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Enhancing the Performance of a Wind Turbine Based DFIG Generation System Using an Effective ANFIS Control Technique

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ABSTRACT

This paper gives a look on producing energy using wind turbines and imposing robust Maximum Power Point Tracking (MPPT) technique to operate around an optimal rotational speed. A mechanical speed control based on PI controller is presented in order to extract the maximum power and optimizing the conversion efficiency of wind's kinetic energy into electric energy. A doubly-fed induction generator (DFIG) is utilized because it is preferable for applications in wind energy systems referring to the capability to regulate the output voltage and improve the stability of the grid. Its operational characteristics and the regulating procedures such as Indirect Vector Control (IVC) and other sophisticated strategies for instance the ANFIS controller enhance operating flexibility and optimum performance under diverse conditions. This has attributed the split to the improved ANFIS in that it includes the artificial neural networks besides the fuzzy logic since they improve on learning as well as parameter fine tuning. Some of them are working with a comparatively fewer number of data sets; and therefore, it can be useful in classification, modeling and control. This configuration enables to regulate the generator's magnetic flux, torque, and reactive power, adjusting to changes inside wind velocity and disruptions within the grid. The performance of the proposed MPPT-IIVC method is examined by way of simulations in Matlab/Simulink. The simulations concerned a dynamic model incorporating the wind turbine, the DFIG, and the electric grid. The results show that the proposed technique can incredibly enhance the wind energy, maintain precise regulation over speed, and effectively adjust and regulate grid voltage and frequency. The performance of the proposed ANFIS controller is compared with a PI controller and discovered that ANFIS enhances the robustness, precision, dynamic response, total harmonic distortion THD (%) of the injected current into the grid, the reference tracking ability and Overshoot (%).

1. Introduction

One of the most promising forms of renewable energy in recent years has been recognized as wind power. Wind energy is renewable, inexpensive, and clean. The investigation of renewable energy technologies and their implementation in power generation is a highly topical issue. It is crucial for sustainable development [1]. Wind energy is one of these technologies that offers a number of advantages, such as lowering installation costs, diversifying the energy portfolio, reducing greenhouse gas emissions, and creating jobs locally [2]. However, intermittency, unpredictability, and resource uncertainty, which require adequate technical solutions to guarantee the quality and stability of the power system, are the challenges posed for wind energy.

Wind energy can be exploited by installing wind energy conversion systems (WECSs). A WECS converts wind energy to mechanical and electrical energy. WECS is often divided into two categories: electric and mechanical energy conversion systems. The former include systems that use pulleys and gears to transform the linear movement of the blades into rotational movement and drive a generator. The latter include systems that use power electronic circuits to convert the electrical power from the generator into grid power [3].

Furthermore, there is a difference between WECS that operate at fixed and variable speeds. For fixed-speed WECS, grid power quality is affected by power fluctuations caused by wind turbulence. This is due to the connection of the DFIG to the grid [4]. On the other hand, variable-speed WECS offer a number of advantages, such as the Maximum Power Point Tracking (MPPT) control algorithm. MPPT is a method utilized to optimize the power extraction, from wind turbines by adapting the rotor's position and speed to match the changing wind conditions [5]. On the hand DFIG is a generator that enables power flow in both directions between the rotor and the grid resulting in control and efficiency. The integration of these two technologies has potential, for transforming wind energy systems and improved power quality, maximum energy capture, reduced mechanical stress on turbine components, grid compatibility, and reduced noise emissions [6]. Therefore, variable-speed WECS are the most widely used wind power generation system.

The most popular power generators for variable-speed wind turbines are DFIG, permanent magnet synchronous generators (PMGS), and synchronous machines with wound rotors [7]. Due to its ability to control both active and reactive power, lower noise levels, and less strain on mechanical components, the DFIG has gained popularity in the wind energy industry [8]. Its manufacturing design allows it to operate at low speeds. This makes it suitable for low wind speeds. DFIG technology is economically competitive with other wind generator technologies. It offers a good balance between performance and cost, making it a good choice for wind energy conversion systems also can generate and absorb active and reactive power in all four quadrants. This flexibility allows better control and integration into the grid [9]. Effective control of active and reactive power can be achieved by simplifying the DFIG control method by ignoring the stator resistance and aligning the stator flux vector with the d-axis [10].

To optimize wind energy extraction, MPPT algorithms are applied in WECS. Despite the great advantages of the DFIG, it presents a challenging control problem. It is a nonlinear multivariable system and is highly coupled [11] The general difficulties within DFIG control are internal parametric changes, nonlinearities, and how to receive the best performance when the wind is variable. The aforementioned challenges are expected to be solved by using the proposed ANFIS technique because of its functionality to provide accurate and adaptive control of the respective active and reactive components of the DFIG. However, the proposed approach serves to improve the stability and dynamics of the system as well as the extraction of power from wind energy systems in view of the factors that come with inherent system instability, fluctuation in wind speed, and energy conversion.

New developments in the control of DFIG and other methods have concentrated on the objectives of optimizing, stability, and flexibility in WECS [12]. DPC and FOC have incorporate advancements in switching strategies and sensorless techniques respectively, but are still and burdensome by high-frequency switching losses and variations of parameters. MPC provides the best next control actions but relies on large computations and accurate models of the system [13]. Optimal tuning of the sliding mode control (SMC) has been developed to compromise disturbance rejection and hence chattering effects [14]. Artificial intelligence and machine learning methods such as Artificial Neural Network, Fuzzy Logic Controller, and Adaptive Neuro-Fuzzy Inference System give intelligent and self-learning control methods, where ANFIS amalgamated the features of Artificial Neural Network, Fuzzy logic, and Adaptive Neuro Fuzzy Inference System for proper control without needing a lot of mathematical modeling [15]. Some bio-inspired optimization such as genetic algorithms and particle swarm optimization provide solutions to parameter optimization though they are generally resource consuming [16]. It is believed the use of hybrid control strategies seeks to enhance the effectiveness of number of strategies to yield better results [17]. As a result, a decoupled active and reactive power control technique is mandatory to realize a constant operating frequency at variable wind speeds [18]. Recently, DFIG control techniques have been studied in several papers. The author of [19] suggests a space vector modulation-based direct power control method for a wind turbine driving a DFIG. This control strategy has some limitation as complex implementation and control algorithm, sensitivity to parameter variations and uncertainty, limited ability to handle grid disturbances, and Potential for increased levels of harmonics and power quality problems. In addition, indirect vector control is widely used for its robustness and can helps to overcome the challenges of nonlinearity and uncertainties in the system, such as wind turbine aerodynamics and generator magnetic saturation [20], it is therefore essential to determine the appropriate control methods for this system. Traditional indirect vector control (IVC) usually uses a control mechanism based on proportional-integral (IVC-PI) or proportional-integral-derivative (IVC-PID) PI and PID controllers are more suitable for linear model within a certain operating range, despite their ability to control certain aspects of non-linear system. To control non-linear systems, like wind turbines and electrical machines, PI and PID controllers are frequently employed [21], [22]. In [23] the author proves that the PI controller may have difficulty maintaining accurate control in systems with large variations in operating conditions or disturbances and may not be optimal for systems with nonlinear dynamics or time-varying parameters because they rely on fixed gains. Also, may not be able to accurately control systems with complex control requirements or multiple inputs and outputs. They lack inherent adaptive capabilities and cannot automatically adjust their parameters to changing system dynamics or operating conditions. The NDPC-4L-NSVPWM method is used in [24] to improve direct power control in DFIG-DRWT systems. It offers advantages such as improved dynamic behaviour and reduced power ripple. The approaches employed in [25] entail developing a hybrid control strategy that combines sliding mode strategy and fuzzy logic techniques. The control strategy is implemented and tested through simulation using Matlab/Simulink. Fuzzy logic handles uncertainties by using linguistic variables, fuzzy sets, membership functions, fuzzy rules, and fuzzy reasoning algorithms. These methods enable the representation and manipulation of ambiguous or imprecise data, facilitating control and decision-making in the face of uncertainty. The design and use of a hybrid control approach based on DFIG for a grid-connected WECS is the main topic of this paper. The outcomes show how well the suggested control approach performs in terms of providing the best possible power supply and resilience to system fluctuations. The simulation study provides a practical evaluation of the control strategy's performance.

In addition, PI controllers and DPC make the conventional control strategies apart of non-linearity in the system, variations in parameters, and improper working in variation in the wind circumstances. It is required to tune PI controllers better as they are not very robust and DPC has high torque ripples and has bulky structure [26]. The ANFIS based indirect vector control system differs from several other control systems in a way that it has the self-adjusting quality where there is no necessity of time to time tuning and in addition, much precise mathematical models are not mandatory in this system. Because it can apply control actions acquired through a set of signals, it provides a superior dynamic response, better robustness, and improved efficiency in comparison to the standard controllers; therefore, it is the best option for enhancing DFIG in wind energy systems [27].

Furthermore, the application of ANFIS has shown promising results for overcoming different control issues in power systems. Nevertheless, it is an appropriate use for the control of WECS against external and internal variations such as WS variations, resistance variations, and inductance variations in the DFIG [28].

In this context, and to overcome the deficiencies of the aforementioned controllers and utilize the power of ANNs, the first contribution of this work consists of a system that combines ANNs and fuzzy logic to design controllers (Adaptive Neuro Fuzzy) and combine them with an IVC technique of a grid-connected DFIG-based WECS, which is different from other published works. Thus, ANFIS is a hybrid intelligent controller that combines Takagi-Sugeno fuzzy inference systems and ANNs and effectively overcomes the above problems.

