Artificial Intelligence for Grid-Integrated PV/Wind Hybrid Power System

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***Abstract*--This paper presents a study on a Solar-Wind hybrid system that is connected to the electrical grid in a three-phase power grid configuration. The system integrates a PV station and a wind farm at the Point of Common Coupling (PCC) to improve its performance. The Maximum Power Point Tracking (MPPT) technique is used to obtain maximum power output under different weather conditions for both the PV and wind energy conversion systems. An Artificial Neural Network (ANN) controller is developed to track the maximum power point of the PV array and is evaluated under various weather conditions. The Vector Control technique is used to control the three-phase neutral point clamped multilevel inverter with the ANN controller to regulate the DC-link voltage to the desired level. The simulation of hybrid system is conducted using MATLAB/SIMULINK and compare the performance of the ANN controller with a PI controller in terms of the step responsiveness of the DC-link voltage and the efficiency of the MPPT technique. The results indicate that the ANN controller efficiently maintains a constant grid voltage, provides unity power factor, and optimally utilizes the injected active power from the Solar-Wind hybrid power system, regardless of the fluctuations in environmental conditions. Overall, the paper proposes a comprehensive approach for developing a Solar-Wind hybrid system that enhances its performance and optimizes power output under various weather conditions, using the MPPT technique and ANN controller for effective control of the DC-link voltage.**

Index terms—Solar array, wind energy, photovoltaic, MPPT, PI controller, Fuzzy Logic Controller (FLC).

I. Introduction

The world is currently facing a critical issue in meeting the increasing demand for energy, while also addressing the depletion and exhaustible nature of conventional power sources. This has led to a surge in research efforts towards exploring alternative and renewable sources of energy, among which, wind and photovoltaic (PV) energy are considered the most promising technologies for electricity generation. However, the intermittent nature of these energy sources and their dependence on environmental conditions, such as variations in solar irradiance and wind speed, limit their effectiveness. To overcome the intermittency issue and improve the reliability and quality of power generation, there has been a growing interest in integrating PV and wind energy sources as a hybrid power system. Such a system can utilize the complementary nature of the two renewable energy sources to generate more reliable power. In recent years, many studies have been carried out on PV/wind hybrid power systems, including modeling and control systems, integration of asymmetric inverters with backup batteries, and development of sliding mode control strategies. One commonly used technology in PV/wind hybrid power systems is the Doubly Fed Induction Generator (DFIG) due to its simplicity, decoupled control of active and reactive power, partially rated converters, and ability to extract maximum power from wind turbines. Studies have also investigated the integration of PV station and wind farm-based DFIG as a hybrid power system, including simulation analysis and proposed control strategies for maximum power extraction and improving power quality. This study focuses on a detailed dynamic modeling, design, and control strategy of a grid-connected PV/wind hybrid power system. The system consists of a 1MW PV station and a 9 MW wind farm, which are integrated through a main AC-bus to inject the generated power and enhance system performance. The Maximum Power Point Tracking (MPPT) technique is applied to both the PV station and wind farm to extract the maximum power from the hybrid power system during variations in environmental conditions. The effectiveness of the MPPT technique and control strategy for the hybrid power system is evaluated under different environmental conditions, including variations in solar irradiance and wind speed. Simulation results show that the MPPT technique is effective in extracting the maximum power from the hybrid power system during variations in environmental conditions. Additionally, the hybrid power system successfully operates at unity power factor since the injected reactive power from the hybrid power system is equal to zero. The control strategy is also effective in maintaining the grid voltage constant regardless of the variation of environmental conditions and the injected power from the hybrid power system. In conclusion, the integration of PV and wind energy sources as a hybrid power system is a promising solution to overcome the intermittency issue and improve the reliability and quality of power generation. The use of DFIG technology and MPPT techniques, along with effective control strategies, can enhance the performance of PV/wind hybrid power systems. This study provides a detailed modeling and control strategy of a grid-connected PV/wind hybrid power system, which can be useful for the design and development of similar systems in the future.

II. PV/Wind Hybrid System Integration Study

The studied PV/wind hybrid power system is a combination of a photovoltaic (PV) station and a wind farm, integrated through a main point of common coupling (PCC)-bus to inject generated power and improve the system's performance. The PV station has a power rating of 100KW, while the wind farm has a power rating of 9 MW. These two renewable energy sources are located in different locations. The PV station consists of many PV modules, which are electrically connected in parallel-series combinations to achieve the desired power capacity. It is equipped with a DC/DC boost converter that steps up the array output voltage, and an aggregated DC/AC inverter that converts the generated DC power to AC power. An incremental conductance maximum power point tracking (MPPT) technique is implemented to extract the maximum power from the PV station under variation of the solar irradiance.

