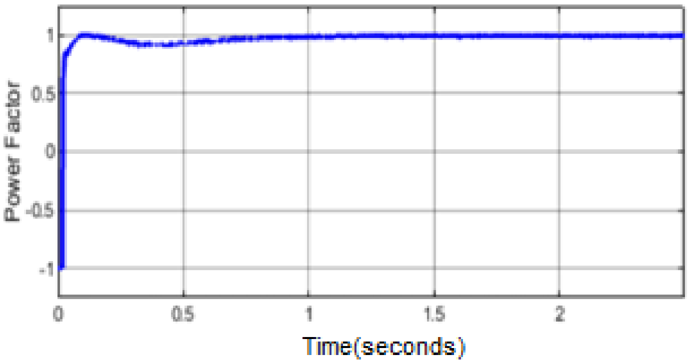

Figure 6(c). Inverter Power Factor Control Utilizing ANN

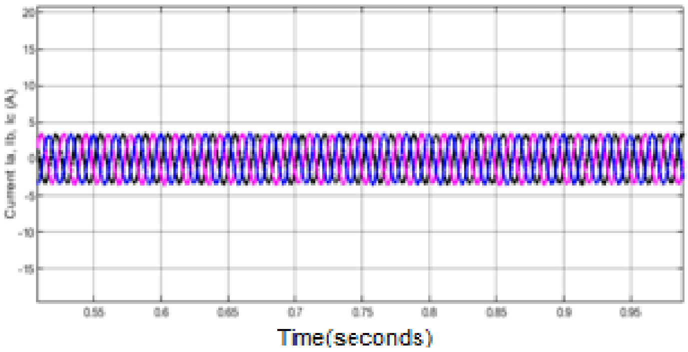

Figure 6(d). Injected Photovoltaic Station Current

C). Wind Farm Efficiency across Fluctuating Wind Speeds

In Figure 7(a), the dynamic reaction of the wind farm to fluctuating wind speeds is presented, illustrating the alterations in wind velocity. Remarkably, the GSC controllers consistently maintain the DC bus voltage, as demonstrated in Figure 7(b), throughout the range of wind speed changes.

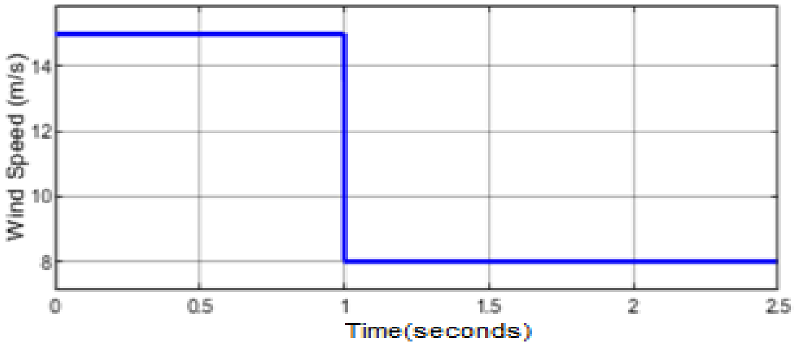

Figure 7(a). Wind Velocity Profile

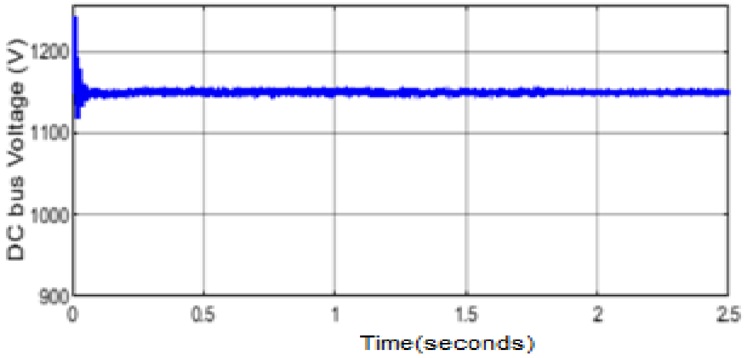

Figure 7(b). DC-Link Voltage of Doubly-Fed Induction Generator (DFIG)

