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Optimization of the Powers Exchanged between a Cascaded Doubly Fed Induction Generator and the Grid with a Matrix Converter

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Abstract: The use of an electromagnetic converter of great reliability in wind energy, like the cascaded doubly fed induction generator (CDFIG), can solve several problems compared to the doubly fed induction generator (DFIG), among them the elimination of the brushes and copper rings. The work consists of studying the performance of a CDFIG-based wind system using a matrix converter and a variable pitch control system. The traditional PI is able to successfully solve a number of linear control problems. The fuzzy logic controller used can dramatically improve the system's performance. The active and reactive energy transferred between the CDFIG and the grid can be controlled by adjusting the machine inverter. The DC bus voltage has been kept stable by controlling the grid inverter. The pitch controller's objective is to maximise aerodynamic power while staying within the converter's power limits. Numerical simulation results implemented in the MATLAB/Simulink package will be provided in this study to show that the suggested control strategy is both possible and effective.

Keywords: Variable speed wind turbine, Cascaded doubly fed induction generator, Fuzzy logic controller, Matrix converter

Introduction

The penetration rate of renewable energies in many countries continues to increase because the geopolitical context in the world. Wind energy is one of the promising energies among these renewable energies. Wind turbines are installed all over the world whether in the offshore or onshore. The structure described in this study includes the utilization of a cascaded doubly-fed induction generator with variable speed, which is interconnected with the grid by a matrix converter using variable pitch control system. The cascaded doubly fed induction generator (CDFIG) is made up of two induction generators with p1 and p2 pole-pairs that are mechanically and electrically connected in cascade via their rotors to eliminate the brushes and copper rings observed in typical doubly fed induction machines. (DFIM). (Maafa et al., 2022 ; Admowicz et al. 2008 ; Maafa, et al. 2016 ;Achkar et al. 2017 ;Moazen et al., 2016 ; Zahedi Abdolhadi et al., 2021 ;Yan & Cheng, 2019). The increasing costs associated with maintaining conventional doubly-fed induction generator

(DFIG) resulted in a need to explore alternate generator systems. Because they behave similarly, the CDFIG is a good choice to replace the DFIG. (Poitiers et al., 2009 ; Aouzellag et al., 2009 ; Adjoudj et al., 2011 ; Ghedamsi et al., 2008 ;Kerboua & Abid, 2012).

The three-phase matrix converter (MC) is one of the most recent types of direct-power AC-AC converters. There are a total of nine bidirectional switches. The capacity to invert the direction of power transmission through the MC is one of the many advantages of the MC over typical AC-AC converter topologies (Alesina & Venturini, 1989). The effect of the nonlinearities has been minimized successfully when applying the fuzzy logic controller (Tokachichu & Gaddam, 2022 ;Kerboua & Abid, 2012). The superiority of the studied control strategy over the traditional PI regulator has also been proved through a number of numerical simulation results.

A wind turbine with variable pitch control was designed. The wind turbine's rotating speed can be kept constant by adjusting the variable pitch angle of the blade, allowing rated electric power to be produced even when the wind speed exceeds the rated wind speed.

CDFIG Modeling

In this research, we focus on a cascaded doubly fed induction machine, which comprises of two induction machines, IM 1 and IM 2, with identically-pole wound rotor poles. The rotors of the two DFIMs can be connected in two different ways. Connecting the identical phases produces a direct connection, while connecting the phases in the opposite order produces an inverse connection (Maafa, et al., 2022 ;Maafa, et al., 2016 ;Taka & Shibata, 1992). The second configuration is the focus of our study. Two wound rotors are mechanically and electrically coupled in Figure. 1.

