Wind energy conversion system based on DFIG using three-phase AC-AC matrix converter

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ABSTRACT

Due to the development of power electronics technology, the use of a new generation of power converter AC-AC matrix converters has received special attention, which provides direct power converter AC-AC, bidirectional power flow, near-sinusoidal input, and output waveforms. The performance analysis of a variable-speed wind turbine based on a doubly fed induction generator and connected to the main grid through a three-phase matrix converter is presented in this paper. Additionally, this paper proposes the utilization of a space vector modulation approach in the three-phase matrix converter. Other benefits of the space vector modulation approach include lower total harmonic distortion of output voltage and lower switching loss. The simulation analysis of the proposed power conversion system using MATLAB/Simulink/ SimPowerSystems toolbox R2021a is presented in this paper.

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1. INTRODUCTION

The growing demand for electrical power, combined with the depletion of conventional energy sources and fossil fuels, is regarded as one of the most pressing critical issues highlighting the importance of renewable energy sources (RESs). Wind energy is attracting research interest because it is one of the fastest growing RESs and is gradually becoming widely popular and competitive with traditional sources of energy [1]. In the literature, various wind energy conversion systems (WECSs) have been proposed and validated. Fixed speed wind turbines (FSWT) and variable speed wind turbines are the two basic categories into which these systems can be split (VSWT) [2]. Variable speed WECSs are more effective because they have the ability to adjust the generator speed based on variations in wind velocity to capture the most power, despite the fact that FSWTs are simpler and less expensive than VSWTs. Wind turbine design technologies that combine power electronics and control strategies include squirrel cage induction generators (SCIG) [3], wound rotor synchronous generators (WRSG) [4], doubly fed induction generators (DFIG) [5], and permanent magnet synchronous generators (PMSG) [6]. The doubly fed induction generator (DFIG) based on back-to-back converters has already demonstrated its superiority over other configurations for the generation of variable speed wind power. Rather than utilizing traditional back-to-back converters with DC-link capacitors, the matrix converter with lowered passive element (DC-bus capacitor, and the line filter elements) can be a suitable option for this kind of power generation system.

Three-phase matrix converters (MC) are capable of producing a three-phase AC output of variable amplitude and frequency from a three-phase AC source [7]. They have attracted considerable attention as they provide bidirectional power flow and sinusoidal waveforms at the input as the output. Furthermore, the matrix converters have high reliability, long lifetime, and compact design because there is no bulk electrolytic capacitor for intermediate power storage [8]. In the literature, there are two types of matrix converter topologies: direct matrix converter (DMC) and indirect matrix converter (IMC) [9].

Because of the aforementioned benefits, the use of MCs has expanded beyond electrical drives to integrate the renewable resources to the main networks. A comprehensive review of matrix converter technology including different modulation techniques and commutation methods has been proposed in [10]. Svinkunas and Petrauskas [11], presented the performance of a grid-connected wind energy conversion system, based on a DFIG fed by a matrix converter. Bedoud *et al.* [12], explained a modest control scheme has been done for DFIG based wind electric conversion system with matrix converter under harmonic and unbalanced grid conditions. On the other side, the difficulty of the matrix converter technique makes it challenging to study and determine appropriate modulation strategies. To address this issue, two different mathematical methods have been investigated in the past, namely, the space vector modulation strategy and the modulation duty cycle matrix strategy which was initially used to establish a solid theoretical base for matrix converter theory [13].

To date, space vector modulation (SVM) is a well-known and widely used modulation technique due to its high performance and the use of orthogonal two-dimensional vectors commonly found in variable speed drives of AC motors as well as in the wind energy conversion systems [14]. In order to control the input power factor independently of the output power factor, utilize the full of the input voltages and decrease the number of switch commutations per cycle period. Additionally, this approach permits an immediate understanding of the modulation method, even without the requirement of a fake DC link, and refraining from including the third-harmonic elements [15], [16].

In this paper a wind power conversion system based on the traditional AC-DC-AC converter has been replaced by an enhanced three-phase to three-phase matrix converter topology, which conned to a doubly fed induction generator. Furthermore, a brief description of the system under study is provided. Then, it is presented how the wind energy can be caught and transformed to electric energy, using a wind turbine, a DFIG, and a matrix converter. Finally, to back up the theoretical expectations, several simulation results based on the proposed studied system are presented.

The remainder of this paper is organized as follows: section 2 is devoted to the structure and modeling of the system under study, the modeling of the wind turbine and the matrix converter. The space vector modulation strategy is presented in section 3. In section 4, results of computer simulations performed using MATLAB/Simulink/SimPowerSystems are presented and discussed. Finally, section 5 concludes the paper.

