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Fuzzy SVM Inverter-Based Field-Oriented Control of a DFIG used in a Wind Turbine

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Abstract: This research paper presents an advanced control strategy for Doubly Fed Induction Generators (DFIGs) used in wind turbines (WT), focusing on the implementation of a Field-Oriented Control (FOC) method combined with a fuzzy space vector modulation (FSVM) inverter approach. The proposed FSVM inverter-based direct vector control aims to optimize the performance of the DFIG by reducing stator current harmonics and active and reactive power ripples under varying wind conditions. The control strategy utilizes the FSVM algorithm to enhance the voltage and current control of the system, ensuring improved dynamic performance and stability. The paper outlines the mathematical modeling of the DFIG system, the design of the FSVM-based control algorithm, and simulation results demonstrating the effectiveness of the approach in achieving higher efficiency and better system response compared to traditional control techniques.

Keywords: Doubly fed induction generators (DFIGs), Fuzzy logic, Space vector modulation (SVM)

Introduction

Although the doubly-fed induction generator (DFIG) has the disadvantage of requiring collector brushes, which reduce its robustness and necessitate frequent maintenance, its adoption in renewable energy systems continues to grow. This is due to its operational principle, which enables power adjustment on the rotor, facilitating the control of the power delivered to the grid through the connection between the rotor and the grid [Khati (2024)-Decai (2020)]. This widespread interest is reflected in the extensive body of research and publications that focus on the application of DFIG in Wind Turbine Systems (WTS) (Maksud, 2024; Yaichi, 2023).

On the other hand, various control techniques have been employed for torque and power management of the DFIG, such as Sliding Mode (SM) (Kouadria, 2024), Neural Network (NN) (Sharadbhai,2021), Field Oriented Control (FOC) (Zoubir, 2018) and Backstepping (Anwar ,2016; Adekanle, 2017) among others. However, these methods often result in high Total Harmonic Distortion (THD) in the stator currents and significant power ripples (Benbouhenni, 2018), particularly when combined with Pulse Width Modulation (PWM) inverters, which are commonly used in electrical machine control. Unfortunately, these inverters also introduce additional harmonics in flux, power, and torque.

To solve this problem, Gouaamar (2025) proposed a new method for controlling the converter, known as Space Vector Modulation (SVM). The advantage of SVM is its ability to minimize THD, with its underlying principle discussed in Reghioui (2019). However, this method also has some limitations, such as variable switching frequency and high ripples caused by hysteresis regulators.

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To enhance the control of active and reactive powers in DFIG, this study suggests substituting the hysteresis blocks in SVM with fuzzy logic controllers for improved performance. This approach is referred to as Fuzzy SVM (see Fig. 5). In addition, fuzzy logic technology is not based on a complex mathematical model (Khati, 2020). Moreover, the Fuzzy SVM minimizes harmonic distortion in the stator currents.

This article is structured as follows: first, we introduce the DFIG using the d-q reference model. Next, we provide a detailed explanation of the DVC of DFIG with inverter SVM. We then describe the fuzzy logic system to be applied to the inverter SVM. Finally, we simulate the overall control strategy of the system.

DFIG Model

The DFIG is represented in the Park (d-q) model by the following equations [2]:

$$\begin{cases} V_{sd} = R_s.I_{sd} + \frac{d\psi_{sd}}{dt} - \omega_s.\psi_{sq} \\ V_{sq} = R_s.I_{sq} + \frac{d\psi_{sq}}{dt} + \omega_s.\psi_{sd} \\ \omega_r = \omega_s - p.\Omega \\ V_{rd} = R_r.I_{rd} + \frac{d\psi_{rd}}{dt} - \omega_r.\psi_{rq} \\ V_{rq} = R_r.I_{rq} + \frac{d\psi_{rq}}{dt} + \omega_r.\psi_{rd} \end{cases} \quad (1)$$

$$\begin{cases} \psi_{sd} = L_s.I_{sd} + M.I_{rd} \\ \psi_{sq} = L_s.I_{sq} + M.I_{rq} \\ \psi_{rd} = L_r.I_{rd} + M.I_{sd} \\ \psi_{rq} = L_r.I_{rq} + M.I_{sq} \end{cases} \quad (2)$$

