



# Direct Torque Control with SVM and PI Regulation for Wind Energy Conversion Systems: Modeling and Performance Analysis

Bouras Lakhdar<sup>1\*</sup>, Lalalou Rachid<sup>1</sup>, Mezhoud Nabil<sup>1</sup>

<sup>1</sup> Electrical Engineering Department, Faculty of Technology, LES Laboratory, Université 20 Août 1955-Skikda, Algeria

Corresponding Author Email: [l.bouras@univ-skikda.dz](mailto:l.bouras@univ-skikda.dz)

## ABSTRACT

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This paper presents the implementation of Direct Torque Control (DTC) for an asynchronous machine powered through a rectifier placed at the output of a Permanent Magnet Synchronous Machine (PMSM), following a voltage regulation loop. The study focuses on controlling the output voltage of a wind energy conversion system based on a PMSM, utilizing a Proportional-Integral (PI) controller integrated into the system. A comprehensive mathematical model is developed to simulate the entire system using MATLAB software. Simulation results with closed-loop regulation demonstrate that this control technique significantly enhances power quality and proves to be highly effective for this type of application.

## 1. INTRODUCTION

Control can be defined as the process of ensuring a system follows a desired reference by applying commands tailored to the system's characteristics and dynamic behavior. A wide range of control strategies and structures, from simple to complex, are well-documented in the literature. The selection of an appropriate control structure depends on several criteria, with ease of implementation and robustness against disturbances being the most critical. Typically, each method is suited to a particular application context. Control techniques are generally categorized into two main groups: conventional methods, such as PID control and state feedback, ...etc. and more advanced or modern approaches.

The DTC technique, introduced by Takahashi et al. in 1988, was presented as a response to the limitations of the vector control strategy [1]. The continued advancement of vector control methods in the field of AC electrical machines has spurred the development of alternative modern control strategies, particularly for static inverter applications. The original DTC scheme is notably straightforward, consisting of hysteresis comparators, torque and flux estimators, a switching lookup table, and a voltage-source inverter (VSI). One of its key advantages is that it eliminates the need for coordinate transformations, PWM generation, and current controllers. Additionally, it relies minimally on machine parameters, making it both efficient and robust [2].

To implement this method, stator flux orientation is used, enabling the control voltages to be generated through a PI controller and applied using Space Vector Modulation (SVM) [3-4]. Torque and flux estimation is performed using the

machine's voltage model [5-6]. This control architecture combines the strengths of both vector control and DTC, helping to address the conventional drawbacks of standard DTC approaches [7-8]. Furthermore, the integration of the PI controller with VM allows for a constant switching frequency, reducing both torque ripple and flux pulsations [9-11]. In this paper, our contribution is to propose a new control architecture based in a PI controller to stabilize the output voltage of a PMSM driven by a wind energy conversion system, with the development and analysis of each element of the conversion chain presented and the impact of wind speed variations is also examined.

Our contribution also focuses on improving system performance by reducing switching losses by powering the PMSM with an output rectifier followed by an inverter controlled by the DTC-SVM technique [12-19].

## 2. DESCRIPTION AND MODELING OF THE CONVERSION CHAIN

Figure 1 illustrates the essential components involved in converting wind energy into electricity. This process utilizes a permanent magnet synchronous generator (PMSG) mechanically coupled to a wind turbine via a reduction gear, all driven by a modeled wind profile.

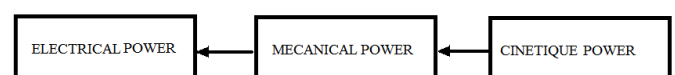


**Figure. 1** Principle of wind power conversion

Wind energy systems generate electricity by converting the kinetic energy of moving air into electrical power. Understanding wind's dynamic behavior is crucial to optimizing this energy conversion chain. Two main types of wind turbines are employed, horizontal-axis and vertical-axis, both following a two-stage process: wind drives the blades to produce mechanical energy, which is then converted into electricity via a shaft-connected generator using electromagnetic conversion principles.

Each turbine component is engineered to maximize energy extraction. As wind power gains prominence, electrical engineers have intensified efforts to enhance electromechanical conversion efficiency and the quality of the generated power. To substantiate theoretical models, practical implementation or simulation of the wind energy conversion process is essential.

