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An Analysis Comparing the Performance of Wind Energy Conversion Systems Utilising FLC Controllers

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Abstract: This research gives a comparative analysis of Proportional-Integral (PI) and Fuzzy Logic Control (FLC) controllers for control systems of wind energy conversion systems (WECS). The PI controller is a conventional control technique that is extensively employed due to its simplicity and efficacy in regulating system behaviour through the adjustment of proportional and integral gains. FLC, on the other hand, utilises language rules and fuzzy logic reasoning to imitate human decision-making processes, providing a flexible and adaptable control strategy. The selection between PI and fuzzy controllers is dependent on the particular demands and limitations of the control application. The comparison study evaluates the performance of PI and Fuzzy controllers in various control scenarios, specifically in the scenario of speed control of cascaded doubly fed induction generator (CDFIG). Wind energy conversion systems consist of CDFIG connected to the grid via a matrix converter or rectifier and inverter. This study will present numerical simulation results conducted using the MATLAB/Simulink program to demonstrate the feasibility and efficacy of the proposed control technique

Keywords: Fuzzy logic control, Wind energy, Cascaded doubly fed induction generator, Power converter

Introduction

The employment of approaches that are based on artificial intelligence in the management of the energy that is produced by wind turbines is becoming more than essential in today's world due to the complexity of the control of these turbines and the intermittent nature of the wind. Fuzzy logic is one of these new methods that we have discovered. The use of fuzzy logic allows for more accurate regulation of wind turbine power by taking into account variables that are uncertain or imprecise, such as the speed and direction of the wind and the changing weather conditions. In comparison to conventional controls, it enables adjustments to be made to the rotation speeds or blade angles in a more smooth and effective manner (Nasrullo, et al., 2022; Aghaloo et al., 2023)

Pitch angle control and dynamic vibration absorbers are incorporated into (Jiawei et al., 2024), in order to enhance the performance of wind turbines in environments that are challenging. For the purpose of controlling a variable-speed wind energy conversion system (WECS), the primary focus of this study in (Dendouga & Essounbouli, 2022) is on the research and design of a type-2 fuzzy logic controller (T2-FLC). Under these circumstances, the maximum power point tracking (MPPT) method has been implemented in order to collect the maximum amount of power that is available from the wind system, despite the fact that the wind conditions

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have been changing (Maafa, 2024). Significant research has been done about fuzzy controllers, but, a noticeable absence of comparison with other controllers to derive conclusions is evident. Therefore, this work aims to address this gap.

Comparing a conventional controller (PI) with an intelligent controller (FLC) is the objective of this work. The purpose of this comparison is to identify the most suitable control method for more effectively managing the generation of wind energy. The majority of wind turbines are equipped with a double fed induction generator (DFIG), which enables the generation of electrical energy at varying speeds. However, the existence of the ring-brush system diminishes the dependability of the machine. In order to address this issue, our proposal includes the electrical and mechanical coupling of two DFIGs through their rotors. The entire system is referred to as a cascade of asynchronous machines, often known as CDFIG (Maafa, 2016, 2022, 2024).

Description and Modelling of the CDFIG

The cascaded doubly fed induction machine (CDFIM) is a system that comprises two induction machines, each with a different number of pole-pairs (p1 and p2), coupled in a cascade configuration (Maafa et al,. 2023), (Hossain et al., 2023; Dauksha et al., 2020). The technology utilises two successive induction machines to avoid the need for brushes and copper rings in the conventional Doubly Fed Induction Machine (DFIM). The coupling is illustrated in Figure 1. There are two potential configurations for the rotor connections of both DFIMs. The connection of the same phases results in a direct connection, while the reverse order of two phases results in an opposite connection. Each coupling type of the CDFIM has distinct advantages. For direct connection, these include the elimination of copper contacts and brushes, power segmentation, and improved reliability. For a reverse connection, there is a represented rise in the number of paired poles, resulting in the elimination of the copper rings and brushes that make contact. For the rest of our study, we will focus on the inverse relationship.

