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Research paper

Control of a Wind Turbine based on DFIG by Improved Direct Torque Control using Fuzzy Logic

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ABSTRACT

The capacity of doubly-fed induction generators (DFIGs) to regulate both active and reactive power makes them a well-liked option for wind turbines. Direct Torque Control (DTC) is a commonly employed method for managing DFIGs, but it has limitations such as torque and flux ripples, which can reduce efficiency and cause stress on the turbine components. This study proposes a novel approach that combines DTC with a fuzzy logic controller (FLC) to address these limitations. Fuzzy logic control is a rule-based technique that can handle complex systems and nonlinearities. By incorporating FLC into DTC, the proposed Fuzzy Logic-based DTC (FH-DTC) seeks to enhance the WT-DFIG system's overall performance. MATLAB/Simulink simulations are used to evaluate the effectiveness of FH-DTC. The results are expected to demonstrate that FH-DTC significantly reduces torque and flux ripples compared to conventional DTC, leading to improved efficiency, reduced stress on turbine components, and ultimately, better overall performance of the WT-DFIG system.

1. INTRODUCTION

Wind turbines are a popular choice for renewable energy because they generate clean electricity and fight pollution and global warming. Among generators for these wind farms with varying speeds, doubly-fed induction generators (DFIGs) are known for their excellent performance, the capacity to manage both active and reactive power, and a broad variety of speeds [1].

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In the mid-1980s, a technique called direct torque control (DTC) was introduced [2]. DTC aims to find the best voltage vector for the rotor by considering errors, the rotor's flux sector, and pre-defined switching tables. A major challenge of DTC is the presence of significant fluctuations. Researchers have proposed various complex solutions to address this issue [3-6].

This research explores how a fuzzy logic controller can better the DTC's performance applied to a wind turbine with a DFIG (WT-DFIG) across its different operating modes. The goal is to minimize the drawbacks of conventional DTC (C-DTC) while keeping its benefits. This will be achieved by proposing an improved DTC based on fuzzy controllers (FH-DTC). The effectiveness of this approach will be demonstrated through comprehensive simulations conducted using MATLAB/Simulink software.

This paper makes three key contributions:

- Development of an FH-DTC system for DFIG wind turbines.
- Design of fuzzy hysteresis controllers for both torque and flux.
- Evaluation of the FH-DTC's performance through simulations under various WT-DFIG operating modes.

Ultimately, this study aims to prove the effectiveness of the proposed FH-DTC method for achieving high-performance wind energy conversion systems that utilize DFIGs.

The format of the paper is as listed below:

- DFIG wind turbines and conventional DTC concepts are introduced.
- Presentation of the proposed FH-DTC scheme and fuzzy controller designs.
- Analysis of MATLAB/Simulink simulation results to assess the proposed strategy's performance under changing wind speeds.
- Conclusion summarizing the key findings.