The ANFIS control technique deals with non-linearities and parameters variation which are involved in the DFIG systems to ensure consistent performance without the need for the accurate mathematical models and basic adjustment. Hence, by increasing the dynamic response and minimizing the torque oscillations, ANFIS improves the power quality and the stability of the grid, and consequently increases the sturdiness of the system against any kind of disturbances. These innovations present a superior level of enhancement over the conventional methods of control, and it gives further substantiation for the efficacy of the ANFIS algorithm in achieving control over both MPPT and DFIG for WECs [29].The proposed ANFIS control technique distinguishes itself from its counterparts by incorporating adaptability, learning feature, and ease of implementing, which adjusts the MPPT and DFIG's performance optimally without requiring significant parameter tuning, making it a strong contender for the current conventional and other advanced methodologies.

It is convenient to state that the proposed way of combining ANNs and fuzzy logic with Indirect Vector Control (IVC) technique is original due to the fact that the advantages of all the methods meet the needs and eliminate the drawbacks of others. In contrast to PI controllers, which show difficulties with non-linear systems, variable parameters, and tuning to the required values, the developed ANFIS-based IVC has the characteristics of learning and advanced control. This work's significance is the application of ANNs' learning properties together with fuzzy logic reasoning in the IVC platform, which allows for the real-time adaptation of control approaches and does not rely on comprehensive mathematical models. Some of the expected benefits are enhanced dynamic response, low torque pulsations, better quality and efficient MPPT in different wind conditions.

This paper aims at developing a robust yet simple control strategy for DFIG control by combining MPPT and indirect vector control. An intelligent IVC method with ANFIS controllers is proposed, which has the following main features:

The literature points out the major drawbacks of conventional controllers, which are addressed with ANFIS controllers. Our proposed approaches aim to eliminate the need for accurate system modeling and make performance immune to uncertainties and internal and external disturbances. This includes robust control of the quadratic components of the stator current, the electromagnetic torque, the AC current injected into the grid, the DC link voltage, and the active and reactive power injected into the grid.

- The wind turbine system's complexity is decreased by the hybrid technique used in the ANFIS controller, which combines artificial neural networks and fuzzy logic control
- Unlike approaches based on an accurate model, ANFIS does not require the system's exact model, making the control process simpler

The composition of the paper is as follows: Sec. 1 contains the detailed mathematical models of the wind turbine, MPPT strategy, and DFIG modeling; Sec. 2 covers the controller's design; Sec. 3 offers more insights about the procedure by which the proposed ANFIS works; Secs. 4 and 5 display the simulation results, which illustrate how the proposed IVC-ANFIS and the traditional IVC strategies compare; and finally, Sec. 6 provides the conclusions.

2. Complete System Modeling and Control

The WECS have become a vital technology in transitioning to renewable energy sources. By combining various mechanical and electrical techniques, these systems transform the kinetic energy of wind turbines into clean and green renewable energy. The core element of these systems is a wind turbine. The various parameters, from mathematical modeling to energy conversion of a wind turbine, are covered in this section.

The aerodynamic modeling of wind turbine blades specializes in the interaction between the wind and the blades to create lift and drag forces that apply torque to the rotor. The efficiency of a wind turbine is determined by the dimensions, shape, and angle of its blades. While the drag force works against the direction of the wind to lower the turbine's efficiency, the lift force rotates the rotor by operating perpendicular to the wind. The Blade Element Momentum (BEM) concept is commonly used to predict the overall performance of the blades. This is done by dividing the blades into small sections and studying the forces acting on them [30]. The mechanical dynamic aspect focuses on the transformation of aerodynamic forces on the blades into rotational rotor's motion. This is related to the design and operation of the rotor shaft and the gear box. The blades' rotating motion is transferred to the gearbox via the rotor shaft. In order to effectively generate renewable energy, the gearbox adjusts the rotational speed to meet the generator's input speed. When modeling the mechanical dynamics, it's critical to take into account such characteristics as material strength, fatigue, and vibration in order to ensure structural integrity and efficiency. Finally, the energy is converted from mechanical to electrical using a generator. There are generally two types of generators, synchronous and induction. Within the wind turbines, mechanical energy can be transformed into electrical energy using either sort of generator [31]. The electrical version of the generator consists of the conversion efficiency, which is influenced by parameters that include magnetic area depth, coil resistance, and rotational speed.

The topology of a DFIG-WT is normally as illustrated in Fig. 1, where the stator windings are connected directly to the grid and the rotor windings are connected to the grid via back-to-back converters. The PWM-managed back-to-back converters allow electricity to be exchanged between the grid and the rotor windings in both directions. Under normal operation, the grid-side converter (GSC) is controlled to maintain a constant DC link voltage and provide a specific reactive power, while the rotor-side converter (RSC) is managed to regulate the output active power of the generator via imposing the suitable voltages into the rotor windings [32]. Reactive power management, voltage control, frequency control, and MPPT using various control approaches are among the control objectives that the DFIG-WT can achieve [33].

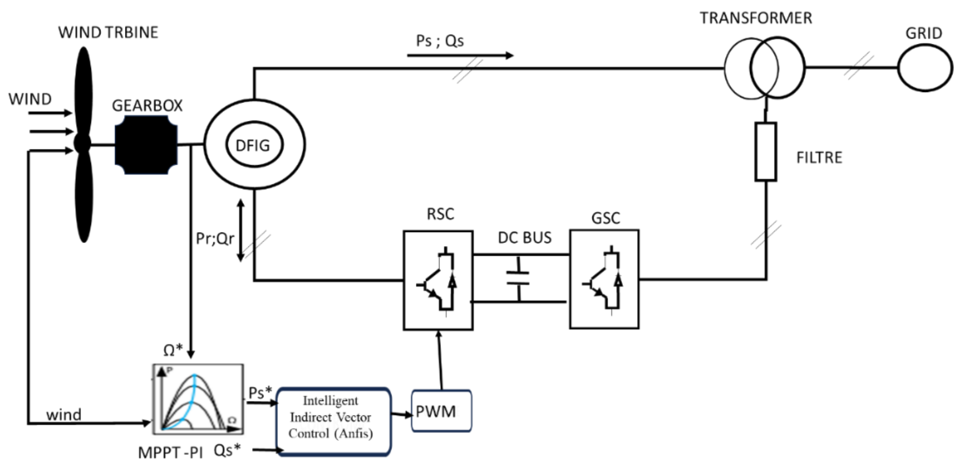

Fig. 1. Scheme of the DFIG-based wind power system

2.1. Modeling of Wind Turbine and MPPT Algorithm

Fig. 2 shows the three main areas where wind turbines generally operate: below nominal wind speed, at nominal wind speed, and above nominal wind speed. The turbine runs in a stall-controlled mode, where the rotor blades are tilted to regulate the rotor speed, when the wind speed is below the nominal wind speed. To maximize power extraction from the wind, the turbine runs in MPPT mode at nominal wind speed. When the wind speed exceeds its rating, the turbine enters roll mode, when the blades are feathered to reduce power output and safeguard the turbine from harm [34].

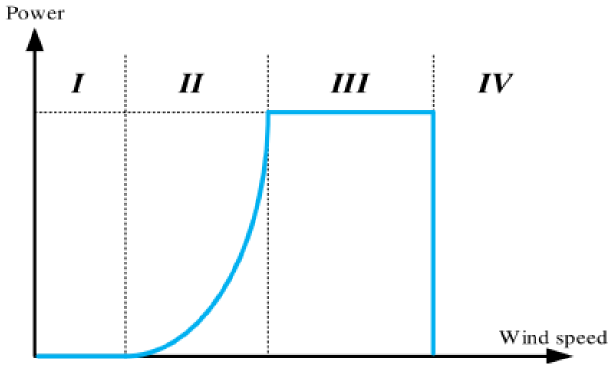

Fig. 2. Different operation zones of a wind turbine

The following formula can be used to estimate the total power P that a wind turbine can produce [35]:

$$P_t = \frac{1}{2}\rho A v^3\, C_p(\lambda,\beta) \tag{1}$$

Where:

$$C_p(\lambda,\beta) = 0.517 - \left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{-\frac{21}{\lambda_i}} + 0.0068\lambda \tag{2}$$

With,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3}$$

Where ρ is density of the air (kg/m³), A is the blades' swift area (m²), v is the wind velocity (m/s), Cp is the turbine power coefficient, β is the blade pitch angle, Ωt is the turbine speed and λ is the tip speed ratio defined by

$$\lambda = \Omega t . R / v \tag{4}$$

Fig. 3 shows the variations in the power coefficient as a function of λ and β. This Fig indicates that the ideal speed ratio for Cpmax=0.48 when operating in MPPT mode with β=0° is λopt=8.1. The generator's shaft dynamic can be described by.

Where C_{em} is the torque generated by the DFIG and $C_g = C_t/G$ is the mechanical torque applied on the shaft as illustrated in Fig. 4.

In Fig. 4, among the most crucial elements to take into account while using MPPT is the reference speed rate (Ωg*). It is greatly influenced by the generator's mechanical and electrical characteristics, wind speed, and rotor blade dynamics. The torque which is supplied to the generator is regulated by the TSR-based MPPT technique for operating it more effectively to gain maximum power from the wind. This approach optimizes and enhances the wind turbine efficiency and operating performance [36].

