International Journal of Engineering and Technology Innovation, vol. 13, no. 1, 2023, pp. 70-85

Using Feedback Control to Control Rotor Flux and Torque of the DFIG-Based Wind Power System

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Received 07 July 2022; received in revised form 26 September 2022; accepted 28 September 2022

DOI: https://doi.org/10.46604/ijeti.2023.10471

Abstract

Direct torque control (DTC) is a method of controlling electrical machines that are widely used, and this is due to its simplicity and ease of use. However, this method has several issues, such as torque, rotor flux, and current fluctuations. To overcome these shortcomings and improve the characteristics and robustness of the DTC strategy of the doubly-fed induction generator (DFIG), a new DTC scheme based on the feedback control method (FCM) and space vector modulation (SVM) is proposed. In the proposed DTC technique, a proportional-integral controller based on feedback control theory is used to control and regulate the torque and rotor flux of the DFIG. On the other hand, the SVM technique is used to control the rotor side converter (RSC) to obtain a high-quality current. The simulation result shows that the proposed DTC technique has the advantages of faster dynamics and reduced harmonic distortion of current compared to the conventional technique.

Keywords: doubly-fed induction generator, direct torque control, feedback control, total harmonic distortion, wind power systems

1. Introduction

The direct torque control (DTC) technique is among the methods that appeared in the last 80 years of the last century. This method was used for the first time to control the asynchronous motor, and this is due to the characteristics and advantages that it has compared to other methods. This technique was used to control the doubly-fed induction generator (DFIG) [1], asynchronous motor (AS) [2], multi-phase synchronous motor [3], multi-phase induction motor [4], and synchronous motor [5]. This method has several problems, including fluctuations in rotor flux, torque, and current [6].

To overcome these shortcomings and improve the robustness and effectiveness of the DTC technique, several methods, such as neural networks (NN), genetic algorithms (GA), and fuzzy logic (FL), have been designed. Refaat et al. [7], a neural DTC control technique was designed to control the AS drive. The switching table is replaced by the NN algorithm in this DTC strategy. NN was used to overcome the current and torque fluctuations and reduce the voltage's total harmonic distortion (THD) value. Another intelligent method to improve the dynamic response to DTC is proposed in [8].

Intelligent control based on the fuzzy logic technique has taken the place of the switching table. As a result, the flaws of the traditional DTC method are overcome, and the results demonstrate the fuzzy logic technique's efficacy in improving dynamic response. Boudjema et al. [9], a DTC strategy based on a second-order sliding mode controller to control DFIG-based

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wind turbines has been proposed. The use of this nonlinear method improves the performance and robustness of the DTC strategy compared to the traditional technique. In addition, the use of this nonlinear method makes the DTC strategy more robust, especially in the case of changing the generator parameters.

Chen et al. [10], DTC is presented based on the space vector modulation (SVM) technique, and the proportional-integral (PI) controller is used to control the torque and rotor flux of the DFIG. Compared to the traditional DTC technique, the dynamic responsiveness and THD value of electric current are improved when a PI method is used in this proposed method of DTC strategy. Benbouhenni and Boudjema [11], the neural-based DTC method controls the active and reactive powers. However, this technique reduced the current and torque ripples of the DFIG. On the other hand, simplicity, durability, and ease of implementation are the most important features of this smart method.

A DTC scheme based on the super twisting algorithm for the asynchronous motor is presented in [12]. However, robustness is the best feature of this method. Lascu et al. [13], a DTC strategy with feedback linearization is proposed for the asynchronous motors. However, the proposed DTC strategy improves the performance of the asynchronous motor compared to the traditional DTC technique. An improved SVM was proposed in [14] to overcome the disadvantages of the traditional DTC technique. However, the PI controllers were proposed to regulate the torque and rotor flux of the asynchronous motor.

This work proposes a new DTC scheme for a 1.5 MW DFIG-based wind power system. In this study, a new control strategy is proposed to design the wind electric power generation system to highlight the effectiveness of the proposed system and then improve closed-loop system performance. The proposed control combines the SVM-based DTC (DTC-SVM) and the proposed modified proportional-integral (MPI) controller. MPI controller is the main contribution and novelty of this work, and this controller is used to improve the features of the DTC technique. In addition, the MPI is a PI controller based on feedback control in which feedback control theory is used to improve the performance and effectiveness of the traditional PI controller. The objectives of the present work were to control the rotor side converter of the DFIG, improve the performance of the DFIG, and improve the steady-state performance of the rotor flux and torque. A comparative analysis of electromagnetic torque ripples and rotor flux of the proposed DTC based on the MPI controller and the traditional DTC technique was carried out and is presented in the results section. The following objectives outline the potential improvements discussed in this work:

- A new PI controller is presented.
- Electromagnetic torque and rotor flux are both improved.
- The quality of the current is improved.
- A new DTC technique is proposed and confirmed.
- Electromagnetic torque and rotor fluxes ripples are reduced to the greatest extent possible (hysteresis comparator, variability in the parameters of the DFIG, torque estimators, rotor fluxes, and inverters).
- The rotor and stator currents' total harmonic distortion (THD) rate is minimized.

The results of the comparison confirmed the good performance of the proposed DTC based on a feedback PI controller, where the torque and rotor flux ripples and the generated currents' THD were significantly minimized, especially under the changing parameters of the system.

2. Doubly-Fed Induction Generator (DFIG) Model

In wind systems, the DFIG generator is widely used because of its durability and ease of control. It is ideal for variable wind speed conditions [6]. In addition, this generator is characterized by less maintenance than other generators, such as DC generators. On the other hand, the DFIG is widely applied in high-power wind turbines because variable speed operation may be obtained through a fractional-sized back-to-back converter designed for 30% of the nominal power [9, 11].