2. SYSTEM STRUCTURE AND MODELING

Figure 1 depicts the structure of a wind energy conversion system (WECs) based on a matrix converter, which is usually divided into two parts. The first is the mechanical component, which transforms the kinetic energy of the wind into mechanical energy through the blades of the turbine. The second one is the electrical component, which directly transforms mechanical energy into electrical energy through DFIG, and then feeds it into the main grid through a matrix converter.

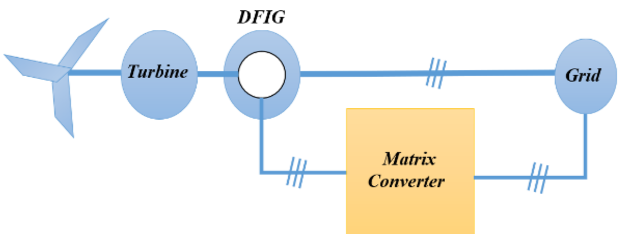

Figure 1. Schematic representation of the suggested wind energy conversion system

2.1. Wind turbine

The output power of the wind turbine can be calculated using the as follows [5]:

$$P_w = \frac{1}{2}\rho A v_w^3 \quad (1)$$

where ρ : air density in kg/m^3 ($1.2\ kg/m^3$); A : sweep area in m^2 ($A = \pi R_T^2$, with R_T is the radius of the rotor blades; and v_w : wind speed in m/s. The wind power captured by the blade and converted into mechanical power can be calculated by (2).

$$P_M = \frac{1}{2}\rho A v_w^3 C_p \quad (2)$$

According to the following equation, the power coefficient depends on the rotor blade pitch angle θ and the tip speed ratio γ_M:

$$C_p(\gamma,\theta) = 0.73\left(\frac{151}{\gamma_i} - 0.58\theta - 0.002\theta^{2.14} - 13.2\right)e^{-18.4/\gamma_i} \quad (3)$$

where (4):

$$\gamma_i = \frac{1}{\frac{1}{\gamma - 0.02\theta} - \frac{0.003}{\theta^3+1}} \quad (4)$$

and (5).

$$\gamma = \frac{\omega_M R_T}{v_w} \quad (5)$$

In the above equation, ω_M represents the turbine shaft angular speed. According to Betz's Law [17], the theoretical upper bound of C_p is 0.59, but the actual range of variation is between 0.2 and 0.4. The rotor pitch angle is supposed to be constant in this work. A typical $C_p$versus profile γ is shown in Figure 2 [18].

2.2. Matrix converter

An AC-AC converter named the three-phases to three-phases matrix converter (MC), as illustrated in Figure 3, is made up of nine bi-directional, four quadrant power electronic switching devices arranged in a 3 x 3 matrix. To modulate the output voltage waveform a switching device are used with varying frequency and voltage whereas drawing an input current sinusoidal. The switching devices in matrix converters are configured in such a way that any output line can be connected to any input phases. Compared to many other AC-AC converters, the matrix converter has numerous advantages. The main advantages of the matrix converter are [19]: i) It is a converter with a single stage without significant energy storage components. As a result, it can fit into a smaller chassis; ii) It has the ability to generate a variable output voltage sinusoidal and draws an input current sinusoidal; iii) It has a controllable input displacement factor that is unaffected by the load attached to the output; and iv) It is a four-quadrant switching system with bi-directional power capability.

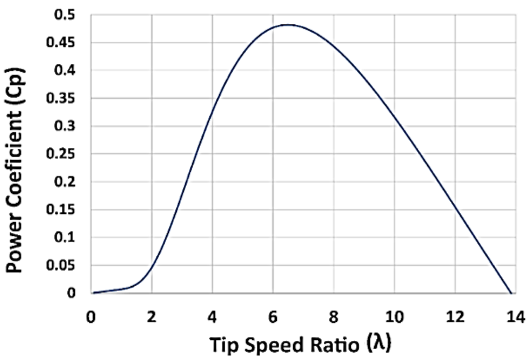

Figure 2. Power coefficient according of the speed ratio

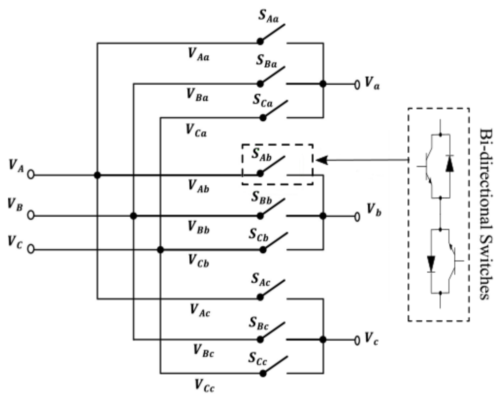

Figure 3. Topology of a matrix converter

2.2.1. Matrix converter fundamentals

Figure 1 depicts a simplified topology of a three-phase to three-phase Matrix Converter. In terms of input voltages (V_A, V_B, V_C), the three phase output voltages (V_a, V_b, V_c) are defined as (6) [13].