Where, R_s, R_r, L_s, L_r and M : Parameters of the generator.
ψ_{sdq} and ψ_{rdq} : Stator and rotor flux.
ω_s and ω_r : Stator and rotor pulsation.
Ω: Mechanical speed.
p: Number of pair of poles

The mechanical equation of the system is expressed as:

$$T_e = T_r + J\frac{d\Omega}{dt} + f\Omega \quad (3)$$

Where: T_e: Electromagnetic torque
T_r: Load torque
J: Inertia
f: Viscous friction coefficient

And the electromagnetic torque can be expressed as:

$$T_e = p.M\left(I_{rd}.I_{sq} - I_{rq}.I_{sd}\right) \quad (4)$$

Similarly, the active power and reactive power of the stator are given by the following expressions:

$$\begin{cases} P_s = \frac{3}{2}\left(V_{sd}.I_{sd} + V_{sq}.I_{sq}\right) \\ Q_s = \frac{3}{2}\left(V_{sq}.I_{sd} - V_{sd}.I_{sq}\right) \end{cases} \quad (5)$$

Where: P_s: Stator's active power, Q_s: Stator's reactive power

Field-Oriented Control

The principle of this control is to align the stator flux vector with the "d" axis, thereby eliminating it along the "q" axis [4] (Fig. 1), also called Direct Vector Control (DVC).

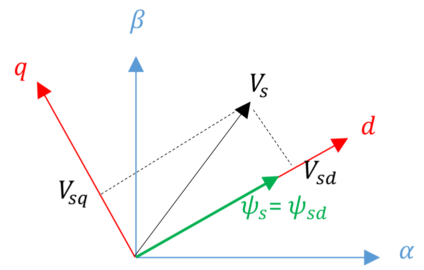


Figure 1. Stator flux oriented along the "d" axis

$\psi_s = \psi_{sd}$ and $\psi_{sq} = 0$

With negligible R_s from (1), we can write:

$$\begin{cases} V_{sd} = 0 \\ V_{sq} = \omega_s . \psi_{sd} \end{cases} \tag{6}$$

$$\begin{cases} I_{sd} = -\frac{M}{L_s} I_{rd} + \frac{\psi_s}{L_s} \\ I_{sq} = -\frac{M}{L_s} I_{rq} \end{cases} \tag{7}$$

And (5) becomes:

$$\begin{cases} P_s = -\frac{3}{2} \frac{\omega_s \psi_s M}{L_s} I_{rq} \\ Q_s = -\frac{3}{2} \left(\frac{\omega_s \psi_s M}{L_s} I_{rd} - \frac{\omega_s \psi_s^2}{L_s} \right) \end{cases} \tag{8}$$

Also (4) becomes:

$$T_e = -\frac{3}{2} p . \frac{M}{L_s} . I_{rq} . \psi_s \tag{9}$$

Figure 2 depicts the concept of the DVC technique using an SVM inverter to control the DFIG. In contrast,