The PV station is interconnected with the PCC-bus through a 260 V/25 KV Δ/Y transformer. The wind farm contains one equivalent aggregated doubly-fed induction generator (DFIG) that is driven by a large aggregated wind turbine. Additionally, it includes a grid side converter (GSC) for maintaining the DC-bus voltage constant and a rotor side converter (RSC) for extracting the maximum power from the wind turbines. Moreover, a modified MPPT technique based on mechanical power measurement is implemented to capture the maximum power from the wind farm during variation of the wind speed. The wind farm is interconnected with the PCC-bus through a 575 V/25 KV Δ/Y transformer. The hybrid power system is controlled to operate at unity power factor, and the injected active power is transmitted to the electrical grid through 30 km transmission lines and a 25 KV/120 KV Y/Δ transformer. The integration of these two renewable energy sources enhances the system performance, reduces the impact on the environment, and provides a reliable and sustainable source of energy. The hybrid system also enables better utilization of resources, as the wind farm and PV station can generate power under different weather conditions.

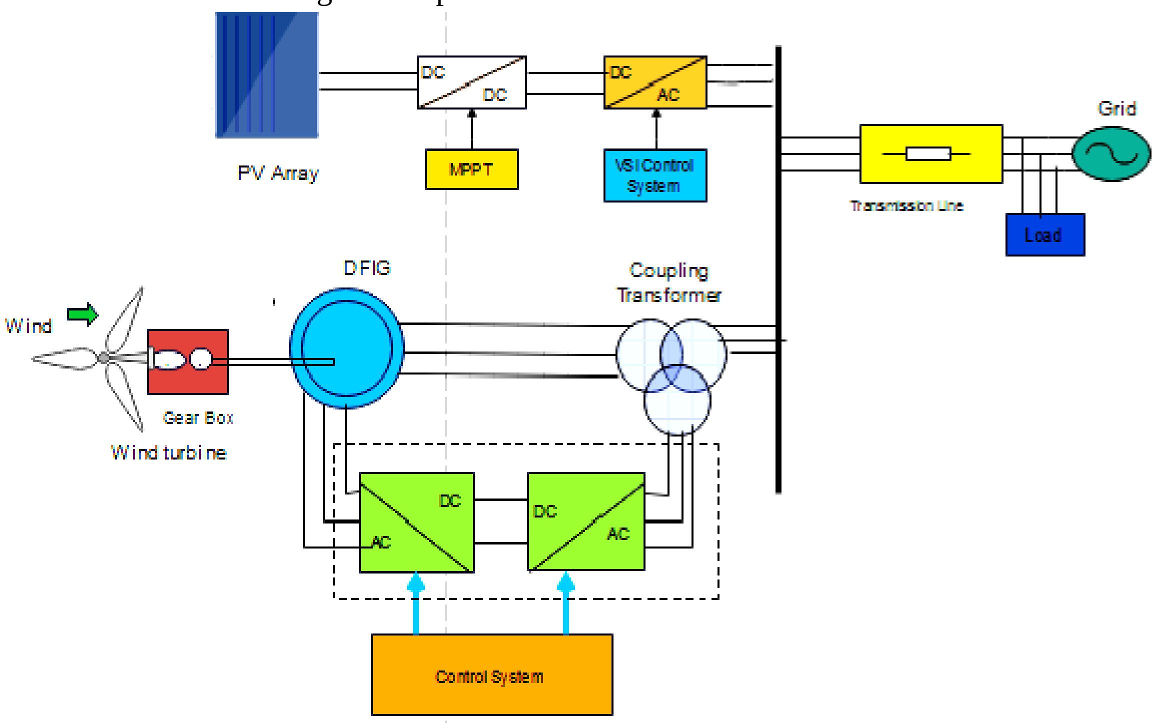

Fig. 1 Configuration of Solar-wind hybrid power system

III. Photovoltaic (PV) Conversion System

The PV conversion system is a vital element in solar energy systems, responsible for maximizing power output through the electrical modeling and characterization of PV arrays. These arrays are formed by electrically connecting multiple PV modules in series to create a string, with several strings parallel-connected to form a PV array with the desired power capacity. The PV arrays are connected to a DC/DC boost converter to extract maximum power from the solar irradiation, with the resulting power connected to the main DC/AC inverter to control active power and achieve the demanded reactive power. This configuration offers several advantages, such as cost-effectiveness, low losses, and higher efficiency, with constant DC-link voltage. PV arrays are modeled using the Shockley diode, and their electrical characteristics can be simulated under various environmental conditions. The incremental conductance maximum power point tracking (MPPT) algorithm ensures the system operates at maximum power point (MPP) for optimal energy generation, with the DC/AC inverter controller regulating active power injection and achieving required reactive power. Figure 2 shows the I-V and P-V characteristics of the PV array under varying solar irradiance. The modeling and characterization of PV arrays for maximum power extraction are crucial for efficient and effective operation of solar energy systems.