2. DESCRIPTION OF THE PROPOSED SYSTEM

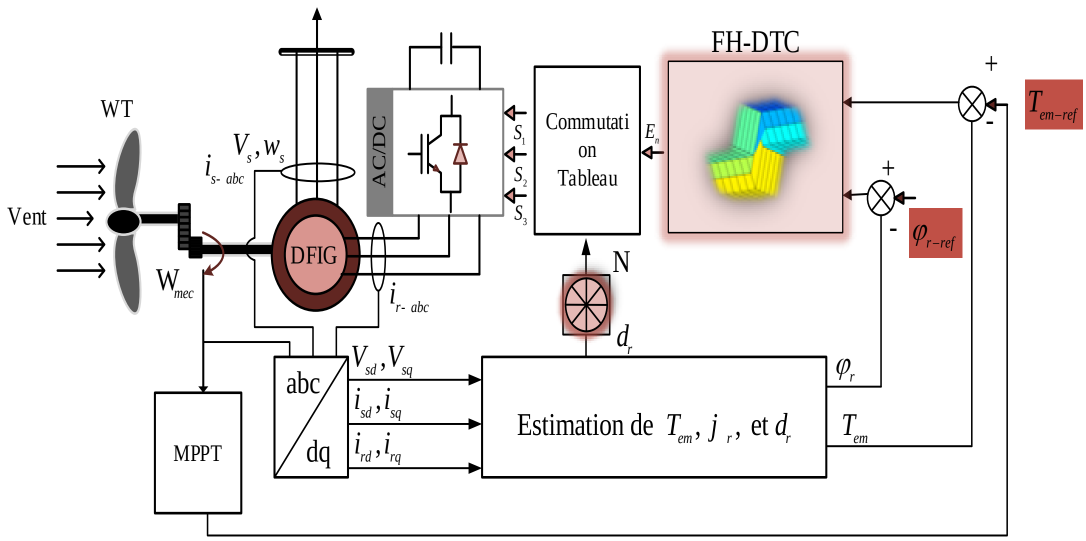

Fig 1. FH-DTC method applied to the WT-DFIG.

The Wind turbine-DFIG (WT-DFIG) system controlled by the proposed FH-DTC technique is illustrated in Fig. 1. This setup consists of a DFIG, a gearbox, and a wind turbine. While the DFIG rotor is connected to a two-level back-to-back power converter (an AC/DC and a DC/AC), Direct connection between the AC grid and the stator. The first rotor converter is connected to the DFIG rotor regulated by the suggested technique, the other converter is connected to the AC grid, and it delivers a sinusoidal current (50 Hz) with a unity power factor.

Then the MPPT algorithm allows the system to extract maximum power when the generated power is below the rated value [7].

The wind turbine's mechanical power is a function of wind speed v and power coefficient Cp, as presented in the following equation:

$$P_{mec}=0.5\rho\pi R^2 v^3 C_P(\lambda,\beta) \tag{1}$$

The DFIG's mathematical model in the d-q frame is given by:

$$\begin{cases} v_{sd}=R_s i_{sd}+\frac{d\varphi_{sd}}{dt}-\omega_s\varphi_{sq} \\ v_{sq}=R_s i_{sq}+\frac{d\varphi_{sq}}{dt}+\omega_s\varphi_{sd} \\ v_{rd}=R_r i_{rd}+\frac{d\varphi_{rd}}{dt}-\omega_r\varphi_{rq} \\ v_{rq}=R_r i_{rq}+\frac{d\varphi_{rq}}{dt}+\omega_r\varphi_{rd} \end{cases} \tag{2}$$

$$\begin{cases} \varphi_{sd}=L_s i_{sd}+Mi_{rd} \\ \varphi_{sq}=L_s i_{sq}+Mi_{rq} \\ \varphi_{rd}=L_r i_{rd}+Mi_{sd} \\ \varphi_{rq}=L_r i_{rq}+Mi_{sq} \end{cases} \tag{3}$$

In the d-q frame, the stator and rotor currents are denoted by I_sd, I_sq, and I_rd, respectively, and the stator and rotor voltages are represented by V_sd, v_sq, v_rd, and v_rq;

The mutual inductance between the rotor and stator is denoted by M. The electrical variable pulsations of the stator and rotor phase are denoted by ω_s and ω_r, respectively. The resistances of the rotor and stator are R_s, R_r.

3. DIRECT TORQUE CONTROL

To manage the DFIG, the DTC advanced approach adjusts the machine's rotor's magnetic flux and electromagnetic torque. It was first proposed by Takahashi and Noguchi in 1986 as an alternative to field-oriented control (FOC). DTC aims to directly select the AC/DC converter switching states to rapidly regulate flux/torque based on the errors between their references and estimated values. This differs from FOC which involves regulating current components through PI controllers. The principle of DTC is explained in [8]. The system under study is illustrated in Fig. 1.

The components along the α and β axes of the rotor currents and voltages are used to estimate the rotor magnetic flux, then the calculated values of the currents (irα, irβ) and the estimated flux values (φrα, φrβ) are used to estimate the electromagnetic torque. As illustrated by the equations that follow.

$$\begin{cases} \varphi_{r\alpha}(t)=\int_0^t (v_{r\alpha}-R_r i_{r\alpha}) \\ \varphi_{r\beta}(t)=\int_0^t (v_{r\beta}-R_r i_{r\beta}) \end{cases} \tag{4}$$

$$\varphi_r(t)=\sqrt{\varphi_{r\alpha}^2+\varphi_{r\beta}^2} \tag{5}$$

$$\theta_r=\tan^{-1}\left(\frac{\varphi_{r\beta}}{\varphi_{r\alpha}}\right) \tag{6}$$

$$T_{em}=P\left(\varphi_{r\alpha}i_{r\beta}-\varphi_{r\beta}i_{r\alpha}\right) \tag{7}$$

The hysteresis controller outputs (torque and rotor flux controllers) and the rotor flux vector position are used to select the optimal vector required using a switching table, As outlined in Table 1 [8].