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = T \times \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \tag{6}$$

Where T stands for an instantaneous transfer matrix. The switching functions (S_{jk}) define the transfer matrix T of the matrix converter as (7).

$$S_{jk} = \begin{cases} 1, & S_{jk}\ closed \\ 0, & S_{jk}\ Open \end{cases} \quad , \quad j \in (A, B, C)\ and\ k \in (a, b, c) \tag{7}$$

The switching constraint is defined as follows in order to avoid open circuits to the output terminals or short circuits between input terminals:

$$S_{ja} + S_{jb} + S_{jc} = 1 \ , \quad j \in (A, B, C) \tag{8}$$

We know that the transfer matrix of calculating input currents is the transpose of the transfer matrix of calculation the outputs voltage. As a result, the output currents (Ia, Ib and Ic) can also be used to calculate the input currents (IA, IB and IC) as (9):

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = T^T \times \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{9}$$

2.2.2. Bidirectional switch topologies

The three-phase matrix topology consists of nine four-quadrant bidirectional switches positioned in a matrix, these switches are capable of conducting current and blocking voltages of either polarity. The simplest switch cell is a single-phase diode bridge with an IGBT connected at the center, as shown in Figure 4 [20].

The key advantage of that kind of switch is the fact that one active device is required. This method lowers the power circuit cost as well as the complexness of the control. Each switch cell requires only one transistor gate drive circuit. The drawback is that the line loss is relatively high. During the conduction phase, three components (one IGBT transistor and two diodes) are conducted [21], [22].

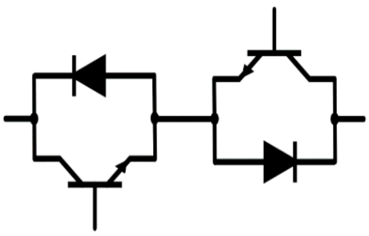

Figure 4. A diode bridge with a bidirectional switch cell and an IGBT configuration

3. SPACE VECTOR MODULATION

Space vector modulation (SVM) is a form of pulse width modulation (PWM) based on the two-phase representation of three-phase quantities. Certain benefits of SVM over other PWM techniques are [23]: i) It has better total harmonic distortion (THD) characteristics because much of the disturbance is centred on the switching frequency; ii) A large range of linear modulation; and iii) The switching frequency is much higher than the fundamental frequency of the input supply, so a low-pass filter can be used to remove high-frequency switching components. Because of the aforementioned advantages, a space vector modulation is employed in this paper. In this type of modulation technique, the input current vector and the output voltage vector are combined simultaneously.

3.1. Space vector modulation principle

The fundamental concept of the space vector modulation is to decouple the control of the output current and the control of input current, so that the instantaneous transfer matrix T is given as follows [24], [25]:

$$T = I \times R \tag{10}$$

$$\begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \tag{11}$$

Where R and I are the rectifier and inverter transfer matrix, respectively. By substituting the (11) into (6), the output voltage of the matrix converter becomes as (12):

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix}$$
$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} S_7S_1 + S_8S_2 & S_7S_3 + S_8S_4 & S_7S_5 + S_8S_6 \\ S_9S_1 + S_{10}S_2 & S_9S_3 + S_{10}S_4 & S_9S_5 + S_{10}S_6 \\ S_{11}S_1 + S_{12}S_2 & S_{11}S_3 + S_{12}S_4 & S_{11}S_5 + S_{12}S_6 \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \tag{12}$$

3.2. Simulation of space vector modulation

Initially, the matrix converter's Simulink implementation is completed. The matrix converter is made up of 9 bidirectional sectors with reverse blocking capability, which are organized in three sets of three, allowing any of the three input phases to be connected to any of the three output phases. For blocking the voltage in matrix converter, a bidirectional 18 diode is used. When the voltage mod input is used to generate (v_1, v_2, v_7, v_8) with the switching pattern, the space vector modulation's inversion matrix sequence created as shown in Figure 5.