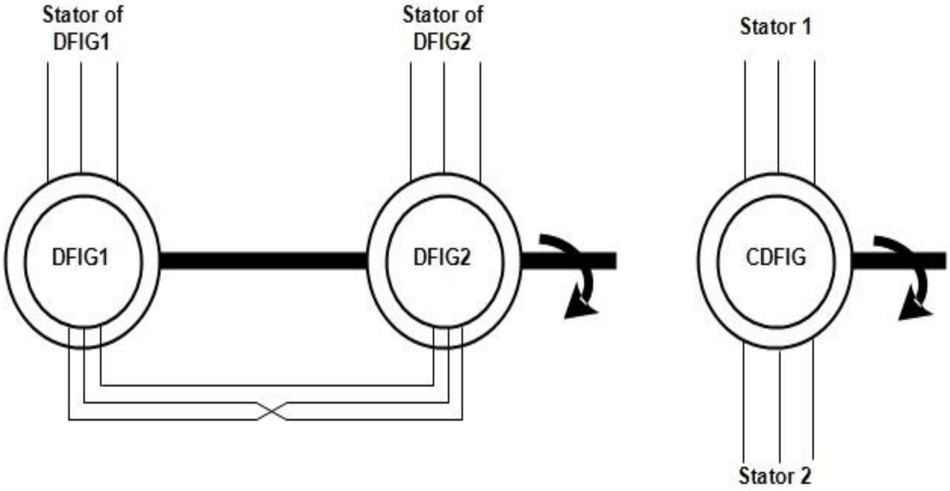


Figure 1. The mechanical and electrical coupling of two (DFIGs)

In the Park frame, all equations are written in a frame of reference that is related to the rotating field. The following equations can be used to determine the voltage and flux of the two DFIGs:

- The DFIG 1:

$$\begin{cases} v_{ds1} = R_{s1} i_{ds1} + \frac{d}{dt}\varphi_{ds1} - \omega_s \varphi_{qs1} \\ v_{qs1} = R_{s1} i_{qs1} + \frac{d}{dt}\varphi_{qs1} + \omega_s \varphi_{ds1} \\ v_{dr1} = R_{r1} i_{dr1} + \frac{d}{dt}\varphi_{dr1} - (\omega_s - \omega_{r1})\varphi_{qr1} \\ v_{qr1} = R_{r1} i_{qr1} + \frac{d}{dt}\varphi_{qr1} + (\omega_s - \omega_{r1})\varphi_{dr1} \end{cases} \tag{1}$$

-The DFIG 2:

$$\begin{cases} v_{dr2} = R_{r2} i_{dr2} + \dfrac{d}{dt}\varphi_{dr2} - (\omega_s - \omega_{r1})\varphi_{qr2} \\ v_{qr2} = R_{r2} i_{qr2} + \dfrac{d}{dt}\varphi_{qr2} + (\omega_s - \omega_{r1})\varphi_{dr2} \\ v_{ds2} = R_{s2} i_{ds2} + \dfrac{d}{dt}\varphi_{ds2} - (\omega_s - \omega_{r1} - \omega_{r2})\varphi_{qs2} \\ v_{qs2} = R_{s2} i_{qs2} + \dfrac{d}{dt}\varphi_{qs2} + (\omega_s - \omega_{r1} - \omega_{r2})\varphi_{ds2} \end{cases} \quad (2)$$

The flux of stators and rotors in a CDFIG may be mathematically represented as:

$$\begin{cases} \Phi_{ds1} = L_{s1} i_{ds1} + L_{m1} i_{dr} \\ \Phi_{qs1} = L_{s1} i_{qs1} + L_{m1} i_{qr} \\ \Phi_{dr1} = L_{r1} i_{dr} + L_{m1} i_{ds1} \\ \Phi_{qr1} = L_{r1} i_{qr} + L_{m1} i_{qs1} \end{cases} \quad (3) \text{ and } \begin{cases} \Phi_{ds2} = L_{s2} i_{ds2} - L_{m2} i_{dr} \\ \Phi_{qs2} = L_{s2} i_{qs2} - L_{m2} i_{qr} \\ \Phi_{dr2} = -L_{r2} i_{dr} + L_{m2} i_{ds2} \\ \Phi_{qr2} = -L_{r2} i_{qr} + L_{m2} i_{qs2} \end{cases} \quad (4)$$

Electric coupling between the two rotors is represented by the following model:

$$\begin{cases} v_{\mathrm{dr}1} = v_{\mathrm{dr}2} = v_{\mathrm{dr}} \\ v_{\mathrm{qr}1} = v_{\mathrm{qr}2} = v_{\mathrm{qr}} \end{cases} \quad (5) \text{ and } \begin{cases} \mathrm{i}_{\mathrm{dr}1} = -\mathrm{i}_{\mathrm{dr}2} = \mathrm{i}_{\mathrm{dr}} \\ \mathrm{i}_{\mathrm{qr}1} = -\mathrm{i}_{\mathrm{qr}2} = \mathrm{i}_{\mathrm{qr}} \end{cases} \quad (6)$$

