

A Matrix Converter-Powered Cascaded Doubly Fed Induction Generator for an Improved Sliding Mode Control Strategy

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Article Info

Article history:

Received , 15/04/2025

Revised , 17/05/2025

Accepted , 07/06/2025

Keywords:

Matrix Converter
sliding mode control
Cascaded Doubly Fed Induction
Generator
Wind Energy

ABSTRACT

This article deals with the application of a sliding mode controller (SMC) for a Cascaded Doubly-Fed Induction Generator (DFIG) integrated with a Matrix Converter (MC) in a wind energy conversion system (WECS). The proposed sliding mode controller (SMC) employs a continuous control approach, aiming to realize a chattering-free sliding mode control while enabling independent regulation both the active and reactive powers of the first stator. A matrix converter is used instead of regular voltage source inverters to control the flow of current to the second rotor of the CDFIG. Space-vector pulse-width modulation (SVM) and indirect field-oriented control (IFOC) are used to manage the two converters that are being used. The suggested power generation method is employed to track the maximum power point of the wind energy conversion system, even when there are disturbances like rough wind. At the end of this paper, the final results are shown to show how the control method created in this paper works well.

I. Introduction

There is a growing interest in wind energy as a result of the necessity of developing systems that can produce energy that is more accessible cleaner, and sustainable, and that can be relied upon over the long run. Wind Energy Conversion Systems (WECS) convert the kinetic energy of moving air masses into electrical energy. The electrical components of a WECS typically consist of electrical machines coupled with power converters, while the control system plays a crucial role in regulating and conditioning the generated power for efficient injection into the electrical grid. It is the wind speed that is captured by the rotor of the wind turbine, which is what impacts the quantity of power that is produced. It is important to note that the meteorological conditions, in addition to the mechanical qualities of wind turbines, also play a considerable effect [1-3].

Researchers in the discipline of electrical engineering have been working hard to enhance the quality and efficiency of electromechanical conversion in response to the increased installation of wind turbines around the globe. Asynchronous or synchronous alternating current machines driven by static converters make up the new generation of electrical drives, which can be either single-machine or multi-machine. One alternative to the squirrel-cage asynchronous machine for variable speed wind power is the doubly fed induction machine (DFIM) [4-8].

While the rotor of the generator connects to the network through a frequency converter, the stator of the generator is directly coupled to the network. The existence of brush rings or collector brushes in the majority of electrical generators constitutes a significant disadvantage. Difficulties related to the maintenance of wind turbines are becoming increasingly significant, especially with offshore wind turbines or when the nacelle is positioned at

considerable heights. We propose to both electrically and mechanically connect two doubly fed induction generators through their rotors. This coupler facilitates the removal of sliding ring-brush contacts [9-17].

The three-phase matrix converter is an advanced generation of the direct power AC-AC converter. It comprises nine bidirectional switches. The matrix converter possesses numerous advantages compared to traditional topologies, as it allows for bidirectional power flow; that is, it operates in all four quadrants of the voltage-current plane, permitting functionality both as a motor or generator. In the absence of any energy storage component, the instantaneous power input must equal the power output, assuming idealized zero-loss switch connections [18-21].

This work presents a sliding-mode control utilizing a perturbation observer for the CDFIG connected with a matrix converter to achieve optimal power extraction.

The paper is structured as described below. Section 2 elaborates on the ideas and model of the matrix converter. Section 3 will provide a concise presentation of the CDFIG paradigm. Section 4 presents the design of a SMC for an IFOC of CDFIG. Section 5 presents the simulation results, demonstrating the optimal performance of the suggested system. Section 6 closes the document.

II. Analysis And Modeling of MC

The direct matrix converter comprises nine bidirectional switches which enable the connection of any input phases a, b, c to any output phases A, B, C. Each output phase is linked to three switches connected to three input phases, as illustrated in Fig. 1.

The sinusoidal output voltages, characterized by changing frequency and/or amplitude, must be derived based on input voltages with fixed frequency and amplitude [20].

functionality of a matrix converter is subject to two constraints. The three input phases must never be short-circuited. Secondly, the three output phases must never be configured as open circuits.