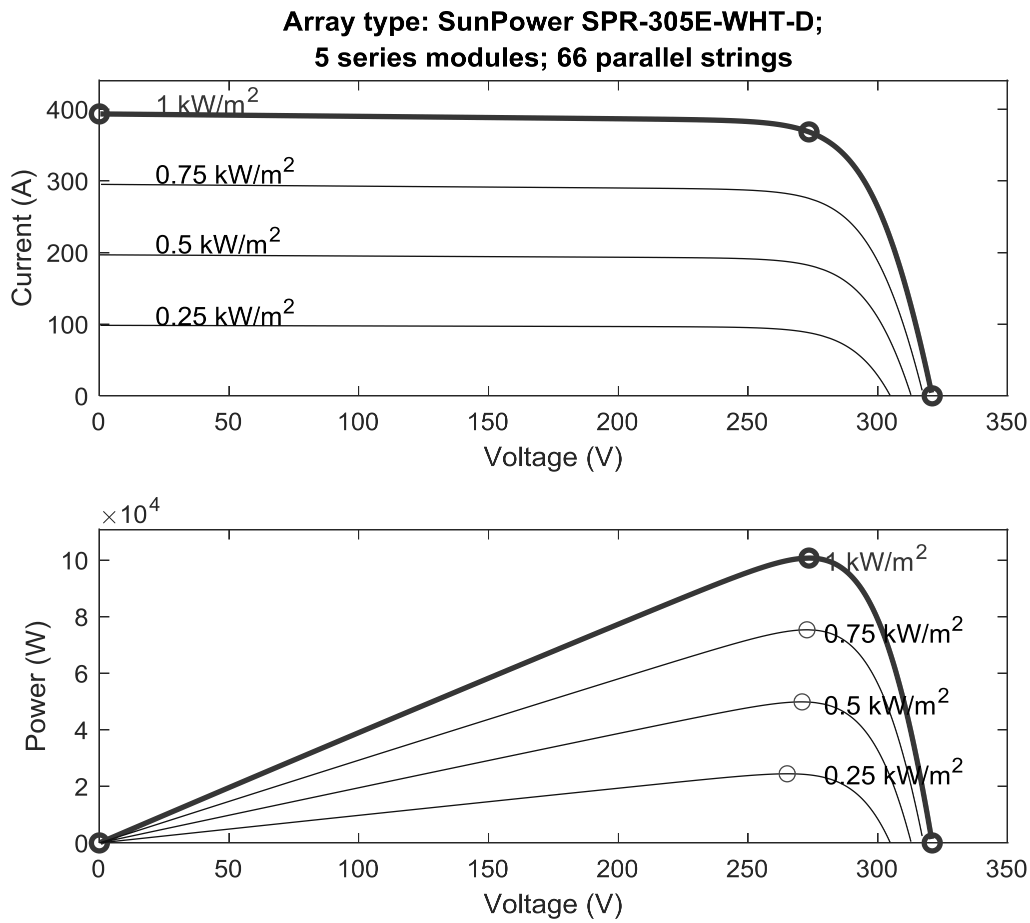

Fig .2. PV array's performance characteristics under varying solar irradiance.

1.Incremental Conductance MPPT Technique

Incremental Conductance Maximum Power Point Tracking (MPPT) is an algorithm used in photovoltaic (PV) systems to optimize the energy generation from solar panels. The purpose of MPPT is to constantly adjust the voltage and current of the solar panels to ensure they are operating at their maximum power point (MPP) regardless of external factors such as temperature and irradiance.

The incremental conductance MPPT algorithm uses the change in power with respect to a change in voltage to determine the direction of the MPP. It compares the conductance of the solar panel to the change in power and adjusts the voltage in the appropriate direction to approach the MPP. This process continues until the MPP is reached.

Incremental conductance MPPT has some advantages over other MPPT algorithms, particularly in systems where temperature and irradiance conditions are rapidly changing. It is a simple algorithm that can track the MPP quickly and accurately, resulting in maximum energy generation. It is widely used in PV systems due to its effectiveness and relatively low cost of implementation.

In summary, incremental conductance MPPT is an important algorithm that enables PV systems to operate at their maximum efficiency, generating the most power possible from the solar panels.

2. ANN MPPT

An artificial neural network (ANN) is a machine learning technique that is inspired by the structure and function of the human brain. In the context of maximum power point tracking (MPPT) for solar power systems, an ANN can be used to optimize the power output of a solar panel by ensuring that it operates at its maximum power point (MPP).

In an ANN MPPT system, the neural network is trained using input data such as solar irradiance, temperature, and voltage, as well as the corresponding power output of the solar panel. The neural network learns the relationship between these variables and outputs a control signal that adjusts the operating point of the panel to track the MPP.

One advantage of using an ANN for MPPT is that it can adapt to changing conditions and improve its accuracy over time as it receives more data. ANNs are also able to handle non-linear relationships between variables, which makes them well-suited for optimizing the performance of a solar panel.

However, ANN MPPT systems require a significant amount of training data and computational resources for running the neural network, which can increase the cost of the system. Additionally, the performance of the ANN MPPT system may depend on the quality of the input data and the complexity of the neural network, which can make it challenging to optimize the system for maximum efficiency.

