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A Novel Adaptive Controller with Lyapunov Analysis for Strategy Grid Intelligent Integrated Wind Turbine Maximum Power Point Tracking System

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Abstract: By continuously changing the operating point to the maximum power point (MPP) of the turbine, the Maximum Power Point Tracking (MPPT) control approach has been widely used in wind turbine (WT) systems to improve the generated power. The power production, however, fluctuates since the present MPPT systems have trouble adjusting to shifting wind speeds, turbulence, and other factors. To overcome these issues, a novel hybrid adaptive controller integrating the Fire Hawk Optimizer (FHO) with a Dynamic evolving neural fuzzy controller (DENFC) for a wind turbine MPPT system was proposed in this article. A power converter, a wind turbine generating model, and an MPPT control technique make up the three primary parts of the suggested model. The proposed adaptive controller can handle uncertainties in the wind speed and other system parameters and track the MPP of the wind turbine. Furthermore, a Lyapunov analysis was utilized to analyze the stability of the closed-loop system and to design the adaptive law for the controller. The simulation outcomes prove that the proposed approach is effective in tracking the MPP of the wind turbine system and potentially improves the performance and stability of the WT system.

Keywords: *Fire Hawk Optimization, Dynamic evolving neural fuzzy controller, Wind turbine system, Maximum Power Point Tracking*

1. Introduction

Currently, the demand for electrical energy around the world is increasing rapidly because of rapid population growth and improving industrial and economic activities [1]. Typically, fossil fuels are deployed to satisfy the energy requirements around the world. However, the exhaustion of fossil fuels and other harmful environmental challenges leads to the utilization of renewable energy resources like wind, solar, hydro, etc., for electricity generation [2].

These sources can act as an alternative source of energy generation in an eco-friendly manner without harmful waste products [3]. In recent times, Wind Turbines (WTs) have gained more attention, and it acts as one of the most promising renewable energy sources because of several reasons [4]. The foremost reason is the advancement of materials, design, and manufacturing processes has led to more efficient and reliable turbines [5]. Wind power also produces no emissions, making it an eco-friendly and sustainable energy source [6]. Thirdly, wind energy is abundant and available in many parts of the world, including offshore regions and remote areas where developing other energy sources is impractical or expensive [7]. Moreover, wind power generation is cost-effective, especially in areas with high wind speeds. Wind power systems are often designed to rotate at a constant speed, which limits their ability to adapt to changes in wind speed and direction [8]. As a result, especially in conditions when the wind speed was variable, the power production and efficiency were reduced [9].

Wind turbine systems adopted a method called Maximum Power Point Tracking (MPPT) to overcome this issue [9]. The ability of turbines to modify their rotational speed in response to variations in wind speed and direction thanks to this technology improves the performance and efficiency of wind power plants [10]. The MPPT method continually monitors the turbine's ideal operating position, when it operates most efficiently and produces the most electricity [11]. The MPPT makes sure that the turbine functions at its highest efficiency [13] regardless of changes in wind speed and direction [14] by maintaining the rotational speed at this ideal position [12]. The wind turbine can produce more electricity with the same input since it boosts power output and overall efficiency [15]. Additionally, the MPPT method prevents overspeeding and assists to safeguard the turbine from harm brought on by high wind speeds [17].

However, theMPPT controllers are expensive, and the cost

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increases with the size of the wind turbine [18]. On the other hand, the MPPT controllers can improve the efficiency of wind turbines; they may not always provide a significant increase in power output [19]. Moreover, the MPPT controller may not be able to adjust quickly enough to maximize power output [20]. In addition, the MPPT controller from stability issues. Although various MPPT-based control strategies, such as MPPT-based automatic control strategy [21], MPPT control model with adaptive fault-tolerance ability [22], etc., are developed, they cannot provide solutions to these problems. To resolve these issues, an optimized adaptive fuzzy-based MPPT controller was developed in this article.

The proposed work is arranged as follows, the works related to the presented work are described in 2nd section, the system model and the problem statement of the WT system are illustrated in 3rd section, the proposed methodology is explained in 4th section, the results of the proposed model is analyzed in 5th section, and the conclusion of the article is described in 6th section.

2. Literature Survey

Some of the recent literature related to the proposed work is listed below:

Billel Meghniet al. [21] developed a novel MPPT-based automatic control strategy to enhance the extraction capacity of hybrid wind turbines. The presented work integrates multi-objective optimization and second-order sliding mode control designs to perform as a perfect and reliable control system. The developed model enhances the power conversion efficiency compared to the traditional approaches. However, the developed model is sensitive to changing parameters such as wind speed and direction.

Jian Chen et al. [22] presented an MPPT control model with adaptive fault-tolerance ability. This method utilizes the adaptive feedback-linearizing algorithm to manage the variable speed of the WT. The simulation outcomes describe that the proposed model minimized the tracking errors and improved the performances compared to the conventional MPPT techniques. However, the proposed MPPT system requires high-precision sensors to accurately measure the system state variables.

Marwa M. Ahmed et al. [23] designed three scalar methodologies to confirm MPPT and stability in wind turbines. The first strategy attempts to maximise the power produced during synchronisation, the second model optimises synchronous power for improved stability, and the third plan aims to increase overall power generation. Finally, the performances of this model are evaluated and compared in terms of stability, efficiency, and power gain ratio. However, the system prioritizes power conversion over stability, which leads to oscillations in the system.

Anderson José Balbino et al. [24] proposed an enhanced MPPT model without the usage of voltage and mechanical sensors for small wind power systems. This methodology is appropriate for small wind turbines (SWT), which deploy a permanent magnet synchronous generator. The simulation outcomes demonstrate that the developed model enhances the tracking efficiency to 97.64%. However, the proposed algorithm has limited accuracy in tracking the maximum power point.