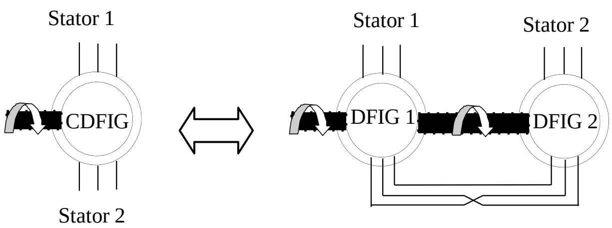

Figure 1. Two DFIGs connected mechanically and electrically to make the CDFIG

The method of analysis employs the Park transformation. Here are the voltage and flow equations for the two DFIGs:

- The machine 1:

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

- The second machine:

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

The CDFID stators and rotors flux can be written as:

$$\begin{cases} \varphi_{ds1} = L_{s1} i_{ds1} + L_{m1} i_{dr} \\ \varphi_{qs1} = L_{s1} i_{qs1} + L_{m1} i_{qr} \\ \varphi_{dr1} = L_{r1} i_{dr} + L_{m1} i_{ds1} \\ \varphi_{qr1} = L_{r1} i_{qr} + L_{m1} i_{qs1} \end{cases} \quad (3)$$

$$\begin{cases} \varphi_{ds2} = L_{s2} i_{ds2} - L_{m2} i_{dr} \\ \varphi_{qs2} = L_{s2} i_{qs2} - L_{m2} i_{qr} \\ \varphi_{dr2} = -L_{r2} i_{dr} + L_{m2} i_{ds2} \\ \varphi_{qr2} = -L_{r2} i_{qr} + L_{m2} i_{qs2} \end{cases} \quad (4)$$

The modeling of the electric coupling of the two rotors will be in the following way:

$$\begin{cases} v_{dr1} = \gamma\ v_{dr2} = v_{dr} \\ v_{qr1} = \gamma\ v_{qr2} = v_{qr} \end{cases} \quad (5) \qquad \begin{cases} i_{dr1} = -\gamma\, i_{dr2} = i_{dr} \\ i_{qr1} = -\gamma\, i_{qr2} = i_{qr} \end{cases} \quad (6)$$

Powers Control of CDFIG

Matrix Converter

The direct matrix converter consists of a total of nine bidirectional switches, facilitating the interconnection of the input phases (a, b, and c) with the output phases (a, b, and c) in a flexible manner. Figure 2 shows that each output phase is connected to three input phases by three switches. The input voltages with fixed amplitude and frequency must be converted into frequency and/or variable amplitude sinusoidal output voltages (Casadei, et al. 1993 ;Huber & Borojevic, 1995).

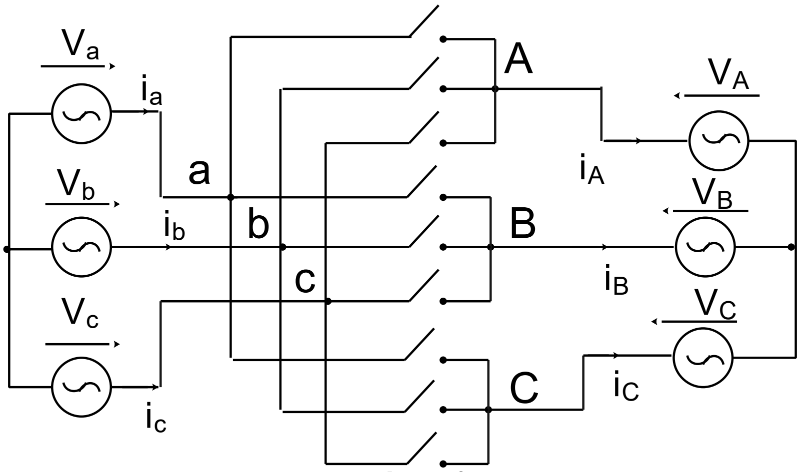

Figure 2. Topology of a matrix converter

The switching function of switch S_{ij} in Figure 1 is formally defined as.

$$S_{ij} = \begin{cases} 1 & Sw_{ij} \text{ is closed} \\ 0 & Sw_{ij} \text{ is open} \end{cases} \qquad i \in \{A, B, C\},\ j \in \{a, b, c\}, \qquad (7)$$