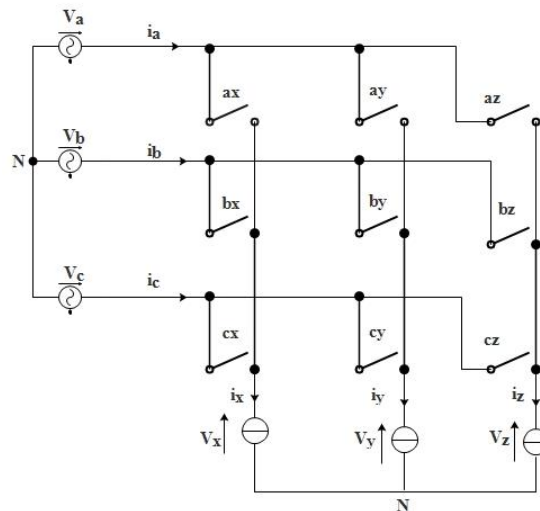


Figure 1. Topology of matrix converters

For the use of space vector PWM,

The matrix converter is defined as a bidirectional power electronic device that enables direct AC-to-AC conversion without a real intermediate DC stage. It is typically modeled as a two-stage structure connected through a hypothetical DC link: the first stage functions as an input current-source rectifier, while the second stage operates as an output voltage-source inverter.

The transfer function of the MC can be expressed as:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_7 S_1 + S_8 S_2 & S_7 S_3 + S_8 S_4 & S_7 S_5 + S_8 S_6 \\ S_9 S_1 + S_{10} S_2 & S_9 S_3 + S_{10} S_4 & S_9 S_5 + S_{10} S_6 \\ S_{11} S_1 + S_{12} S_2 & S_{11} S_3 + S_{12} S_4 & S_{11} S_5 + S_{12} S_6 \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

The transformation is employed to express the input current space vector I_{in} as a space vector:

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

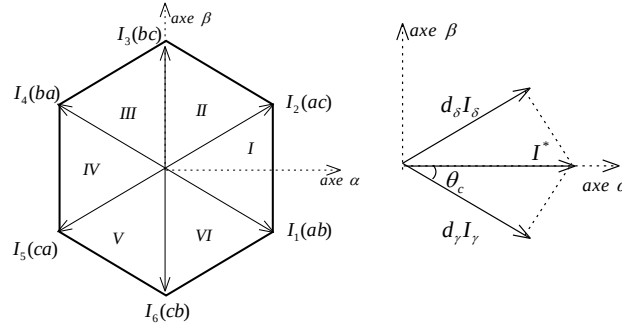


Figure 2. Synthesis of reference current vector

The I^* is synthesized by impressing the adjacent switching vectors I_γ and I_δ with the duty cycles d_γ and d_δ , respectively

$$I^* = d_\gamma I_\gamma + d_\delta I_\delta \quad (3)$$

With:

$$\begin{cases} d_\gamma = m_c \sin(\frac{\pi}{3} - \theta_i) \\ d_\delta = m_c \sin(\theta_i) \\ d_o = 1 - (d_\gamma + d_\delta) \end{cases} \quad (4)$$

Where: m_c , is the current modulation index, set to be unity and θ_i represents the angle of the reference input vector within its corresponding sector.

The output voltage vector is defined as follows:

$$V_{out} = \frac{2}{3} (V_A + V_B e^{j\frac{2\pi}{3}} + V_C e^{-j\frac{2\pi}{3}}) \quad (5)$$

The seven discrete space vectors can be represented as a hexagon in the complex plane, as illustrated in Fig. 3.

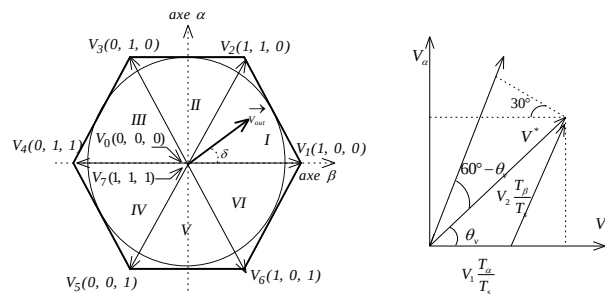


Figure 3. Output voltage modulation for rectification stage

The reference output voltage space vector is synthesized using two adjacent switching vectors v_α and v_β , with corresponding duty cycles d_α and d_β , respectively:

$$V^* = d_\alpha v_\alpha + d_\beta I_\beta \quad (6)$$

The duty cycles of the active vectors are calculated as follows:

$$\begin{cases} d_\alpha = \frac{T_\alpha}{T_s} = m_v \sin(\frac{\pi}{3} - \theta_v) \\ d_\beta = \frac{T_\beta}{T_s} = m_v \sin(\theta_v) \\ d_0 = \frac{T_0}{T_s} = 1 - (d_\alpha + d_\beta) \end{cases} \quad (7)$$

where θ_v denotes the angle of the reference voltage vector within the corresponding hexagon sector, and m_v is the voltage modulation index, representing the desired voltage transfer ratio.

III. Model OF CDFIG

The two induction generators with pole-pairs respectively p_1 and p_2 are the most important components of the cascaded doubly fed induction generator (CDFIG), in the traditional doubly fed induction machine (DFIM), for eliminating the copper rings and brushes, they are connected in cascade [11,13]. The electrical and mechanical coupling of two wound rotors is shown in Figure 4.

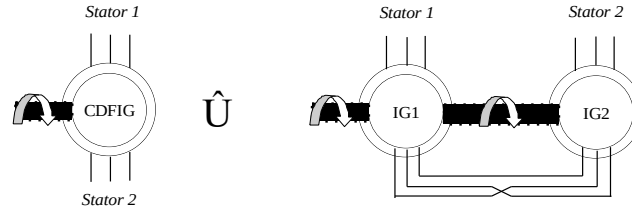


Figure 4. Electric and mechanical coupling of two IG equivalent of the CDFIG

In a synchronously rotating d-q frame, the machines equations written are:

- The machine 1:

$$\begin{cases} v_{ds1} = R_{s1} i_{ds1} + \frac{d}{dt} \phi_{ds1} - \omega_s \phi_{qs1} \\ v_{qs1} = R_{s1} i_{qs1} + \frac{d}{dt} \phi_{qs1} + \omega_s \phi_{ds1} \\ v_{dr1} = R_{r1} i_{dr1} + \frac{d}{dt} \phi_{dr1} - (\omega_s - \omega_{r1}) \phi_{qr1} \\ v_{qr1} = R_{r1} i_{qr1} + \frac{d}{dt} \phi_{qr1} + (\omega_s - \omega_{r1}) \phi_{dr1} \end{cases} \quad (8)$$

- The machine 2:

$$\begin{cases} v_{dr2} = R_{r2} i_{dr2} + \frac{d}{dt} \varphi_{dr2} - (\omega_s - \omega_{r1}) \varphi_{qr2} \\ v_{qr2} = R_{r2} i_{qr2} + \frac{d}{dt} \varphi_{qr2} + (\omega_s - \omega_{r1}) \varphi_{dr2} \\ v_{ds2} = R_{s2} i_{ds2} + \frac{d}{dt} \varphi_{ds2} - (\omega_s - \omega_{r1} - \omega_{r2}) \varphi_{qs2} \\ v_{qs2} = R_{s2} i_{qs2} + \frac{d}{dt} \varphi_{qs2} + (\omega_s - \omega_{r1} - \omega_{r2}) \varphi_{ds2} \end{cases} \quad (9)$$

The rotor and stator fluxes of CDFIG can be expressed as:

$$\begin{cases} \Phi_{ds1} = L_{s1} i_{ds1} + L_{m1} i_{dr} \\ \Phi_{qs1} = L_{s1} i_{qs1} + L_{m1} i_{qr} \\ \Phi_{dr1} = L_{r1} i_{dr} + L_{m1} i_{ds1} \\ \Phi_{qr1} = L_{r1} i_{qr} + L_{m1} i_{qs1} \end{cases} \quad \text{and} \quad \begin{cases} \Phi_{ds2} = L_{s2} i_{ds2} - L_{m2} i_{dr} \\ \Phi_{qs2} = L_{s2} i_{qs2} - L_{m2} i_{qr} \\ \Phi_{dr2} = -L_{r2} i_{dr} + L_{m2} i_{ds2} \\ \Phi_{qr2} = -L_{r2} i_{qr} + L_{m2} i_{qs2} \end{cases} \quad (10)$$