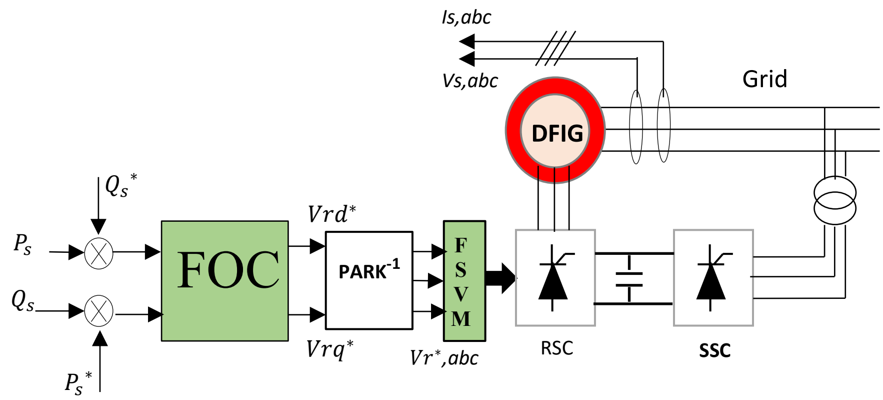


Figure 2. DVC of DFIG scheme

Fuzzy SVM

The inverter can be controlled using various methods. Many studies have utilized the Pulse Width Modulation (PWM) technique, while others have applied alternative methods such as Discrete Pulse Width Modulation (DPWM), as shown in Gaballah (2013). Additionally, Su (2025) proposed the Space Vector Modulation (SVM) technique, which is also commonly used to modulate inverters. This method relies on calculating the angles and parameters of sectors. However, Benbouhenni (2018) introduced a new SVM inverter that eliminates the need for sector and angle calculations. Instead, it computes the maximum and minimum of balanced voltages (Fig. 3). This version of SVM offers several advantages, including the absence of sector identification, no need for angle information, and no reliance on lookup tables to calculate switching times. Furthermore, it delivers high performance in real-time control systems (Qiu,2025).

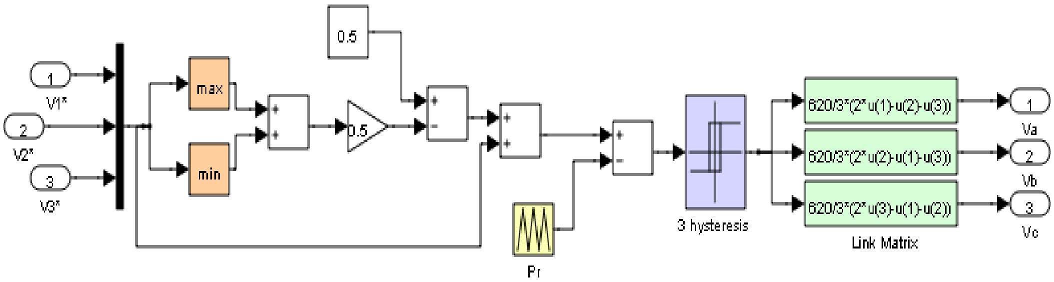


Figure 3. SVM inverter command

In this section, we propose replacing the hysteresis blocks in SVM with fuzzy logic controllers to improve the control performance. This approach is referred to as Fuzzy SVM (Fig. 4). On the other hand, fuzzy logic technology does not require a complex mathematical model (Khati, 2020). Additionally, the Fuzzy SVM minimizes harmonic distortion in stator currents.

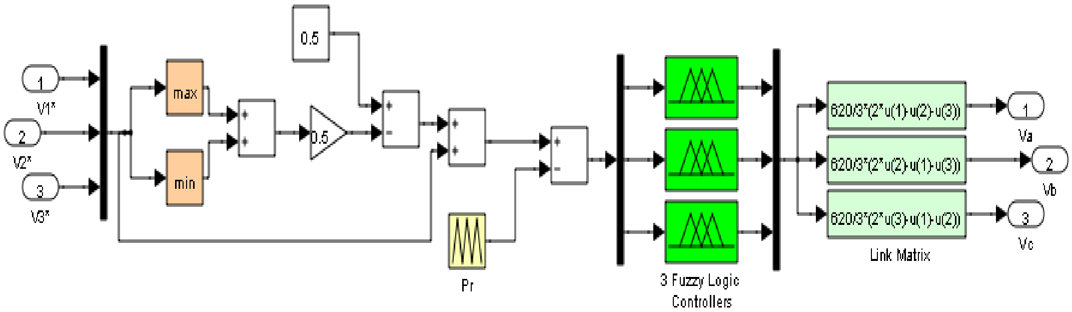


Figure 4. Fuzzy SVM inverter

Figure 5 illustrates the main structure of the Fuzzy logic controller. The proposed Fuzzy Logic controller is based on hysteresis controllers. The most commonly used fuzzy controller is the *e*-Δ*e* controller, which is a two-input fuzzy controller that generates a command output. Here, *e* represents the error, and Δ*e* denotes the variation in error.

