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Inverter Control using ANN in Grid linked PV, Wind & Battery system

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This research investigates the implementation of an Artificial Neural Network (ANN) control strategy for a hybrid grid-linked scheme that integrates PV, wind, and battery energy sources. As the demand for renewable energy solutions grows, the focus on hybrid systems that leverage the strengths of multiple energy sources is critical for enhancing stability and efficiency in power generation. The study compares the performance of the proposed ANN controller to control techniques, such as Proportional-Integral (PI) and Fuzzy Logic Controllers , in managing the dynamic interactions among the energy sources and ensuring optimal power output under varying environmental conditions. A MATLAB Simulink model was developed, which utilized P&O MPPT to achieve an efficiency of 98.5%.The results demonstrate that the ANN controller outper-forms both PI and Fuzzy controllers in maintaining a stable DC link voltage of approximately 600V, thereby enhancing grid synchronization and power quality during fluctuating condi-tions.This research contributes valuable insights towards the design of more resilient and efficient grid-connected renewable energy systems, highlighting the potential of ANN-based control methods in managing complex energy generation and storage dynamics
Keywords: Grid linked system, Artificial Neural network (ANN), Fuzzy logic Controller (FLC), Inverter control. Renewable Energy sources (RES).

1. Introduction

In recent years, integrating RES like PV and wind into grid-linked schemes has obtained substantial consideration as a resolution to lower use on fossil fuels and minimize environmental impact. Hybrid schemes, which combine PV, wind energy, and battery storage, offer enhanced stability and flexibility in power generation, addressing the intermittent nature of renewable sources. These systems are commonly connected to the grid via inverters, enabling efficient power flow and energy management. The inverter is typically controlled by various algorithms to maintain optimal power output and ensure grid stability. Controllers such as PI, Fuzzy Logic, and ANN-based systems are increasingly employed to manage the dynamic interactions between generation sources, energy storage, and grid demands.

In [1], a grid-linked scheme having PV, battery & wind is presented. Here, the grid's reactive power is maintained by the use of integrator control, which also controls the dc-link voltage across the converter at the grid side. It also improved the quality of power in the system during fault conditions. The battery input & output power depended on the Power variation in the RES connected to it. The outcomes are presented during variation PV irradiance and change in speed from wind turbine & dynamic conditions. A PV-wind hybrid scheme linked to grid is presented in [2], The grid to designed to work in both islanded & Grid linked modes. Effective transfer of power to batteries, loads, and the grid is provided by the PMU, which is intended to measure from several locations in the system.

In [3], Elman neural network (ENN) rule-based structure is used in PV -Wind system. The Stateflow technique is used in the design of the EMS to obtain the datasets used for training and testing for the ENN controller's creation. A PV, diesel, and wind energy with battery storage was presented in [4], which is regulated by an ANN using a Multi-Level Feed Forward Network (FFN).The LM process is employed to train the ANN, which enables the hybrid system to function precisely in time-varying scenarios. To determine if the method is feasible, MATLAB R2016a is utilized for simulation, comparing ANN to a fuzzy logic controller (FLC). The real time adaptability is limited using ANN complexity in training. In [5], PV, wind & battery-based microgrid using ANN-based MPPT is implemented. An inverter control for the converter at the grid regulates the current flow depending on battery charging state and the photovoltaic current received. DC bus voltage uses a bidirectional converter with a battery to achieve voltage control. Additionally, the microgrid system has a PLL to synchronize the frequency and phase of the grid and an LCL filter to eliminate harmonics from the single-phase grid. The system’s performance vary significantly under rapidly fluctuating load conditions.[6] presented a wind energy system that consists of four wind turbines coupled with battery storage and a 5-level inverter. Without requiring the characteristic Cp(λ, β), the FLCcontrol method maximizes power extraction by regulating the turbine's rotational speed. Compared to traditional five-level modulation, space vector modulation improves performance by reducing computing complexity.The system is evaluated under limited scenarios, which may not reflect diverse operational conditions