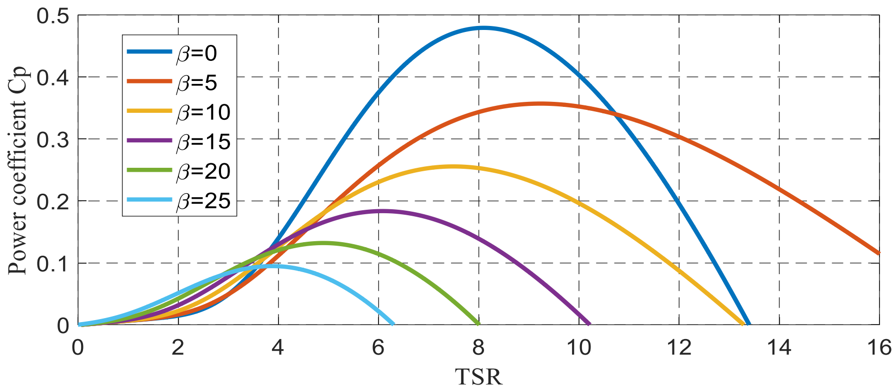

Fig. 3. Relationship between Cp and λ for different values of β

$$J\frac{d\Omega_g}{dt} = C_{méc} = C_g - C_{em} - C_f \tag{5}$$

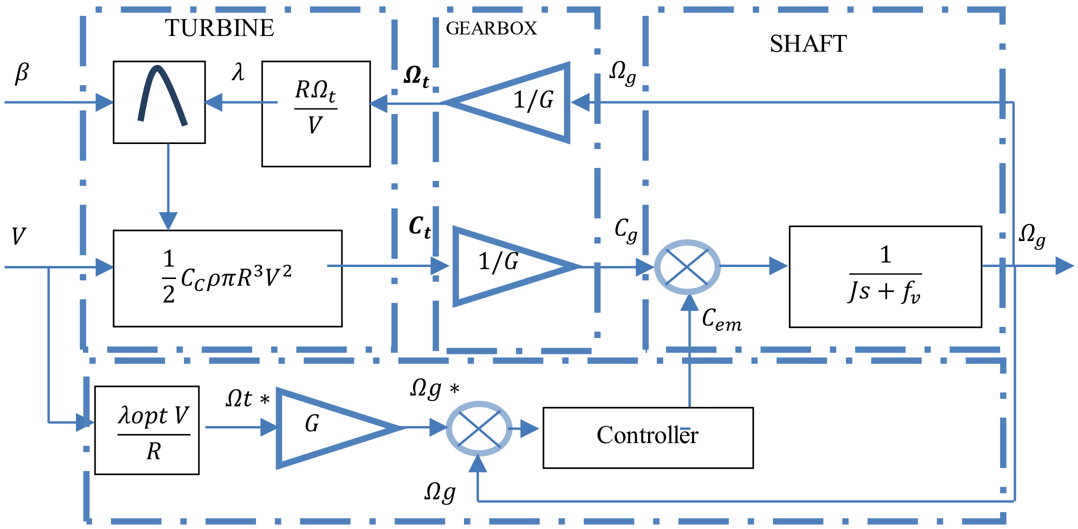

Fig. 4. Turbine and MPPT model

2.2. Mathematical Modeling of DFIG

For a DFIG, a mathematical model can be created by observing, analyzing and evaluating the dynamic nature of its electromagnetic factors. In this mathematical approach, the d-q reference frame for the representation of AC values is utilized. The stator and rotor voltage equations can be utilized to examine the electrical properties of the DFIG within the d-q reference frame [37], [38]. Stator Voltage Equations:

$$\begin{cases} V_{ds} = R_s I_{ds} + \dfrac{d\phi_{ds}}{dt} - \phi_{qs}\omega_s \\ V_{qs} = R_s I_{qs} + \dfrac{d\phi_{qs}}{dt} + \phi_{ds}\omega_s \end{cases} \tag{6}$$

Rotor Voltage Equations:

$$\begin{cases} V_{dr} = R_r I_{dr} + \dfrac{d\phi_{dr}}{dt} - \phi_{qr}(\omega_s - \omega_r) \\ V_{qr} = R_r I_{qr} + \dfrac{d\phi_{qr}}{dt} + \phi_{dr}(\omega_s - \omega_r) \end{cases} \tag{7}$$

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Where:

V_{ds}, V_{qs}, V_{dr} and V_{qr}: are the d-q voltage components of the stator and rotor.

I_{ds}, I_{qs}, I_{dr} and I_{qr}: are the d-q current components of the stator and rotor.

$\phi_{ds}, \phi_{qs}, \phi_{dr}, \phi_{qr}$: are the stator and rotor flux linkages.

ω_s and ω_r: are the synchronous and rotor speeds.

The electromagnetic torque (T_e) of the DFIG can be derived from the power equation and is given by:

$$T_e = \frac{3}{2}\frac{P}{\omega_s}\left(\phi_{ds}I_{qs} - \phi_{ds}I_{ds}\right) \tag{8}$$

Where P is the pole pairs.

2.3. Indirect Vector Control of DFIG

A decoupled control of active and reactive powers of DFIG can be achieved through managing the RSC converter [39]. The adopted control technique adjusts the d-q rotor voltages (V_{dr} and V_{qr}) to control respectively the active power (P) and reactive power (Q). This is typically achieved using vector control techniques, where: active power regulation is accomplished via adjusting the rotor current I_{dr} and reactive power management is realized via adapting the rotor current I_{qr}.

The IVC control of a DFIG is a usually employed regulation technique in variable speed wind turbines. This technique permits for the decoupled management of both active & reactive generated power, improving the effectiveness of wind power conversion systems. Here is a simple explanation of the way the Inverter Voltage Control (IVC) system operates for a Doubly Fed Induction Generator (DFIG) [40]. IVC, additionally called field-orientated control it aligns the rotor magnetic field with an axis in a revolving reference frame. This alignment enables DFIG management through keeping apart torque (associated with active power) and magnetizing current (associated with reactive power), corresponding to operating a DC motor. The core objective of IVC is to correctly determine the rotor's location to align the control.

Field-Oriented Control (FOC) aligns the rotor flux vector with one axis of a two-dimensional rotating frame (d-q frame), which spins in rhythm with the rotor flux [41] This alignment simplifies the control of AC machines by separating the control of torque (related to active power) and flux (related to reactive power), allowing for independent control akin to DC machines.

Then, from Fig. 5 and under FOC, it gives Φds=Φs and Φqs=0.

Therefore, the electromagnetic torque of Eq. (8) then becomes:

$$\mathrm{T}_e = -\frac{3}{2}pL_m\left(I_{ds}I_{qr}\right) \tag{9}$$

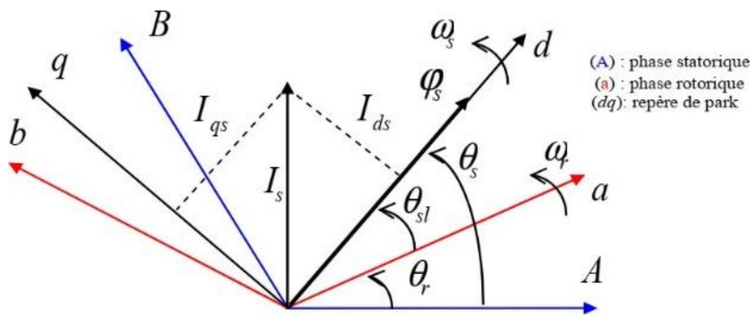

Fig. 5. d-q axis orientation to the stator flux

This choice is not arbitrary. It is justified by the hypothesis that the DFIG is often connected to a high-power supply with constant voltage and frequency, which leads to a statement about the stator flux of the DFIG. The stator resistance is usually not considered in high rating machines because the values are small as compared to the competitor parameters that govern the behaviour of high rating machines [42]. However, the system of equation (6) can be simplified as follows:

$$\begin{gathered} V_{ds} = 0 \\ V_{qs} = V_s = \phi_s \omega_s \end{gathered} \tag{10}$$

The stator active and reactive power can be expressed by

$$\begin{cases} P_s = \frac{3}{2}\left(V_{ds} I_{ds} + V_{qs} I_{qs}\right) \\ Q_s = \frac{3}{2}\left(V_{qs} I_{ds} - V_{ds} I_{qs}\right) \end{cases} \tag{11}$$

From Eq. (10) and (11), we obtain:

$$\begin{cases} P_s = \frac{3}{2} V_s I_{qs} \\ Q_s = \frac{3}{2} V_s I_{ds} \end{cases} \tag{12}$$

Stator currents are given by:

$$\begin{cases} I_{ds} = \dfrac{\phi_s - L_m I_{dr}}{L_s} \\ I_{qs} = \dfrac{L_m}{L_s} I_{qr} \end{cases} \tag{13}$$

The rotor voltages are obtained by substituting equation (13) with equation (7).

$$\begin{cases} V_{dr} = R_r I_{dr} + \sigma L_r \dfrac{dI_{dr}}{dt} - \omega_s\, g \sigma L_r I_{qr} \\ V_{qr} = R_r I_{qr} + \sigma L_r \dfrac{dI_{qr}}{dt} + \omega_s\, g \sigma L_r I_{dr} + g \dfrac{L_m}{L_s} V_s \end{cases} \tag{14}$$

By examining equations (13) and (14), the following diagram can be established DFIG block diagram illustrated in Fig. 6.

Where σ is the leakage factor, g represents the mutual coupling in the airgap, Lm is the mutual inductance, L_s and L_r are the stator and rotor self-inductances.

3. Proposed Intelligent Indirect Vector Control (ANFIS)

Different ANFIS controllers applied to Wind Energy Conversion Systems (WECS) have been widely discussed in the existing literature pertaining to experimental analysis of proposed controllers. Several research works have employed ANFIS-based control strategies for WECS that are justified through computer simulations and testing. For example, studies have shown that the application of ANFIS-based Direct Torque and Flux Control (DTFC) regarding the Doubly Fed Induction Generator (DFIG) systems achieves better dynamic performance and better efficiency compared to the conventional methods [43]. Furthermore, ANFIS algorithms are used in the MPPT of converting photovoltaic panels where it recently proved to be more efficient and productive than other fuzzy logic controls [44], [45]. These results are supporting the applicability and the improved performance of ANFIS controllers in WECS through simulation and experimental works.