IV. Wind Energy Conversion System

The wind turbine model is a mathematical representation of the behavior of a wind turbine under different operating conditions. In this model, the wind turbine is considered as an aerodynamic input torque that drives a doubly-fed induction generator (DFIG). The power characteristic curve for the wind turbine at different wind velocities is shown in Fig.3. The curve shows the relationship between the wind speed and the mechanical power output of the wind turbine.

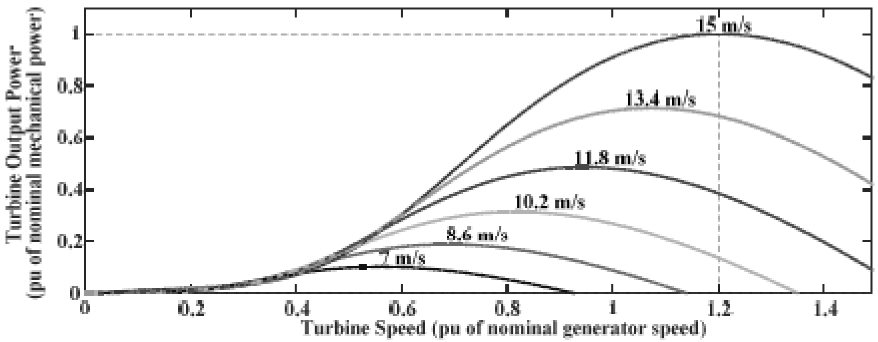

Fig.3. Wind turbine performance curve.

The mechanical power output of the wind turbine, Pm, can be expressed as:

$Pm = 0.5 * \rho * A * Cp * \lambda * V^3$

where ρ is the air density, A is the swept area of the rotor, Cp is the power coefficient, λ is the tip speed ratio (the ratio of the speed of the blade tips to the wind speed), and V is the wind speed.

The power coefficient, Cp, is a function of the tip speed ratio and is given by:

$Cp = 0.22 * (116 / \lambda - 0.4\lambda - 5) * \exp(-21 / (116 / \lambda - 5))$

The tip speed ratio, λ, is given by:

$\lambda = \omega r * R / V$

where ωr is the rotational speed of the rotor, R is the radius of the rotor, and V is the wind speed.

The wind turbine model also takes into account the mechanical losses in the system, such as friction and drag. These losses can be modeled as a constant torque, Tloss, subtracted from the aerodynamic input torque:

$Tm = (Pm - Tloss) / \omega r$

where Tm is the mechanical torque output of the wind turbine.

The output mechanical torque is used as the input to the DFIG, which converts the mechanical power into electrical power that can be fed into the grid. The behavior of the DFIG can be modeled using the principles of electrical circuit theory. The modeling of the DFIG and the complete wind turbine system can be used for control and optimization purposes in a wind energy conversion system.

1.Modified MPPT Technique for Enhancing Wind Power Generation

The modified MPPT technique based on mechanical power measurement aims to accurately calculate the optimum rotational speed of a wind turbine without relying on wind speed measurements. The technique calculates the mechanical power and uses it to determine the optimum rotational speed of the rotor (wref) that corresponds to the maximum power output of the wind farm.

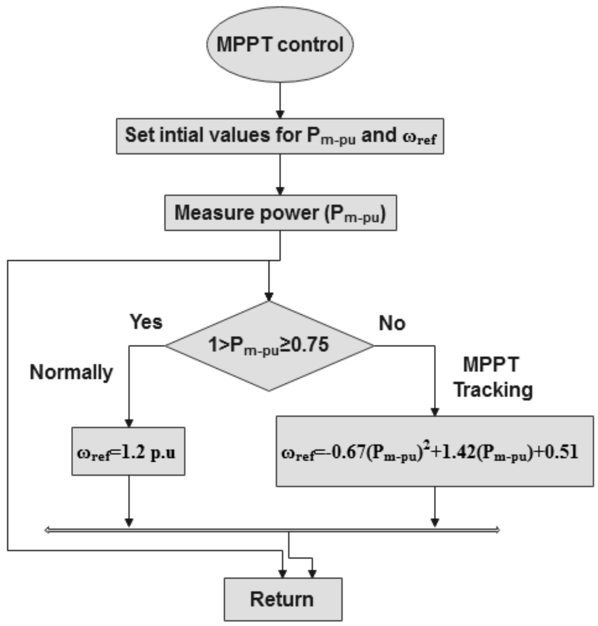

Figure. 4. Enhanced MPPT Technique Flowchart based on Mechanical Power Measurement

The flow chart of the improved MPPT strategy involves setting initial values for mechanical power (Pm-pu) and optimum rotational speed (wref), followed by calculating the actual mechanical power to determine the optimum rotational speed. When the mechanical power is greater than 0.75 p.u.(per unit), the optimum rotational speed is normally set to 1.2p.u., which corresponds to the maximum power output of the wind farm (9 MW). On the other hand, when the mechanical power is lower than 0.75p.u., the optimum rotational speed is calculated based on below equation.

$$\omega_{ref} = \begin{cases} 1.2 & 1 \geq P_{m\_pu} \geq 0.75 \\ -0.67\left(P_{m-pu}\right)^2 + 1.42\left(P_{m-pu}\right) + 0.51 & P_{m\_pu} < 0.75 \end{cases}$$

The improved MPPT control strategy is designed to accurately track the maximum power output of the wind turbine, even in the presence of modeling errors or inaccuracies in wind speed sensors. The technique uses the measured mechanical power as a reliable indicator of the power output of the wind turbine, which is then used to determine the optimum rotational speed of the rotor. By eliminating the need for wind speed measurements, this modified MPPT technique simplifies the control system and makes it less susceptible to errors, leading to improved efficiency and performance of the wind energy conversion system.