A PV,Wind & battery based Grid linked scheme is presented in [7], A FLC is employed for Energy management. The charging & discharging based on supply-demand balance and includes an MPPT to maximize energy capture are managed by FLC. Limited adaptability to sudden load changes due to the rule-based nature of FLC.A MPPT utilizing FLC from a individual hybrid power system is presented in [8]. It consists of a PV and PMSG branch-based wind turbine. In the changing load scenario, Good precision in current transition and constant voltage is indicated by the fuzzy controller for the PV wind MPPT scheme, which shows a minimal overshoot and a minor steady state inaccuracy. No real-time operational testing is included in this study, Which limits insights into performance stabilityIn [9], a comparison of PI & FLC is presented. The system has PV, Wind & battery system, The constant and erratic changes in wind speed have an impact on the quality of the electricity generated by the WT. Therefore, to maintain constant voltage and frequency at the load terminals, voltage-stabilizing controllers must be incorporated into the system. For performance validation, a fuzzy logic-based controller is suggested and contrasted with a traditional PI controller for the regulating voltage of the planned hybrid system. Absence of data for controller performance under real-world disturbances, reducing practical applicability

In [10], a hybrid system consisting of PV & Wind is presented. is chosen. In order to achieve design and demand goals, the power management system (PMS) in this article applies three control strategies: sliding mode control, fuzzy-PI, and proportional-integral controller (PI). The objective of this work is to examine and compare the performance of the previously mentioned control methods while accounting for hydrogen consumption, fuel/fuel-cell efficiency, shorter settling time, and less fluctuations around the reference value. The two cases of random and constant loads are considered.

In this research, we investigate the performance of PI, Fuzzy, and ANN controllers in a hybrid solar-wind-battery scheme linked to the grid. Each control strategy brings distinct advantages: PI controllers offer simplicity and fast response, Fuzzy Logic Controllers (FLC) provide adaptive control in handling non-linear systems, and ANN controllers deliver robust performance under complex, varying conditions by learning from system behaviour. By comparing these control techniques, this study aims to analyze their effectiveness in maximizing energy utilization, enhancing stability, and achieving seamless grid integration in hybrid renewable systems. The insights gathered will contribute to designing more resilient and efficient grid-connected renewable energy systems suitable for sustainable energy application.

2. System Description

The block diagram represented in Fig.1 shows a hybrid RES that integrates a PV array, wind , and battery connected to the grid through a DC bus and an inverter. The PV array and wind turbine are each connected to individual boost converters, which are controlled by P&O MPPT procedures to maximize power extraction under varying environmental conditions. The battery is connected through a bidirectional converter, allowing it to either store excess energy or supply additional power when needed. All three sources PV, wind, and battery converge at the DC bus, which then feeds into a DC/AC inverter controlled by an ANN to efficiently manage power flow and ensure stable output to the grid. This structure enables optimal utilization of renewable resources while maintaining consistent power supply to the grid.

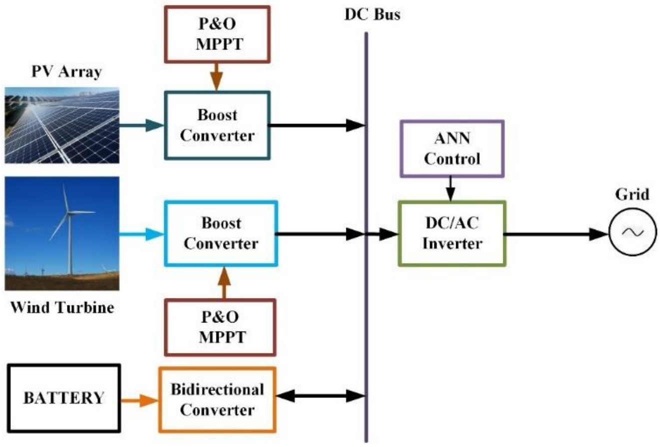

Fig.1 Representation of the Proposed system

2.1 PV Model

As seen in Fig. 2, an electrical model of a PV cell is created by connecting a current source anti-parallel with a diode.