Adaptive Neuro- Fuzzy Inference system (ANFIS) is basically a combination of two systems Neural networks and the Fuzzy logic systems. So, it has the properties and characteristics of both these approaches [46]. When the condition changes it also changes its regulating approach just because of the Neural network ability. To handle uncertainties and imprecision against the variations it uses Fuzzy logic approaches.

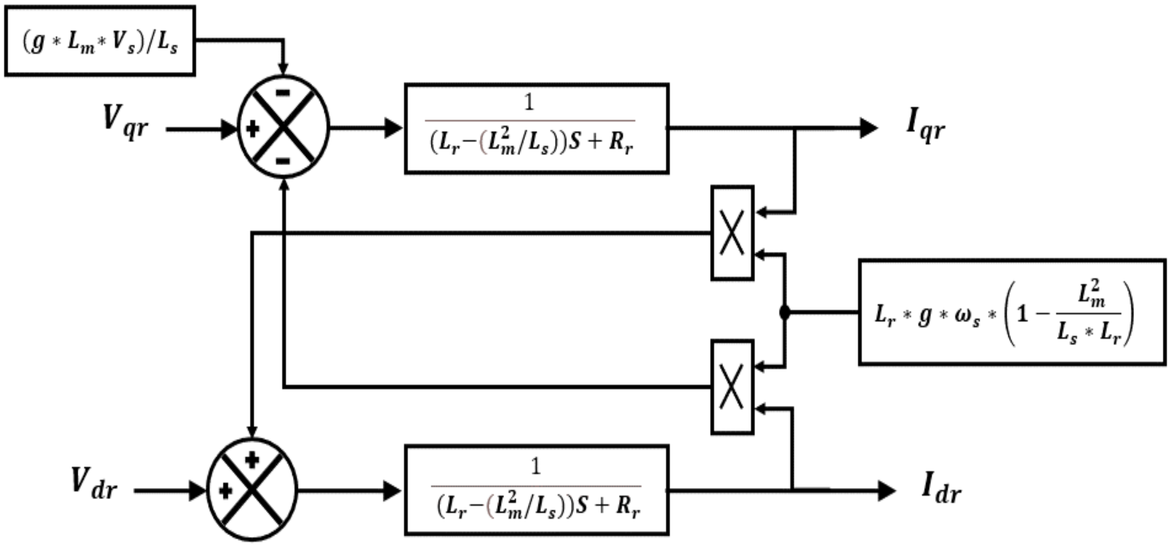

Fig. 6. Block scheme of the simplified model of the DFIG

3.1. The ANFIS Model

The ANFIS model is an advanced computational method that combines the qualitative features of fuzzy logic with the quantitative abilities of neural networks. It offers a structure for addressing intricate problems that are challenging to model accurately using mathematics. The ANFIS design combines neural network structures with fuzzy inference algorithms to create a synergistic multi-layered system. This is a thorough examination of the ANFIS architecture, focusing in particular on its five-layer structure, each serving a distinct role in the Takagi-Sugeno fuzzy inference process [47].

3.1.1. Layer 1: Fuzzification

Every node in the first layer has a specific node function and is adaptable. These nodes receive precise values as inputs and produce a membership grade indicating the degree to which these inputs belong to fuzzy sets. Each node in this layer represents a linguistic label (e.g., “low”, “medium”, “high”) determined by a membership function. Typically, membership functions are selected to be Gaussian, bell-shaped, or trapezoidal. During training, the parameters of these functions, such mean and standard deviation for Gaussian functions, can be modified, rendering this layer adaptable [48].

3.1.2. Layer 2: Regulations

The second layer consists of stationary nodes that execute the fuzzy logic function of multiplication. Every node in this layer symbolizes a fuzzy rule. Each node's output is determined by multiplying the input signals, which represent the membership grades from the first layer. This procedure essentially simulates the fuzzy AND operation in rule antecedents, generating a firing strength for each rule [49].

3.1.3. Layer 3: Normalization

In addition, nodes in layer three are stationary. Every node calculates the ratio by summing the firing strengths of all rules and dividing it by the firing intensity of each rule. This serves to standardize the firing strengths of the rules, ensuring that their sum does not exceed 1 in preparation for the defuzzification process; this layer's output modifies the effect of each rule according to its discharge intensity [50].

3.1.4. Layer 4: Defuzzification

The fourth layer comprises adaptive nodes once more. Every node represents a rule. These nodes receive normalized firing strengths from layer 3 and the output parameters of each rule, which represent the coefficients of the linear equations in the Takagi-Sugeno model. This layer calculates the impact of each rule on the final output by considering its firing strength and the corresponding output function.

3.1.5. Layer 5: The Process of Summation

The fifth layer includes a solitary stationary node responsible for summing all incoming signals. This node calculates the final output of the ANFIS model by combining all rule outputs using a weighted total. This layer consolidates the contributions from all rules to generate the ultimate precise output [51].

3.2. Training in Adaptive Neuro-Fuzzy Inference System (ANFIS)

By modifying the parameters of the layer 1 membership functions and layer 4 rule outputs, an ANFIS model is trained to minimize the error between the ANFIS output and the desired output. This is done typically by using back-propagation, gradient descent and a combination of both as hybrid learning [52].

The entire training of the ANFIS model is implemented using the MATLAB-SIMULINK environment. This environment provides four controllers necessary for vector control, to monitor and maintain the required speed, to monitor and hold the d-q current components at the reference values, and to monitor and maintain the active and reactive powers. In this paper, only the current and power control is provided as depicted in Fig. 8. Using the proposed ANFIS controllers, the current and power control is performed. The input and output parameters of the ANFIS model for the current and power controllers are shown in Table 1. The learning data used are obtained by conducting extensive MATLAB simulations of the traditional vector controller PI [53], where the PI regulator is employed in all four controllers. As ANFIS is with certain generalization property, it reacts very well to unseen data. Its performance is very superior as compared to blurred logic controllers. In the implementation of the ANFIS model, the antecedence is linked to the consequences using linguistic rules. The antecedence and the consequences are the functions of the input and output variables respectively. The more the rules a fuzzy logic-based controller has, the more its knowledge. If the rules are reduced, a fuzzy controller will be able to capture the expert's partial knowledge. The neuro-fuzzy system developed is a first-class Sugeno type with a single input variable, which includes seven membership functions and a membership function. It is composed of seven conditional rules. Fig. 7 illustrates the structural layout of the proposed neuro-fuzzy system. For the 15 iterations, learning is performed with the error signal of the controlled variable, i.e., active or reactive power, and with the current for the 35 iterations with hybrid back-propagation method [54], [55].

Table 1. Parameters of the used for the WECS

Parameters	Value
P	1.5 MW
V_s	398 V
F_s	50 Hz
P	2
R_s	0.012 Ω
R_r	0.021 Ω
L_s	0.0137 H
L_r	0.0136 H
L_m	0.0135 H
J	1000 $\mathbf{Kg.m^2}$
F	0.24 Nm/s

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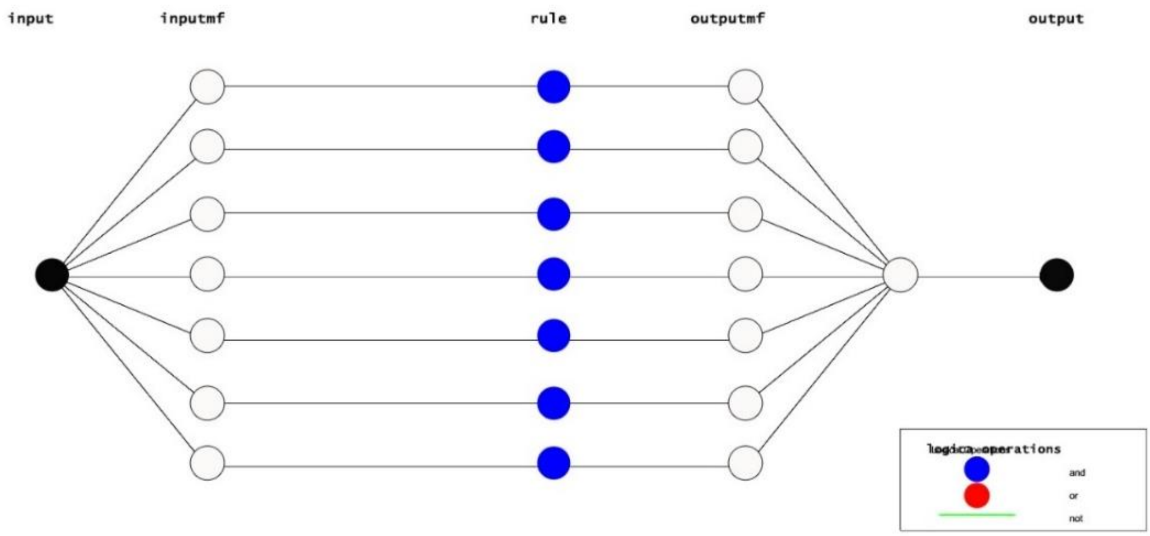


Fig. 7. The structure of the ANFIS

4. Simulation and Results

The proposed ANFIS built for this study has an input and an output, with the input being the error signal and the output being the control signal required to follow the power and current signal.