The structure of the interconnections between the rotor circuits is designed in such a way that it is possible to add up the torques of each machines:

$$T_e = p_1.L_{m1}\left(i_{dr}.i_{qs1} - i_{ds1}.i_{qr}\right) + p_2.L_{m2}\left(i_{dr}.i_{qs2} - i_{ds2}.i_{qr}\right) \quad (7)$$

Through the process of aligning the axis d of the mark (dq) with the flux of the first stator ϕs1, the model that is obtained from CDFIG is achieved through simplification.

$$\begin{cases} \varphi_{ds1} = \varphi_{s1} \\ \varphi_{qs1} = 0 \end{cases} \quad (8)$$

The voltages can be automatically represented by the rotor currents in the following manner:

$$\begin{cases} v_{ds2} = R_{s2} i_{ds2} + (L_{s2} - C.L_{m2})\dfrac{di_{ds2}}{dt} - s.\omega_s\,(L_{s2} - C.L_{m2}).i_{qs2} \\ v_{qs2} = R_{s2} i_{qs2} + (L_{s2} - C.L_{m2})\dfrac{di_{qs2}}{dt} + s.\omega_s\,(L_{s2} - C.L_{m2}).i_{ds2} + s.\dfrac{L_{m1} V_s}{L_{s1}} \end{cases} \quad (9)$$

The two-phase components of the voltages of the second stator that are to be forced on the machine in order to generate the ids2 and iqs2 currents that are needed are expressed as vds2 and vqs2, respectively.

It is possible to regulate the powers of stator 1 by manipulating the currents of stator 2 using the following equation system:

$$\begin{cases} P_{s1} = -C.V_s\,\dfrac{L_{m1}}{L_{s1}}\,i_{qs2} \\ Q_{s1} = \dfrac{V_s^2}{\omega_s.L_{s1}}\left(1 + \dfrac{C.L_{m1}^2}{L_{s1}.L_{m2}}\right) - C.V_s\,\dfrac{L_{m1}}{L_{s1}}\,i_{ds2} \end{cases} \quad (10)$$

With: $s=\frac{\omega_s-(p_1+p_2)\Omega_r}{\omega_s}$ and $C=\frac{L_{m2}}{L_{r1}+L_{r2}-\frac{L_{m1}^2}{L_{s1}}}$

Control Method of the CDFIG

PI Controller

Regulation of wind power systems using proportional-integral has been the subject of a significant number of papers that have been published in the academic literature (Yessef et al, 2024; Preeti et al, 2024; Ramirez-Cabrera et al., 2024). Figure 2 depicts the closed loop system, which is then rectified by a PI controller. The form of the transfer function of the PI controller is as follows:

$$G_{PI}(S)=k_p+\frac{k_i}{S}$$

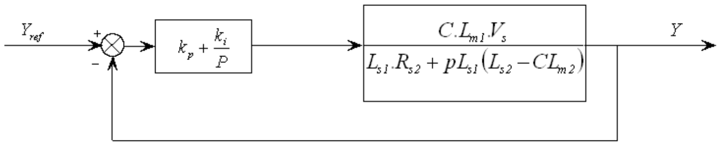


Figure 2. Design of PI controller

The response time of the system is around ten milliseconds, which is a sufficient amount of time for its application on wind turbines, which are characterized by moderate wind fluctuations and considerable mechanical time constants. Lowering the value may not boost overall performance, but it could potentially produce in disturbances during transient scenarios, resulting in undesirable exceeds its and instabilities. It is evident that the pole compensation approach is not the only appropriate way for the synthesis of the PI controller; however, we chose to utilize it because of its speed in this particular instance.

FLC Controller

In control systems when it is difficult or impossible to develop exact mathematical models, fuzzy controllers are employed. Their foundation is in fuzzy logic, a methodology capable of managing uncertainty and imprecision by employing truth values that are not binary "true" or "false", but rather degrees of truth. A significant number of academic papers have been published on the FLC controller (Kumbasar, 2016; Rubaai & Jerry, 2014; Nethaji & Kathirvelan, 2024; Majid, et al., 2023; Mukesh & Pradipta, 2024).