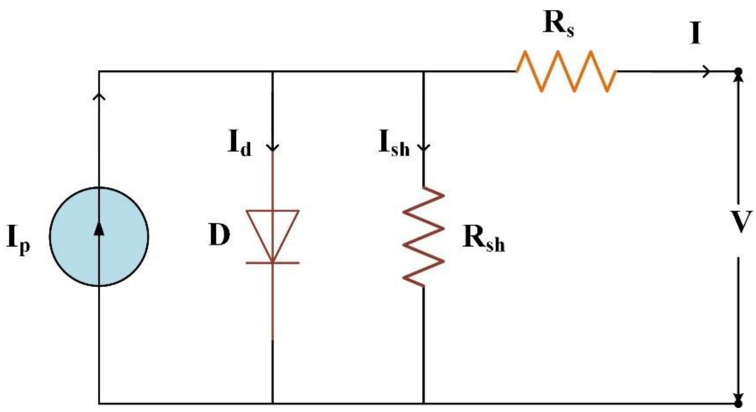

Fig.2 Circuit of PV cell

$$I = I_p - I_d - I_{sh} \tag{1}$$

The diode current (I_d) can be calculated as,

$$I_d = I_o\left[e^{\left(\frac{V+IR_S}{nkT_c/q}\right)} - 1\right] - \left(\frac{V+IR_S}{R_{sh}}\right) \tag{2}$$

This equation describes the diode current I_d in a PV cell, where: $I_o$is the saturation current. V is the terminal voltage. R_s is the series resistance. n is the ideality factor.   is Boltzmann's constant. T_c is the cell temperature.   is the charge of an electron. Rsh is the shunt resistance. I_p relies on solar irradiation and temperature and can be expressed as,

$$I_p = I_{scref}\frac{G}{G_{ref}}[1 + \alpha_t(T_c - T_{cref})] \tag{3}$$

This equation calculates the photocurrent I_p generated by the PV cell, where: I_{scref} is the reference short-circuit current. G is the irradiance. G_{ref} is the reference irradiance. α_t is the temperature coefficient. T_c is the cell temperature. T_{cref} is the reference cell temperature

2.2 Wind Turbine Modeling

The WT converts the wind's kinetic energy into rotational energy in the form of a torque. Equation (4) provides the wind's available power:

$$P_{wind} = \frac{1}{2}\rho A V_{wind}^3 \quad (4)$$

Where, P_{wind} is the Wind available power , ρ is the air density, A is the Areas swept by the blades, V_{wind}- Speed of the Wind

Equation (5) provides the power that the turbine extracts from the wind's available power:

$$P_{wt} = \frac{1}{2}\rho\pi R^2 V_{wind}^3 C_p(\lambda, \beta) \quad (5)$$

Where, R is the radius of turbine $C_p(\lambda, \beta)$ is the Power coefficient & C_p is the function of tip speed ratio λ & the pitch angle β.

2.3 MPPT Control

The P&O MPPT is used in PV & Wind scheme to trace maximum power from them, The P&O algorithm is a popular MPPT technique commonly used in both PV and wind energy systems to optimize power extraction. In this algorithm, the system’s operating voltage or current is slightly perturbed, and the resulting alteration in output power is observed. If the perturbation increases power output, the adjustment continues in the same direction; if power reduces, the direction is reversed. This process enables the system to dynamically locate and operate at the MPP despite variations in environmental conditions such as solar irradiance, wind speed, and temperature. For PV systems, this approach allows efficient energy harvesting by constantly adapting to sunlight changes, while in wind systems, it adjusts to varying wind speeds. Although simple and easy to implement, P&O can create oscillations around the MPP, slightly affecting efficiency. However, its balance between cost-effectiveness and reliable performance has made it a widely chosen method for MPPT in both PV and wind energy applications.

2.4 Control of PV, Wind , Battery & Inverter

The Control of the PV & Wind using P&O MPPT is represented in the Fig.3 & Fig.4 respectively. In PV control the V_{pv} & I_{pv} is fed to the P&O MPPT according to the change in the input parameters the MPPT adjusts the duty cycle , which is fed to the boost regulator & a persistent DC voltage is linked to the DC bus. Similarly, the Vr & Ir from the Wind rectifier is fed to the P&O MPPT, the input parameters will change if the velocity of the wind varies, As per the changes the MPPT procedure adapts the duty cycle to boost regulator associated with the Wind model.