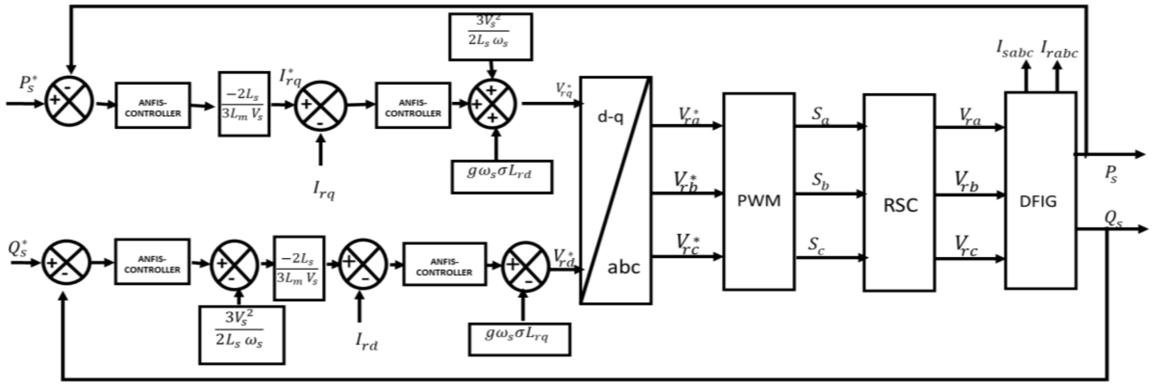


Fig. 8. Block scheme intelligent indirect vector control (ANFIS)

Simulation of the proposed control strategies for a DFIG machine are conducted by using the Matlab/Simulink package. The DFIG is connected to a 398V/50Hz grid. On the other hand, the DFIG is rated at 1.5MW, and its parameters are listed in the Table 1.

The wind speed profile, with a rated speed of 12 m/s, is chosen based on typical operational conditions in commercial wind farms, ensuring the study's relevance to actual wind energy applications. The 1.5 MW DFIG model represents a common capacity in modern wind turbines, making the findings applicable to a wide range of industry applications. The parameters for the DFIG and various control strategies (neuro-fuzzy, PI, and Mamdani-type FLC) are selected based on industry standards and previous research, ensuring optimal performance and practical relevance. The simulation includes diverse fault conditions and parameter variations to test controller robustness, mirroring common challenges in wind energy systems. This comprehensive approach in parameter selection and simulation conditions enhances the study's applicability to real-world wind energy systems, providing valuable insights for manufacturers, operators, and researchers in the field.

The both control strategies IVC-ANFIS and IVC-PI are simulated and compared in terms of reference tracking, stator current harmonics distortion, powers ripples and robustness against DFIG parameter variations.

Fig. 9 depicts the simulated wind speed profile, which ranges from 7 m/s to 11 m/s, and was used to mimic the WECS control system using a genuine wind profile of the city of Laayoun in southern Morocco.

Fig. 10, show that the value of Cp (λ, β) is close to Cp (λ, β) max = 0.38 for β = 0◦. The "Cp" is remarkably stable, showing a constant value slightly above 0.38 Var throughout the 5-second duration, indicating a steady Power Coefficient output during this interval.

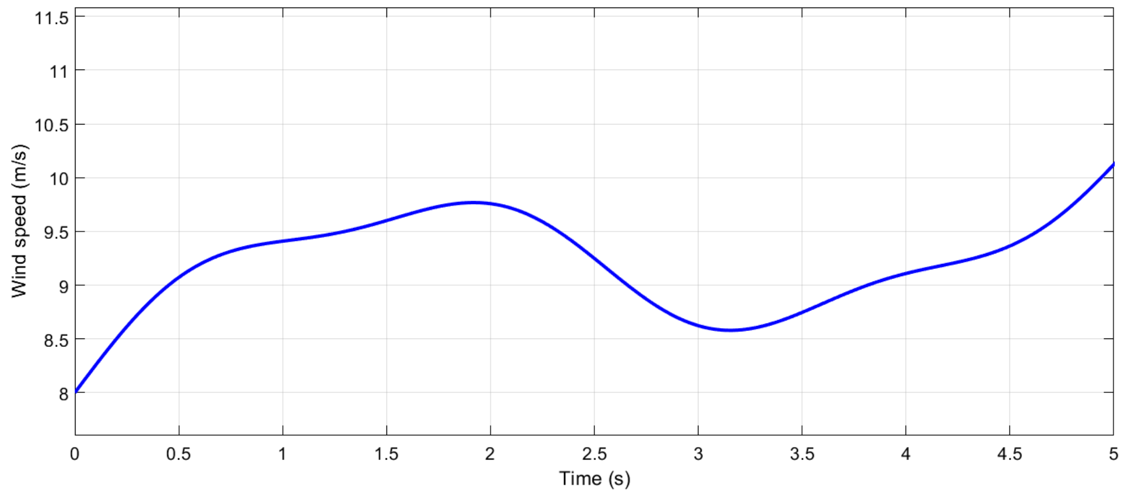


Fig. 9. Wind profile

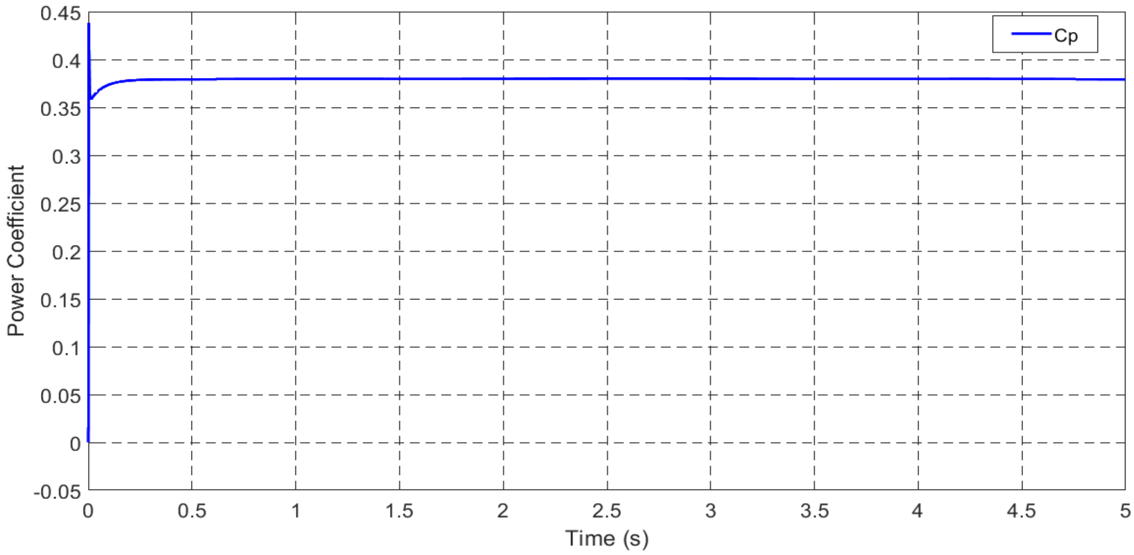


Fig. 10. Power coefficient

The Fig. 11 gives an overview of the Electromagnetic torque as computed. the torque (Te) is negative so the machine in this case operates as a generator. The response of the electromagnetic torque with respect to the mechanical torque. Thus, as it could be noted from the above Figs, the electromagnetic torque Te is well regulated such that it coincides with the mechanical torque. Thus, the considered control system enables one to control the electromagnetic torque Te of DFIG at the right and temporal changes of wind speed.

Fig. 12 shows the quadrature rotor current varies between approximately 750 A and 1250 A, influenced by the active power. It has been established that the proposed controller offers a short transient response because of non-synchronization of the DFIG with the grid. Compared with the PI controller.