The preceding restrictions can be expressed as

$$Sw_{Aj} + Sw_{Bj} + Sw_{Cj} = 1 \qquad j \in \{a, b, c\}, \qquad (8)$$

In order to effectively manage the active and reactive power exchange between the machine and the grid, we propose a control for the machine inverter. The wind energy conversion system incorporates reactive power regulation to achieve a power factor of unity between the stator 1 and the grid. Meanwhile, the active power output is adjusted in response to variations in wind speed.

SVM for the Rectifier Stage

Using a transformation like this, the present input current space vector I_{in} is expressed as a space vector:

$$I_{in} = \frac{2}{3}(I_a + I_b e^{j\frac{2\pi}{3}} + I_c e^{-j\frac{2\pi}{3}}) \quad (9)$$

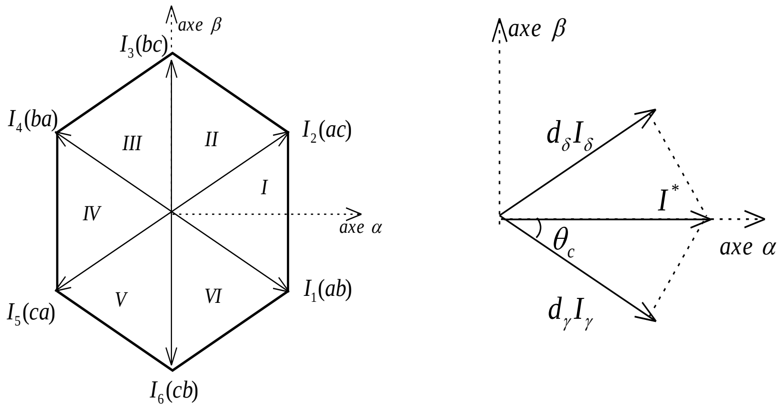

Figure 3. Reference current vector synthesis

The group of discrete seven-dimensional vectors can be organized in a hexagonal structure within the complex plane, as depicted in Fig 4.

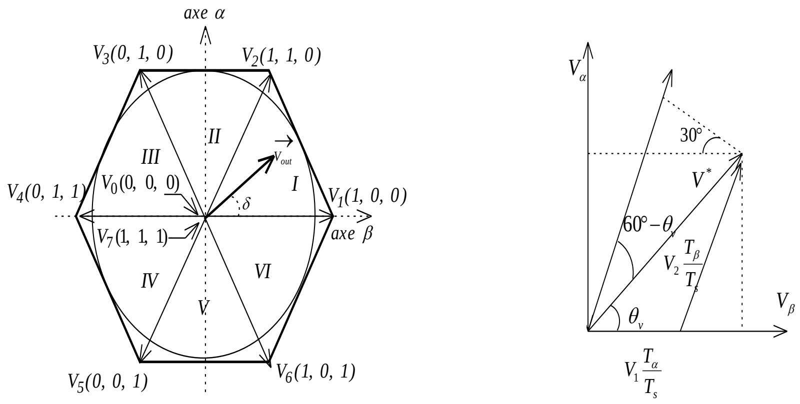

Figure 4. Output voltage modulation for rectification stage

Two adjacent switching vectors v_α and v_β with the duty cycles d_α and d_β, respectively, generate the reference output voltage space vector.

$$V^* = d_\alpha v_\alpha + d_\beta I_\beta \tag{13}$$

The duty cycle of the active vectors is calculated by:

$$\begin{cases} d_\alpha = \dfrac{T_\alpha}{T_s} = m_v \sin\left(\dfrac{\pi}{3} - \theta_v\right) \\ d_\beta = \dfrac{T_\beta}{T_s} = m_v \sin(\theta_v) \\ d_0 = \dfrac{T_0}{T_s} = 1 - (d_\alpha + d_\beta) \end{cases} \tag{14}$$

where θ_v is the angle of the reference voltage vector within the hexagon sector itself. The voltage modulation index, m_V, specifies the desired voltage transfer ratio, such as