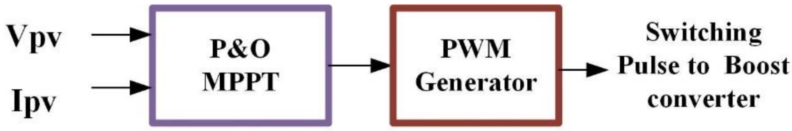

Fig.3 PV Control logic using P&O MPPT

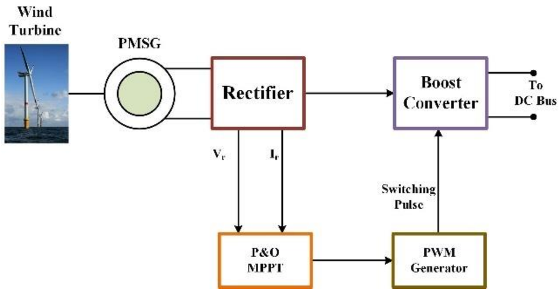

Fig.4 Wind Control with P&O MPPT

The battery is linked to the DC link through a bidirectional regulator, Fig.5 represents the voltage control of the battery, here the reference voltage is compared with the dc bus voltage & the error is fed to the PI regulator, Here the PI controller adjust the gain value the optimal point is given to the PWM generator, It will produce the switching pulses to the bidirectional regulator connected to the battery.

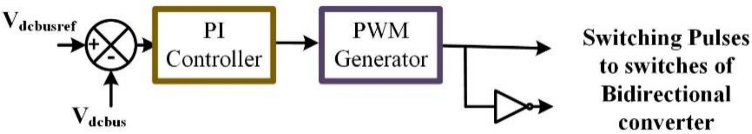

Fig.5 Voltage Control of battery

In this inverter control system, an ANN is used to regulate the operation of a grid-linked PV, wind, and battery system. The ANN controller receives power references, generated from the sum of the power of the PV array and the wind system. Based on this combined reference power, the ANN generates the necessary direct and quadrature axis currents, Id and Iq , to meet the grid's power demand efficiently. The current references are used to ensure that the inverter outputs the necessary active and reactive power by aligning with the grid voltage parameters.

The ANN controller processes these inputs, adjusting the output dynamically to respond to variations in PV and wind power and to maintain stability and efficiency. After the ANN controller determines the necessary currents, they are converted from the dq0 frame to the abc frame for compatibility with the PWM generator. The PWM generator then produces switching pulses to drive the inverter, ensuring that power from renewable sources is effectively synchronized with the grid. Compared to conventional controllers like PI and fuzzy controllers, ANN provides adaptive learning capabilities, allowing it to handle nonlinearities and variations more effectively. This results in smoother control, improved response time, and enhanced system stability under varying environmental and load conditions.

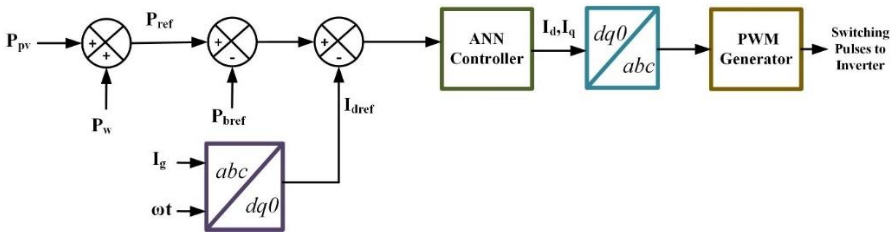

Fig.6 Control of Inverter using ANN

3. Simulation Results & Discussions

The simulation of the proposed scheme is carried out in MATLAB Simulink. A 23.4 KW PV system is used in this work. Here the PV is operated with irradiance of 1000 W/m2 up to 0.5s & then it is reduced to 500 W/m2. The PV parameters is represented in the Fig.7. The power obtained is around 23.4 KW & achieves an efficiency of 98.5% using P&O MPPT. The power obtained from PV is linked to the DC bus (i.e DC link).