The mechanical energy is gained from the wind into electrical energy by the DFIG generator. The Park transform is used in this section to provide the mathematical form of the generator used in this system [15-16]:

$$\begin{cases} \psi_{dr} = MI_{ds} + L_r I_{dr} \\ \psi_{qr} = MI_{qs} + L_r I_{qr} \\ \psi_{ds} = MI_{dr} + L_s I_{ds} \\ \psi_{qs} = MI_{qr} + L_s I_{qs} \end{cases} \tag{1}$$

where L_r is the inductance of the rotor, M is the mutual inductance, L_s is the inductance of the stator, I_{dr} and I_{qr} are the two-phase rotor currents, Ψ_{dr} and Ψ_{qr} are the two-phase rotor fluxes, I_{ds} and I_{qs} are the two-phase stator currents, finally, Ψ_{ds} and Ψ_{qs} are the two-phase stator fluxes.

Stator and rotor voltages:

$$\begin{cases} V_{dr} = R_r I_{dr} - \omega_r \psi_{qr} + \dfrac{d}{dt}\psi_{dr} \\ V_{qr} = R_r I_{qr} - \omega_r \psi_{dr} + \dfrac{d}{dt}\psi_{qr} \\ V_{ds} = R_s I_{ds} - \omega_s \psi_{qs} + \dfrac{d}{dt}\psi_{ds} \\ V_{qs} = R_s I_{qs} - \omega_s \psi_{ds} + \dfrac{d}{dt}\psi_{qs} \end{cases} \tag{2}$$

where V_{ds} and V_{qs} are the two-phase stator voltages, R_r is the resistance of the rotor windings, V_{dr} and V_{qr} are the rotor voltages, and R_s is the resistance of the stator windings.

Active and reactive powers [17]:

$$\begin{cases} Q_s = 1.5\left(-V_{ds} I_{qs} + V_{qs} I_{ds}\right) \\ P_s = 1.5\left(V_{qs} I_{qs} + V_{ds} I_{ds}\right) \end{cases} \tag{3}$$

where Q_s is the reactive power and P_s is the active power.

Torque is done as:

$$T_e = pM\left(I_{dr} I_{qs} - I_{qr} I_{ds}\right) \tag{4}$$

where p is the number of pole pairs and T_e is the electromagnetic torque.

The rotating part of the generator can be expressed by Eq. (5):

$$T_e = T_r + J\frac{d\Omega}{dt} + F_r \Omega \tag{5}$$

where T_r is the load torque, Ω is the mechanical rotor speed, T_e is the load torque, J is the inertia, and F_r is the viscous friction coefficient.

3. Proposed PI Controller

Traditionally, the PI controller is one of the most commonly used industrial controllers and the most well-known of them. It is used to control systems and get a fast dynamic response. Furthermore, the PI controller is one of the simplest and least expensive controls to implement, as it can be achieved by using a µ741 type integrated circuit [2]. The PI controller is used to control the speed of motors in a closed loop and provides satisfactory results in changing the speed of the motors [4]. In this controller, both integration and derivation are used. A PI controller was used to ameliorate the efficiency and robustness of both direct power control (DPC) and DTC strategies [18-19]. The results showed its effectiveness compared to a traditional controller in reducing torque and current fluctuations. The following equation expresses the traditional PI controller.

$$u = K_p \times e + K_i \int e \times dt \tag{6}$$

where e is the error, K_i and K_P are the constant values of the proportional and integral of the PI controller, respectively.

To ameliorate the response of any system controlled by the traditional PI controller, the change is made in both K_i and K_P. In some cases, we do not get the desired response, such as the existence of ripples at the torque and current levels, which necessitates the use of alternative methods, such as artificial intelligence, to enhance the responsiveness and performance of the PI controller. Ayrir et al. [20], the performance and effectiveness of DFIG are improved by combining PI controller and fuzzy logic. Another smart method was used to ameliorate the performance of the PI controller [21], which reduced the current and active power fluctuations of DFIG-based wind generation by using neural networks to boost the effectiveness of the conventional PI controller. Another technique for improving the response of the PI controller is suggested in [22]. A PI controller based on feedback control theory was used in this work to minimize the ripples of torque, active power, and stator current of the DFIG wind power system.

In this section, a new idea is presented to improve the PI controller's robustness while reducing current and active power fluctuations. Feedback control is used to ameliorate the efficiency of the PI controller control to achieve a high-quality DFIG current. In addition, it maintains the simplicity and ease of implementation of the traditional PI controller that characterized it. Eq. (7) represents this paper's proposed feedback PI controller.

$$w = K_p \times e + K_i \int (e - y) \times dt \tag{7}$$

Fig. 1 represents the proposed PI controller technique in this paper for controlling the rotor flux and torque of the generator (DFIG) and improving the robustness of the traditional DTC method. The designed PI controller method is robust, simple, inexpensive, and can be implemented easily. It also applies to any system, regardless of its type, whether linear or nonlinear. This proposed PI controller method does not require a specialist or a mathematical form of the studied system.