Wind speed can be modeled by the following equation:

$$v_v = f(t) \quad (1)$$

Wind speed as a function of harmonics [2]:

$$v_v(t) = A + \sum_{n=1}^i a_n \sin(b_n w_v t) \quad (2)$$

The a uncertain model of winds rotating is illustrated by the follows equation :

$$v_v(t) = 11 + 0.2\sin(0.10477.t) + 2.\sin(0.2665.t) + \sin(1.293.t) + 0.2\sin(3.6645.t) \quad (3)$$

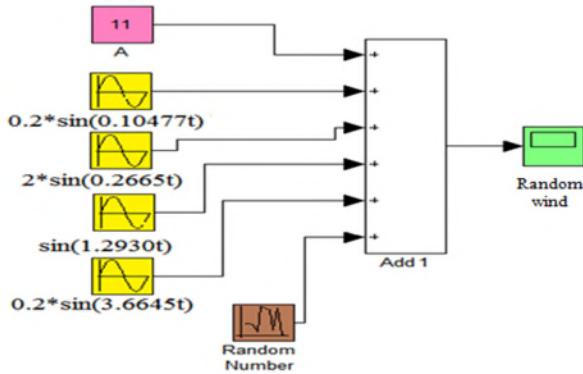


**Figure. 2** The diagram block of Uncertain wind profile

## 2.1. Wind turbine modeling

A three-dimensional wind turbine, with its dynamic form immersed in airflow, transforms the wind's kinetic energy into mechanical power characterized by rotational speed, mechanical torque, and motion [3].

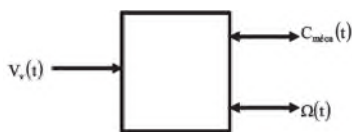


**Figure. 3** Input and output of wind

The kinetic energy of an air mass is [6]:

$$E_c = \frac{1}{2} m V^2 \quad (4)$$

The instantaneous power is calculated using the following equation:

$$P_v = \frac{1}{2} \rho S V^2 \quad (5)$$

The ratio between the extracted and available power gives us the power coefficients described by the following equation:

$$C_p = \frac{P_e}{P_v} \quad (6)$$

With:

$$P_e = 0.5 \rho S C_p V^3 \quad (7)$$

Equation (7) represents the back wind power. Where  $C_p$ ,  $\rho$ ,  $S$ , and  $V$  are, respectively, the power coefficient, density of air (1.25 Kg/m<sup>3</sup>), area swept by the turbine and the wind speed.

The wind turbine is characterized by its curve  $C_p = f(\lambda)$  with  $\lambda$  is the ratio between the tip peripheral speed of blades and the wind speed.

$$\lambda = \frac{R \cdot \Omega}{v} \quad (8)$$

With:  $\Omega$ : the angular speed;  $R$ : the turbine rayon.

The power coefficient  $C_p$  is represented by the following equation:

$$C_p = C_c \cdot \lambda \quad (9)$$

Where

$$C_c = a_0 + a_1 \lambda + a_2 \lambda^2 + a_3 \lambda^3 + a_4 \lambda^4 + a_5 \lambda^5 + a_6 \lambda^6 \quad (10)$$

## 2.2 PMSM mathematical modeling

Park frame is used to derive the model of PMSM. The electrical dynamic equation in terms of dq phase variables can be written as

$$V_d = R_s i_d + L_d \frac{d}{dt} i_d + w_r L_q i_q \quad (11)$$

$$V_q = R_s i_q + L_q \frac{d}{dt} i_q + w_r (L_d i_d + \phi_f) \quad (12)$$

The transformation from three-phase to dqo-phase quantities can be written using Park transformation matrix form as

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (13)$$

The coupling electromagnetic equations are given by

$$\phi_d = L_d i_d + \phi_f \quad (14)$$

$$\phi_q = L_q i_q \quad (15)$$

The electromagnetic torque  $C_{em}$  and the dynamic equation of motor can be represented respectively as

$$C_{em} = \frac{3}{2} P \left[ (L_d - L_q) I_d I_q + I_q \sqrt{\frac{3}{2}} K_1 \right] \quad (2)$$

$$J \frac{d\Omega}{dt} + f\Omega = C_{em} - C_{eol} \quad (2)$$

Figures 4 and 5 represents, respectively, the uncertain wind profile and the PMSM output voltage with uncertain wind.