To reduce the quantity of commutations in the arms of the AC/DC converter, the V0 and V7 vectors are alternated.

Table 1. Switching Table C-DTC

Hφ_r	**HT$_{em}$**	**N**					
		I	**II**	**III**	**IV**	**V**	**VI**
+1	-1	V_6	V_1	V_2	V_3	V_4	V_5
	0	V_7	V_0	V_7	V_0	V_7	V_0
	+1	V_2	V_3	V_4	V_5	V_6	V_1
-1	-1	V_5	V_6	V_1	V_2	V_3	V_4
	0	V_0	V_7	V_0	V_7	V_0	V_7
	+1	V_3	V_4	V_5	V_6	V_1	V_2

4. THE PROPOSED DIRECT TORQUE CONTROL

The suggested FH-DTC uses a fuzzy logic controller, rather than two hysteresis controllers to improve C-DTC performance. The FH-DTC design process includes fuzzification, defuzzification, and fuzzy logic rule-based control. The fuzzification process converts. By establishing membership functions for each input variable, the system converts input variables into linguistic variables, see Fig. 2. Fuzzy inference results are transformed into a quantitative output through the defuzzification procedure. The defuzzification method chosen is Bi sector and the output is a single numerical value with 6 singleton membership functions (E1, ..., E6), see Fig. 3.

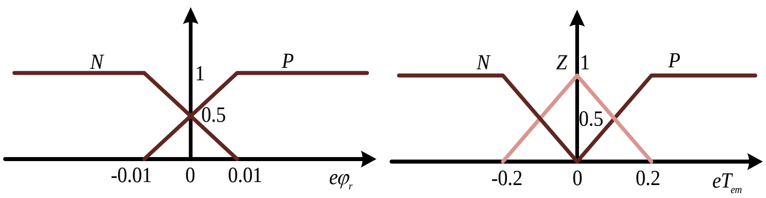

Fig 2. Inputs membership functions.

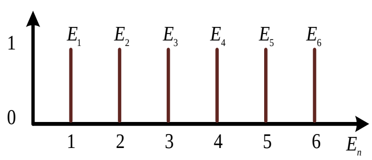

Fig 3. Output membership functions.

Finally, the fuzzy rules are designed according to a hysteresis operating principle and consist of 6 rules due to the number of membership functions per table 2 input. Based on the Max-Min decision rule, the Mamdani inference method is used to create the fuzzy logic switching controller.

The output of the numerical error powers (En) and the rotor flux sector utilizing switching table 3 will be used to determine the appropriate rotor voltage vector (Vn) for the inverter.

Table 2. Fuzzy Rules

eTem/eφ	**P**	**Z**	**N**
P	E_1	E_2	E3
N	E_4	E_5	E_6

Table 3. Switching Table FH-DTC

En	**N**					
	I	**II**	**III**	**IV**	**V**	**VI**
$\mathbf{E_1}$	V_2	V_3	V_4	V_5	V_6	V_1
$\mathbf{E_2}$	V_7	V_0	V_7	V_0	V_7	V_0
$\mathbf{E_3}$	V_6	V_1	V_2	V_3	V_4	V_5
$\mathbf{E_4}$	V_3	V_4	V_5	V_6	V_1	V_2
$\mathbf{E_5}$	V_0	V_7	V_0	V_7	V_0	V_7
$\mathbf{E_6}$	V_5	V_6	V_1	V_2	V_3	V_4

5. SIMULATION RESULTS

The three working modes of the DFIG are made possible by the effectiveness of the proposed approach, which is applied to control a WT-DFIG system. MATLAB/Simulink is used to conduct the investigation. wherein [7] describes the system parameters.