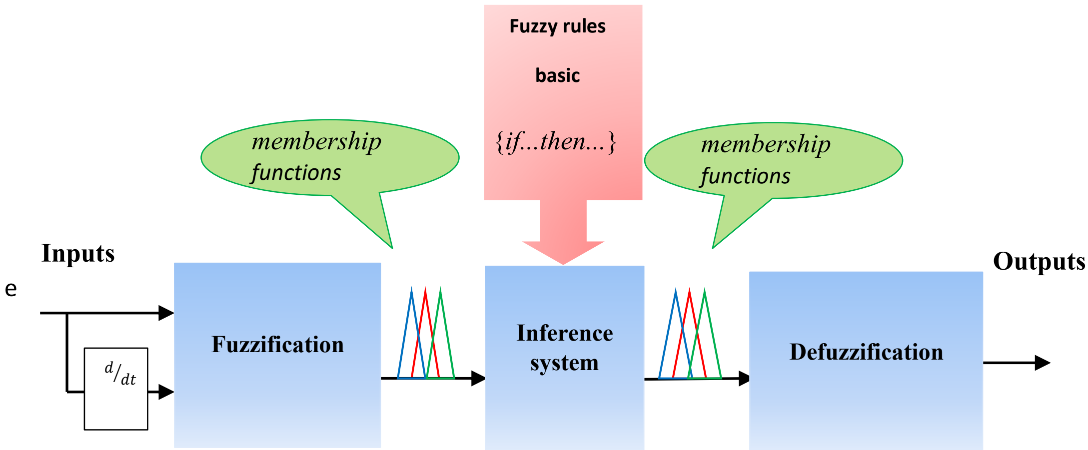


Figure 5. Internal structure of fuzzy rules

To generate a fuzzy command, several components must be chosen, including the linguistic information model, the inference process, the aggregation process, and the defuzzification process. For the linguistic variables *e* (error) and Δ*e* (error variation), the following linguistic values are defined: Negative Big (**NB**), Negative Middle (**NM**), Negative Small (**NS**), Positive Small (**PS**), Positive Big (**PB**), Positive Middle (**PM**), and Equal Zero (**EZ**). The definition of the membership function for both the input and output is provided in Figure 6.

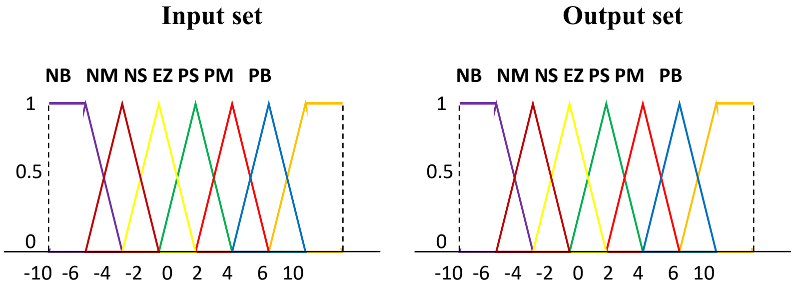


Figure 6. Membership function for the input and output

The fuzzy rules governing this system are formulated as follows:

{IF e is NB and Δe is NB THEN s is NB
(IF e is NB and Δe is NM THEN s is NB
{IF e is PB and Δe is PM THEN s is PB*T*

The seven fuzzy sets, defined by their membership functions for both *e* and Δ*e*, allow the construction of 49 distinct rules. These rules are presented in Table 1 **(**Sunori, 2025).

Table 1. Inference matrix

e / Δe	NB	NM	NS	EZ	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	EZ
NM	NB	NB	NB	NM	NS	EZ	PS
NS	NB	NB	NM	NS	EZ	PS	PM
EZ	NB	NM	NS	EZ	PS	PM	PB
PS	NM	NS	EZ	PS	PM	PB	PB
PM	NS	EZ	PS	PM	PB	PB	PB
PB	EZ	PS	PM	PB	PB	PB	PB

Figure 7 illustrates the parameters of the fuzzy controller. To view this figure, simply type ">> fuzzy" in the MATLAB workspace window.