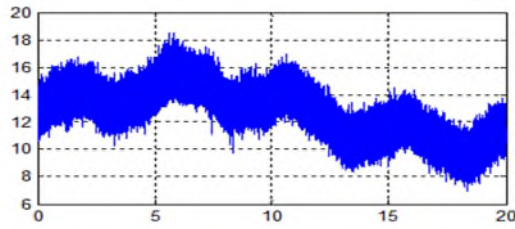


Figure. 4 The curve of Uncertain wind

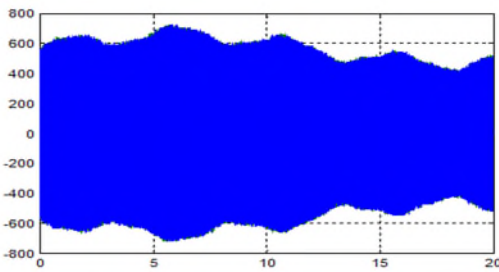


Figure. 5 The curve of PMSM output voltage.

In industrial applications, and without control system, it is not recommended to use the output voltage of the simulation chain according to Figure 5 subject to the wind variability profile shown in Figure 4.

This requires the use of structural control elements that have a stable output voltage regardless of the wind energy variability.

### 3. PROPOSED STRUCTURE

Based on the block diagram shown in Figure 6 based in a PI controller, the voltage regulation of the conversion chain can be performed.

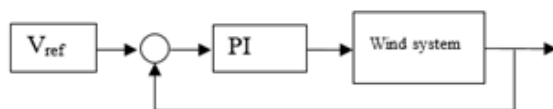


Figure. 6 Control principle using a PI controller

In the figure 7 we illustrated the integration of this controller with our wind conversion chain. The input of the controller based on the error between output voltages and the rotor reference frame  $V_d$  and  $V_q$ .

To facilitate the injection of the PMSM output voltages, we use the Park transformation. This operation results in

using the obtained current voltages for comparison with the reference voltage to minimize the error.

A PI controller begets a command based on the maximum error, thereby controlling the PMSM drive speed. This speed control is achieved through a variable transformation ratio provided by a controlled gearbox, ensuring an optimal relationship between turbine and generator rotational speeds.

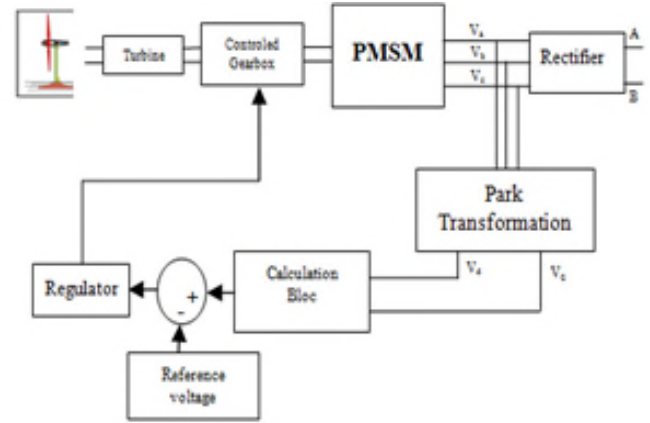


Figure. 7 wind chain voltage control architecture.

Where the coupling in points A and B of power block and DTC control is shown in Figure 8.

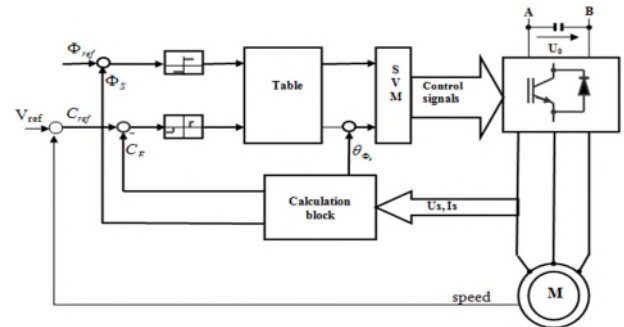


Figure. 8 DTC with SVM4 control architecture.

This architecture based on the power inverter presented by following figure (Figure 9). This inverter gives eight configurations according to the position of the possible switches [4].