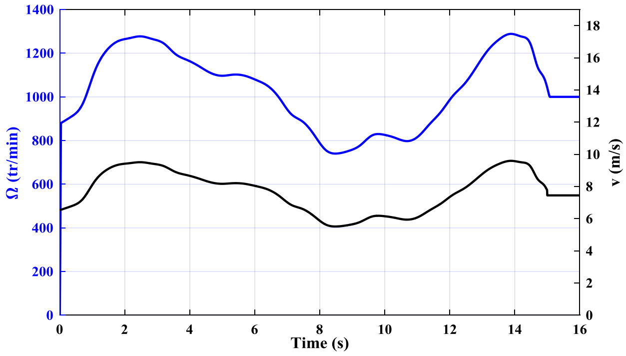

Fig 4. Ω and v responses.

The figures included in the research paper serve as a testament to the system's performance under varying operational conditions. Figure 4 convincingly demonstrates operation in all three modes by directly comparing wind speed with the DFIG's rotational speed. This figure establishes that the control system effectively regulates the DFIG's speed to match the wind speed across the entire operational range. Figures 5 and 6 delve deeper into the system's internal characteristics, portraying torque/rotor flux, respectively. The torque response in Figure 5 exhibits excellent tracking of both the wind speed and its reference value, signifying the control system's ability to maintain the desired torque output despite fluctuations in wind conditions. Furthermore, Figure 6 reveals that the rotor flux maintains a constant value at its reference, indicative of stable magnetic field conditions within the DFIG. These observations collectively provide strong evidence that the proposed control method (FH-DTC) outperforms conventional methods (C-DTC).

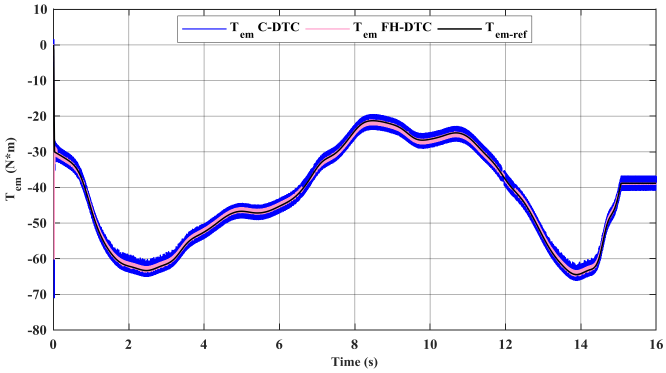

Fig 5. Electromagnetic torque and its reference.

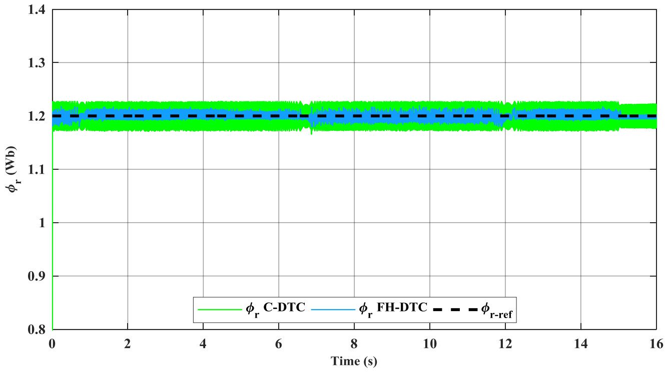

Fig 6. Rotor flux and its reference.

Figs. 7 and 8 depict the rotor flux in a circular pattern, with a consistent amplitude of 1.2 Wb. This is because the flux components exhibit sinusoidal variations across all operational modes. Figure 9 reveals that the stator current amplitude increases as the rotational speed rises, but the frequency remains constant at 50 Hz regardless of mode changes.

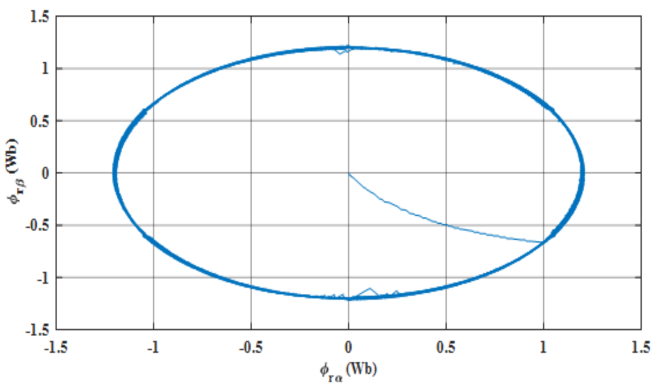

Fig 7. Rotor flux.