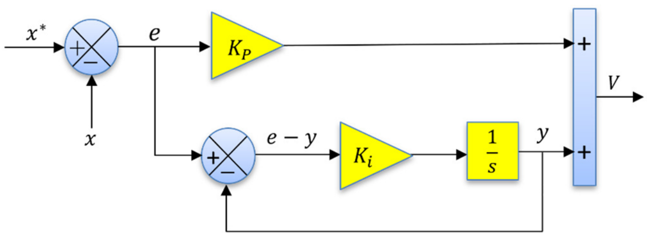

Fig. 1 Proposed PI controller

4. The Traditional DTC Strategy

The traditional DTC strategy for the DFIG installed in a wind system is shown in Fig. 2. The classical DTC technique is among the linear methods proposed for controlling electrical machines. Compared to the traditional indirect FOC strategy, the DTC technique is the simplest and easiest strategy, as it can be accomplished easily. Furthermore, the lack of inner loops in the DTC technique increases the speed of the dynamic response. This control scheme has been used for decades to control DFIG-based wind turbine systems due to its simplicity, ease of implementation, and low cost [23]. This control scheme is based on the direct regulation of torque and rotor flux by selecting the optimum voltage vector without measuring rotor speed, torque, or flux to obtain the required torque [24]. In this method, both the voltage and currents of the generator are measured to estimate both torque and flux.

As shown in Fig. 2, the traditional DTC technique is a simple algorithm and easy to implement compared to the indirect FOC strategy. From Fig. 2, both the torque and the flux are estimated to calculate the error in the flux and the torque. Therefore, measuring devices of very high accuracy must be used, where measuring voltage and current is necessary. Choosing a high-quality and efficient method for controlling the generator inverter inevitably leads to reducing the ripples of the effective power and electric current and thus maintaining the stability of the network.

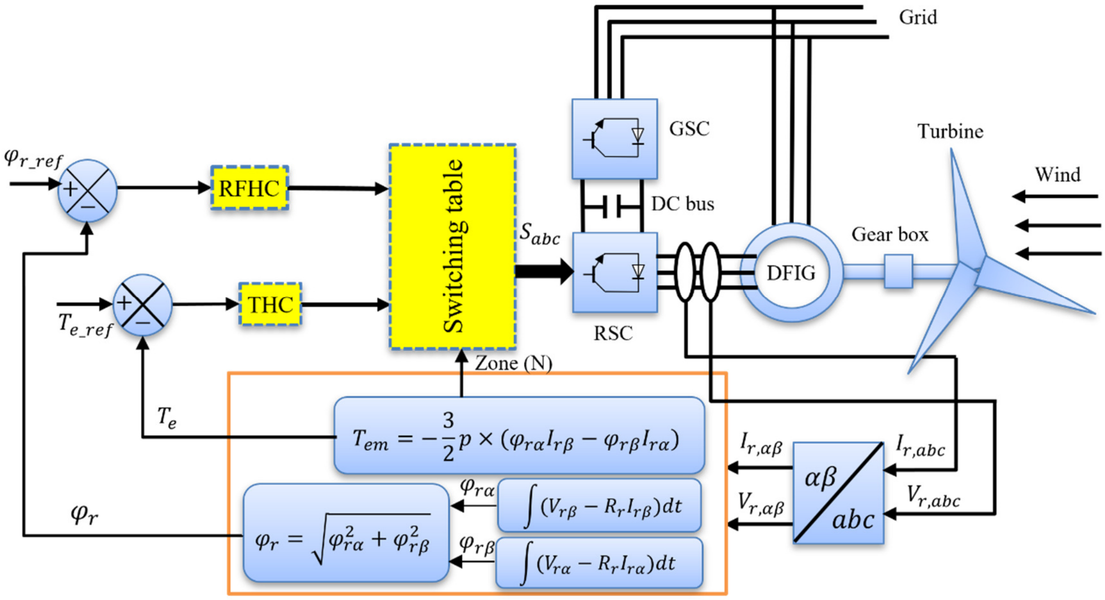

Fig. 2 Scheme of the classical DT C strategy of DFIG

The DTC's goal is to regulate the torque and rotor flux of the DFIG-based wind turbine system without using internal current loops. The traditional DTC technique obtains a fast response time and less dependence on DFIG parameters compared to the FOC control scheme [25]. The control of torque and rotor flux leads to the control of current and active power, where the technique of control greatly affects the quality of the current and the fluctuations of the active power and torque. The more robust and efficient the control scheme used, the higher quality of the results obtained.

In the traditional DTC strategy, the rotor flux and torque are directly controlled by using two hysteresis comparators. A switching table is used to control the inverter of DFIG. This switching table is employed to get the inverter transistor's control signals (*Sa*, *Sb*, and *Sc*).

This technique estimates the torque and the rotor flux, where the rotor flux is estimated according to Eqs. (8)-(9). As is well known, to estimate the rotor flux, we need to measure the rotor current and voltage of the DFIG.

$$\varphi_{r\alpha} = \int_0^t \left(-R_r I_{r\alpha} + V_{r\alpha}\right) \times dt \tag{8}$$

$$\varphi_{r\beta} = \int_0^t \left(-R_r I_{r\beta} + V_{r\beta}\right) \times dt \tag{9}$$

where $V_{r\alpha}$ is the rotor voltage linkage of the α-axis, $I_{r\alpha}$ is the rotor current linkage of the α-axis, $V_{r\beta}$ is the rotor voltage linkage of the β-axis, $\varphi_{r\alpha}$ is the rotor flux linkage of the α-axis, $I_{r\beta}$ is the rotor current linkage of the β-axis, and $\varphi_{r\beta}$ is the rotor flux linkage of the β-axis.

To calculate the rotor flux amplitude Eq. (10) is used.

$$\varphi_r = \sqrt{\varphi_{r\alpha}^2 + \varphi_{r\beta}^2} \tag{10}$$

where φ_r is the flux of the rotor.