On

Figure. 9 Control diagram of the PWM with DTC

In the figure 10a we illustrate the eight voltage vectors of the stator in the  $\alpha\beta$  frame. With  $\vec{v}_7$  and  $\vec{v}_0$  are null. The others vectors define six angular sectors of  $\pi/3$  rad. The vectors are modeling by the following equations.

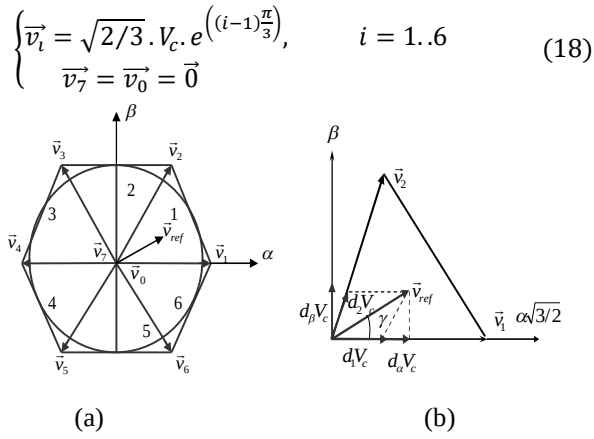


**Figure. 10** Diagram of the vectorial control of the inverter output voltages

The eight defined voltage vectors represent the measurable voltages when the switches are held in fixed states. However, the goal is to produce a voltage according to the desired reference. To achieve this, within a modulation period  $T$ , we apply vector  $\vec{v}_i$  for time  $T_i$ , then  $\vec{v}_{i+1}$  for  $T_{i+1}$ . This weighted approach, on average, we can obtain any desired voltage. Figure 10b illustrates how each vector is applied according to its weight proportionally, summarized by the following relation.

$$\begin{aligned} d_1 \cdot \vec{v}_1 + d_2 \cdot \vec{v}_2 &= \vec{V}_{ref} = m \cdot V_c \cdot e^{jy} \\ d_1 + d_2 + d_0 &= 1 \end{aligned} \quad (19)$$

If we take the case of the first sector, by projection we obtain the passage matrix of the vectors weights  $d\alpha$  and  $d\beta$  defined in reference mark  $\alpha\beta$  towards  $d1$  and  $d2$  (application during  $T_i$  and  $T_{i+1}$ ) (Fig. 10b).

$$\begin{bmatrix} d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} 1 & -1/\sqrt{3} \\ 0 & 2/\sqrt{3} \end{bmatrix} \cdot \begin{bmatrix} d_\alpha \\ d_\beta \end{bmatrix} \quad (20)$$

The passage matrix for the various vectors is summarized in the following table.

**Table. 1** Various sectors passage matrix

| Sector 1                                                           | Sector 2                                                            | Sector 3                                                           |
|--------------------------------------------------------------------|---------------------------------------------------------------------|--------------------------------------------------------------------|
| $\begin{bmatrix} 1 & -1/\sqrt{3} \\ 0 & 2/\sqrt{3} \end{bmatrix}$  | $\begin{bmatrix} 1 & 1/\sqrt{3} \\ -1 & 1/\sqrt{3} \end{bmatrix}$   | $\begin{bmatrix} 0 & 2/\sqrt{3} \\ -1 & -1/\sqrt{3} \end{bmatrix}$ |
| 4                                                                  | 5                                                                   | 6                                                                  |
| $\begin{bmatrix} -1 & 1/\sqrt{3} \\ 0 & -2/\sqrt{3} \end{bmatrix}$ | $\begin{bmatrix} -1 & -1/\sqrt{3} \\ 1 & -1/\sqrt{3} \end{bmatrix}$ | $\begin{bmatrix} 0 & -2/\sqrt{3} \\ 1 & 1/\sqrt{3} \end{bmatrix}$  |

After the validity of vectors periods are calculated, we need to determine the switches commutation moments. But the problem is we have several commutations for the same fundamental input and for each sequence produces harmonics and different losses in commutation.