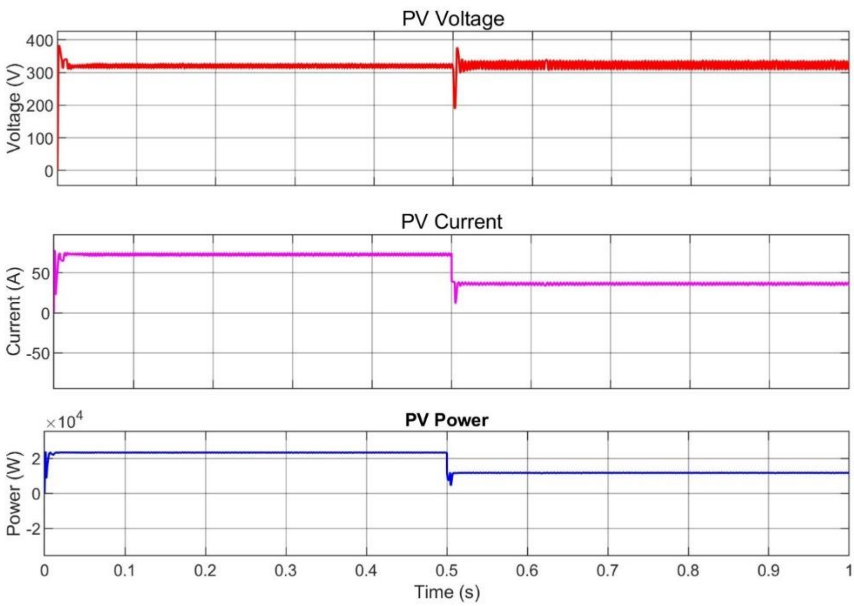

Fig.7 PV Parameters with P&O MPPT

In Fig.8, the wind parameters are depicted, showing the operation of the wind turbine at a steady wind speed of 12 m/s. With this constant velocity, the generated wind power remains stable, producing approximately 9.6 kW. This generated wind power is directed to the DC link, where it contributes to the overall power system.

Fig.9 illustrates the battery parameters. Initially, the battery is assumed to have a State of Charge (SOC) of 50%. When the PV system experiences an irradiance level of 1000 W/m², the PV array generates sufficient power, placing the battery in a charging state. After 0.5 seconds, however, the PV irradiance decreases to 500 W/m². Consequently, the power produced by the PV scheme decreases, leading to a reduction in the charging power supplied to the battery. This drop in charging power demonstrates the direct impact of irradiance fluctuations on battery charging, highlighting the importance of consistent PV output for maintaining optimal battery charge levels in the system. to drive the inverter, ensuring that power from the renewable sources is effectively synchronized with the grid. Compared to conventional controllers like PI and fuzzy controllers, ANN provides adaptive learning capabilities, allowing it to handle nonlinearities and variations more effectively. This results in smoother control, improved response time, and enhanced system stability under varying environmental and load conditions.

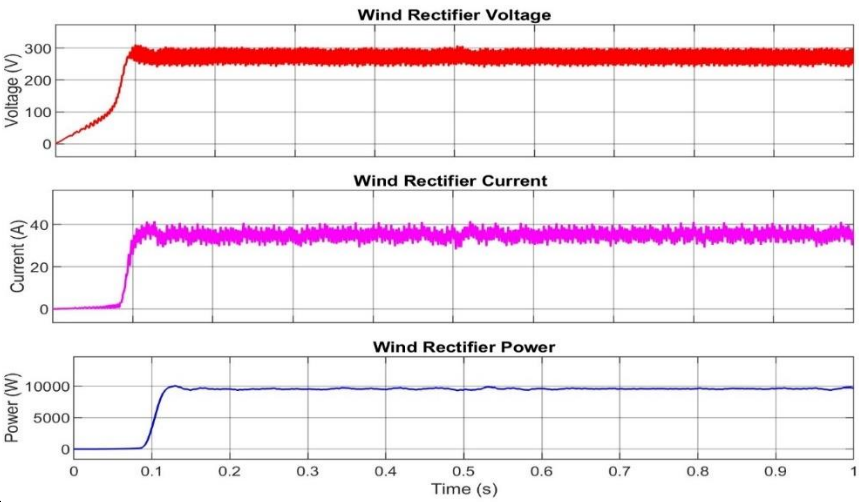

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Fig.8 Wind Parameters with P&O MPPT