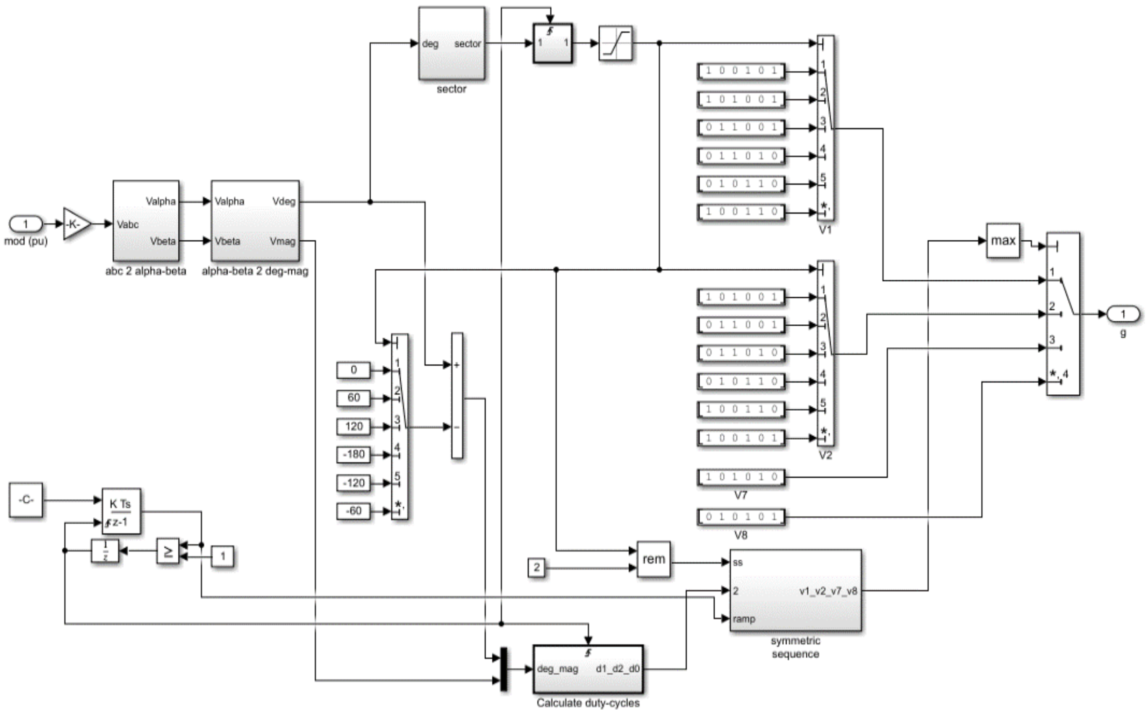

Figure 5. SVM symmetric switching in the voltage mod input of the matrix converter

In the first position $(0 - 60)$ degrees, torque decreases and flux increases. There is flux ambiguity at $(60 - 120)$ or $(-120 - (-60))$ position, torque and flux reduction at $(-180 - (-120))$ position, torque at last position $(180 - 120)$ increases as the magnetic flux increases. There are two positions between $(30 - (30))$ that are not used because the torque increases or decreases depending on the position in the same sector if it is the 30 or -30 position.

The symmetric sequence unit is generated using the current mod as input (v_1, v_2, v_0) as shown in Figure 6. The IGBT transistor uses the combinations from 1 to 9 that are the sectors

$(v_0, v_1, v_2, v_3, v_4, v_5, v_6, v_7, v_8, v_9)$ as a gate signal, As can be seen in Figure 7. The current mode can be used to create the first six states, and the staying six states, which were created using the voltage mode circuit. These 12 signals' combinations are used to build the space vector modulation that controls the matrix converter.