Di Wu, GoranSamanNarimanet al. [25] developed an improved design of the MPPT control approach to achieve maximum power under external weather conditions. This specific model uses a radial basis function neural network to regulate the wind turbine's pitch angle. The proposed method exhibits a quick transient response and enhanced stability performance. However, the developed model is complex to implement and requires a good understanding of the system dynamics.

To reduce the intermittent problem of renewable energy producing units, G. B. Arjun Kumar and Shivashankar [26] devised optimised, integrated solar-wind energy models. By utilising the MPPT algorithm, the created approach seeks to increase power extraction in solar-wind power systems. The system's performance is successfully stabilised by the suggested technique, which also improves transient response. However, weather conditions have a significant impact on the system's performance.

The MPPT algorithm was primarily created to maximise the power coefficient of wind energy installations. A fuzzy logic controller-based MPPT algorithm is suggested by Ali M. Eltamaly et al. [27] for effective wind energy conversion systems. The results of the simulation show that the suggested strategy improves the MPPT's accuracy and speed. To optimise the performance in relation to the environmental conditions, the designed model does, however, require substantial tuning.

A multivariable super-twisting control strategy was created by Jie Wang et al. [28] to achieve MPPT in wind energy conversion systems. In order to reduce the uncertainty problems in wind turbines, this method takes into account the complexity of the nonlinear model's parameters and structures. Additionally, it uses the Lyapunov operation to demonstrate the model's convergence in finite time. The developed model, however, necessitates substantial computational resources, which may restrict its use in some settings.

A. Ruban Periyanayagam and Y.H. Joo's work [29] concentrated on maximising a variable-speed wind turbine system's capacity for power extraction. To solve the problem of maximising wind energy extraction, their model used the sliding control method. They sought to obtain quick convergence of error dynamics within a finite time by using a Lyapunov technique. It's vital to remember, nevertheless, that the suggested method might not be able to handle all kinds of disruptions, including sensor noise or parameter drift.

Ganesh P. Prajapat et al. [30] proposed an effective control mechanism to improve energy extraction in variable-speed WT systems. The developed algorithm utilizes the differential-algebraic function and Kalman filter to overcome the uncertainty issue of WT systems. However, the implementation cost is more in the proposed technique, which can be higher than fixed speed systems due to the additional components required for the variable speed control system.

3. System Model and Problem Statement

A wind turbine system is a renewable energy technology that utilizes wind power to produce electricity. The major components present in the WT system include a wind turbine, generator, power converter, and grid connection. The wind turbine contains blades, which rotate when the wind blows that turn a shaft connected to the generator. The wind turbine's output power is influenced by things including wind direction, wind speed, turbulence, and blade pitch angle. AC power is created by the generator, which converts the mechanical energy from the wind turbine into electrical energy.

The outcomes of the generator are variable and depend on the speed of the wind turbine. The power converter transforms AC power from the generator into DC power. The DC power is further converted into AC power, which is synchronized with the grid. The power converter uses a control strategy to manage the voltage and frequency of the electrical output and modifies the turbine's output power to match the grid requirements. The grid connection produces a stable interconnection between the wind power generation and the electrical grid. The wind power system aims to enhance the output power of the wind turbine while maintaining a stable and reliable connection to the grid. However, the output power depends on factors like wind direction, speed, and turbulence, which change constantly.

The major problem in grid-integrated WT-MPPT system is to develop a control strategy, which optimizes the output power of the WT in real-time, confirming the safe and reliable function of the turbine. Another difficulty is creating a control system that can monitor the MPP of the wind turbine under variable wind conditions and load needs. Moreover, the MPPT control system must modify the generator's output voltage and frequency to match the optimal operating point of the turbine. To resolve these challenges, an optimized intelligent MPPT control strategy was presented in this article.

4. Proposed Optimized Mppt Control Strategy

The wind power generation system includes the conversion of wind energy into electrical energy using a turbine. The amount of power generated by a WT system depends on different factors like wind speed, turbine efficiency, rotor diameter, etc. However, the WT systems experience disturbances like variations in wind speed, turbulence, noise, etc., which affect their performance and stability adversely. Typically, the wind turbine produces both active and reactive power. Active power defines real power, which is utilized to perform useful works. On the other hand, reactive power represents the power that is used to establish and maintain the electromagnetic fields in the generator. The reactive power is important for the proper functioning of the electrical grid, but too much reactive power causes voltage instability. In the proposed study, a Doubly Fed Induction Generator (DFIG) was used to address these problems in the WT system. The wind turbine's power output is stabilised by the DFIG. It is a specific kind of induction generator that is linked to the grid through a power converter. The amount of active and reactive electricity provided to the grid is thus under its control. Moreover, it can function in a variable speed model that enables it to track changes in wind speed and maintain stable power output. The power generated by the wind turbine is represented in Eqn. (1).

$$P_{out} = \frac{1}{2}\left(\rho * A_R * V^3 * P_{tc} * \lambda\right) \tag{1}$$

Where P_{out} denotes the power generated by the turbine, ρ indicates the air density, A_R refers to the swept area of the rotor blades, V represents the wind speed, P_{tc} denotes the power coefficient of the turbine, and λ indicates the tip speed ratio, which denotes the ratio of the speed of the rotor to the wind speed. The DFIG is managed and controlled using a variety of methods by adjusting the rotor voltage and frequency using a control system, which considers the wind speed, rotor speed, and other wind parameters. Additionally, it makes it possible for the turbine to run dependably and effectively despite interruptions like varying wind speeds and noises. Fig. 1 shows the suggested framework in action.