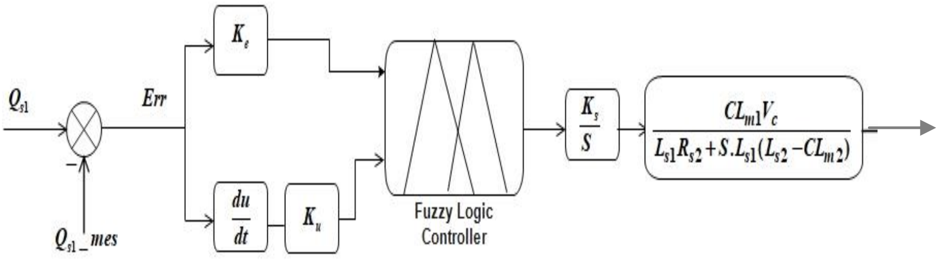
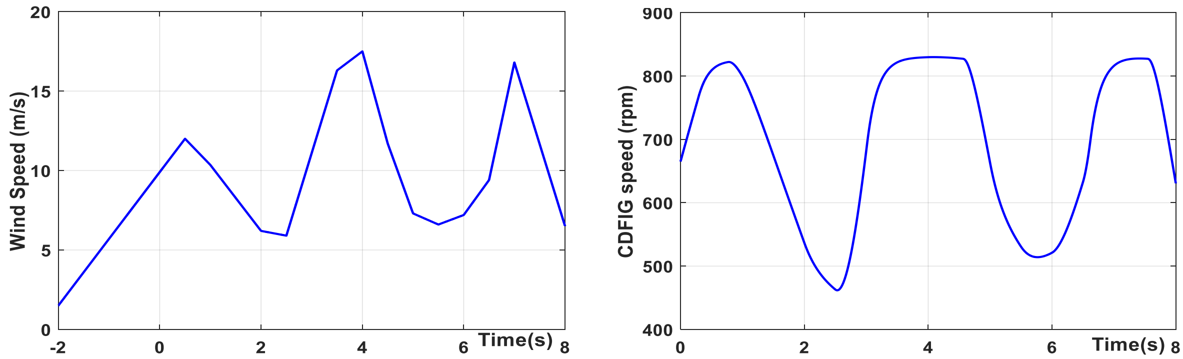


Figure 3. Design of fuzzy logic controller

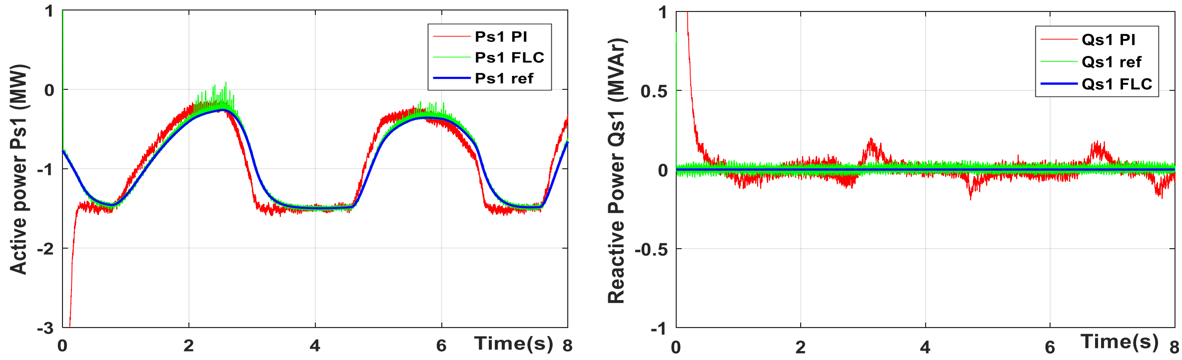
In order for a fuzzy controller to produce accurate results, it must undergo four stages: input fuzzying, rule base application, inference to integrate rule results, and defuzzification.