Noted that the commutation losses are proportional to the current amplitudes in commutation. SVM is an algorithm which minimizes the commutation losses based on the choice to commute the weakest current in module [17-19]. If we suppose that the voltage vector located in the first area, we use that vectors  $\vec{v}_1, \vec{v}_2, \vec{v}_0$ , and using a band of hysteresis  $B_{xi}$  we request the  $\vec{v}_1$  vector to decrease current in the phase B and C or the  $\vec{v}_2$  vector to increase the currents in the phases A and C. which is enough to keep the three currents inside the hysteresis band. Since commutation losses are proportional to current amplitude during switching, Space Vector Modulation (SVM) aims to minimize these losses by choosing to switch the phase with the lowest current. Assuming the voltage vector lies in the first sector, vectors  $\vec{v}_1, \vec{v}_2, \vec{v}_0$ , are used. A hysteresis band  $B_{xi}$  controls the selection:  $\vec{v}_1$  is applied to reduce current in phases B and C, while  $\vec{v}_2$  increases current in phases A and C, ensuring all three currents remain within the hysteresis limits.

A wider hysteresis band, "Bx0", signals when the reference vector moves from one sector to another. Table 2 defines the commutation logic, specifying the position and magnitude of the voltage vector.

**Table. 2** Commutation table

| Ccpl | Cflx | Tension Vector       |                 |
|------|------|----------------------|-----------------|
|      |      | Angle $\Delta\theta$ | Amplitude $ V $ |
| -1   | 0    | $-2/3\pi$            | $2/3 V_c$       |
|      | 1    | $-1/3\pi$            | $2/3 V_c$       |
| 0    | 0    | 0                    | 0               |
|      | 1    | $2/3\pi$             | $2/3 V_c$       |
| 1    | 0    | $1/3\pi$             | $2/3 V_c$       |
|      | 1    | $1/3\pi$             | $2/3 V_c$       |

#### 4. SIMULATION OF THE PROPOSED STRUCTURE

Diagram block implanted under MATLAB/Simulink of wind chain controlled by PI controller is shown in Figure 11.

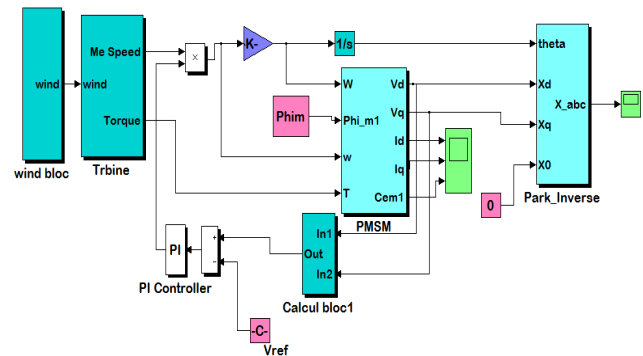


**Figure. 11** Diagram block of wind chain

The integration of the controller with the wind conversion chain can stabilize the output voltage around the desired reference ( $V_{ref} = 280$  V) as shown in Figure 12, whatever the variation of the wind and ensures the possibility of operating a quality energy can be injected to the electric network.

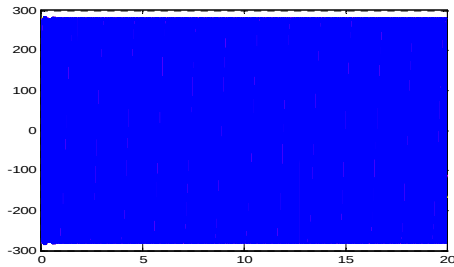


**Figure. 12** PMSM output voltage with PI regulation

In the Figure 13 we noted an robustness of the PI controller with a short response time (0.5s) and an acceptable overshend.

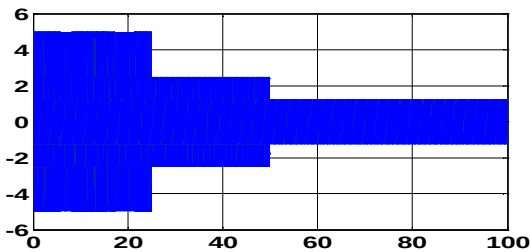


**Figure. 13** PMSM output voltage

As depicted in Figure 14, the results from the DTC simulation indicate that the torque occasionally breaches both the upper and lower thresholds of the designated control band. A noticeable torque ripple is present; however, the flux achieves its reference value, exhibiting only minimal oscillation within the control band. This behavior occurs despite the use of a null voltage vector and without any prior knowledge of the rotor's initial position or the corresponding stator flux orientation.