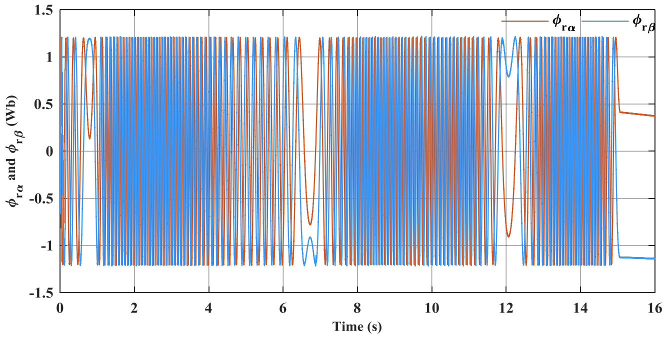

Fig 8. Waveforms of rotor flux.

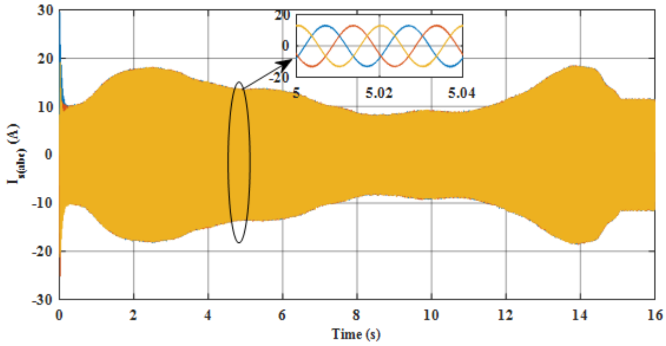

Fig 9. Stator currents.

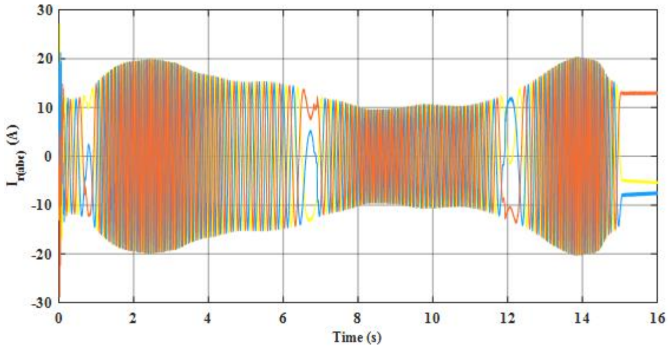

Fig 10. Rotor currents.

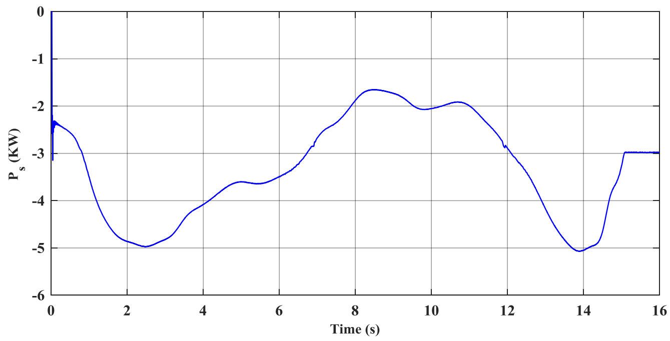

Fig 11. Stator active power.

Figure 10 illustrates how the rotor current amplitude adjusts with the rotational speed, while its frequency is directly impacted by variations in slip. Notably, during synchronous operation, the rotor currents transition to DC with a zero frequency.

Examining Fig 11, the negative stator active power (PS < 0) signifies that the system functions as a generator. The negative symbol indicates that this power is returned to the electrical grid. Fundamentally, the research effectively executed an innovative control method that enables the WT-DFIG to function efficiently in all of its operational modes while ensuring consistent power generation.

6. CONCLUSIONS

This paper presents a novel doubly-fed induction generator (DFIG)-based fuzzy logic control system for DTC in a wind energy system. This fuzzy hysteresis-based direct torque control (FH-DTC) technique is designed to address the shortcomings of traditional DTC approaches.

FH-DTC offers a promising solution to overcome the limitations of Conventional DTC (C-DTC) in WT-DFIG systems. The simulations confirmed that using FH-DTC enhances the overall system's performance.

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