The flux angle is calculated using Eq. (11). This angle is critical in determining the areas of rotor voltage [26].

$$\theta_r = arctg\left(\frac{\varphi_{r\beta}}{\varphi_{r\alpha}}\right) \tag{11}$$

$$\varphi_{r\alpha} = \frac{M}{L_s}\varphi_r + L_r L_{r\alpha}\left(-\frac{M^2}{L_r L_s}+1\right) \tag{12}$$

$$\varphi_{r\beta} = L_r L_{r\beta}\left(-\frac{M^2}{L_r L_s}+1\right) \tag{13}$$

Eq. (14) represents the relationship between voltage and rotor flux.

$$\left|\overline{\psi_r}\right| = \frac{\left|\overline{V_r}\right|}{w_r} \tag{14}$$

On the other hand, in order to estimate the torque, direct and quadrature rotor flux and rotor current are used, where the following equation is used:

$$T_{em} = -\frac{3}{2}p\left(\varphi_{r\alpha}\times I_{r\beta} - \varphi_{r\beta}\times I_{r\alpha}\right) \tag{15}$$

The mathematical form of the DTC technique is not complete until we give a switching table, as this is the cornerstone of this method. The switching table for the traditional DTC strategy is shown in Table 1 [27]. As it is known, using the switching table to control the generator inverter leads to obtaining a current in the inverter output of a non-fixed frequency, which is undesirable.

Table 1 Switching table for traditional DTC strategy

N		1	2	3	4	5	6
Hq	Hp						
1	1	2	3	4	5	6	1
	0	1	2	3	4	5	6
	-1	6	1	2	3	4	5
0	1	3	4	5	6	1	2
	0	4	5	6	1	2	3
	-1	5	6	1	2	3	4

One of the downsides of the DTC strategy is a current of non-constant frequency. This technique uses six zones and three-level hysteresis comparators (HCs) to control the torque. As for the flux, a two-level HC is used. Torque and rotor flux HC are represented in Figs. 3 and 4, respectively.

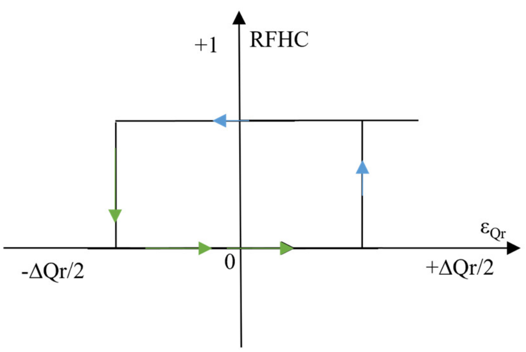

Fig. 3 Rotor flux hysteresis comparator (RFHC)

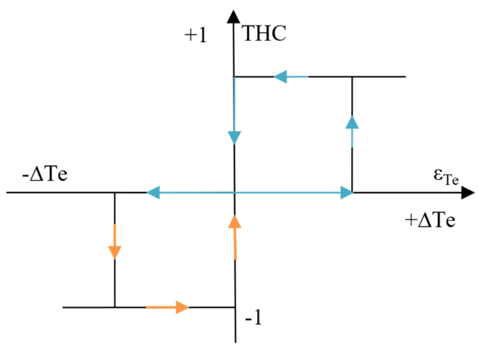

Fig. 4 Torque hysteresis comparator (THC)

5. DTC Strategy Developed

Electromagnetic torque and rotor flux ripples are among the major disadvantages of the traditional DTC technique. This section presents a new idea for the DTC technique based on the new controller proposed in Section 3 of the paper. The use of this proposed control scheme will lead to a significant reduction of electromagnetic torque and rotor flux ripples compared to the classical DTC technique. Also, improving the quality of the network current is the main goal of the work, which is to obtain a high-quality electric current and a constant frequency of 50 Hz to feed the electrical equipment.

This part presents a new control technique for controlling the DFIG-based wind power system without using internal current loops. The new DTC technique was proposed to improve the quality of electric power. This proposed technique is used to control the rotor generator inverter to improve the advantages of the DFIG-based wind turbine system. This proposed DTC technique uses a two-level rotor side converter controlled by the SVM technique. The internal structure of this converter is shown in the Appendix (Fig. A-1). The novel technology described in this part develops the DTC technique by substituting a switching table and a hysteresis controller for the suggested feedback PI controller and the SVM algorithm. The proposed DTC technique is depicted in Fig. 5. According to Fig. 5, the proposed DTC technique is straightforward, uncomplicated, does not require a specialist, and is easily accomplished.