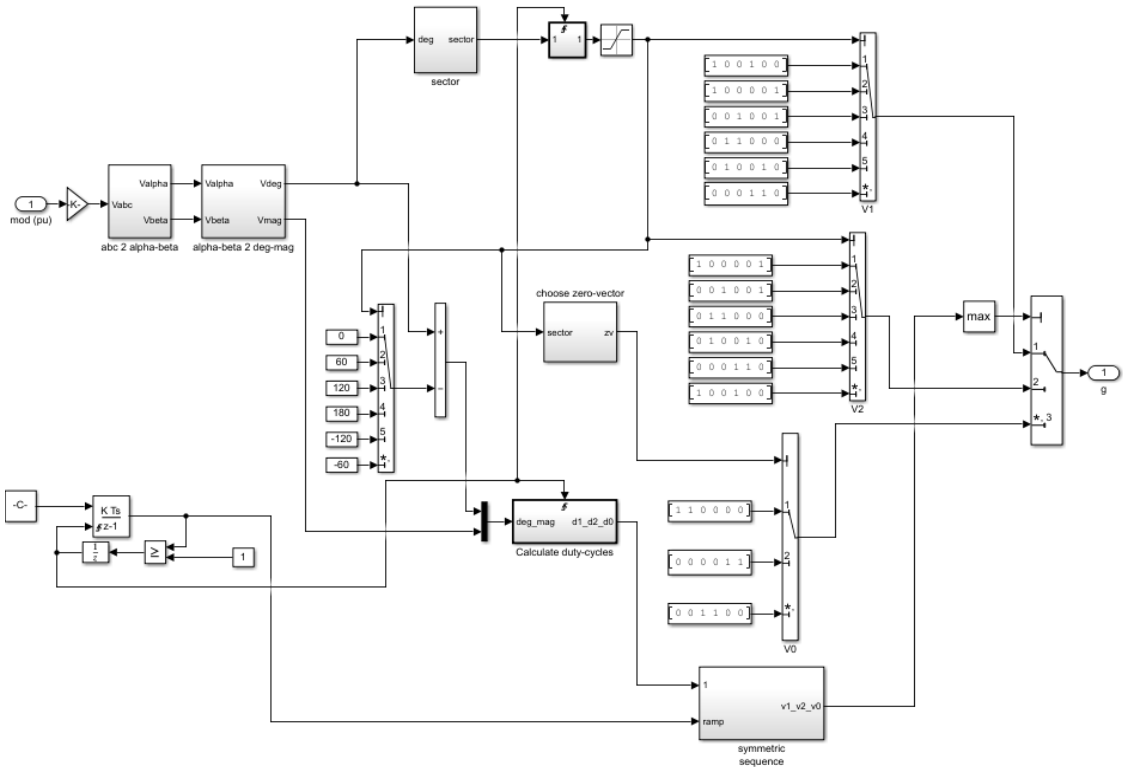

Figure 6. SVM symmetric switching in the current mod input for matrix converters

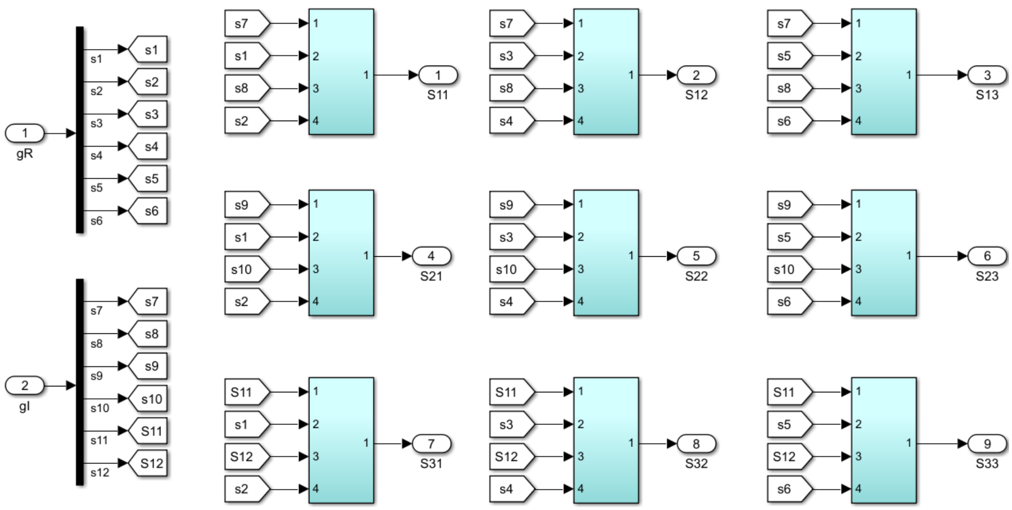

Figure 7. Constructing switching signals

4. RESULTS OF NUMERICAL SIMULATION

The system under study is simulated using the MATLAB/Simulink/SimPowerSystems software in order to investigate its feasibility and performance. The schematic diagram of the setup is depicted in Figure 8. The electrical characteristics of the main grid and the DFIG characteristics are given in Table 1. Two tests will be considered in this section.

4.1. Test with a constant wind speed

In this test, the wind profile taken into account in simulation when the wind speed is constant, and it is equal to $12\ m.s^{-1}$. As shown in Figure 9 that for a wind speed of 12 given by the turbine the power to be recovered has a constant average value. The currents and voltages at the input and output of the matrix converter are shown respectively in Figures 10 to 13. It is clear that these figures show the high performance of the proposed strategy for the system under study. The switching frequency of the IGBTs is 6 kHz.