The electrical connection coupling between the two rotors is modeled as follows:

$$\begin{cases} v_{dr1} = v_{dr2} = v_{dr} \\ v_{qr1} = v_{qr2} = v_{qr} \end{cases} \quad \text{and} \quad \begin{cases} i_{dr1} = -i_{dr2} = i_{dr} \\ i_{qr1} = -i_{qr2} = i_{qr} \end{cases} \quad (11)$$

The reactive and active powers for those provide for grid as well as at both stators 1 and 2 are written as:

$$\begin{cases} P_{s1} = v_{ds1} i_{ds1} + v_{qs1} i_{qs1} \\ Q_{s1} = v_{qs1} i_{ds1} - v_{ds1} i_{qs1} \end{cases} \quad (12)$$

$$\begin{cases} P_{s2} = v_{ds2} i_{ds2} + v_{qs2} i_{qs2} \\ Q_{s2} = v_{qs2} i_{ds2} - v_{ds2} i_{qs2} \end{cases} \quad (13)$$

$$\begin{cases} P_g = P_{s1} + P_{s2} \\ Q_g = Q_{s1} + Q_{s2} \end{cases} \quad (14)$$

The reference frame d-q is chosen where the d-axis is aligned with the stator 01 flux and quadrature component of stator 01 flux is zero [11].

$$\begin{cases} \varphi_{ds1} = \varphi_{s1} \\ \varphi_{qs1} = 0 \end{cases} \quad (15)$$

Then the torque is simplified into:

$$T_e = p_1 \varphi_{s1} i_{qs1} + p_2 (\varphi_{ds2} i_{qs2} - \varphi_{qs2} i_{ds2}) \quad (16)$$

IV. SMC For Control of Stator Powers

Neglecting the resistance of stator 1 R_{s1} , it can be expressed:

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

The voltages of stator 2, the reactive and active powers of stator, can be expressed depending on the rotor currents as:

$$\begin{cases} v_{ds2} = R_{s2} i_{ds2} + (L_{s2} - C L_{m2}) \frac{di_{ds2}}{dt} - s \omega_s (L_{s2} - C L_{m2}) i_{qs2} \\ v_{qs2} = R_{s2} i_{qs2} + (L_{s2} - C L_{m2}) \frac{di_{qs2}}{dt} + s \omega_s (L_{s2} - C L_{m2}) i_{ds2} + s \frac{L_{m1} V_s}{L_{s1}} \end{cases} \quad (18)$$

$$\begin{cases} P_{s1} = -C V_s \frac{L_{m1}}{L_{s1}} i_{qs2} \\ Q_{s1} = \frac{V_s^2}{\omega_s L_{s1}} \left(1 + \frac{C L_{m1}^2}{L_{s1} L_{m2}} \right) - C V_s \frac{L_{m1}}{L_{s1}} i_{ds2} \end{cases} \quad (19)$$

The sliding surfaces $S(i_{ds2}), S(i_{qs2})$ relative to stator 02 currents are defined as :

$$\begin{cases} S(i_{qs2}) = i_{qs2_ref} - i_{qs2} \\ S(i_{ds2}) = i_{ds2_ref} - i_{ds2} \end{cases} \quad (20)$$

In order for the chosen variables converge to their reference values, both surfaces must be zero :

$$\begin{cases} \dot{S}(P) = \frac{d}{dt} (i_{qs2_ref} - i_{qs2}) = 0 \\ \dot{S}(Q) = \frac{d}{dt} (i_{ds2_ref} - i_{ds2}) = 0 \end{cases} \quad (21)$$

According to (18), the dynamics of the stator 2 current components can be obtained as follows :

$$\begin{cases} \frac{di_{qs2}}{dt} = \left[V_{qs2} - R_{s2} i_{qs2} + s \omega_{s1} (L_{s2} - C L_{m2}) i_{ds2} - s C \frac{L_{m1} V_s}{L_{s1}} \right] \frac{1}{L_{s2} - C L_{m2}} \\ \frac{di_{ds2}}{dt} = \left[V_{ds2} - R_{s2} i_{ds2} + s \omega_{s1} (L_{s2} - C L_{m2}) i_{qs2} \right] \frac{1}{L_{s2} - C L_{m2}} \end{cases} \quad (22)$$