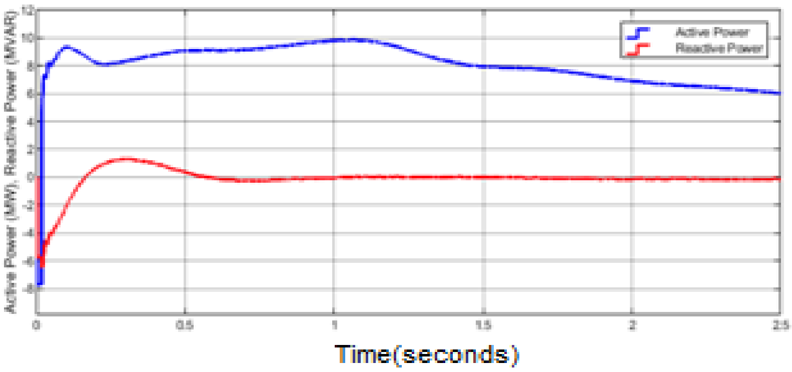

Figure 7(c). Injected Active and Reactive Power from Wind Farm

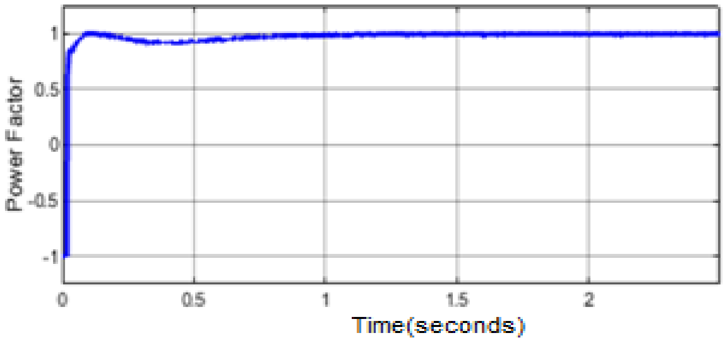

Figure 7(d). Inverter Power Factor

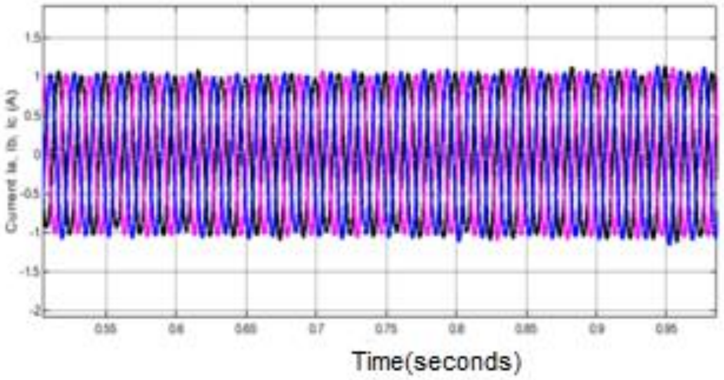

Figure 7(e). Wind Farm-Injected Current

Figure 7 illustrates the wind farm's behavior in response to varying wind speeds. In Figure 7(a), changes in wind velocity are depicted, while Figure 7(b) underscores the consistent maintenance of the DC bus voltage ensured by the effective GSC controllers. Modifications in injected active and reactive power during wind speed fluctuations are presented in Figure 7(c), with the MPPT control closely tracking the reference speed (ωref) to achieve high active power and no reactive power injection, resulting in a unity power factor as illustrated in Figure 7(d). Figure 7(e) showcases the injected current waveforms, highlighting the adept management of active power injection by the RSC controller.

VI. CONCLUSION

In conclusion, this study represents a significant stride in the field of hybrid PV/wind systems, introducing a comprehensive and innovative approach to address the challenges posed by renewable energy integration. The contributions of this research are manifold and distinguish it from prior studies, offering a fresh perspective and enriching the existing body of knowledge in several key aspects.

Contributions and Distinctions:

Integrated Control Strategies: This study pioneers the implementation of advanced control strategies, combining Incremental Conductance MPPT for solar and a power-based modified MPPT approach for wind. The integration of these strategies optimizes energy extraction, enhancing the overall efficiency of the hybrid system.

Detailed System Modeling: The research contributes by providing a meticulous and detailed model of the hybrid PV/wind system using Matlab/Simulink. This model captures the intricacies of the interactions between solar and wind components, providing a valuable resource for future research and practical implementation.

Performance Comparison: Unlike previous studies, this research rigorously compares the performance of the proposed hybrid system against conventional approaches. The utilization of an Artificial Neural Network (ANN) controller in solar energy extraction and its comparison with a conventional Proportional-Integral (PI) controller offers a nuanced understanding of the benefits of advanced control strategies.

Enhanced Power Factor and Stability: The study underscores the achievement of a unity power factor and stability in the hybrid system. The comparison of the ANN controller's step response for the DC-link voltage against the conventional PI controller provides empirical evidence of the superior performance of the proposed approach.

Comprehensive System Integration: The integration of a 100 kW solar station and a 9MW wind facility through a central bus, along with the connection to the Point of Common Coupling (PCC) bus, represents holistic and innovative system architecture. This design ensures optimal resource utilization and grid connectivity, setting this study apart from traditional hybrid systems.

Enrichment of the Research Stream: This article significantly enriches the study of hybrid PV/wind systems by advancing the understanding of control strategies, providing a detailed Matlab/Simulink model, and offering empirical evidence of the benefits of an integrated approach. The comparative analysis and performance evaluation contribute valuable insights to the ongoing discourse on sustainable and efficient renewable energy systems.

Limitations: It is crucial to acknowledge the limitations of this study. Firstly, the proposed control strategies and system architecture are evaluated primarily through simulation. While simulations provide valuable insights, real-world implementation may encounter unforeseen challenges. Additionally, the study focuses on a specific capacity range for the solar and wind components, and the scalability of the proposed model to different capacities requires further investigation. These limitations present opportunities for future research to validate and extend the findings of this study in practical applications and diverse scenarios.

In summary, this research significantly advances the field of hybrid PV/wind systems, offering novel insights, advanced control strategies, and a comprehensive model that collectively contribute to the ongoing evolution of sustainable energy solutions. The limitations identified pave the way for future research endeavors aimed at refining and extending the applicability of the proposed approaches in real-world settings.

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