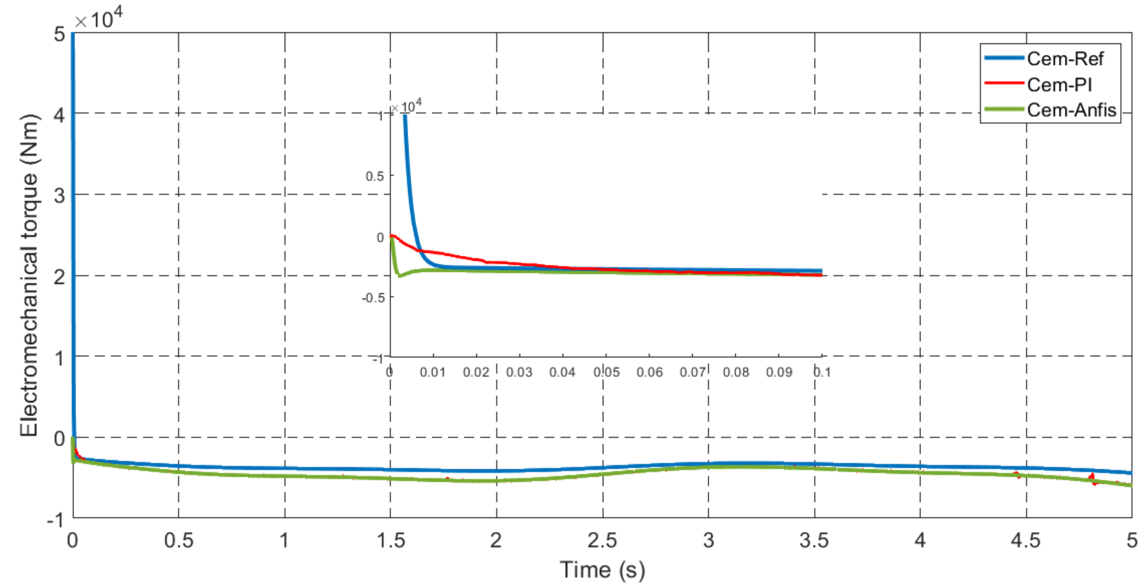


Fig. 11. Electromagnetic torque

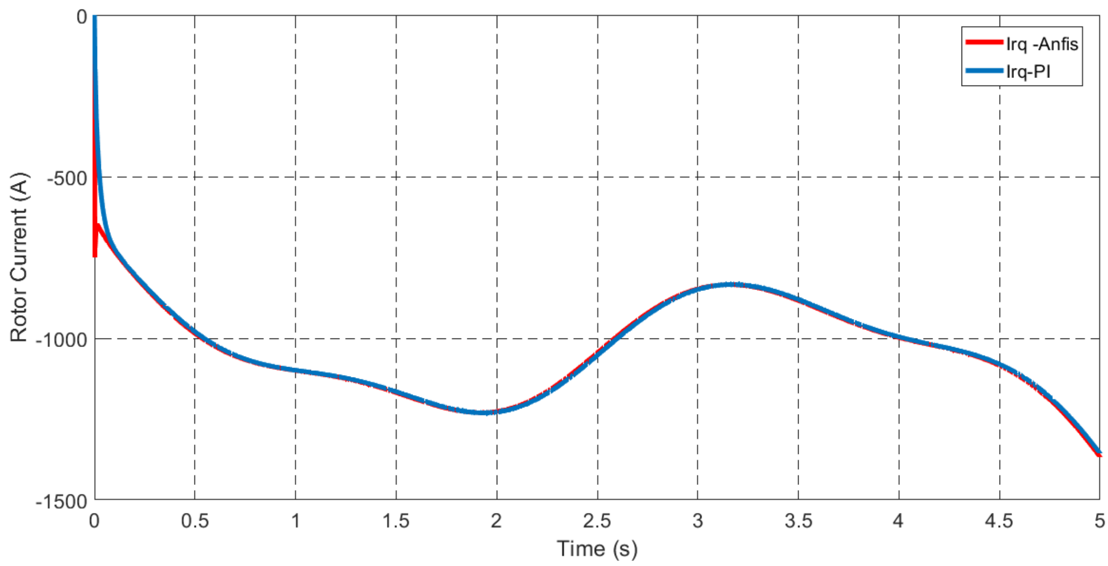


Fig. 12. Current Irq

In Fig. 13 (a) and (b), the active and reactive power converge to its ideal values and Ps and Qs track the reference well. It is observed that the variation in wind speed also causes a variation in the active power extracted using the developed fuzzy control technique that varies in the range of (4 KW to 8KW). The reactive power reference remains fixed at zero to achieve a unity power factor on the network side.

Fig. 14 shows the THD values obtained for the IVC-PI and IVC-ANFIS controls, illustrating that the THD is significantly lower in the IVC-ANFIS strategy (THD 9.12) than in the IVC-PI approach (THD 9.53).

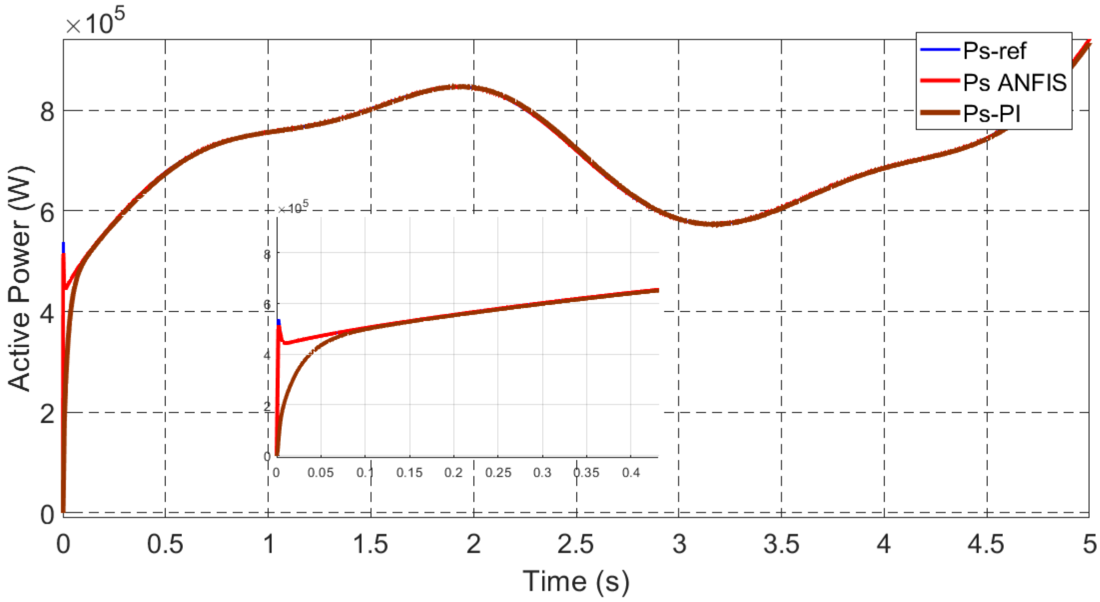
5. Robustness Test

To assess the robustness of the ANFIS controller against unforeseen fluctuations in the DFIG's internal parameters, which may arise from temperature increases or other factors, we have developed a comprehensive robustness test protocol. This protocol involves systematically increasing the rotor and stator resistance and inductance values as follows:

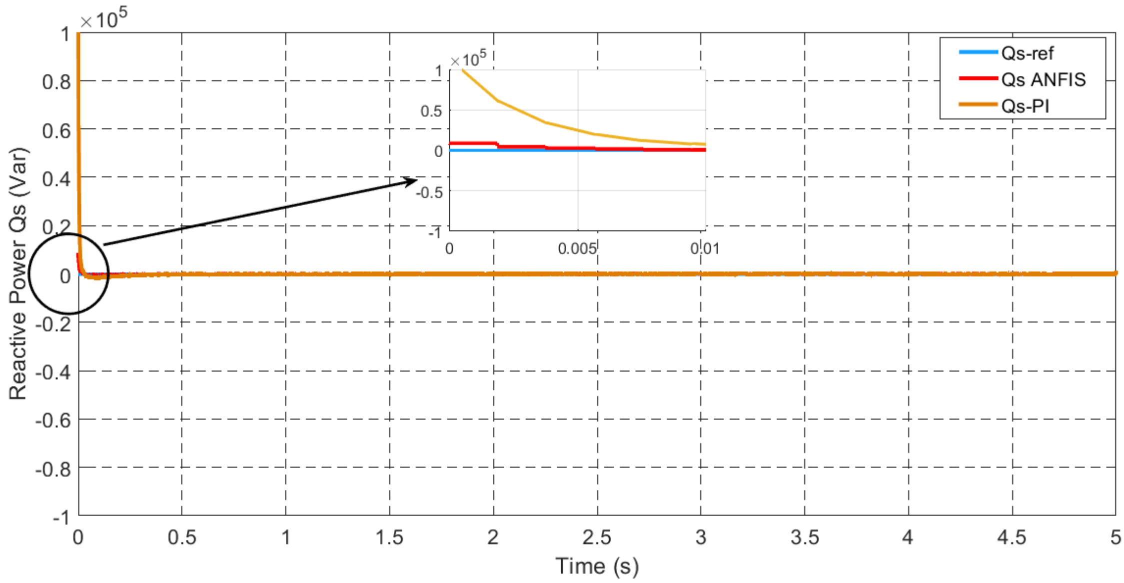
$$\begin{cases} R'_r = R_r \times 2 \\ L'_r = L_r \times 0.5 \\ L'_m = L_m \times 0.5 \end{cases} \tag{15}$$

$$\begin{cases} R'_s = R_s \times 2 \\ L'_s = L_s \times 0.5 \end{cases} \tag{16}$$

These results in Fig. 15 show that excessive parametric variation leads to deterioration of the active and reactive power curves with the influence of static error in the case of the conventional IVC-PI controller. As can be concluded from the results presented in the previous sections, the system response with the proposed IVC-ANFIS controller does not depend on these variations.

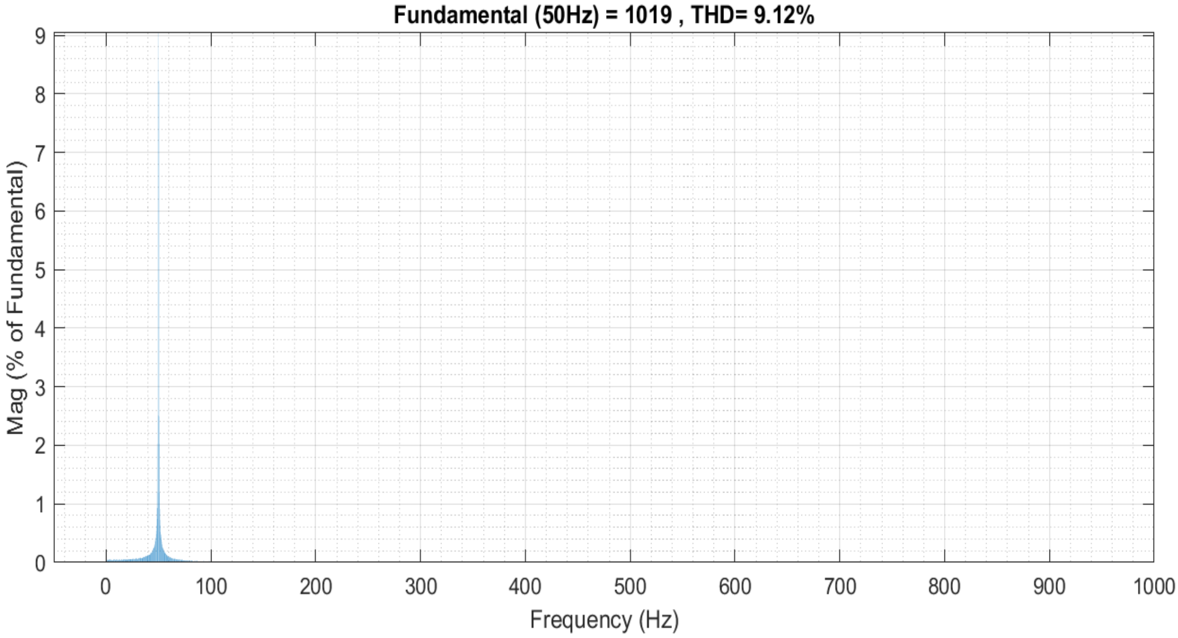


(a)