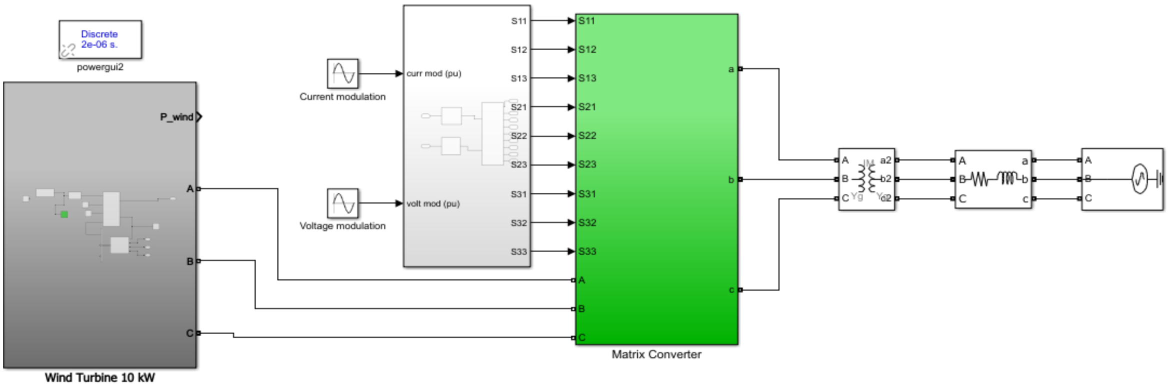

Figure 8. The proposed strategy scheme for the studied system

Table 1. The electrical characteristics of the system under consideration

Variable	Values	Variable	Values
Nominal power of wind turbine	10 KW	Rotor flux	2.2 Wb
Turbine radius	4.5 m	Total inertia	0.015 $Kg.m^2$
Blad pitc	0°	Grid voltage	380 V
Nominal speed	6	Grid frequency	50 Hz
Number of pole pairs	52.33 $rad.\ s^{-1}$	Filter inductor	0.2 mH
Stator resistor	0.52 Ω	Filter resistor	0.2 m Ω
Stator inductor	5.7 mH		