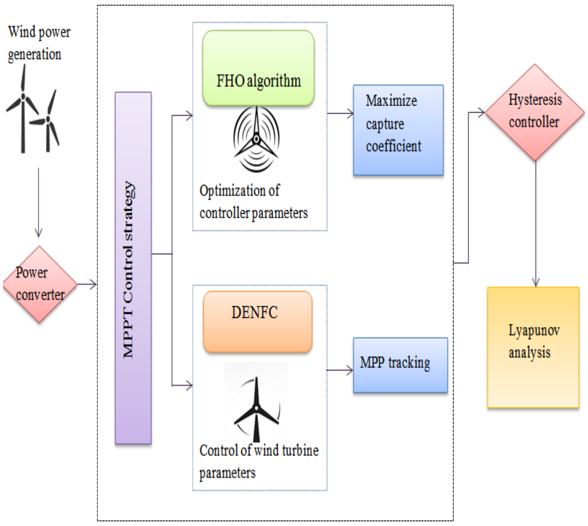


Fig. 1 Proposed Framework

4.1 Power Converter

The stator and the rotor are the two most important parts of the generator in a wind turbine system. The stator is the stationary portion of the generator, which consists of winding where the electrical energy is produced. The rotor is the rotating part of the generator, which produces the magnetic field, which induces the electrical current in the stator. In wind power generation systems, power converters are utilized to transform the electrical energy generated by the generator from one form to another. Additionally, it helps with managing and controlling the power that is created. Power converters are frequently used to control the generator's output of both reactive and active power. Equations (2) and (3) explain how the generator's output power is regulated.

$$P_g = V_l * I_c * \cos(\theta) \quad (2)$$

$$Q_g = V_l * I_c * \sin(\theta) \quad (3)$$

Where P_g denotes the active power output, Q_g represents the reactive power output, V_l denotes the voltage, I_c indicates the current, $\cos(\theta)$ and $\sin(\theta)$ refers to the power factor. To control the output of active and reactive power, the power converter modifies voltage and current. It is also in charge of managing the voltage output of the generator. Equation (4)'s representation of the power converter's DC link voltage illustrates how this voltage regulation is accomplished.

$$V_{DC} = \sqrt{\frac{2}{3} \times V_{RMS}} \quad (4)$$

Here, and stand for the root-mean-square voltage and the DC link voltage, respectively. The power converter can successfully regulate the generator's output voltage to the desired level by adjusting the DC link voltage.

4.2 MPPT control strategy

Renewable energy systems like wind turbines and solar panels frequently employ the MPPT control approach. By continuously monitoring and adjusting the operating point to the Maximum Power Point (MPP) of the energy source, it aims to maximise power production. The MPP designates the point at which the energy source can supply the load with the most power. The MPPT control approach for wind turbines uses a variety of sensors to measure variables including wind speed, rotor speed, and other system variables. These readings are then used to calculate the ideal rotor speed, generator torque, and blade pitch angle, ensuring that the wind turbine functions at its peak efficiency. The proposed MPPT control strategy integrates the Fire Hawk Optimizer (FHO) and the Dynamic evolving neural fuzzy controller (DENFC) to attain the Maximum Power capture coefficient for Wind Turbine (WT) system. By controlling the generator speed and blade pitch angle through the use of Dynamic Evolving Neuro-Fuzzy Control (DENFC), the power capture coefficient can be maximised. To improve the performance of complex systems, DENFC, an intelligent control methodology, integrates fuzzy logic and artificial neural networks (ANN). The DENFC adjusts to shifting system conditions and enhances performance over time by using a dynamic evolving methodology. The input layer, the fuzzy layer, and the output layer are the three basic layers that make up the DENFC algorithm. The input layer takes into account pertinent system-related factors, and the fuzzy layer applies fuzzy logic to translate these input variables into output variables. A set of guidelines are used by the fuzzy layer to determine the connection between input and output variables. These fuzzy rules are defined using linguistic variables, which are descriptive terms such as "low," "medium," or "high," and membership functions quantify the degree of membership of a given input variable to a particular fuzzy set. The output layer provides system's control signal based on the fuzzy rules and inputs. In wind turbine MPPT control, the DENFC considers the inputs variables like wind speed, and other varying parameters that affects the WT performance. The input layer is expressed in Eqn. (5).

$$R = [q_1, q_2, q_3, ..., q_n] \quad (5)$$

Where R denotes the input vector, and q_n represents the n^{th} input variable. The fuzzy layer maps the input parameters to the output variables using the fuzzy logic rules. These fuzzy rules are defined using linguistic parameters and membership functions. The membership functions quantify the degree of membership of a given input variable to a particular fuzzy set. The fuzzy layer is expressed in Eqn. (6).

$$M_{a,b} = M(W_{a,b}, R_a) \quad (6)$$

Where $M_{a,b}$ refers to the membership degree of input variable R_a in the j^{th} fuzzy set $W_{a,b}$. The output layer of the DENFC algorithm consists of the output variables, such as the generator speed, rotor speed, etc. The fuzzy layer and the weights of the ANN define the input layer and it is represented in Eqn. (7).

$$S = [p_1, p_2, p_3, ..., p_n] \quad (7)$$

Where S indicates the output vector, and p_n refers to the n^{th} output variable. The mathematical expression for DENFC approach is represented in Eqn. (8).

$$S = F_d(R, \kappa) \quad (8)$$

Where F_d denotes the DENFC model, and κ indicates the parameters of the DENFC algorithm, including the fuzzy rules.