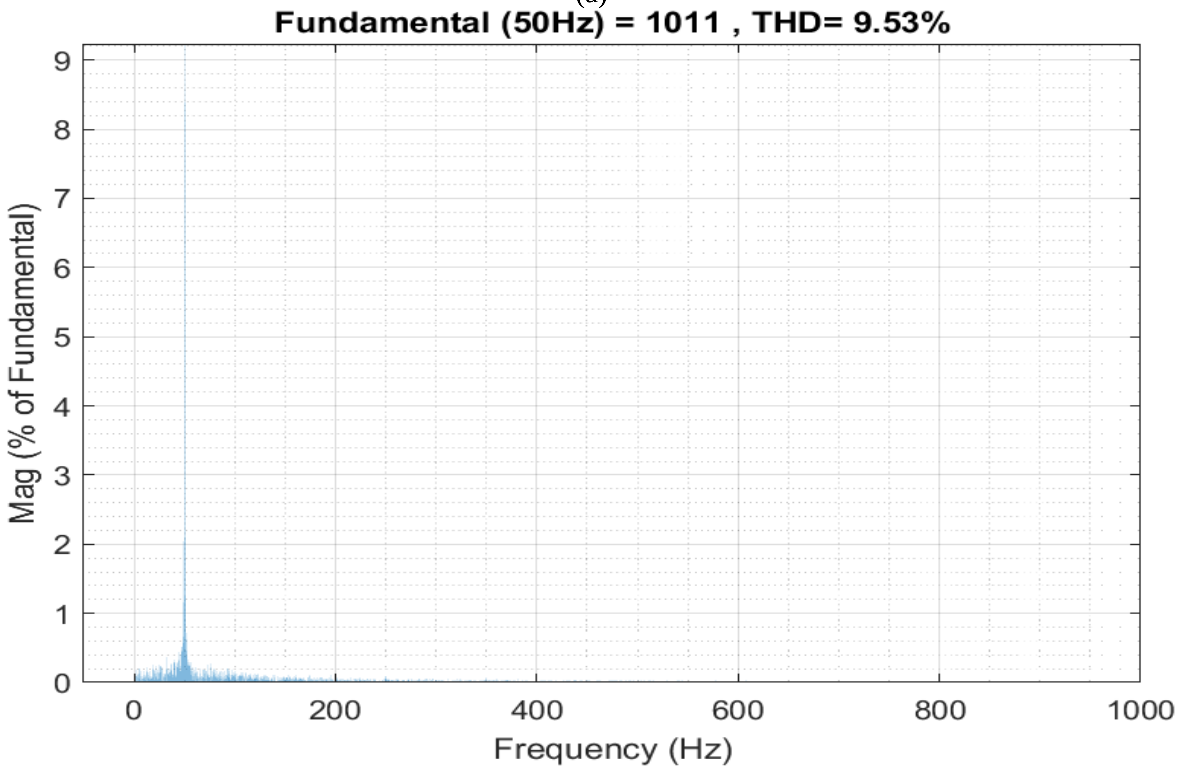


(b)

Fig. 13. Generator powers, (a)Active Ps, (b)Reactive Qs



(a)

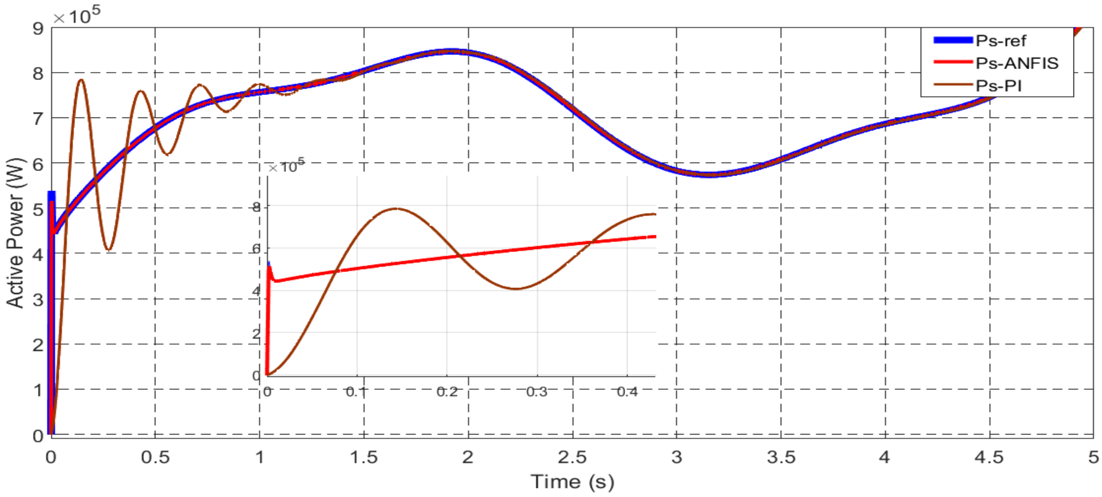


(b)

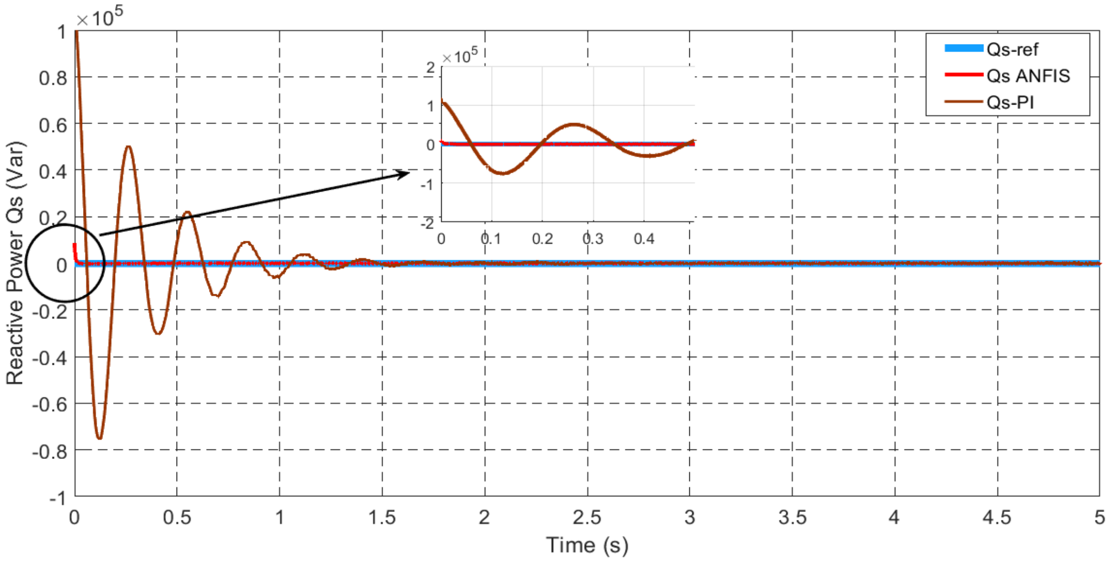
Fig. 14. THD for the stator current Isa of the two controllers: (a) IVC_ANFIS and (b) IVC-PI

The electromagnetic torque is shown in the line graph of Fig. 16 over a 5s time span for three different scenarios or control methods. Cem-Ref, Cem-PI, Cem-Anfis, was shaken at first, but then settled out in all three conditions. This graph mimics the response of the electromagnetic torque to the two control techniques in a typical robustness test.

The THD values obtained from the robustness test for the IVC-PI and IVC-ANFIS controls are displayed in Fig. 17, which clearly reveals that the THD in the IVC-ANFIS strategy (THD 9.12) is much lower than in the IVC-PI technique (THD 9.89).