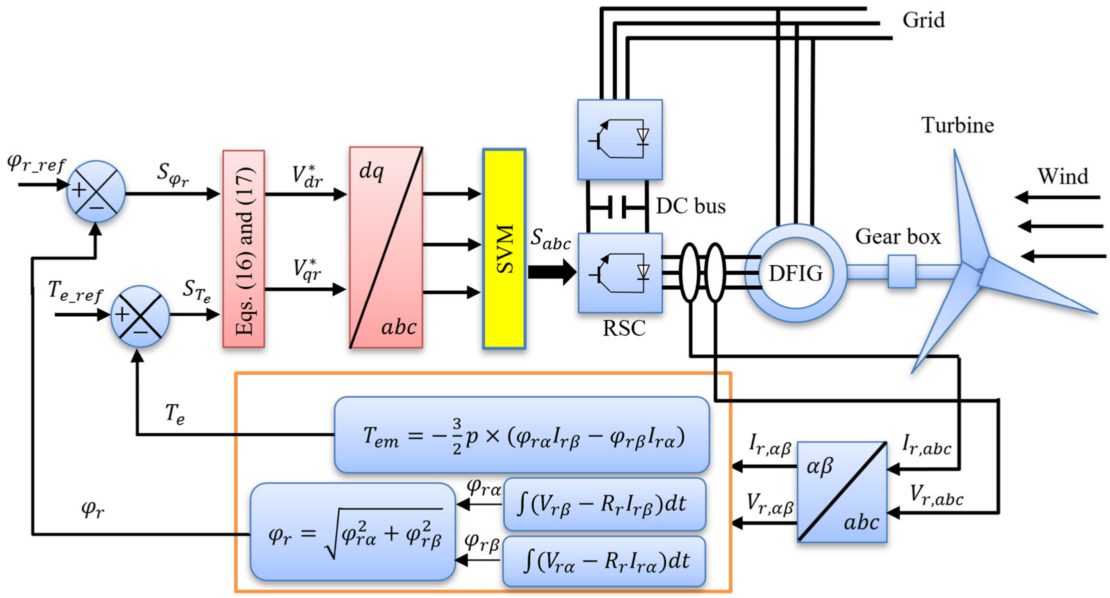

Fig. 5 Structure of the DTC strategy based on proposed feedback PI controllers

The main advantage of the proposed DTC strategy based on the feedback PI controller is its simple implementation while retaining the features of the traditional DTC strategy. This proposed DTC technique is more robust than vector control and traditional DTC techniques. However, the proposed DTC technique modifies the traditional DTC technique by excluding both hysteresis comparators and switching tables and replacing them with the feedback PI controller and SVM technique. In this proposed DTC technique, both torque and flux are estimated to calculate the error in torque and flux. We need to measure only current and voltage to estimate torque and rotor flux. In this proposed DTC technique, we do not need to measure the rotational speed of the generator. The torque and rotor flux error is input into the feedback PI controller. This latter component was introduced to minimize all ripples and reduce the generated current harmonics of the DFIG.

In the proposed DTC, two feedback PI controllers are used in this proposed method to control both torque and rotor flux. Moreover, both torque and flux are estimated in this proposed strategy, which leads to the use of high-accuracy measuring devices. The same estimation equations used in the classical method are used in this proposed strategy. On the other hand, the rotor speed is not measured in this proposed strategy.

The proposed DTC strategy aims to improve the effectiveness of the classical DTC technique by minimizing current ripples and THD values. In addition, a more robust strategy is obtained by relying on the proposed feedback PI controller. On the other hand, this proposed DTC technique is used to control the rotor side converter to control the quality of the electric power generated by the generator. In order to feed the generator inverter, we need another converter called the grid side converter (GSC), where this inverter is necessary to feed the generator rotor. As it is known, the rotor voltage of the generator is lower compared to the value of the stator voltage of the generator, so a transformer is used before the grid side converter.

For the GSC, an uncontrolled inverter is used. This inverter consists of six diodes. Fig. 6 represents the internal structure of the grid-side converter used in this work. This type of converter (GSC) is used to simplify the electric power generation system, reduce production costs and reduce regular maintenance. The proposed GSC used in this work is characterized by simplicity, ease of implementation, low cost of implementation, and no energy consumption compared to some types, such as the controlled converter. A controlled GSC can be used with a thyristor or other component. However, there will be a complexity of control and a high cost.

By comparing Figs. 5 and 6, it is noted that the designed technique is a radical change to the classical technique and was not presented previously. The SVM technique was used to control the rotor side converter instead of the switching table used to control the generator inverter in the traditional DTC technique. The SVM technique was used to obtain a signal outside the rotor inverter with a fixed frequency. Instead of using the SVM technique, pulse width modulation can be used to control the rotor inverter generator. The SVM technique has been studied in several research works [3, 5-6, 8, 10], showing its effectiveness compared to the pulse width modulation technique.

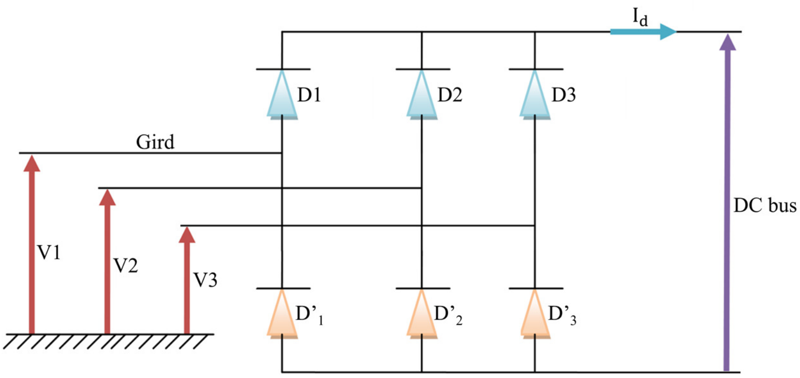

Fig. 6 The block diagram of the grid side converter

This proposed DTC technique uses a two-level SVM technique to simplify the system. The SVM technique obtains control signals for the inverter gears from a balanced three-phase system. This technique is based on calculating both $V_{r\alpha}$ and $V_{r\beta}$ of the rotor voltage and the regions of the presence of the reference rotor voltage (see Appendix). The SVM technique is the best solution for reducing ripples and obtaining a stable frequency signal than pulse width modulation. However, this technique is characterized by complexity and difficulty of implementation compared to the pulse width modulation strategy.

As it is known, using hysteresis comparators creates ripples at the output of the inverter at the current and voltage level, and we obtain an electrical signal (voltage or current) of variable voltage. The latter affects the work of electrical machines. The proposed DTC technique overcomes all the drawbacks of the traditional DTC technique. In contrast, the proposed feedback PI controller is used in place of the hysteresis controller to regulate the rotor flux and electromagnetic torque.