V. Simulation Results

Using the proposed MPPT approach and the control methods. The simulation results show that the proposed MPPT strategy can effectively track the maximum power point of the PV stations and wind farms, and the control methods can maintain the constant voltage at the point of common coupling (PCC) of the electrical grid. Additionally, the proposed hybrid system can achieve unity power factor and zero reactive power injection, even under environmental conditions changes and fluctuations in the generated active power. These results demonstrate the feasibility and effectiveness of the proposed MPPT strategy and control methods for the solar wind hybrid system.

1. PV Performance with PI Controller under Solar Irradiance Variation.

This section analyzes the performance of an MPPT algorithm under various solar radiation conditions, ranging from 1000 W/m2 to 250 W/m2, as shown in Figure 5(a). As demonstrated in Figure 5(b), changes in solar radiation affect the photovoltaic current Ipv, with the output current of the PV array decreasing. Similarly, Figure 5(c) shows that the photovoltaic voltage Vpv is also reduced by the MPPT controller under changed irradiance conditions.

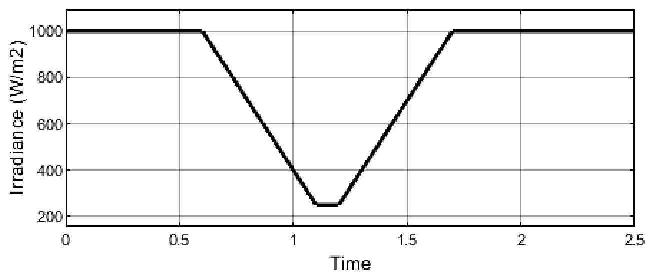

Figure. 5(a) Changes in solar irradiance

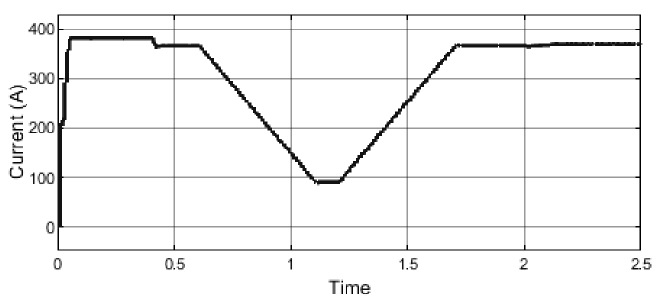

Figure. 5(b) Variation of PV array current

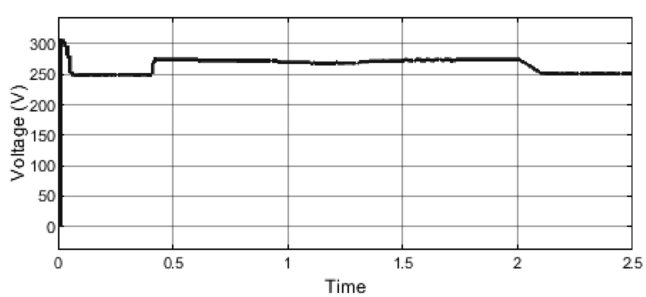

Figure. 5(c) Voltage of PV array

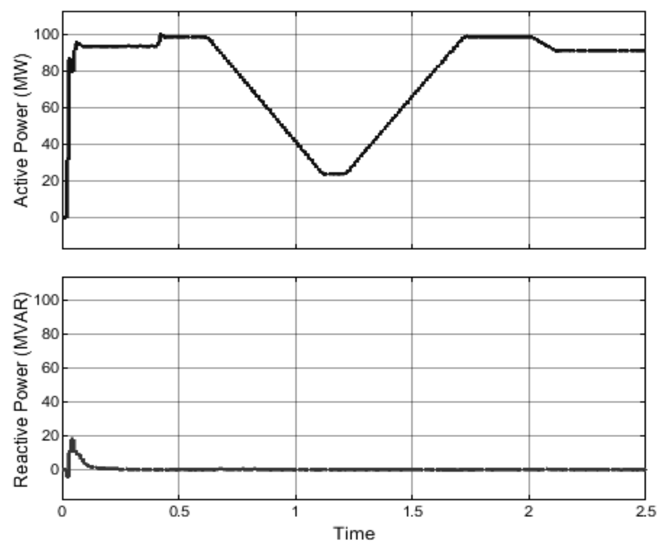

Figure. 5(d) The active power and reactive power injected into the grid

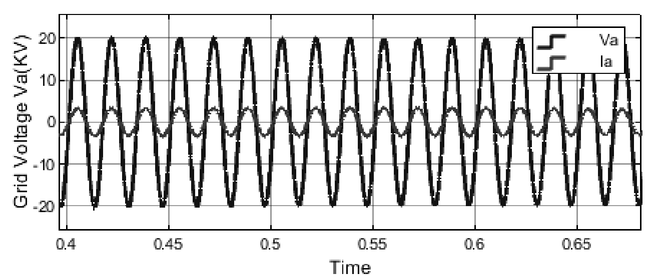

Figure. 5(e) The three phase current and voltage waveforms by PI controller