TABLE 1 FUZZY RULE TABLE

	Inputs		Outputs		
Rule	Wind speed	Generator speed error	Rotor speed	Blade pitch angle	Generator speed
1	Low	Negative	Low	Low	High
2	Low	Zero	Medium	Medium	Medium
3	Low	Positive	High	High	Low
4	Medium	Negative	Low	Low	High
5	Medium	Zero	Medium	Medium	Medium
6	Medium	Positive	High	High	Low
7	High	Negative	Medium	Medium	High
8	High	Zero	High	High	Medium
9	High	Positive	High	High	Low

Here, the input variable wind speed is categorized into three fuzzy sets labeled as "Low," "Medium," and "High," and the other variable input generator speed error is categorized into three fuzzy sets as "Negative," "Zero," and "Positive." The output variables rotor speed, generator speed, and the blade pitch angle are divided into three fuzzy sets "Low," "Medium," and "High." The fuzzy logic rules are framed to control the outcomes based on the variation in input variables. For example, if the wind speed is low and the generator speed error is negative, then the rotor speed will be low, the blade pitch angle will be low, and the generator speed will be high. Depending on how well the system performs, the fuzzy rules may need to be changed or adjusted. On the other hand, the DENFC's parameters are optimised using the FHO algorithm. It is a nature-inspired optimization approach used to resolve optimization issues. The FHO approach is an extended version of Firefly optimization algorithm (FOA), which is based on the flocking characteristics of birds of prey, particularly the hawk and it improves the performance of the FOA algorithm. The algorithm begins with the initialization of hawk population; each indicates a possible solution to the optimization function. The location of each hawk is denoted by a z-dimensional vector in which z denotes the number of decision parameters in the problem. There are three major steps in FHO approach namely, initialization phase, the movement phase and the updating phase. In the first phase, the FHO approach starts by randomly initializing the position of each hawk within the search space. Further, the fitness solution of each hawk was estimated using the objective function. In the second phase, the motion of each hawk is directed by the locations of other hawks in the population. In this phase, each hawk measures its distance relative other hawks in the population. Euclidean distance formula is utilized to determine this distance and it is expressed in Eqn. (9).

$$D_s(x,y) = \|u(x) - u(y)\| \quad (9)$$

Where $D_s(x,y)$ defines the distance between x^{th} and y^{th} hawks, $u(x)$ refers to the location of x^{th} hawk and $u(y)$ indicates the location of y^{th} hawk. After distance estimation, each hawk travel towards the best position of the other hawks in the population. The motion of the x^{th} hawk is represented in Eqn. (10).

$$u(x,k+1) = u(x,k) + rand() * (u(y,k) - u(m,k)) \quad (10)$$

Where $u(x,k+1)$ refers to the position of x^{th} hawk at time $t+1$, $u(x,k)$ denotes the position of x^{th} hawk at time t, $u(y,k)$ indicates the position of the x^{th} hawk at time t, $u(m,k)$ represents the position of m^{th} hawk time t, and $rand()$ defines the random number between 0 to 1. Thus, all hawks travels towards the best location of other hawks, the new positions fitness solution is determined using the objective function. Further, to form the next generation hawks with best fitness values are chosen. The position updation of the x^{th} hawk is expressed in Eqn. (11).

$$u(x,k+1) = u(x,k+1) + Levy() * (u(x,k+1) - u(x,k)) \quad (11)$$

Where $Levy()$ refers to the random number created from the Levy flight circulation, which is utilized to offer randomness into the search process. This approach continues to repeat the movement and updation phase until the desired condition is met. In wind turbine systems, the FHO algorithm is utilized to optimize the performance of the WT and maximize the energy captured by the wind. It is used to optimize the control parameters of the wind turbine system, which include the blade pitch angle, rotor speed, and generator speed. Initially, the FHO algorithm sets the objective function. The objective function is the power capture coefficient of the turbine, which is represented as the ratio of the output power of the turbine to the available wind power. The power coefficient is expressed in Eqn. (12).

$$P_{tc} = \frac{P_{in}}{P_{out}} \quad (12)$$

Where P_{tc} denotes the power coefficient, P_{in} indicates the available wind power, and P_{out} represents the power output of the generator. The available wind power is expressed in Eqn. (13).

$$P_{in} = \frac{1}{2}\left(A_R \times \rho \times V^3\right) \quad (13)$$

The problem optimization is expressed in Eqn. (14).

$$Maximize\, P_{tc}(\omega,\theta) \qquad \omega_{\min} \le \omega \le \omega_{\max}, \quad \theta_{\min} \le \theta \le \theta_{\max} \quad (14)$$

Where ω indicates the generator speed, θ denotes the blade pitch angle, $\omega_{\min}$ refers to the minimum value of the generator speed, $\omega_{\max}$ represents the maximum value of the generator speed, $\theta_{\min}$ denotes the minimum value of the blade pitch angle, and $\theta_{\max}$ indicates the maximum value of the blade pitch angle. The FHO algorithm iteratively updates the position of the fireflies based on their brightness values, which are calculated as the power capture coefficient of the WT system at the corresponding generator speed, rotor speed, and blade pitch angle settings. The hawk movement is expressed in Eqn. (15).

$$X_{i(t+1)} = X_{i(t)} + \beta \times \left(X_{j(t)} - X_{i(t)}\right) + \alpha \times (rand() - 0.5) \quad (15)$$

Where $X_{i(t)}$ denotes the position of hawki at time t, β indicates the attractiveness of hawkj towards hawki, α refers to the randomization parameter, and $rand()$ is the random number generator. The FHO method maximises the power capture coefficient of the wind turbine system by iteratively updating the ideal solution. In order to maintain the wind turbine system's functioning at its peak power, the proposed MPPT control method modifies how it operates.