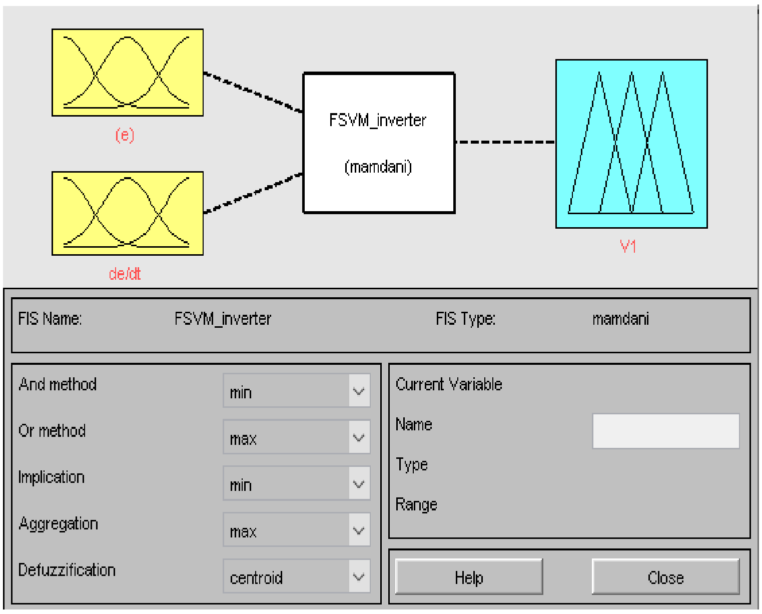


Figure 7. Fuzzy controller parameters

Simulation Results

To simulate the diagram shown in Fig. 2, we used MATLAB/Simulink software. The parameters of the DFIG are provided in the following table. To improve the system's response time and achieve optimal energy performance, it is necessary to maintain the reactive power at zero, ensuring a unity power factor. However, to test the reference tracking, we increased the reactive power reference after one second.

Table 2. DFIG parameters

Pn=*1.5 (MW)*
Vs=*398 (V)*
fs=*50 (Hz)*
P=2
Rr=*0.021 (Ω)*
Rs=*0.012 (Ω)*
Lr=*0.0136* (H)
Ls=*0.0137* (H)
M=*0.0135* (H)
f=*0.0024 (Nm/s)*
J=*1000* $(Kg.m^2)$

Reference Tracking Test

The simulation results for reference tracking of stator currents, torque, active and reactive power are presented in Figs. 8-10. As shown in Fig. 8, both the active power and reactive power successfully track their references with a highly acceptable response time of approximately 0.03s. It is clearly observed that the active power ripples, reactive power ripples, and torque ripples are all zero. This is undoubtedly attributed to the inverter's Fuzzy SVM. Finally, Figs. 9-10 demonstrate that the stator currents and torque track their respective references without any overshoot.

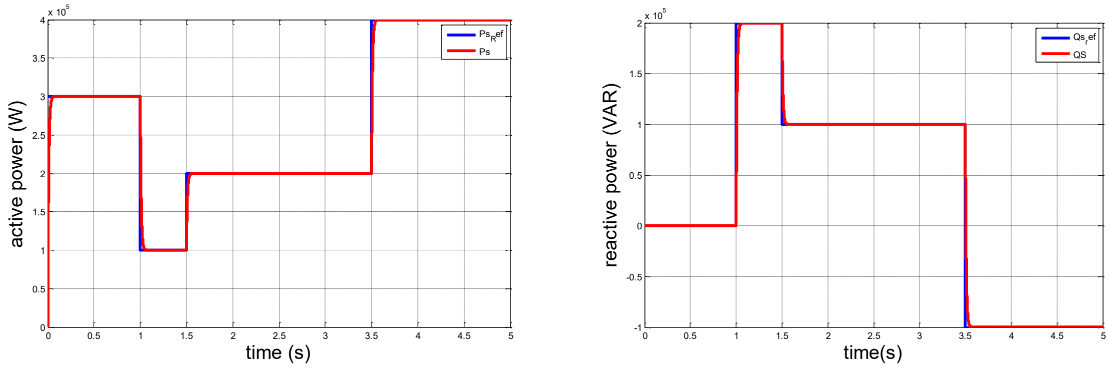


Figure 8. Active and reactive power (Reference tracking test)