The references currents of the stator 2 can be written

$$\begin{cases} \frac{di_{qs2_ref}}{dt} = \frac{L_{s1}}{C L_{m1} V_s} \frac{dP_{s1_ref}}{dt} \\ \frac{di_{ds2_ref}}{dt} = \left(1 + \frac{C L_{m1}^2}{L_{s1} L_{m2}} \right) \frac{V_s}{C L_{m1} \omega_{s1}} - \frac{L_{s1}}{C L_{m1} V_s} \frac{dQ_{s1_ref}}{dt} \end{cases} \quad \text{according to (19) as follows:} \quad (23)$$

The control algorithm is formulated based on the following expressions:

$$\begin{cases} V_{qs2} = V_{qs2_eq} + V_{qs2_n} \\ V_{ds2} = V_{ds2_eq} + V_{ds2_n} \end{cases} \quad (24)$$

where V_{qs2_eq} , V_{ds2_eq} are the equivalent control voltages, employed to keep the controlled variables constrained to the sliding surface. Indeed, the V_{qs2_n} , V_{ds2_n} represent the switching control voltages, which are utilized to ensure the convergence condition is satisfied, particularly in the presence of system parameter uncertainties.

$$\begin{cases} V_{qs2_eq} = R_{s2} i_{qs2} - L_{s1} \frac{L_{s2} - C L_{m2}}{C V_s L_{m1}} \dot{P}_{s1_ref} - s \omega_{s1} (L_{s2} - C L_{m2}) i_{ds2} + \frac{L_{m1}}{L_{s1}} C s V_s \\ V_{qs2_n} = K_1 (L_{s2} - C L_{m2}) \text{sgn}(S(i_{qs})) \\ V_{ds2_eq} = R_{s2} i_{ds2} - \frac{L_{s2} - C L_{m2}}{C L_{m1} \omega_{s1}} \left[V_s \left(1 + \frac{C L_{m1}^2}{L_{s1} L_{m2}} \right) - L_{s1} \dot{Q}_{s1_ref} \right] - s \omega_{s1} (L_{s2} - C L_{m2}) i_{qs2} \\ V_{ds2_n} = K_2 (L_{s2} - C L_{m2}) \text{sgn}(S(i_{ds})) \end{cases} \quad (25)$$