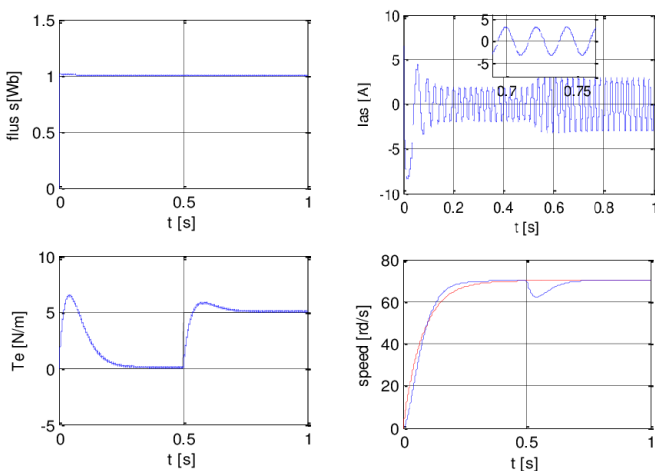


**Figure. 14** Simulation results of the DTC applied to the SVM

Furthermore, the switching frequency in this setup varies over time. In contrast, the SVM-based results shown

in Figure 8, using a switching period of  $T_e = 10 \mu s$  and a frequency of  $F_s = 10$  kHz, illustrate stable flux dynamics in a sensorless synchronous machine. with obtained results, the stator flux is nearly circular with magnitude limited by hysteresis limits. the same observation with the torque. In the Figures 15 and 16 we observe that the commutation frequency (command with SVM) is constant compared to DTC control.

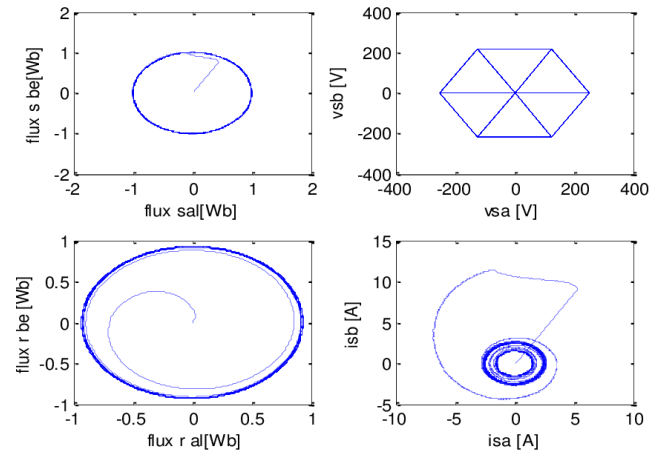


**Figure. 15** DTC applied to the SVM

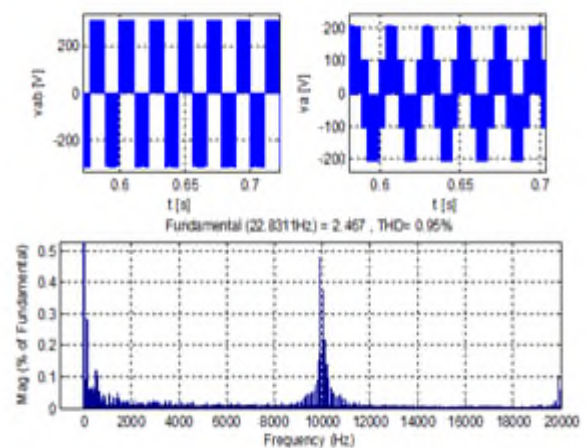


**Figure. 16** Simulation result of the DTC with SVM hysteresis

## 5. Conclusion

This research introduces a novel inverter voltage control method integrated within DTC, blending PWM and the hysteresis control. A comparative analysis between this hybrid approach and conventional DTC reveals that while DTC operates with a fluctuating switching frequency, the SVM component maintains a steady one, offering the benefit of minimizing switching-related energy losses. Furthermore, the study enables simulation of the wind energy conversion system's dynamic response under a stochastic wind profile modeled to resemble natural/true wind variations. The resulting voltage waveform supports the development of a control technique that aligns with controllery requirements for energy production, specifically, ensuring a steady output amplitude. This is achieved through the implementation of a PI controller, the heart of the proposed control loop.

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