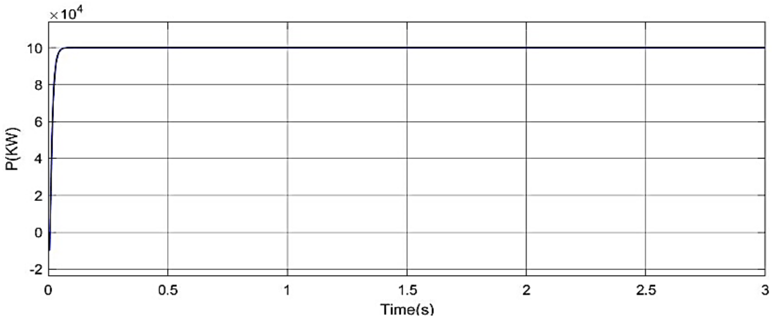

Figure 9. The power delivered by the wind turbine

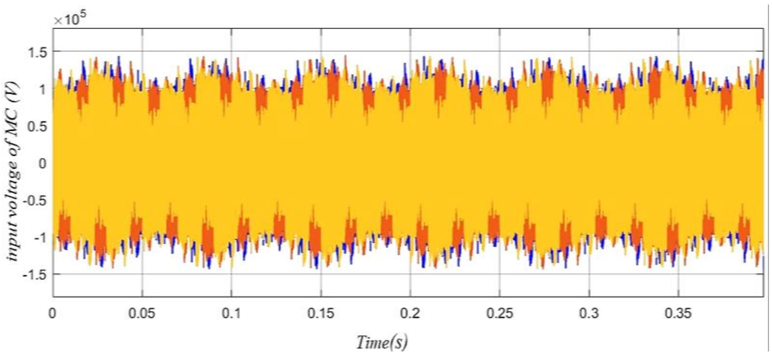

Figure 10. The input voltage of the matrix converter

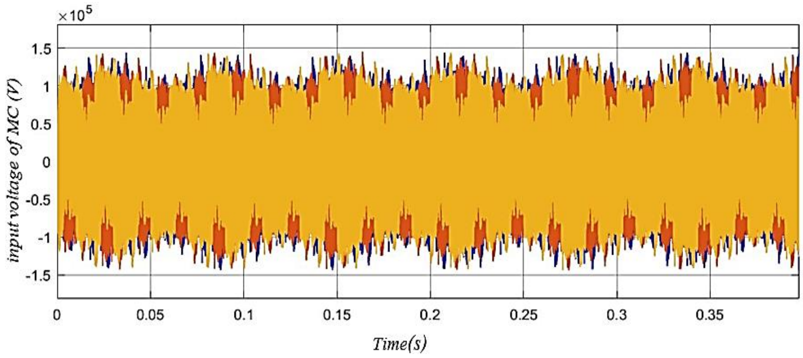

Figure 11. The input current of the matrix converter

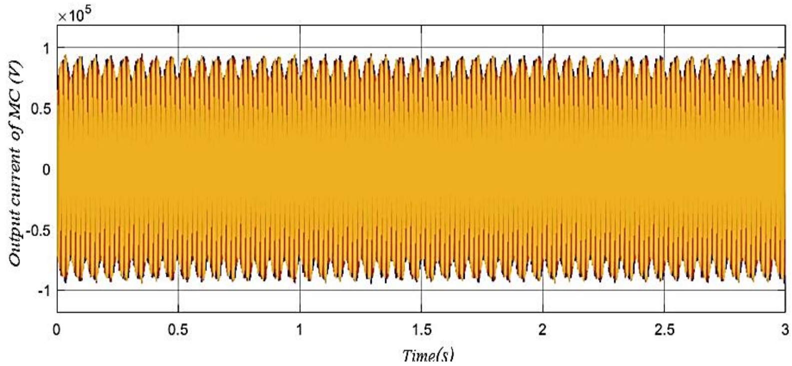

Figure 12. The output voltage of the matrix converter

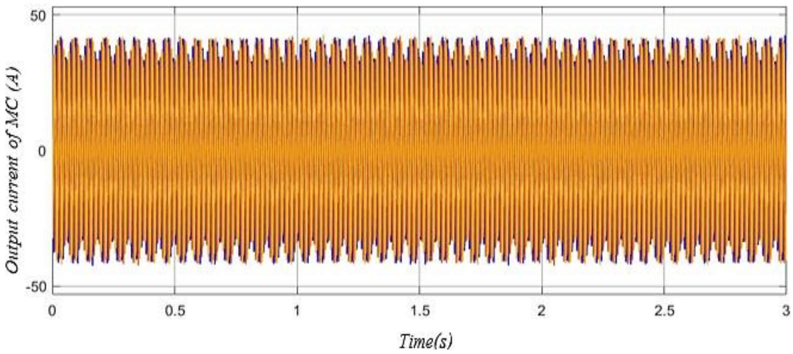

Figure 13. The output voltage of the matrix converter

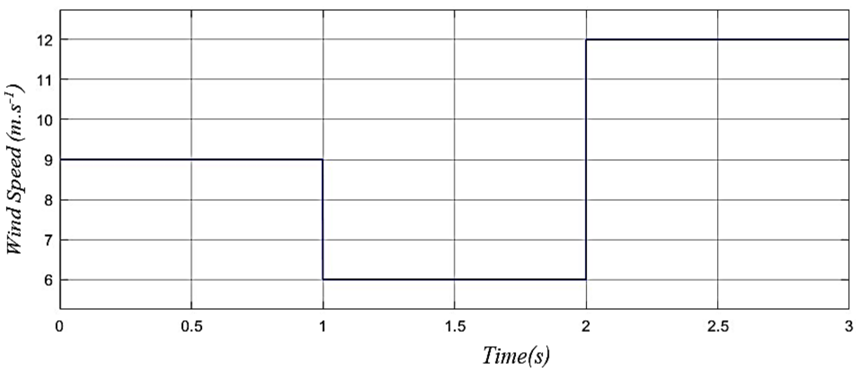

Figure 14. The profile of the wind speed

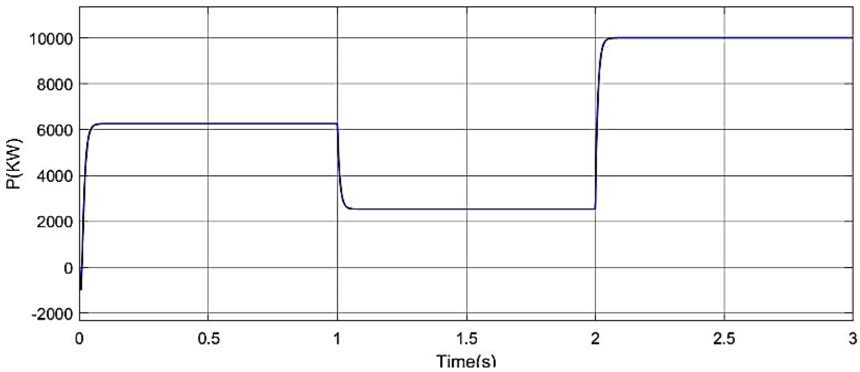

Figure 15. The power recovered by wind turbine under wind speed variation

4.2. Test with a variable wind speed

In this part, a wind speed profile of $9\ m.s^{-1}$ to $6\ m.s^{-1}$ at time $t = 1\ s$ and $6\ m.s^{-1}$ to $12\ m.s^{-1}$ at time $t = 2\ s$ is applied, as shown in the figure bellow. Due to the variations in wind speed, as illustrated in Figure 14, the power recovered by the wind turbine varies proportionally to the wind speed as shown in Figure 15, this explains the robustness and the high performance of the wind turbine. Despite variations in wind speed shown in Figure 14, the matrix converter keeps its operation in good condition. This gives good results for the input-output currents and voltages of the matrix converter despite the variations of the wind speed as shown in the Figures 16 to 19.