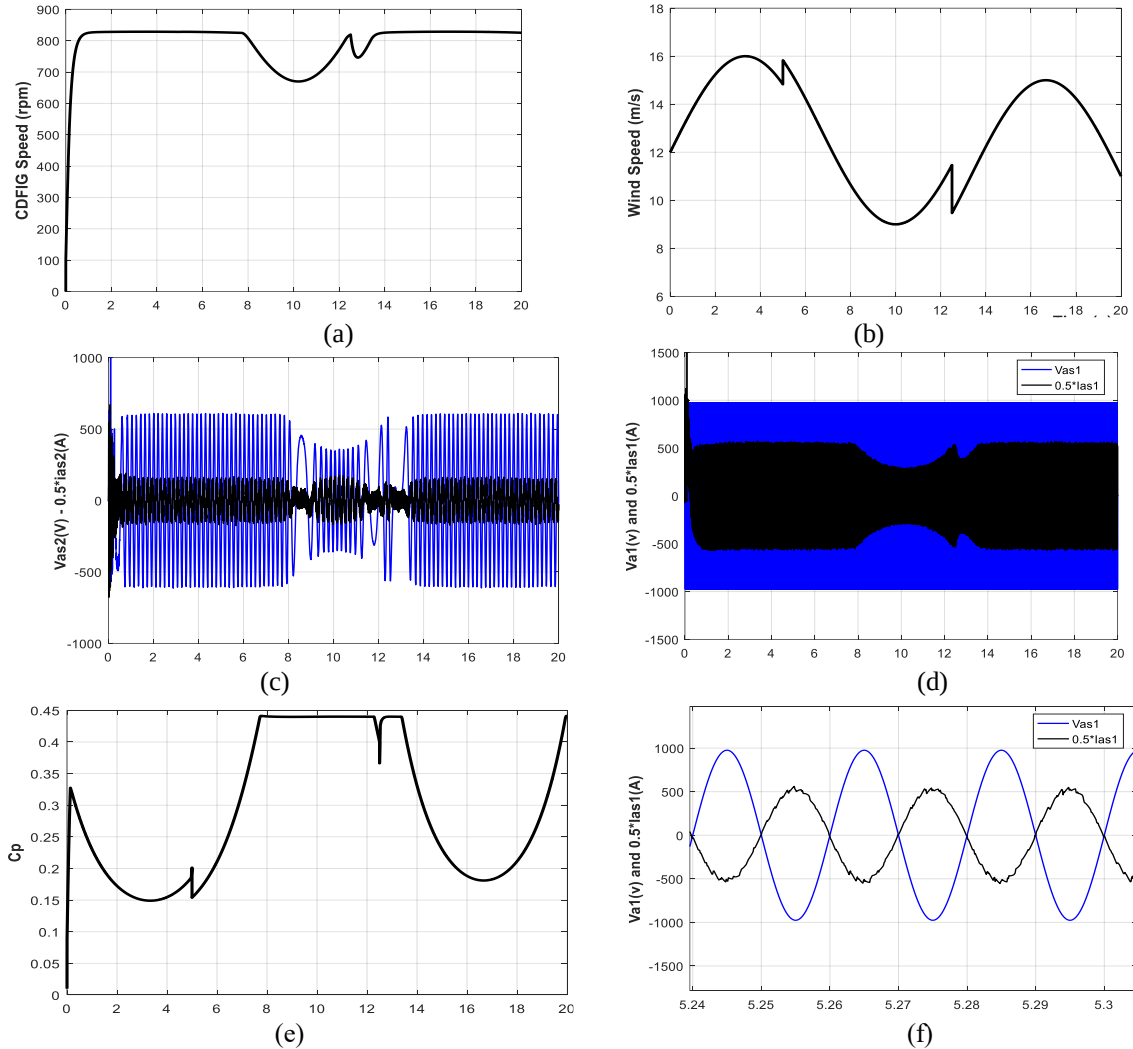
And

$$\begin{cases} V_{ds2_eq} = R_{s2} i_{ds2} - \frac{L_{s2} - C L_{m2}}{C L_{m1} \omega_{s1}} \left[V_s \left(1 + \frac{C L_{m1}^2}{L_{s1} L_{m2}} \right) - L_{s1} \dot{Q}_{s1_ref} \right] - s \omega_{s1} (L_{s2} - C L_{m2}) i_{qs2} \\ V_{ds2_n} = K_2 (L_{s2} - C L_{m2}) \text{sgn}(S(i_{ds})) \end{cases} \quad (26)$$

V. Simulation Results and Discussion

This study presents a simulation of the CDFIG directly connected to the grid via stator 1, with control executed through the stator 2 utilizing an AC/AC direct converter. The simulation results point to a reactive reference power of $Q_{s1_ref} = 0$ MVar and an active reference power of $P_{s1_re} = 1.5$ MW, aligned with the turbine's optimal mechanical power. The system under consideration is regulated to optimize energy generation while reducing loads. The variable wind speed utilized, is illustrated in Fig 5.a. In Fig 5.b, the CDFIG speed is shown.

This profile will demonstrate the transition between sub-synchronous and super-synchronous regimes. The Q_{s1} and P_{s1} exhibit a strong alignment with the corresponding references, $Q_{s1}(ref)$ and $P_{s1}(ref)$, as illustrated in Fig 5.c. The reactive power remains constant (zero) and is unaffected by variations in wind speed, whereas the active power varies in response to these changes. Variations in wind speed directly affect the magnitude of current and torque, with higher wind speeds resulting in increased values of current (see Figures 5.e). Fig. 5.d illustrate the active and reactive powers of stator 2. The sub-synchronous speed indicates positive values, whereas the super-synchronous speed exhibits negative values of P_{s2} and Q_{s2} . Fig 5. f shows the zoom of stator's 1 voltage/current and in fig 5. g the voltage/current of the second stator.