Based on the traditional DTC principle, the proposed DTC uses the same equations to estimate the required parameters: the rotor flux, the electromagnetic torque, and the rotor flux sector. These estimated values are used to calculate the error in torque and flux. In addition, the proposed feedback PI controller is used to calculate both direct and quadrature rotor voltage references according to Eqs. (16)-(17):

$$V_{dr}^{*} = K_p \times e_{Qr} + K_i \int (e_{Qr} - y) \times dt \tag{16}$$

$$V_{qr}^{*} = K_p \times e_{Te} + K_i \int (e_{Te} - y) \times dt \tag{17}$$

where e_{Qr} and e_{Te} are the errors of the flux and torque.

On the other hand, the electromagnetic torque and rotor flux errors were digitalized using two feedback PI controllers, as presented in Fig. 7, instead of the two- and three-level hysteresis of the traditional DTC technique. In Table 2, the similarities and differences between the proposed DTC-feedback proportional-integral (DTC-FPI) and the classical DTC technique are mentioned in several respects. This table is filled out based on the results of this work. From this table, the proposed DTC technique is better than the classical DTC technique in reducing torque and current ripples. Moreover, the proposed DTC strategy is better in terms of dynamic response to the machine's torque and flux.

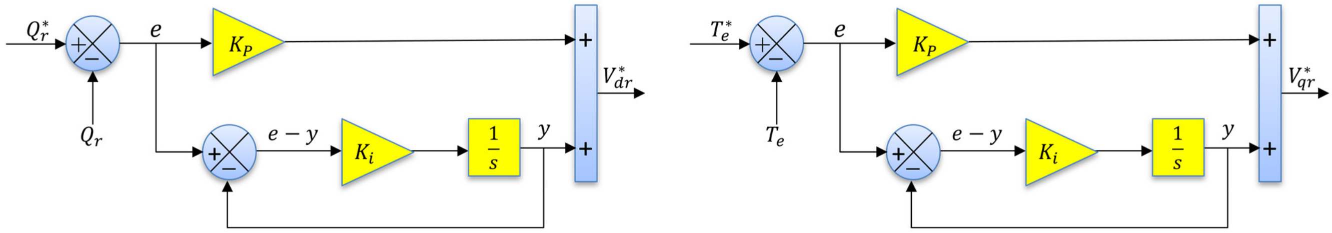

Fig. 7 The Scheme block of the proposed torque and flux feedback PI controllers

Table 2 Comparative study between the DTC and DTC-FPI strategies

	DTC-FPI	DTC
Block of estimation	Yes	Yes
THD value of current	High	Low
Controller used	Feedback PI controller	Hysteresis comparator
Torque ripple	High	Low
Switching table	No	Yes
Simplicity	Simple	Simple
Implementation	Easy	Easy
Hysteresis comparator	No	Yes
Completion cost	Not expensive	Not expensive
Flux ripple	High	Low
Robustness	High	Low
Applied to multi-phase generator	Easily	Easily
Dynamic response	Fast	Slow
Current quality	High	Low
MPPT technique	Yes	Yes

6. Results

In this part, the simulation results for the proposed DTC technique are given, whereby the obtained results are compared with the traditional strategy based on the PI controller. As the parameters of this generator are located in [28-29], a generator with a high power rating of 1.5 MW is used, where Rs = 0.012 Ω, Lr = 0.0136 H, Lm = 0.0135 H, J = 1000 kg.m^2, 380/696 V, Rr = 0.021 Ω, 50 Hz, Ls = 0.0137 H, p = 2, and fr = 0.0024 N.m/s, K_{pf} = 98254, K_{if} = -0.5, K_{pT} = 0.35, K_{iT} = 10.

The two designed methods (DTC and DTC-FPI) were compared in terms of torque, current, and flux ripples. Also, consider the THD value of the electric current. The Matlab software was utilized to validate the methodology using two different tests—the reference tracking test and the robustness test.

6.1. First test

Regarding reference tracking and dynamic response speed, this test intends to compare the behavior of the designed DTC strategy with that of the classical DTC technique. In addition, the ratio of ripples in both directions. The results are illustrated in Figs. 8-12. In Figs. 8 and 9 flux and torque follow the references for the classical and designed DTC strategy. However, the designed DTC-FPI technique provided a faster mechanical response than the traditional DTC strategy.