4.3 Lyapunov stability analysis

We can determine using the stability analysis whether the suggested control method can keep the wind turbine system operating at its peak performance level in the face of disruptions. Usually, wind turbine systems are vulnerable to changes in wind direction and speed, which affect output power. The stability analysis ensures that the control method can adapt to these disturbances and maintain the system at its optimal operating point. In the proposed work, the Lyapunov stability analysis is utilized to analyze the stability of the proposed MPPT control strategy. It is a mathematical approach utilized to estimate the stability of the control systems. It helps to prove that the controller function is stable and maintains the system at its maximum power point. The Lyapunov function to analyze the controller stability is expressed in Eqn. (16).

$$V = \frac{1}{2}\left(e^T * e\right) \quad (16)$$

Where denotes the vector's transposition and indicates the error between the WT system's actual output power and its maximum theoretical output power e. The time derivative of V is expressed in Eqn. (17).

$$\frac{dV}{dt} = e^T * \left(\frac{de}{dt}\right) \quad (17)$$

Here $\frac{de}{dt}$ denotes the derivative of the error relative to time. In the proposed controller, the error is calculated by subtracting the maximum theoretical power from the output power of the WT system, and it is formulated in Eqn. (18).

$$e = P_T - P_{\max} \quad (18)$$

Where P_T defines the actual output power of the WT system and $P_{\max}$ indicates the maximum theoretical output power. For a stable controller system, it $\frac{dV}{dt}$ must be negative; that is, it should be less than or equal to zero. In the proposed MPPT controller, the Lyapunov function V is positive definite and radially unbounded; thus, the time derivative V is negative definite. This illustrates that the proposed controller function is stable and can maintain the wind turbine system at its maximum power point. The flowchart of the proposed framework is illustrated in Fig 2.

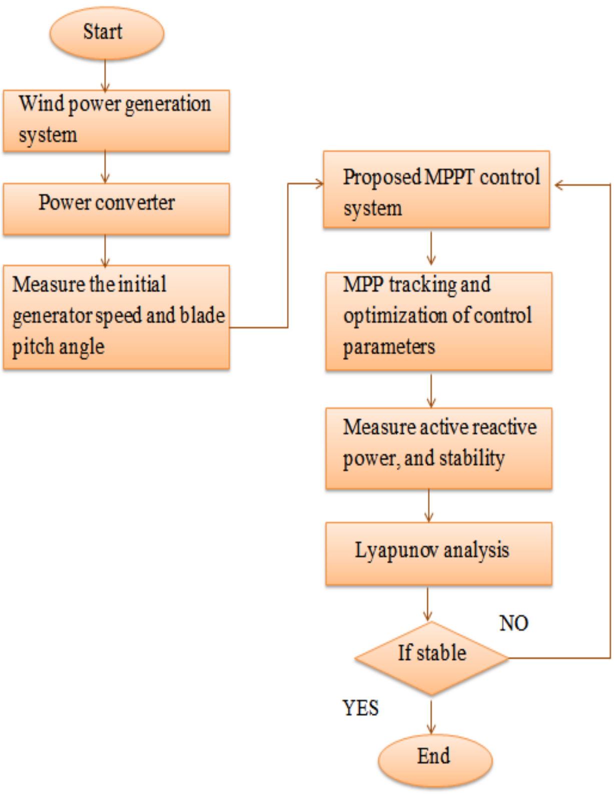


Fig. 2 Flowchart of the developed model

5. Results and Discussion

The power capture coefficient of the wind turbine systems was optimised in this paper using an advanced MPPT control approach. In order for the system to run at its peak power, the created model combines the FHO and DENFC algorithms to regulate and optimise the wind turbine control parameters. Additionally, a Lyapunov analysis was performed to assess the stability of the suggested controller. The created model was applied in the MATLAB software, version R2020a, and key wind turbine parameters, including wind speed, rotor speed, maximum power coefficient, etc., are examined. Finally, the proposed MPPT controller outcomes are compared with the wind turbine system without an MPPT controller for validation purposes. Moreover, the reactive power with and without compensation was analyzed to evaluate the need for reactive power compensation in systems. Furthermore, a Fast Fourier Transform (FFT) analysis was performed to analyze the level of harmonic distortions in the controller output. The implementation parameters and their description is tabulated in Table 2.

5.1 Performance and comparative analysis

The wind turbine system's output parameters are examined and contrasted with systems without MPPT controllers in this section. The results are estimated in terms of wind power, rotor speed, generator speed, rotor speed error, maximum power coefficient, etc. Fig 3 displays the wind speed over time.

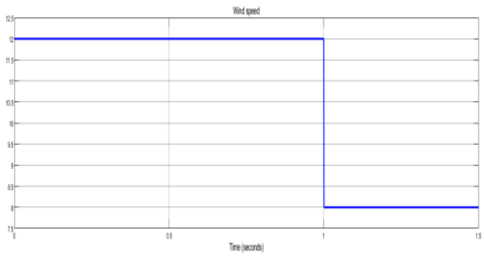
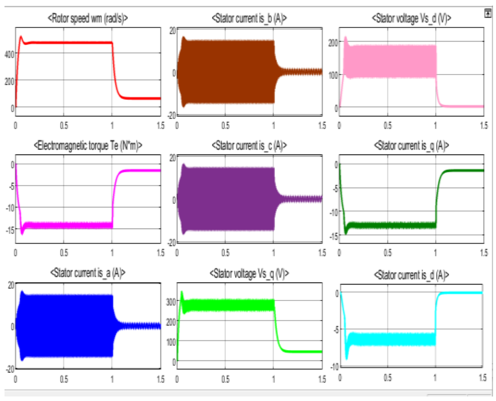
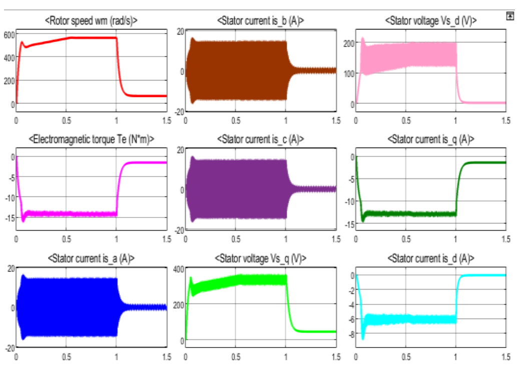