(a)



(b)

Fig. 15. Robustness test- Generator powers, (a) Active Ps, (b) Reactive Qs

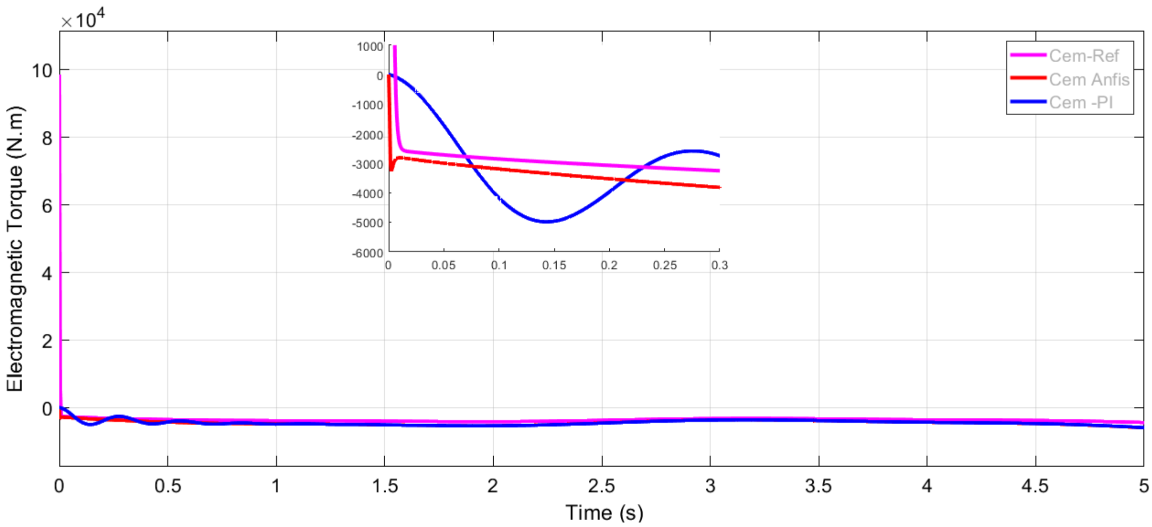


Fig. 16. Robustness test-Generator's torque

According to the obtained results, the MPPT strategy of the turbine with the ANFIS controller for vector control presents evident advantages. The rotational speed closely follows its reference, presenting a slight continuation error during transitional periods and a complete cancellation in permanent mode. On the direct axis, a favorable orientation of the rotary flow occurs, hence the electromagnetic torque is a mirror of the reference torque, which is good evidence of the control law designed with the controller. It presents a high grade in the load-disturbances sensitivity, although the rejection time is relatively short. The active and reactive powers also continue its benchmarks, and a THD rate is 9.12% for IVC-ANFIS and the THD ratio for the IVC - PI command is 9.89% which is higher than IVC – ANFIS.

The comparison of the IVC-PI and proposed IVC-ANFIS in terms of response time, set point tracking, and static error is summarized in Table 2. The impressive enhancements made possible by IVC-ANFIS are displayed in this Table 3. Optimization of the static error, response speed, set point tracking, and resilience are some of these enhancements.

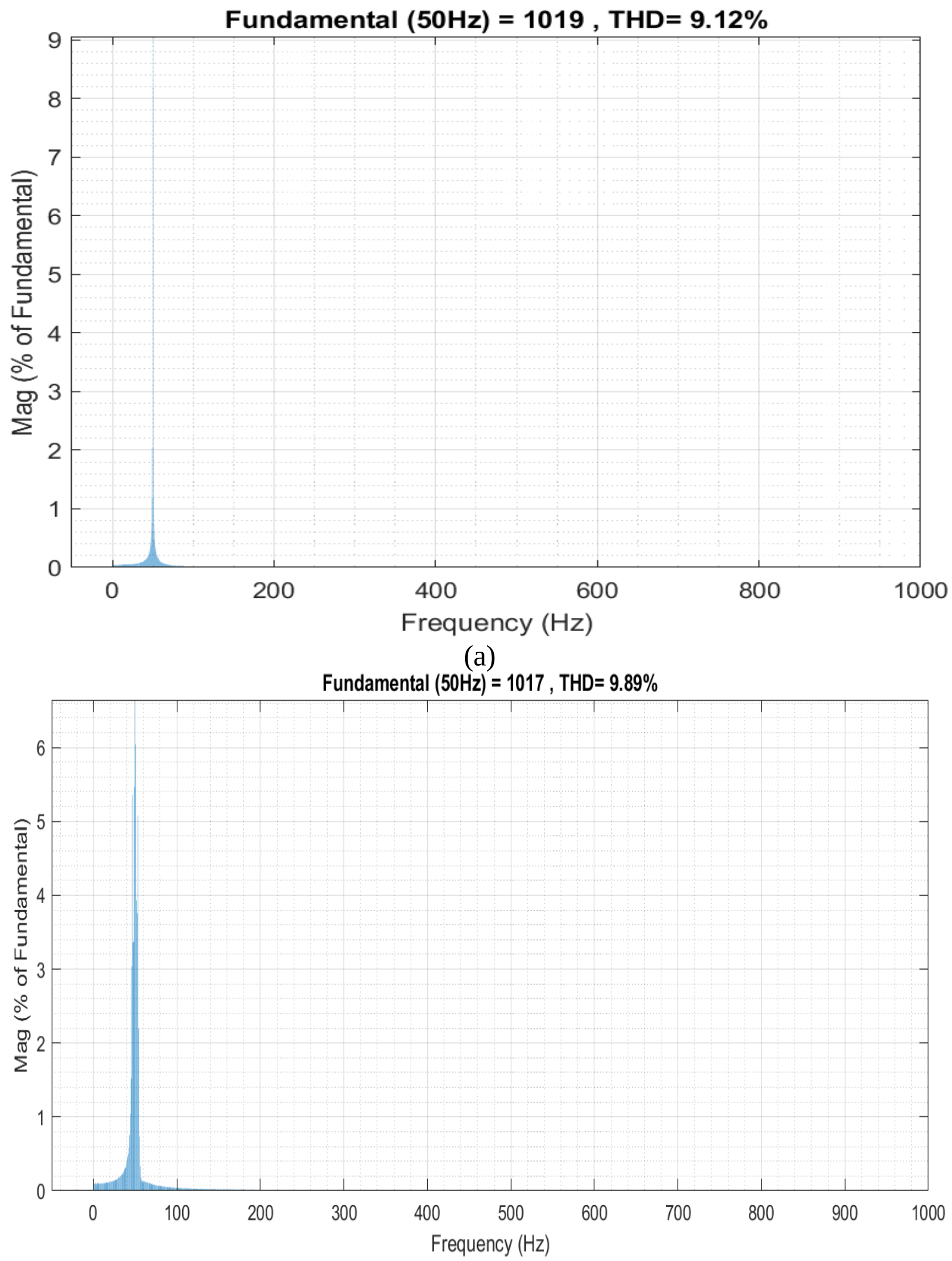


Fig. 17. THD robustness test for stator current Isa of the two controllers: (a) IVC_ANFIS and (b) IVC- PI

Table 2. Comparative study between the IVC-PI and the IVC-ANFIS

Performance	PI	ANFIS
Response time (s)	0.008	0.0013
Set-point tracking	Medium	Very Good
Robustness	Not Robust	Robust

Table 3. Comparison between the proposed ICV-ANFIS technique and those utilized in some existing papers

Reference paper	Technique	Response time (s)	Rise time (s)	Robustness
[56]	FOC used PI	0.56	0.18	Not Robust
[57]	Fuzzy logic	0.28	0.113	Robust
[58]	Backstepping	0.29	0.16	Robust
[59]	ISMC	0.28	0.111	Robust
Proposed	IVC-ANFIS	0.019	0.015	Robust

The ANFIS architecture, combining neural networks and fuzzy logic, can be computationally intensive, particularly for systems with multiple inputs and complex rules, which may affect the control system's response time. Implementation in existing wind turbine systems may require significant hardware upgrades, and integration with current control systems can be challenging. Scalability is a major issue, as the complexity of the ANFIS model grows exponentially with system size, potentially limiting its large-scale application. ANFIS performance heavily depends on the quality and quantity of training data, which may be difficult to obtain for all operating conditions. A trade-off between model interpretability and accuracy must be found. Although our tests showed some robustness, the ANFIS controller's performance under extreme or unforeseen conditions requires further investigation. Regular maintenance and updating of the model, as well as regulatory compliance, pose additional challenges. Integration with energy storage systems may require significant modifications to the current model. Finally, a comprehensive comparison with other advanced control techniques is necessary to fully evaluate the relative advantages and disadvantages of ANFIS in this application. Addressing these limitations and challenges is crucial for a balanced evaluation of the ANFIS control strategy, and future work should focus on mitigating these issues to enhance the practical applicability of ANFIS in DFIG-WT systems.

6. Conclusion

The goal of the research described in this paper is to integrate advanced control and optimization strategies to increase the operational efficiency and reliability of wind energy conversion systems. In order to convert wind energy into electrical energy as efficiently as possible, the main goal of this work is to design and build an Intelligent Indirect Vector Control (IIVC) system for a DFIG using the Adaptive Neuro-Fuzzy Inference System (ANFIS). The proposed ANFIS control strategy for DFIG system has the following benefits in increasing the conversion efficiency 4 – 6 %, Joule losses in the rotor 10 – 12 %, improving the time response by 18 – 22% with less than 6% overshoot. It also improves, on average, the degree of damping the electromechanical oscillations by 30 to 35 percent, frequency of unwanted tripping of the protection of the grid by 22 to 28 percent and the life span of the power converter parts by 15 to 18 percent. Therefore, the paper's fundamental contribution is the application of the ANFIS based IIVC system to the DFIG, which was trained to intelligently tune the DFIG parameters in order to adapt to different wind speed conditions and grid disturbances by selectively controlling the DFIG generator’s magnetic flux, torque, and reactive power. When compared to the traditional MPPT approach based on an IVC controller, the simulation results presented in this paper show the efficacy of the proposed MPPT-IIVC approach, which enhances wind energy capture, maintains generator speed regulation with minimal oscillations, and can support constant voltage as well as frequency at the load end despite the fluctuation in the load demand as well as in wind speed. It is also observed that the ANFIS controllers perform better than the proportional–integral (PI) controllers under several tests, in terms of robustness and precision. As a future study, the scalability and the applicability of the proposed system in different environmental conditions could be further scrutinized, allowing wind power to be an ultimate choice to all different energy resources, hence contributing to the sustainable and reliable energy to the world.

Wind power can be a sustainable source of energy though it is received issues such as intermittency, integration of wind power in the utility grid infrastructure, high cost of upfront investment and negative environmental impacts. These include; Storage technologies that are capable of storing energy for long periods, enhancement of the grid infrastructure and last but not least supportive policies that will promote the development of energy storage systems. These factors signify that there are challenges and solutions existing about the future of wind energy.

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