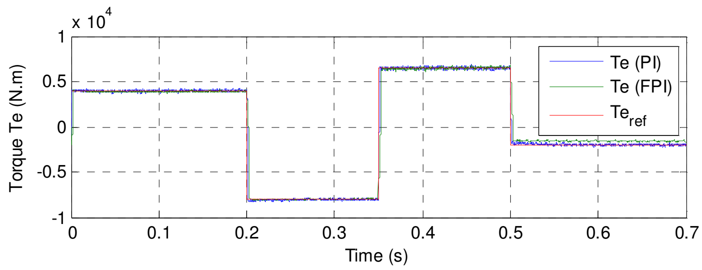

Fig. 8 Torque

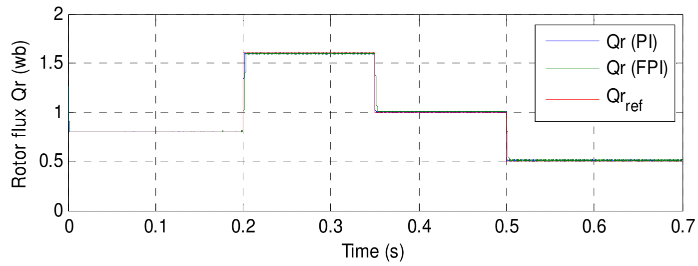

Fig. 9 Rotor flux

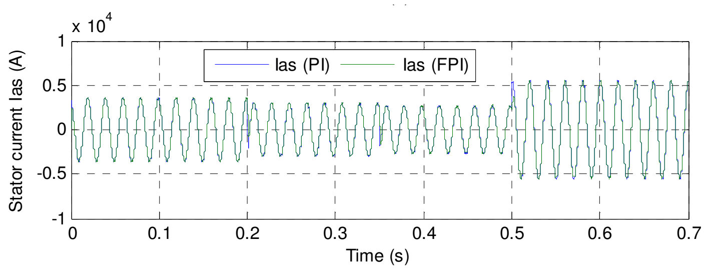

Fig. 10 Stator current

Furthermore, compared to the traditional DTC strategy, the designed strategy reduced both flux and torque ripples (Figs. 13-14). Fig. 10 illustrates the electric current of both strategies. The electric current evolution depends on the electromagnetic torque, where the higher the torque value, the higher the current value, and vice versa. The evolution of the generated currents Isa had a sinusoidal form with a constant frequency (50 Hz). These currents supply the AC grid directly without any filters. The proposed DTC-FPI strategy is designed to improve the quality of the electric current (Fig. 15).

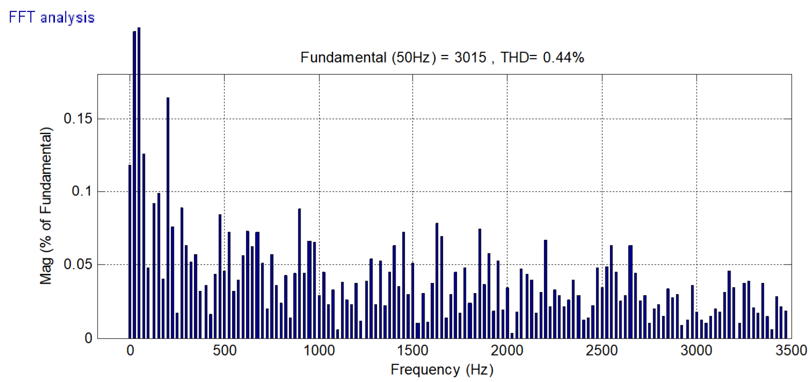

Fig. 11 THD value of stator current (DTC)

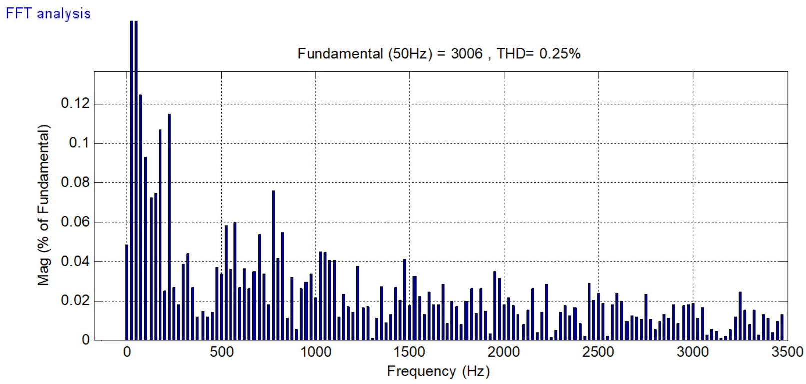

Fig. 12 THD value of stator current (DTC-FPI)

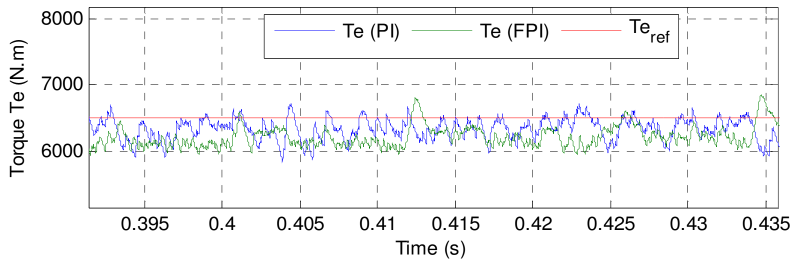

Fig. 13 Zoom in the torque

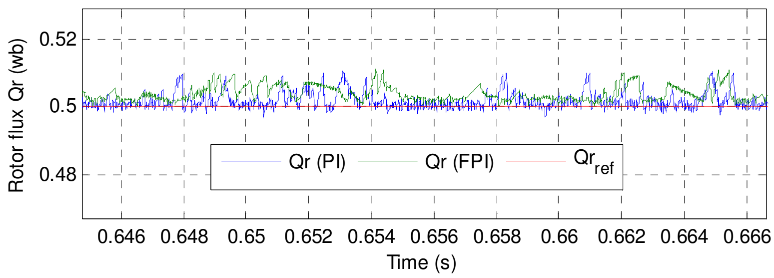

Fig. 14 Zoom in the flux

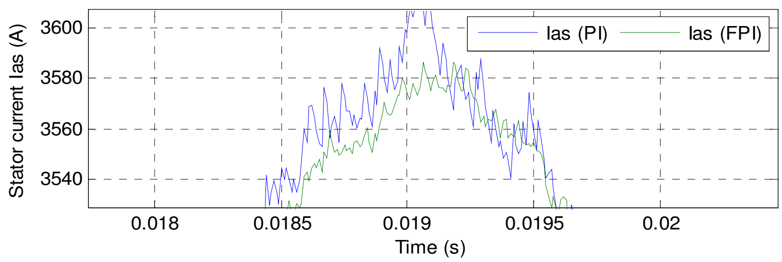

Fig. 15 Zoom in the stator current

The fast Fourier transform (FFT) analysis was made with the generated currents to determine the current THD of both strategies. The results are presented in Figs. 11 and 12. In comparison to the classical DTC method, the proposed DTC-FPI strategy provided a good value for THD of electric current, where the value was 0.25% for the proposed DTC-FPI strategy (Fig. 12) and 0.44% for the classical DTC strategy (Fig. 11). The proposed DTC-FPI strategy improved the current quality by about 43.18% compared to the classical DTC strategy.