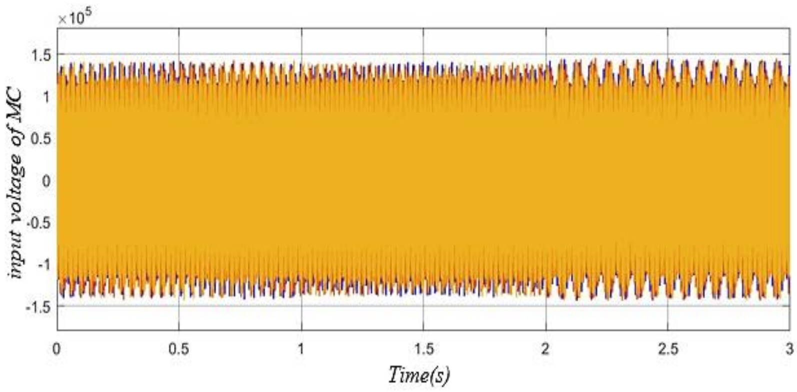

Figure 16. The input voltage of the matrix converter

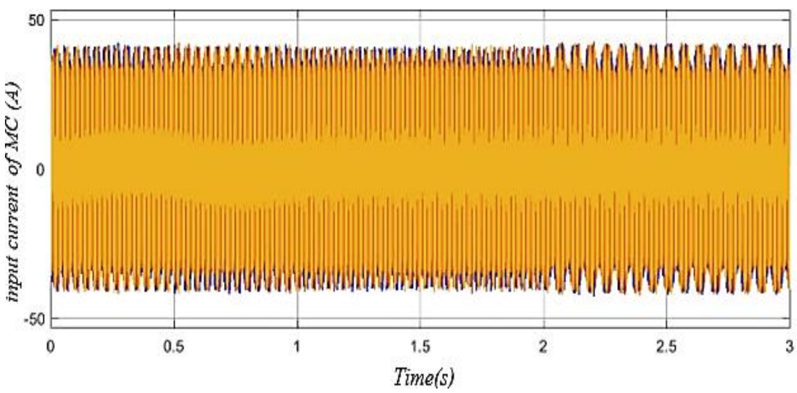

Figure 17. The input current of the matrix converter

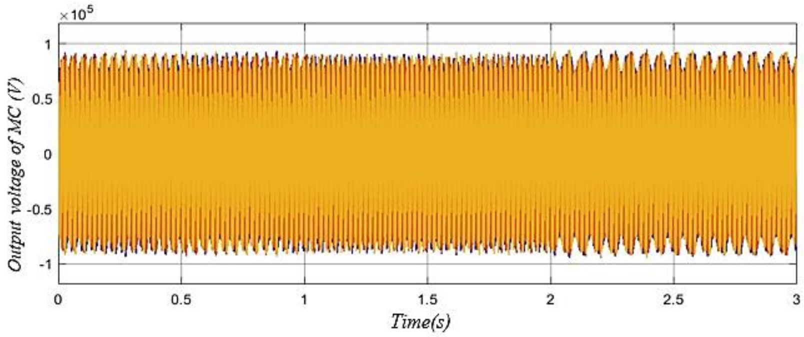

Figure 18. The output voltage of the matrix converter

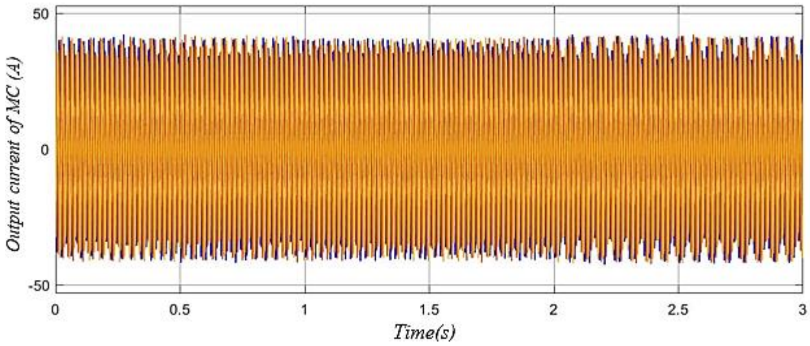

Figure 19. The output current of the matrix converter

5. CONCLUSION

In this work, the modeling and simulation of wind power conversion systems based on DFIG connected to three-phase matrix converters are considered. This is due to cost reduction, simple topology, no need for large DC link capacitors, and other advantages. The suggested matrix converter for DFIG system was further proposed to stabilize a wind power conversion system. The following stage of the paper is elaborate simulations of the presented matrix converter control scheme based on the space vector modulation. Simulation and experimental results verifying various performance aspects of the presented system can be found in the numerical simulation results section of this document.

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