SVM for the Entire Matrix Converter

For the nine bidirectional switched matrix converter, the two independent space vector modulations need to be combined into a single modulation technique.

$$\begin{cases} d_{\alpha\gamma} = d_{\alpha}.d_{\gamma} = m_v \sin\ (\frac{\pi}{3}-\theta_i).\sin(\frac{\pi}{3}-\theta_v) \\ d_{\alpha\delta} = d_{\alpha}.d_{\delta} = m_v \sin\ (\theta_i).\sin(\frac{\pi}{3}-\theta_v) \\ d_{\beta\delta} = d_{\beta}.d_{\delta} = m_v \sin\ (\frac{\pi}{3}-\theta_i).\sin(\theta_v) \\ d_{\beta\delta} = d_{\beta}.d_{\delta} = m_v \sin(\theta_i).\sin(\theta_v) \end{cases} \quad (15)$$

Zero vector is applied throughout the remainder of the switching period (TS).

$$d_0 = 1-(d_{\alpha\gamma}+d_{\alpha\delta}+d_{\beta\gamma}+d_{\beta\gamma\delta}) \quad (16)$$

We select a d-q reference frame that is synchronised with the flux of stator 1.

$$\begin{cases} \varphi_{ds1} = \varphi_{s1} \\ \varphi_{qs1} = 0 \end{cases} \quad (17)$$

We can write: ignoring the stator 1 resistance Rs1:

$$\begin{cases} v_{ds1} = 0 \\ v_{qs1} = V_s = \omega_s.\varphi_{s1} \end{cases} \quad (18)$$

For slip values relatively weak according to the stator 2 currents, the rotor and stator 1 currents, the stator 2 voltages expressions as the active and reactive powers of stator 1 and grid are presented in (19) – (22) respectively:

$$\begin{cases} i_{dr} = C.i_{ds2} - C.\dfrac{L_{m1}.V_s}{\omega_s.L_{s1}.L_{m2}} \\ i_{qr} = C.i_{qs2} \end{cases} \quad (19)$$

$$\begin{cases} i_{ds1} = \dfrac{V_s}{\omega_s.L_{s1}}\left(1+\dfrac{C.L_{m1}^2}{L_{s1}.L_{m2}}\right) - C.\dfrac{L_{m1}}{L_{s1}}i_{ds2} \\ i_{qs1} = -C.\dfrac{L_{m1}}{L_{s1}}i_{qs2} \end{cases} \quad (20)$$

$$\begin{cases} v_{ds2} = R_{s2}i_{ds2} + (L_{s2}-C.L_{m2})\dfrac{di_{ds2}}{dt} - s.\omega_s\,(L_{s2}-C.L_{m2}).i_{qs2} \\ v_{qs2} = R_{s2}i_{qs2} + (L_{s2}-C.L_{m2})\dfrac{di_{qs2}}{dt} + s.\omega_s\,(L_{s2}-C.L_{m2}).i_{ds2} + s.\dfrac{L_{m1}V_s}{L_{s1}} \end{cases} \quad (21)$$

$$\begin{cases} P_{s1} = -C.V_s\dfrac{L_{m1}}{L_{s1}}i_{qs2} \\ Q_{s1} = \dfrac{V_s^2}{\omega_s.L_{s1}}\left(1+\dfrac{C.L_{m1}^2}{L_{s1}.L_{m2}}\right) - C.V_s\dfrac{L_{m1}}{L_{s1}}i_{ds2} \end{cases} \quad (22)$$