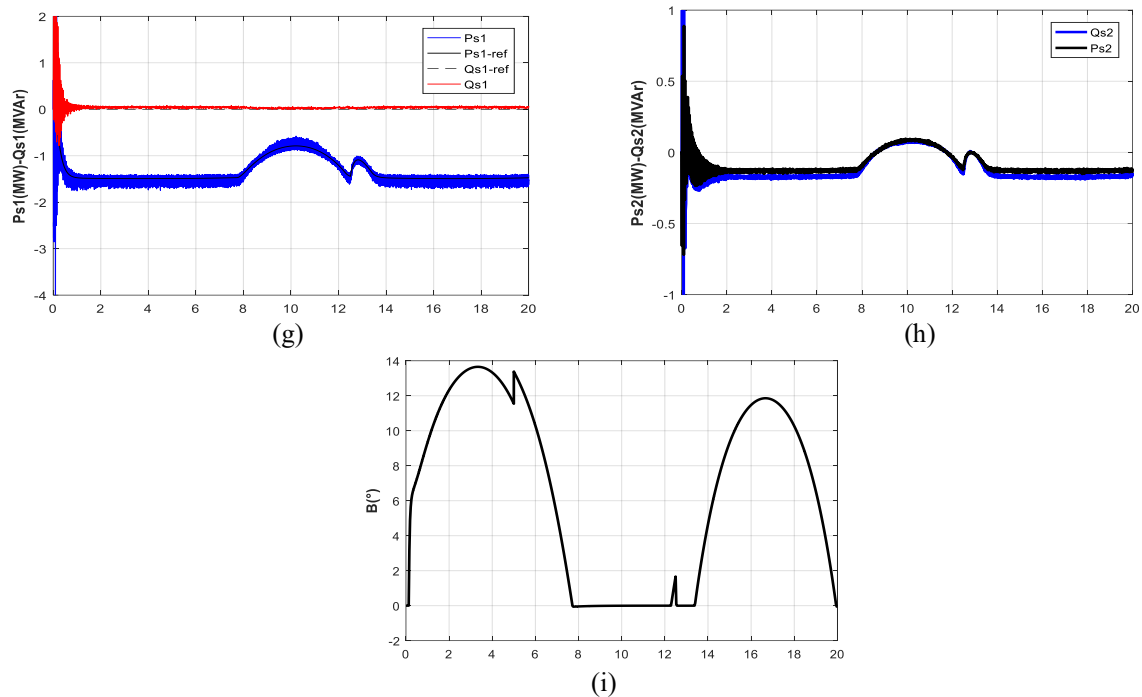


Figure 5. Characteristics of CDFIG with random wind speed

Fig 5.h. presents the power coefficient, demonstrating a decline in C_p within higher wind speed zones, while retaining its maximum value in lower speed regions. The pitch angle β , illustrated in Fig 5.i, reaches a value of zero in low-speed regions. The angle $\beta = 0$ signifies the optimal configuration for achieving maximum C_p . The power coefficient is deliberately decreased to regulate the amount of power produced.

VI. Conclusion

This paper describes a variable speed wind generator (VSWG) linked to a three-phase matrix converter. The CDFIG operates in a two-quadrant mode. For $s > 0$, the CDFIG operates in sub-synchronous mode. For $s < 0$, the CDFIG operates in super-synchronous mode. When $s=0$, the CDFIG functions as a synchronized asynchronous generator, resulting in a stator voltage and current frequency of zero. Simulation results demonstrated that both active and reactive powers strictly adhere to their respective reference values. The input power factor of the matrix converter has been regulated to approach unity. The lack of energy storage components in the matrix converter enhances the longevity of the proposed structure. Additionally, the implementation of CDFIG facilitates the removal of brushes and copper rings, thereby further decreasing the maintenance costs associated with traditional DFIG systems. The proposed SMC aims to reduce the levels of chattering phenomena, as confirmed by the simulation results of a nonlinear controlled system. The simulated MC exhibited the ability to regulate secondary side voltage and frequency, even under conditions of bidirectional power flow.

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