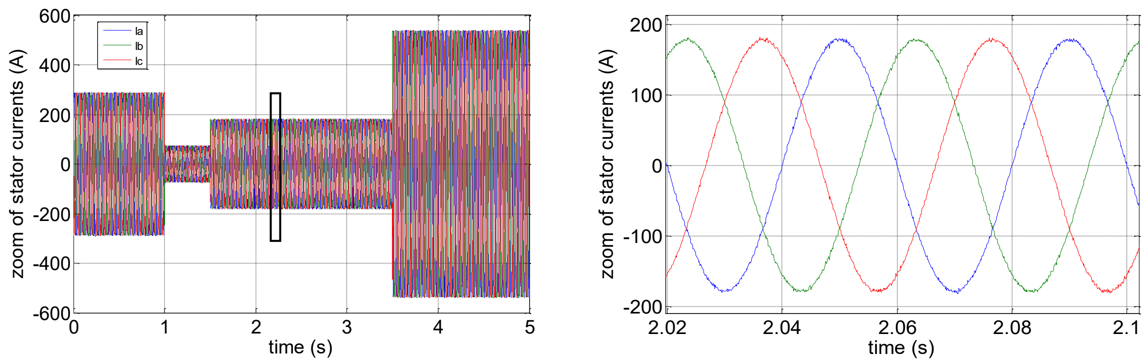


Figure 9. Stator currents (Reference tracking test)

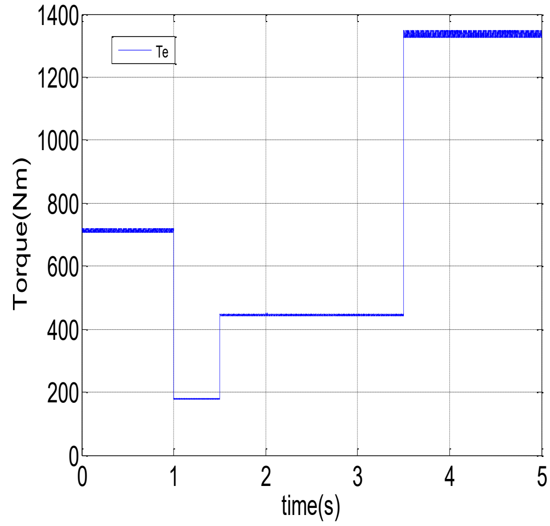


Figure 10. Torque (Reference tracking test)

Robustness Test

The robustness test involves modifying the electrical and magnetic parameters of the machine to evaluate the accuracy and reliability of the proposed control method. In this test, the rotor and stator resistances are increased, while the rotor, stator inductance and mutual inductances are reduced to 75% of their nominal values at the 0.5 second. The results demonstrate that the selected method is insensitive to variations in machine parameters. As shown in Figs. 11-13, the active power, reactive power, torque, and stator currents remain unaffected by these variations, despite some ripples that become noticeable after 0.5 seconds of simulation.

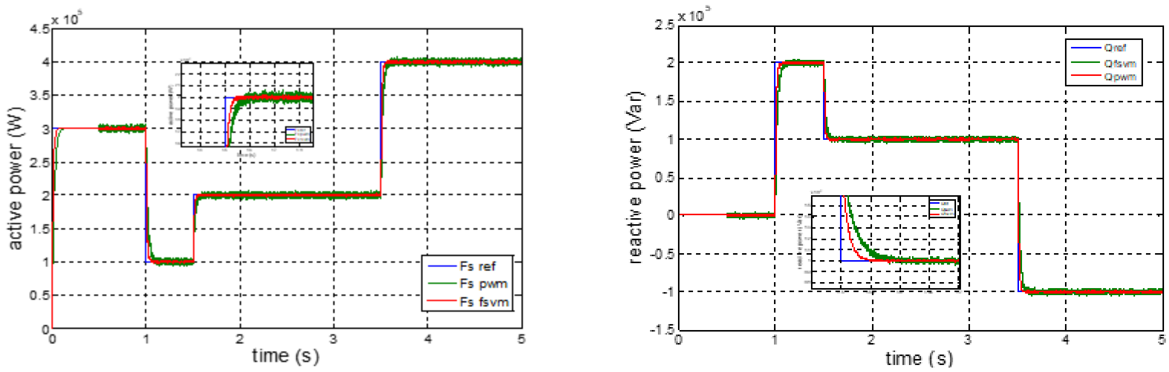
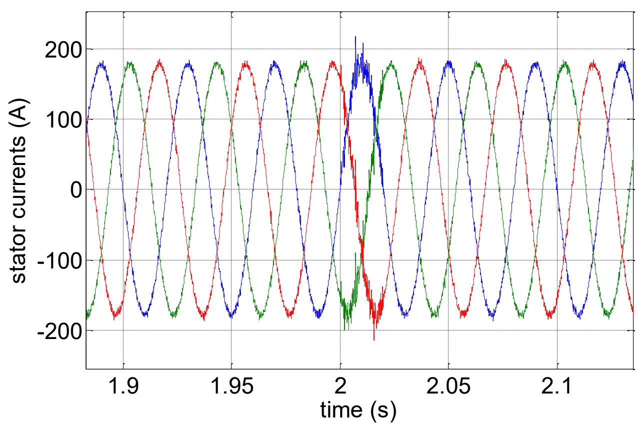