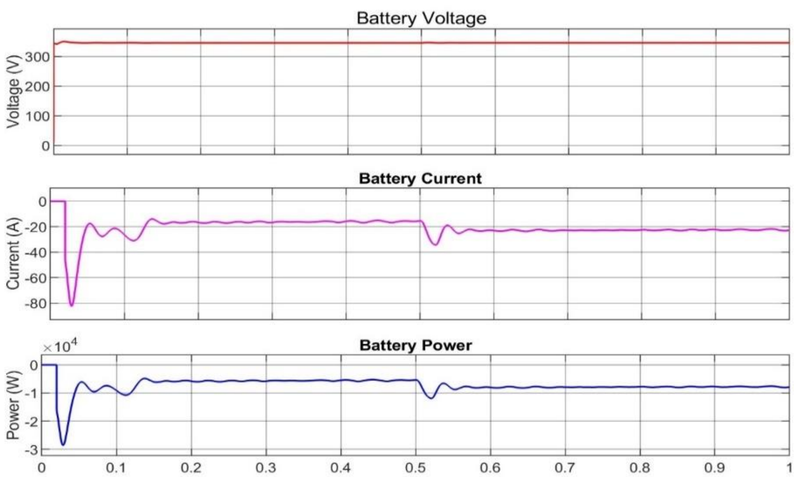

Fig.9 Voltage, Current & Power of the Battery

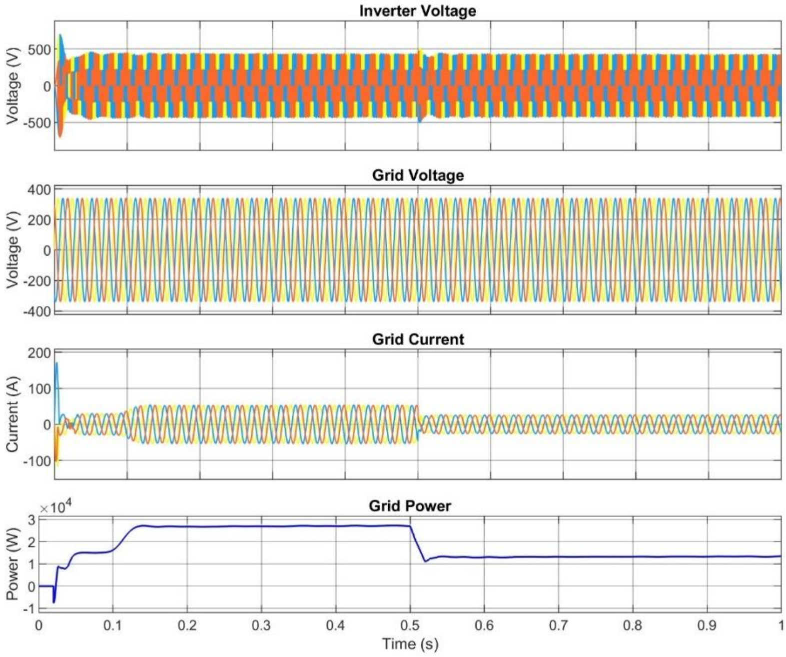

Fig.10 Parameters of Inverter & Grid

Fig.10 presents the parameters related to the inverter and the grid, displaying the inverter voltage, as well as the grid voltage, current, and power levels. During periods of full irradiance from the PV system, the grid receives more power as the PV array generates its maximum output. However, when the irradiance level drops, the power distributed to the grid from the PV scheme gradually decreases, reflecting the lower availability of PV-generated power. This variation in PV output also impacts the battery charging cycles and grid power supply, causing them to fluctuate in response to the changing irradiance conditions.

Figure 11 illustrates the parameters associated with the DC link. The main objective here is to keep the DC link voltage stable at a setpoint of 600 V. To achieve this, an ANN control is implemented within the inverter, effectively regulating the DC link voltage to maintain it close to the target value of 600 V. This stable voltage is crucial for ensuring reliable operation across the system.

Additionally, a comparative analysis of the ANN control method with PI and Fuzzy control is shown in Figure 11. This analysis highlights the performance differences among these control strategies, demonstrating how the ANN control provides superior stability in maintaining the DC link voltage at the required level compared to PI and Fuzzy control. This comparison underscores the advantages of ANN control in achieving more consistent voltage regulation under varying conditions in the PV-integrated system.