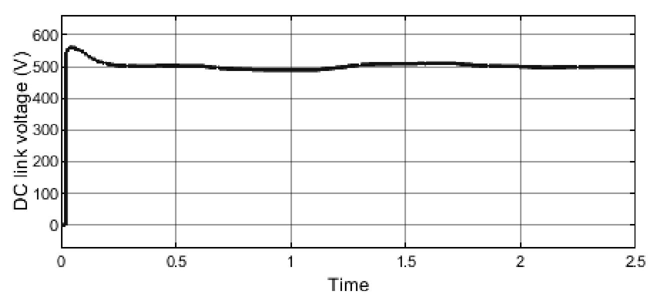

Figure.5(f). DC link voltage with PI controller

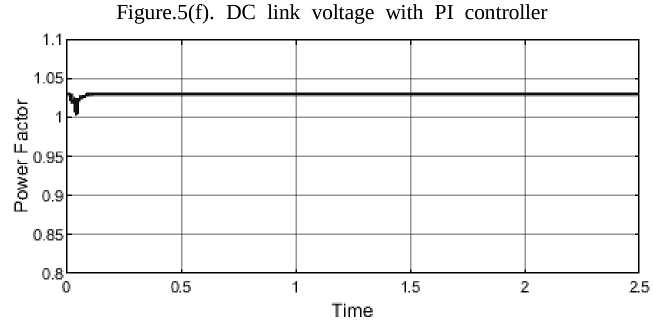

Figure. 5(g) The power factor of the inverter with PI controller

Figure 5 presents the results of the simulation of the PV station under different solar irradiance conditions. In Figure 5(a), various solar radiation levels from 1000 W/m2 to 250

W/m2 are shown for evaluating the performance of the MPPT algorithm. As shown in Figure 5(b), the photovoltaic current Ipv decreases as the irradiance changes. The MPPT controller reduces the photovoltaic voltage Vpv, as depicted in Figure 5(c). Figure 5(d) shows the active and reactive power injected by the PV station, where the active power changes according to solar radiation, while the reactive power injected is zero. The grid voltage and current are shown in Figure 5(e) as clear sinusoidal 3-phase waveforms. The DC-bus voltage controlled by the PI controller is settled slightly higher than the ANN, as demonstrated in Figure 5(f). In Figure 5(g), the inverter power factor measured by the PI is displayed.

2. *Improving PV Performance in Varying Solar Irradiance Conditions using ANN Controller*

Figure 6(a) illustrates the integration of grid voltage and power by the ANN controller. The DC-bus voltage, with very less settling time by the ANN controller, is presented in Figure 6(b). The inverter's power factor during solar irradiance variations is depicted in Figures 6(c) and 6(d), showing the performance of the PV station controlled by the ANN controller.

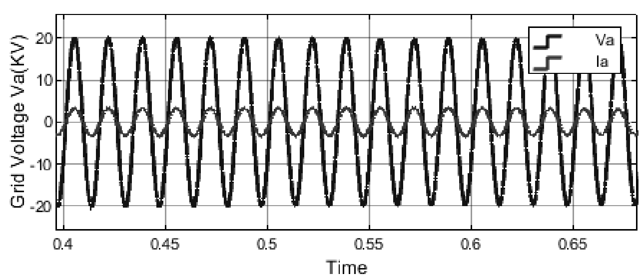

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Figure. 6(a) The three phase current and voltage waveforms with ANN