Fig. 3 Wind speed over time

The wind turbine systems with and without MPPT control differ in several ways, particularly the current, rotor speed, wind power, wind speed, maximum power coefficient, and rotor speed error under varying wind speed conditions. From the simulation outcomes, the variation of WT performance with and without MPPT control is analyzed for validation purposes. In a WT system with MPPT control, the current flowing from the generator to the grid is more stable and consistent, which is because the MPPT control strategy modifies the rotor speed to maximize power output. In addition, it enables the system to maintain a steady current flow in the grid.



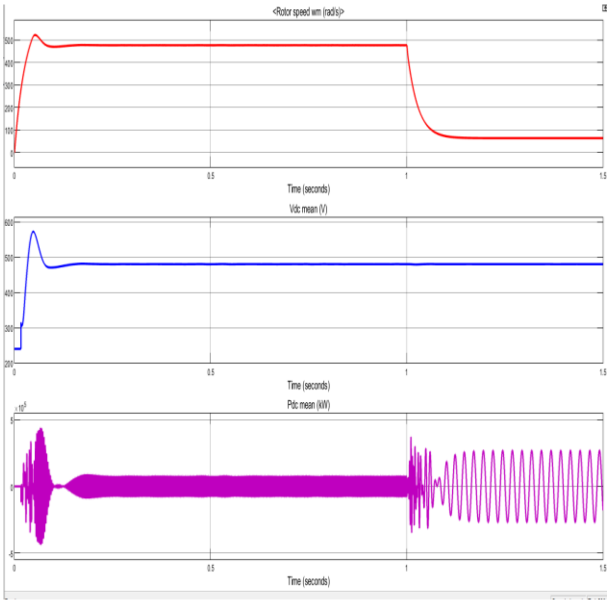
a) **No control in MPPT**



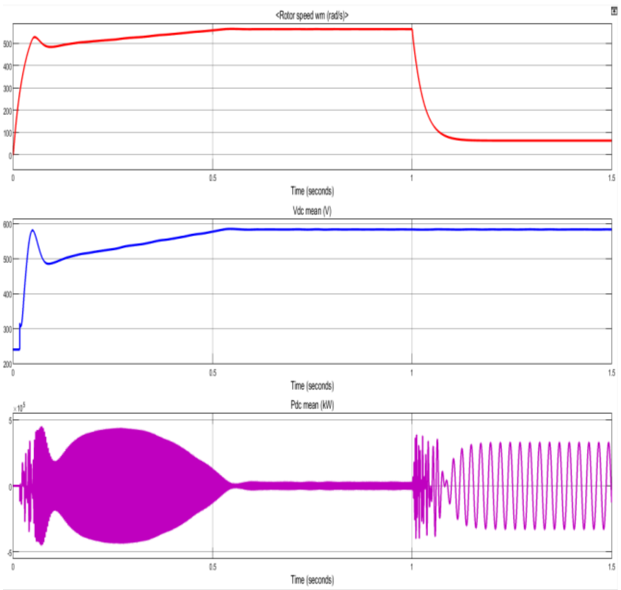
b) **control in MPPT**

Fig. 4 Wind turbine performance: (a) No control in MPPT, (b) control in MPPT

In the case without MPPT control, the current varies relative to the variations in wind speed and other factors. Similarly, the rotor speed is analyzed with and without MPPT control. The WT system with MPPT control adjusts the rotor speed in real-time to confirm that the generator is functioning at the optimal speed for maximum power output. Without MPPT control, the rotor speed of the WT system is constant and leads to suboptimal output power at varying wind speeds. Fig 4 illustrates the wind turbine performance without and with an MPPT controller.



(a) **No control in MPPT**



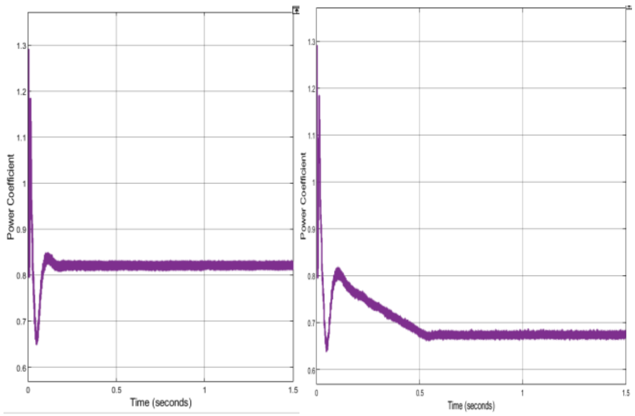
(b) **control in MPPT**

Fig. 5 Wind turbine parameters: (a) No control in MPPT, (b) control in MPPT

The rotor speed error, which is the difference between the real and ideal rotor speed, is decreased with the MPPT control technique, which improves the efficiency of the wind turbine. However, without MPPT control, there is a significant rotor speed inaccuracy, which reduces output power. By allowing the generator to run at its peak power, MPPT control maximises the amount of wind energy that the turbine is able to gather. The WT system without MPPT control, however, is less effective and collects less wind energy. The wind speed at which the turbine is producing its maximum power will be more consistent with MPPT management. This is because the control strategy adjusts the rotor speed to increase output power at all times. Without MPPT control, the captured wind power fluctuates and leads to suboptimal output power. Fig 5 displays the wind turbine parameters without and with the MPPT controller.