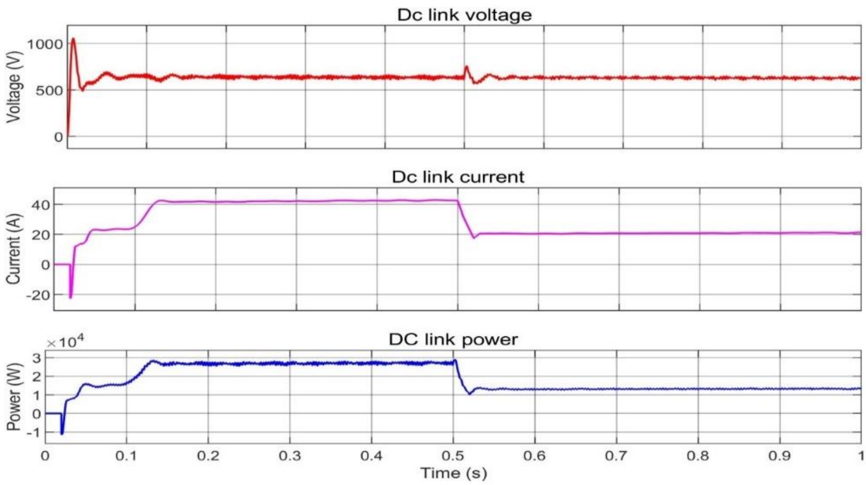

Fig.11 Parameters of DC link

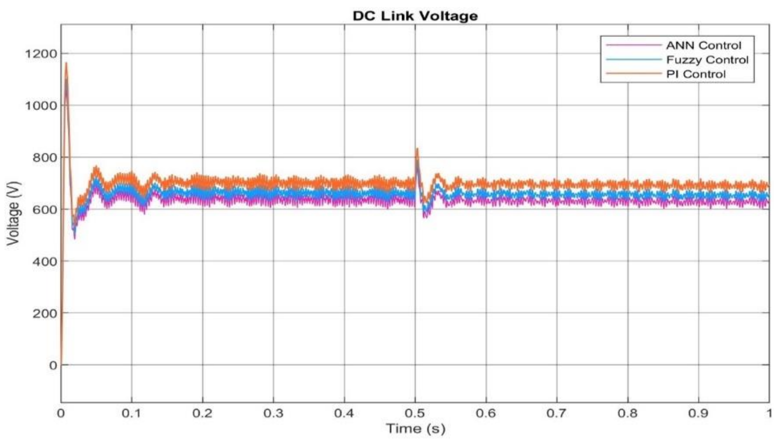

Fig.12 Comparison of DC link Voltage With PI & Fuzzy control

Hence Fig.12 showcases that the PI control having the DC link voltage more than 700V & for Fuzzy it is around 650 V, which are worse compared to the ANN Control, Thereby ANN obtains the optimal inverter control in Grid linked Scheme

4. Conclusion

In conclusion, the research presented an innovative ANN-based control strategy for a grid-linked PV, wind, and battery system, aiming to ensure a reliable power supply under fluctuating environmental conditions. The comparison with traditional PI and Fuzzy Logic control methods highlighted the limitations of these methods under rapid fluctuations in power supply due to environmental variability, emphasizing the need for more adaptable control strategies. Simulation results using a 23.4 KW PV system and constant wind velocity demonstrated the effectiveness of the proposed ANN control method in maintaining a stable power supply, achieving an impressive efficiency of 98.5% using P&O MPPT for the PV system. The integration of battery storage and the management of power flow through the inverter were also successfully demonstrated, showcasing the ability of the ANN controller to optimize power quality and enhance grid synchronization. Additionally, the comparative assessment of ANN with PI and Fuzzy control methods revealed the superior performance of ANN in maintaining the DC link voltage at a constant level of around 600V, outperforming both PI and Fuzzy control methods. Therefore, the research concluded that the ANN control method offers a promising solution for advanced grid-connected systems with multiple renewable sources and energy storage, providing optimal inverter control in a grid-linked scheme.

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