With: $s = s_1.s_2 = \dfrac{\omega_s - \omega_{r1} - \omega_{r2}}{\omega_s} = \dfrac{\omega_s - (p_1 + p_2).\Omega_r}{\omega_s}$, $s_1 = \dfrac{\omega_s - p_1.\Omega_r}{\omega_s}$, $s_2 = \dfrac{s_1.\omega_s - p_2.\Omega_r}{s_1.\omega_s}$

and $C = \dfrac{L_{m2}}{L_{r1} + L_{r2} - \dfrac{L_{m1}^2}{L_{s1}}}$

Fuzzy Logic Controller

Fuzzification, an inference engine, and defuzzification are the three processes that are utilised throughout the FLC strategy. Each of these procedures is necessary for the implementation of FLC. The inputs of the our fuzzy controllers receive the currents and their variations to synthesise the CDFIG reference voltages.

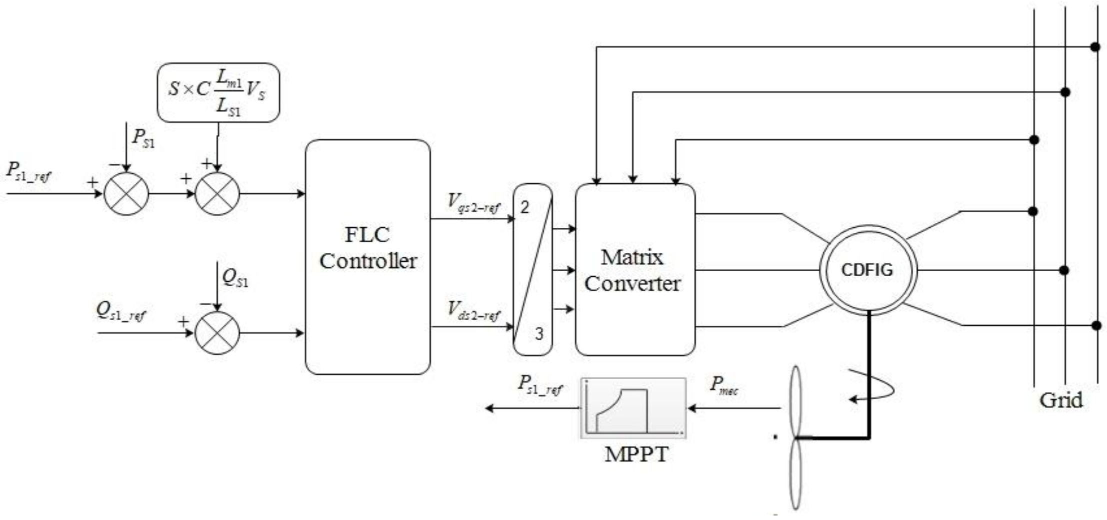

Figure 5. Whole system control

Results and Discussions

The suggested wind system was implemented in Matlab/Simulink as shown in Figure 5. This section presents a simulation of an AC/AC direct converter-controlled direct grid connection of CDFIG. The system under consideration is regulated to produce the most energy possible.