5.1.1 Maximum power coefficient

The maximum power coefficient, which describes the system's effectiveness in capturing wind energy from the turbine in relation to changing wind speeds, is a crucial metric in wind turbine systems. The maximum power coefficient is compared to the wind turbine system without the MPPT control model in order to verify the effectiveness of the suggested MPPT control approach. To ensure that the turbine is operating at the best speed for maximum power output, the proposed MPPT control technique modifies the rotor speed in real-time. The optimization of rotor speed increases the power coefficient, as the system effectively captures available wind energy. In addition, the proposed control system adjusts other system parameters like blade pitch angle and generator speed to optimize the system performance and enhances the maximum power coefficient.



(a) No control over MPPT (b) Control over MPPT (b) Control over MPPT

Fig. 6 Maximum power coefficient: (a) No control over MPPT, (b) Control over MPPT

In a wind turbine system without an MPPT controller, the rotor speed is less optimized for maximum output power. Hence, it results in a low maximum power coefficient. Furthermore, the system is ineffective at utilising the available wind energy. The proposed control approach increases the maximum power coefficient, as shown by a comparison of the maximum power coefficient between systems with MPPT control and systems without MPPT control. Fig 6 displays the maximum power coefficient with and without the MPPT controller.

5.1.2 Grid three-phase voltage and current

The wind turbine system's MPPT controller is in charge of modifying the electrical load on the turbine in order to boost the turbine's output power. Electricity produced by the wind turbines is fed into the electrical grid. The grid three-phase current and voltage study aids in confirming the WT system's grid compatibility. Additionally, it demonstrates the stability and dependability of the power the WT system generates. The fluctuations in the voltage and current waveforms cause' damage to electrical equipment in the grid system.

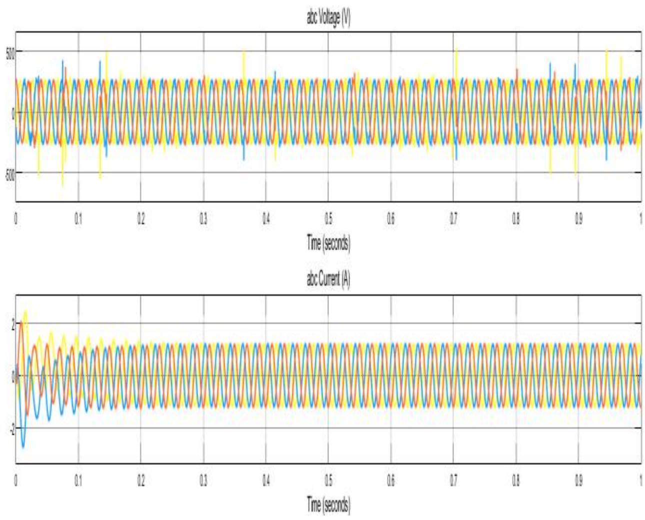


Fig. 7 Grid three-phase voltage and current

In addition, the current and voltage waveforms offer information regarding the WT system's performance. The current and voltage analysis enables to predict the factors such as current harmonics, power factor issues, etc., which affects the system performances. Fig 7 displays the grid voltage and current.

5.1.3 Power both Active and Reactive

The wind turbine system typically generates both active and reactive power. The power that the WT system actively consumes is referred to as active power.

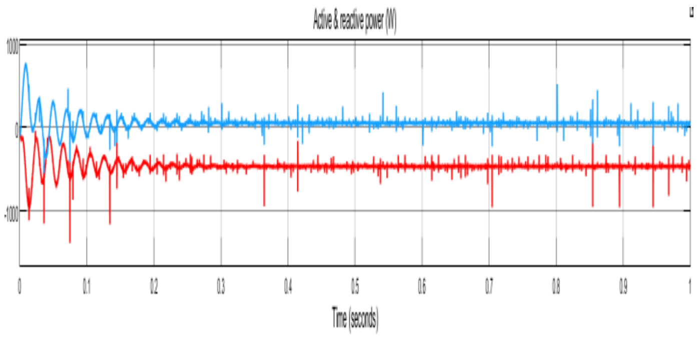


Fig. 8 Active and reactive power

The active power output in the WT system is inversely related to the wind speed and rotor blade area. By changing the rotor speed and blade pitch angle to keep the wind turbine at its maximum power point (MPP), the suggested MPPT control approach seeks to maximise the active power production of the machine. Reactive power, on the other hand, refers to the energy needed to keep the electrical grid's voltage constant. In WT systems, reactive power is crucial because variations in its output can result in voltage sags in the grid and damage to electrical equipment. Both active and reactive power are taken into account in the suggested method, which keeps active power at its peak and makes sure that reactive output power stays within acceptable bounds. To create a balance between active and reactive power, the current and voltage waveforms are modified. The system's active and reactive power are shown in Fig. 8.

5.1.4 FFT analysis

Fast Fourier Transform (FFT) analysis is an approach that is utilized to analyze the frequency spectrum of a signal. FFT analysis is used in wind turbine systems to examine the harmonic makeup of the controller output signal. An essential factor in determining the effectiveness of the suggested MPPT controller is the Total Harmonic Distortion (THD) value. Its definition is the ratio of the root mean square (RMS) of the signal's harmonics to its fundamental component. To guarantee good power quality, the THD value should be less than 3%. If the THD value is found to be greater than 3%, adjustments can be made to the controller parameters or the fuzzy logic rules to improve its performance.