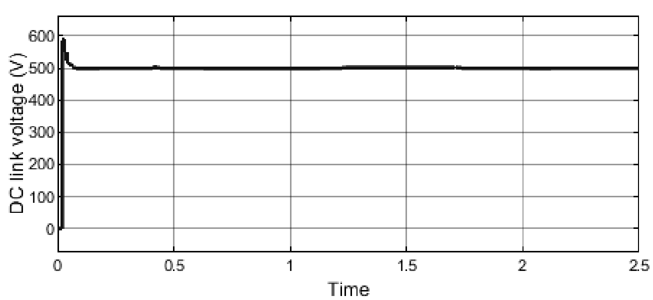

Figure. 6(b). DC link voltage with ANN

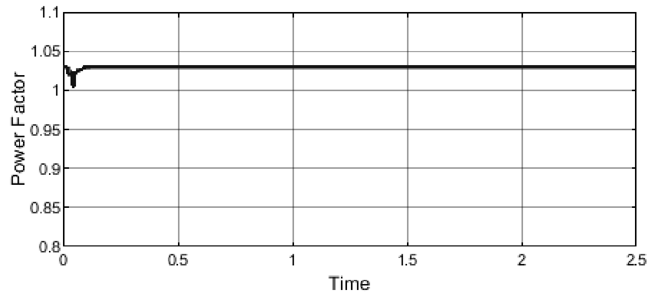

Figure. 6(c) The power factor of the inverter with ANN

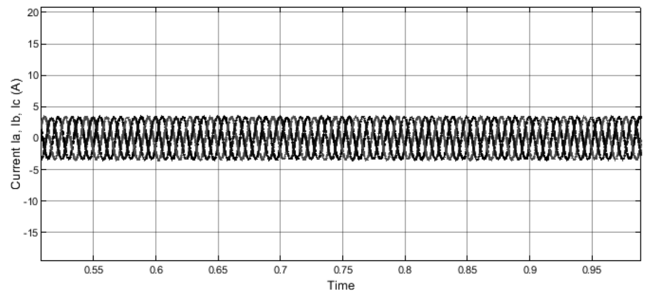

Figure 6(d) Injected current from PV station

3. Wind Farm Performance Under Varying Wind Speeds

Figure 7(a) illustrates the dynamic performance of the wind farm during changes in wind speed. The figure shows the variation in wind velocity. Despite the different variants of wind speed, the DC bus voltage was maintained constant by the GSC controllers, as shown in Figure 7(b).