Results and Discussion

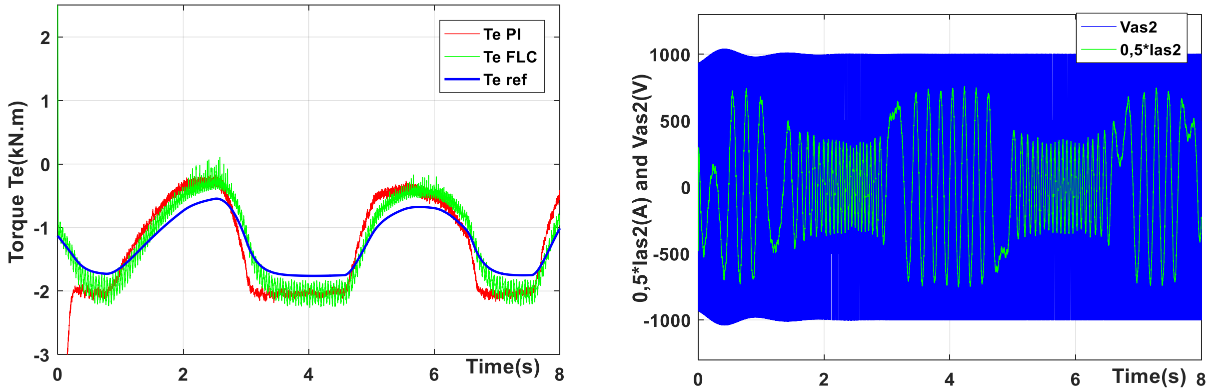
The goal of this part is to look at how the regulators (PI and FLC) responds to changes in the wind speed. We will use active power reference steps to compare the answers from the controls. Figure 4 shows how this test turned out.



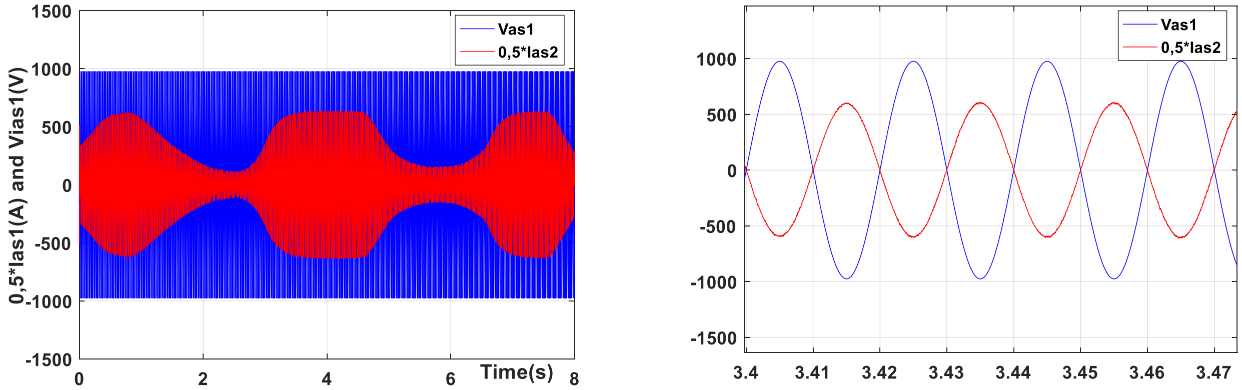
(a) (b)



(c) (d)



(e) (f)



(g) (h)

In Figure 4.a, the wind speed that was applied to the CDFIG is displayed. The speed of the wind is selected at random. The speed obtained by the CDFIG is depicted in Figure 4.b. We have observed that it is limited to a particular variation in wind speeds. The active power, reference, PI controller, and fuzzy controller of the first stator are each displayed in Figure 4.c, respectively.

The results show that the active power using the FLC controller is better compared to those of the PI controller in terms of tracking and disturbance rejection. When compared to the results obtained by the PI controller, the reactive power of stator 2 as shown in Figure 4.d for the FLC controller is in perfect accordance with its reference. A representation of the torque of the CDFIG is shown in Figure 4.e, together with the torque of reference, the torque of the PI controller, and the torque of the FLC controller. When compared to its reference, the torque of the FLC controller is the best.

An illustration of the voltage and current that are produced by the second stator may be found in Figure 4.f. Both the current and voltage of the first stator are depicted in Figures 4g and 4.h, respectively, along with their zoom. In order to demonstrate that the first stator is always the source of supply for the electrical network, it is important to take note that the current and the voltage are in phase opposition.

Conclusion

The management of power generated by wind turbines is increasingly utilizing approaches derived from artificial intelligence. The use of fuzzy controllers is a technique that may be utilized to solve problems that emerge during the process of injecting energy into the electrical network. One of the challenges that is discussed in this article is the process of selecting a controller that will satisfy the requirements that have been put by the electrical network management.

Through an analysis of the simulation data, it is evident that the performance of a fuzzy controller in terms of tracking and disturbance rejection is significantly better to that of a PI controller. Based on this, we can ultimately deduce the following conclusion: The introduction of a fuzzy controller enhances the efficiency of the system. By eliminating sliding ring-brush contacts, CDFIG offers a viable alternative for wind energy generation.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Acknowledgements or Notes

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