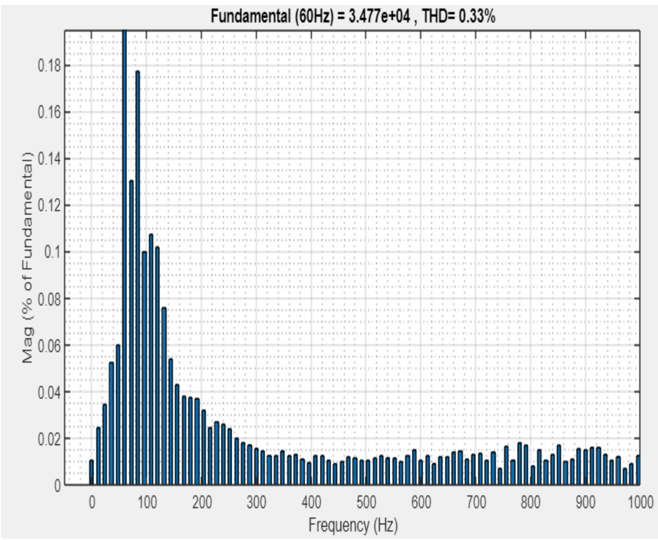
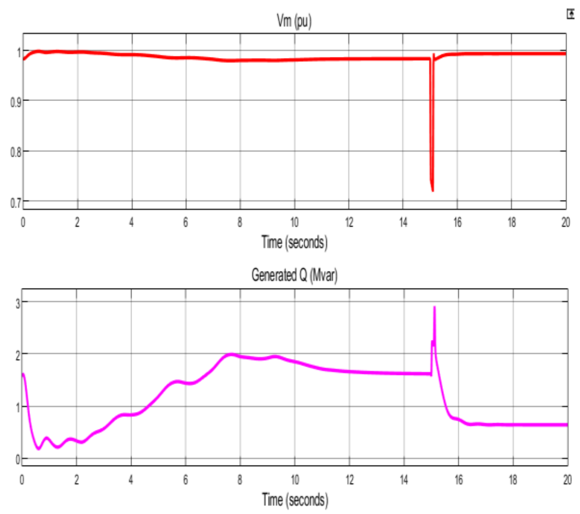


Fig. 9 FFT analysis of the proposed controller

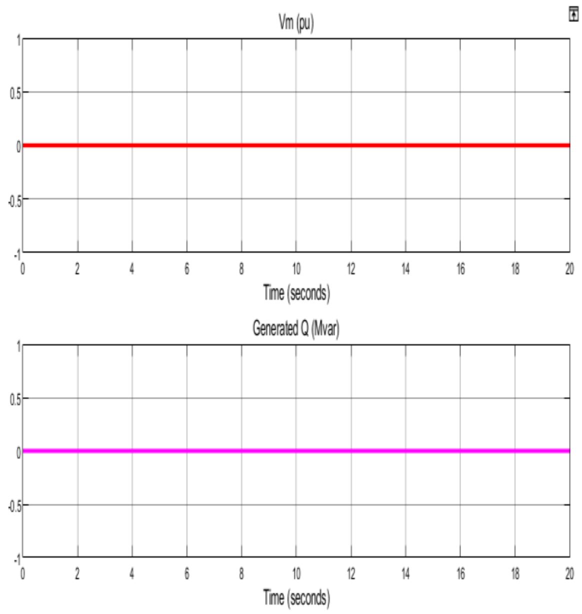
The proposed controller attained less THD value of 0.33%, which indicates that the output of the controller is relatively clean and contains fewer harmonics. This indicates that the controller is effective at monitoring the wind turbine system's maximum power point and producing high-quality power. The stability and dependability of the wind turbine system is ensured by a low THD value in the FFT analysis. The proposed controller's FFT analysis is shown in Fig. 9.

5.1.5 Reactive power with and without compensation

Reactive power plays a significant role in the performance and stability of a wind turbine system. The electricity that alternates between the generator and the grid without actually being used by any loads is known as reactive power. It is crucial for keeping the grid's voltage levels stable. Reactive power compensation is used to stabilise the system and control voltage levels. The WT systems typically generate both active and reactive power.



(a) With compensation



(b) Without compensation

Fig. 10 Reactive power: (a) with compensation, (b) without compensation

The voltage levels in the grid may become unstable if the reactive power generated by the wind turbine is not matched with the reactive power absorbed by the loads. The Lyapunov analysis is used in the proposed work to balance out and stabilise the reactive power generated. By balancing the reactive power generated by the wind turbine with the reactive power used by the load, the system is able to maintain stable voltage levels and carry out its intended function. The voltage level varies, becomes unstable, and harms the system if the reactive power is not corrected. Reactive power is shown in Fig. 10 both with and without compensation.

6. Conclusion

In order to increase the wind turbine's power capture coefficient, a hybrid adaptive MPPT controller is suggested in this article. To track the MPP of the WT system, the controller design incorporates the DENFC and FHO algorithms. The proposed controller is constructed to take into account the uncertainties and disturbances that could impact the performance of the wind turbine. To ensure optimal functioning and maximum power extraction from the wind turbine, the controller makes real-time adjustments to its parameters depending on feedback from the system. Additionally, it makes use of Lyapunov analysis to validate the system's stability and convergence. The results of the simulation show how well the model was able to increase the power output of the wind turbine. Under different wind speeds, the proposed technique's resilience was assessed. Additionally, it successfully offsets the reactive power produced by the wind turbine. Furthermore, the results are confirmed by a WT system's performance without an MPPT controller. The effectiveness study shows that the suggested method has the potential to be used in actual WT systems to improve their functionality and lessen their environmental consequences.

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