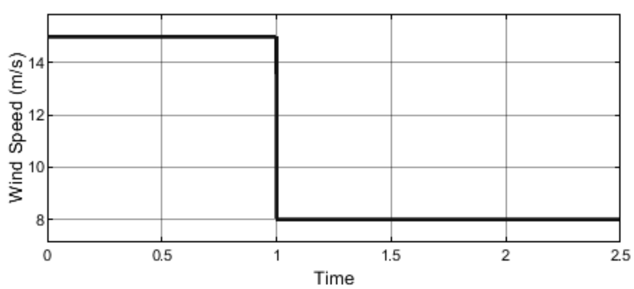

Figure.7 (a) Wind speed profile

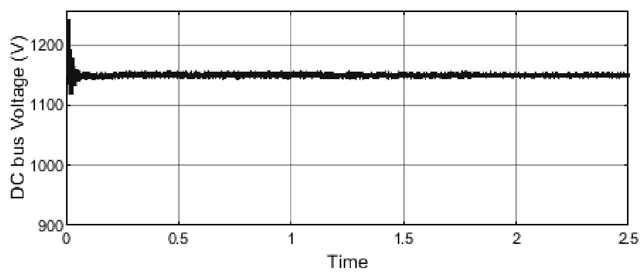

Figure.7 (b) The DC-link voltage of DFIG

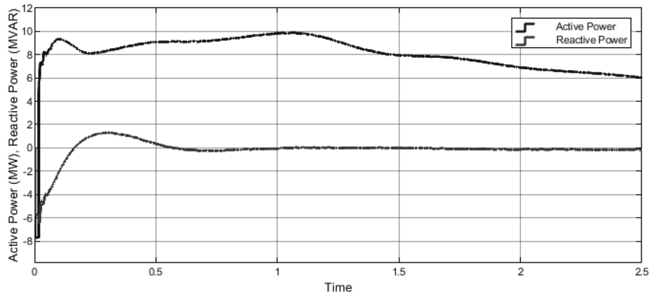

Figure 7(c) Active and reactive power injected from wind farm

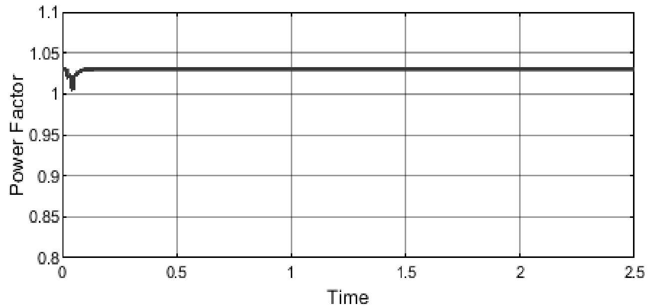

Figure 7(d) Power factor of the inverter

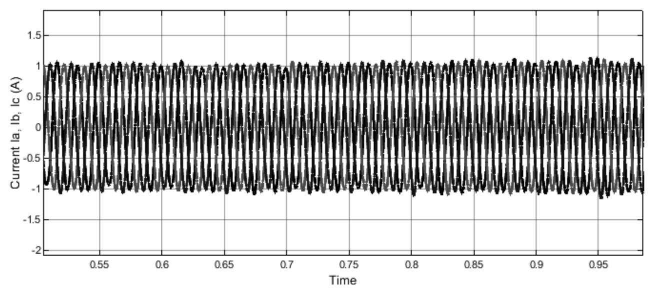

Figure 7 (e) Injected current from wind farm

In Figure 8, the dynamic performance of the wind farm during changes in wind speed is demonstrated. Figure 8(a) shows the variations in wind velocity, while the GSC controllers maintain the DC bus voltage constant, as seen in Figure 8(b). Figure 8(c) illustrates the active and reactive power injected by the wind farm during changes in wind speed. The MPPT control accurately tracks the reference speed (ωref) and displays high active power, while the injected reactive power is kept zero, resulting in a unity power factor as shown in Figure 8(d). Figure 8(e) displays the current injected waveforms, and the RSC controller controls the injection of active power.

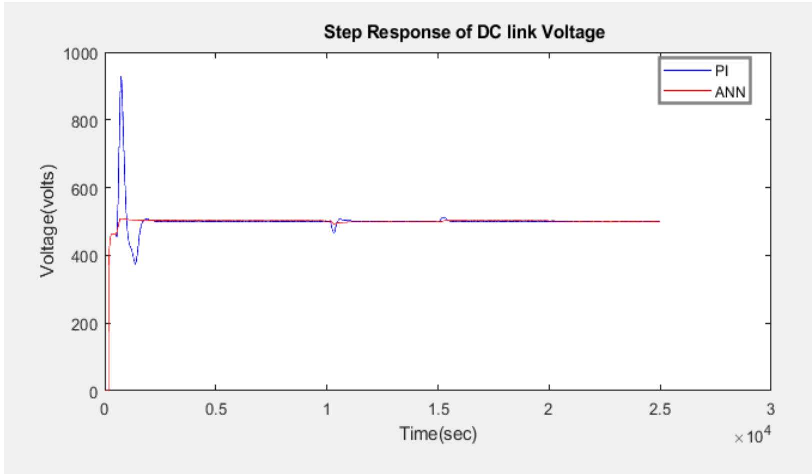

Figure8.Step response of DC link voltage

Table.1 step response of the DC link voltage

Step info of DC link Voltage	**With PI controller**	**With ANN controller**
Rise Time	**77.2573**	**78.0786**
Transient Time	**1.5352e+04**	**620.9334**
Settling Time	**1.5352e+04**	**620.9334**
Settling Min	**374.8848**	**450.7403**
Settling Max	**926.8978**	**507.8464**
Overshoot	**85.4143**	**1.4915**
Undershoot	**0**	**0**
Peak	**926.8978**	**507.8464**
Peak Time	**737**	**694**

The above provided data on two different control strategies for a system, with respect to the step response of the DC link voltage. The two control strategies are PI controller and ANN controller. The step response of the system with the PI controller and ANN controller are compared based on several performance measures, including: *Rise time***:** The time it takes for the system output to go from 10% to 90% of its final value after a step input. The rise time for the PI controller is 77.2573 and for the ANN controller it is 78.0786. *Transient time:* The time it takes for the system output to settle within a certain percentage of its final value after a step input. The transient time for the PI controller is 1.5352e+04 (i.e., 15352) and for the ANN controller it is 620.9334. *Settling time:* The time it takes for the system output to settle within a certain percentage of its final value and stay there. The settling time for the PI controller is 1.5352e+04 (i.e., 15352) and for the ANN controller it is 620.9334. *Settling min:* The minimum value reached by the system output during settling. The settling min for the PI controller is 374.8848 and for the ANN controller it is 450.7403. *Settling max:* The maximum value reached by the system output during settling. The settling max for the PI controller is 926.8978 and for the ANN controller it is 507.8464. Overshoot: The percentage by which the system output exceeds its final value before settling. The overshoot for the PI controller is 85.4143 and for the ANN controller it is 1.4915. *Undershoot:* The percentage by which the system output falls below its final value before settling. There is no undershoot for either controller. *Peak:* The maximum value reached by the system output at any time. The peak for the PI controller is 926.8978 and for the ANN controller it is 507.8464. *Peak time:* The time at which the peak value is reached. The peak time for the PI controller is 737 and for the ANN controller it is 694.

VI. Conclusion

This paper has presented a grid-connected PV-WIND hybrid power system and demonstrated its modeling through simulation in Matlab/Simulink. The system employed the ANN MPPT approach to extract maximum power from the PV system, and an improved MPPT control method was used to extract maximum power from the wind farm during wind speed changes. The VSI's dc link voltage controller was effectively controlled using both PI and ANN controllers, and simulation results showed that the ANN controller outperformed the existing PI controller in terms of step responsiveness of the dc-link voltage. The control system maintained the hybrid power system at unity power factor, even with zero injected reactive power, and the voltage at the PCC bus was precisely maintained constant, regardless of environmental conditions changes and the magnitude of generated active power. Overall, the proposed control system proved to be effective in maintaining the performance of the hybrid power system and ensuring its stability and reliability.

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