Figure 11. Active and reactive power for variations of machine parameters at 2s



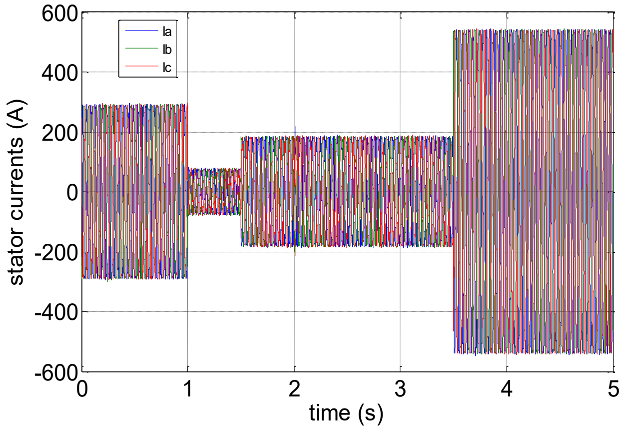


Figure 12. Stator currents for variations of machine parameters at 2s

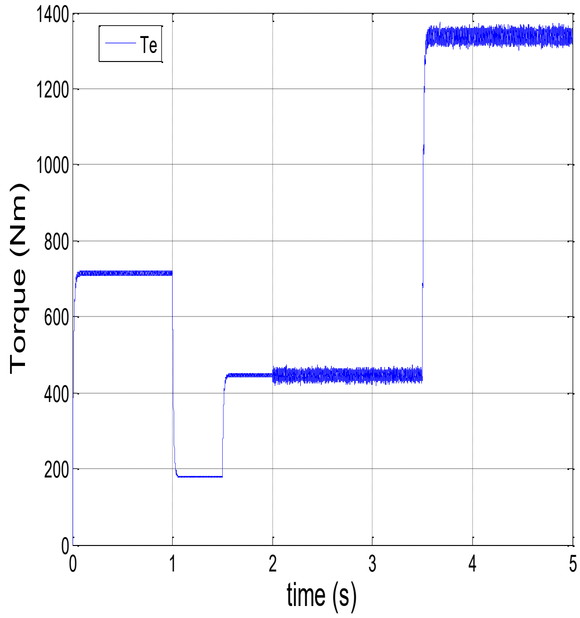


Figure 13. Torque for variations of machine parameters at 2s

Conclusion

This research utilizes artificial intelligence to control the active and reactive power of a DFIG using the Space Vector Modulation (SVM) technique. The proposed method is straightforward to implement and takes into account the estimation of key variables such as electromagnetic torque, stator active and reactive power, and stator currents. Furthermore, the integration of a Fuzzy SVM converter significantly reduces stator current ripples. The combination of the direct Vector Control (DVC) strategy with the Fuzzy SVM-based converter enhances the overall performance of the machine drive system.

Scientific Ethics Declaration

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

Conflict of Interest

* The authors declare that they have no conflicts of interest

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