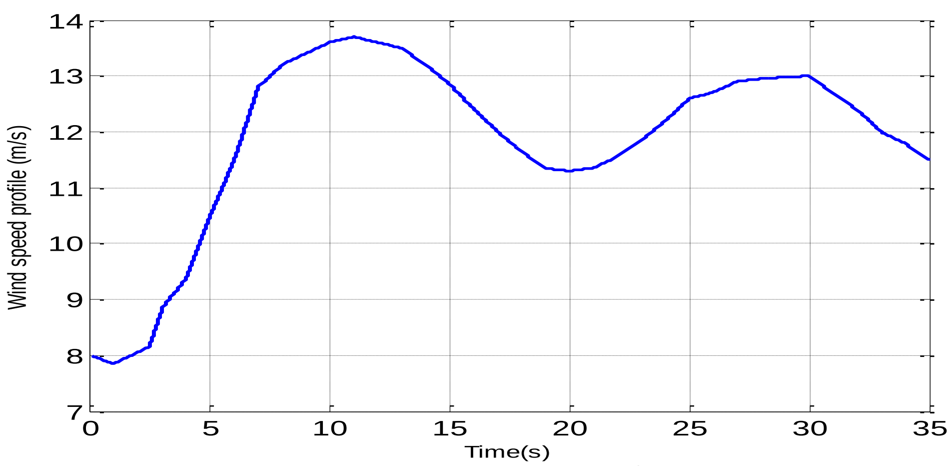

Figure 6. Wind speed profile

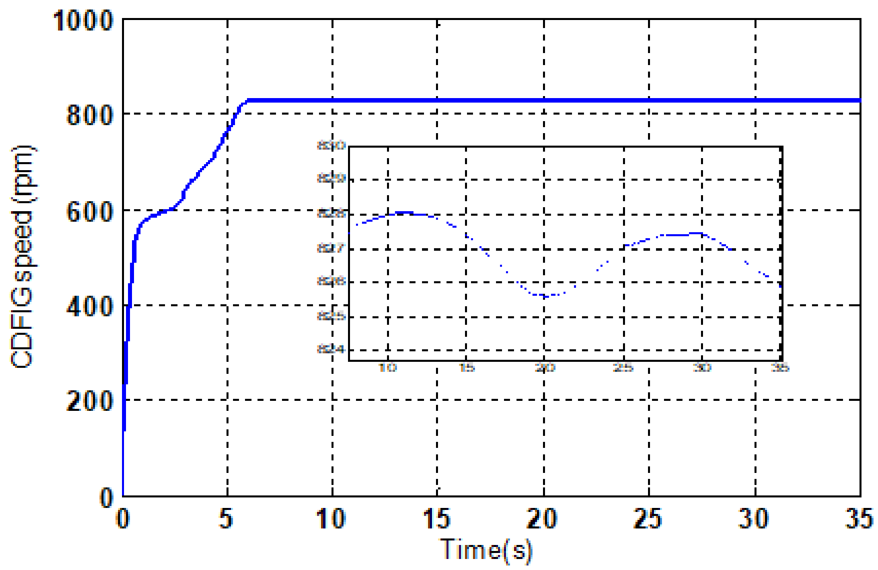

Figure 7. CDFIG speed

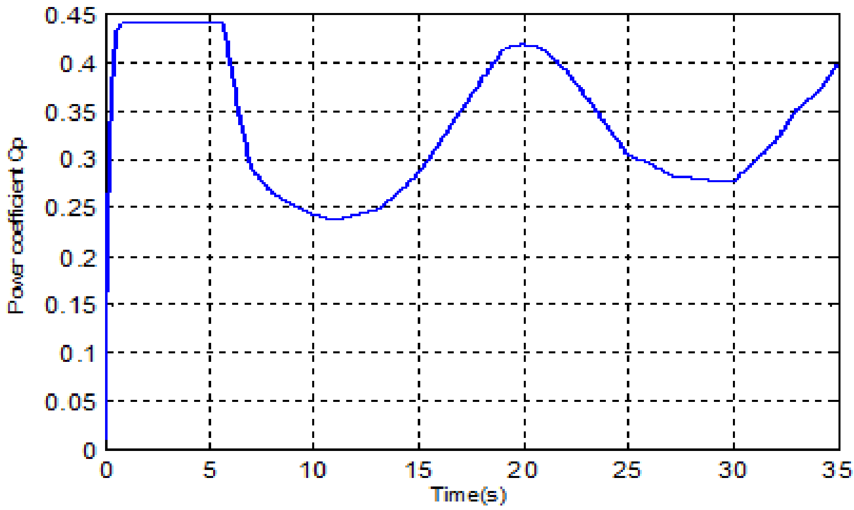

Figure 8. Power coefficient

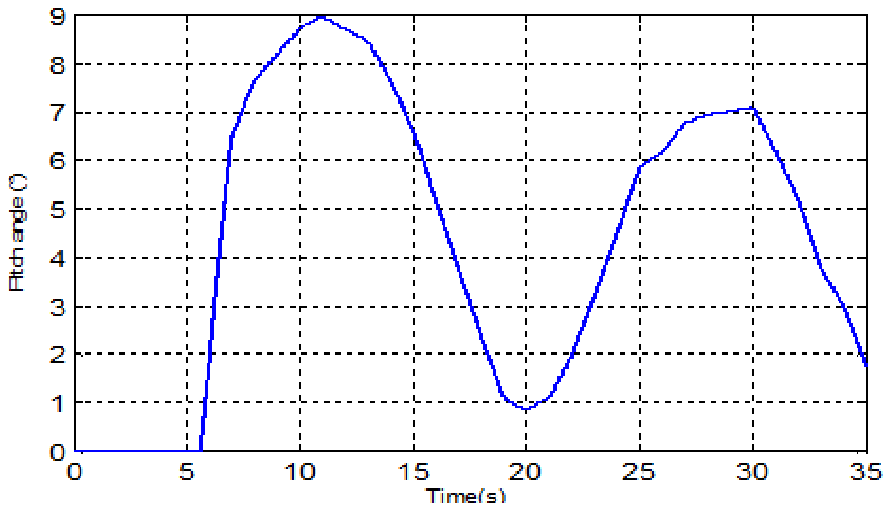

Figure 9. Pitch angle

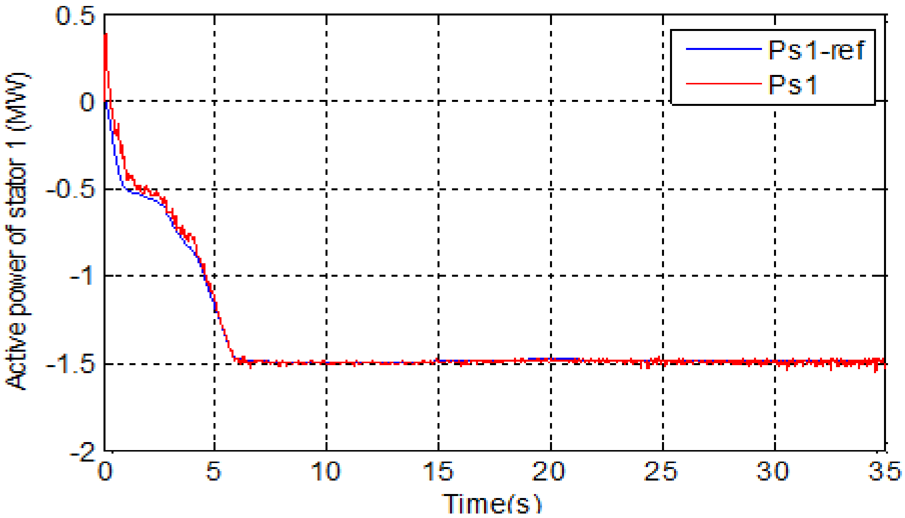

Figure 10. Stator one's active power

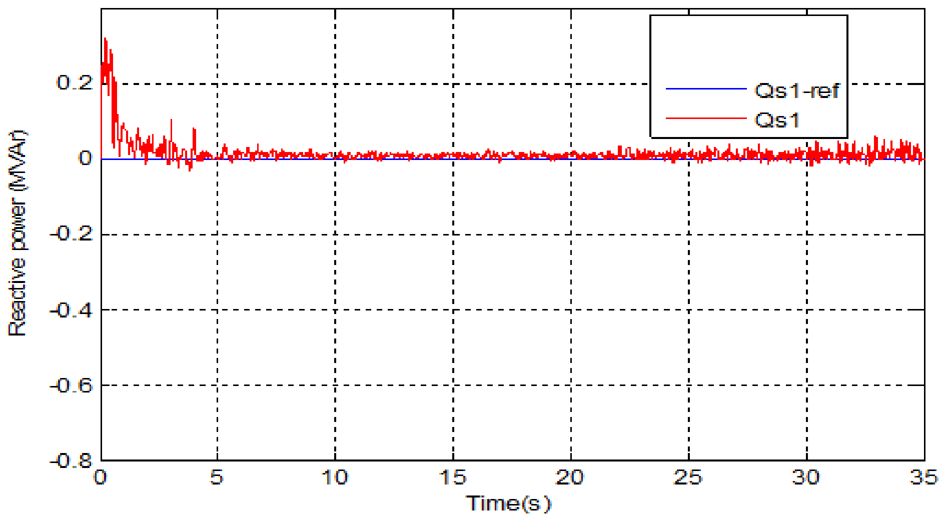

Figure 11.Stator one's reactive power

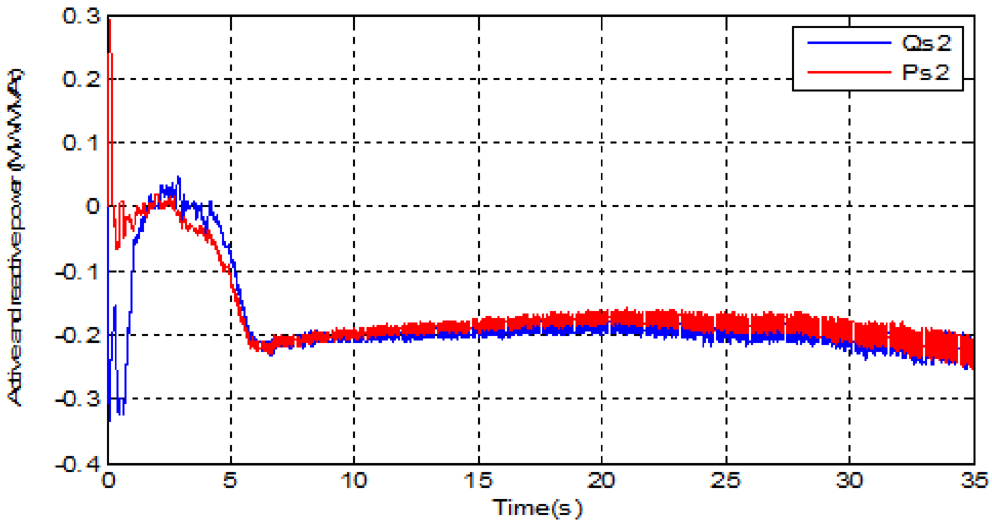

Figure 12. Stator Two's active and reactive

Wind speed is shown in figure 6. The speed and zoom of a CDFIG are presented in figure 7. The power coefficient is displayed in figure 8. In Figure 9, the pitch angle is shown. The wind turbine's pitch angle is managed to achieve the highest C_{Pmax}. Stator 1's active power is shown in Figure 10. The stator one powers properly adhere to their references. Figure 11 represents the reactive power of stator 1. It is kept constant at zero. Figure 12 shows the active and reactive powers of stator two. It is evident that in a hyper-synchronous operation mode, a portion of the active power exceeding 1.5 MW is transferred from the stator 2 side of the CDFIG.

Conclusion

This study focuses on the analysis of a wind energy system that utilizes a CDFIG and is connected to the electrical grid via a matrix converter using logic fuzzy controllers. All of the results can be observed using a DFIG or CDFIG instead; the distinction is that the CDFIG eliminates brushes-ring electrical connectors, resulting in a more reliable and robust structure. The pitch controller's objective is to maximise aerodynamic power while staying within the converter's power limits. Results from the simulation demonstrated that the active and reactive powers were quite similar to their reference values. The proposed structure is preserved and has a longer lifespan because the matrix converter contains no energy storage component. The effectiveness and reliability of the suggested method are demonstrated by the simulation results.

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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