Table 3 Comparison of ripples derived from both strategies

	Traditional-DTC	Designed-DTC	Ratios
Torque ripple (N.m)	About 400	About 200	50%
Rotor flux ripple (wb)	About 0.004	About 0.002	50%
Stator current (A)	About 50	About 10	80%

The ripple value of the current, torque, and rotor flux in the first test are summarized in Table 3. According to Table 3, the designed DTC-FPI technique reduced torque, current, and flux ripples by 50%, 80%, and 50%, respectively, compared to the traditional DTC technique. These results confirmed the high performance of the proposed DTC-FPI technique over the traditional DTC technique. Ripples for both rotating flux and electromagnetic torque directly affect deteriorating power quality and current in the electrical network as well as increasing power losses (in the transformer and generator), which will reduce the efficiency of the generation system. Moreover, these ripples affect the turbine, gearbox, and machine, where the mechanical vibrations are. The latter causes mechanical failures and thus reduces the life of the system.

6.2. Second test

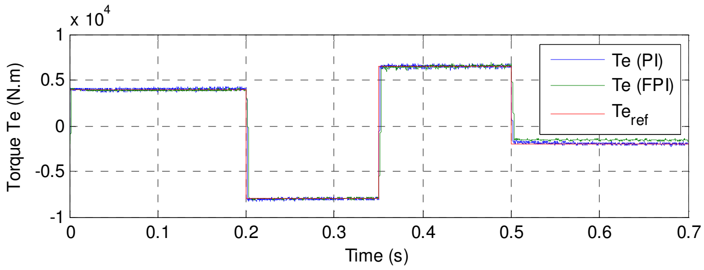

Fig. 16 Torque

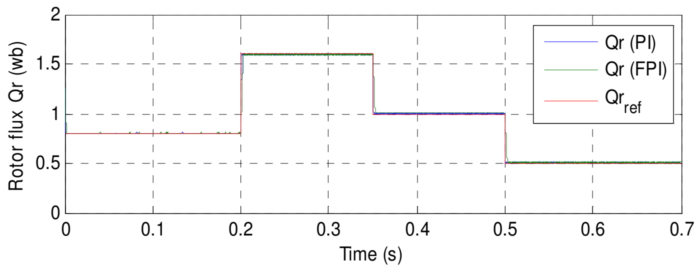

Fig. 17 Rotor flux

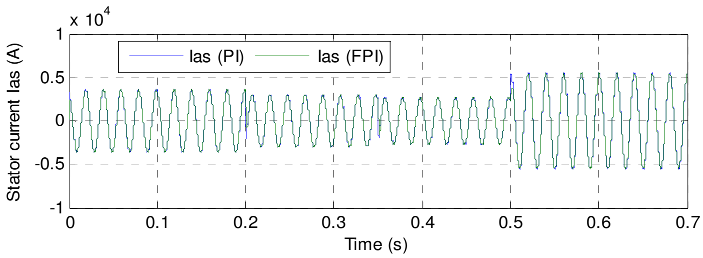

Fig. 18 Stator current

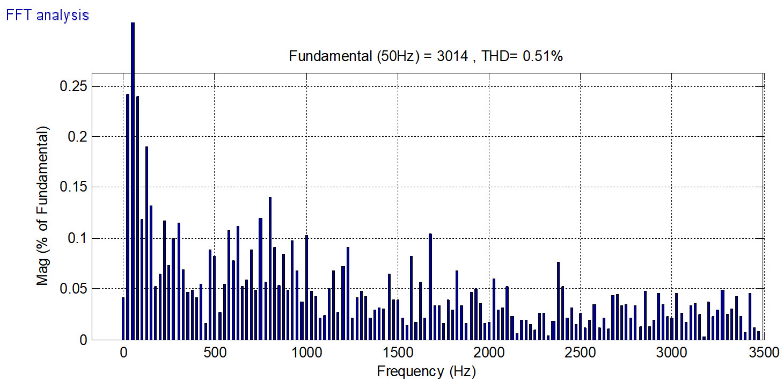

Fig. 19 THD value of stator current (DTC)

In this test, the robustness of the designed DTC technique is confirmed compared to the classical DTC technique by changing the values of R_s, R_r, L_s, L_m, and L_r to values of 0.024 Ω, 0.042 Ω, 0.00685 H, 0.00675 H, and 0.0068 H, sequentially.

The results of this test are represented in Figs. 16-20. Torque and rotor flux keep following the references well (Figs. 16-17), with more fluctuations at the level of the classical DTC technique compared to the proposed DTC-FPI strategy (Figs. 21-22). As for the current, it is shown in Fig. 18. The electric current takes a sinusoidal form, and its value is related to the generated torque. There are more ripples when using the classical DTC method than the proposed method (Fig. 23). The designed DTC method minimized the THD value of the electric current compared to the classical DTC method (Figs. 19-20), and the reduction ratio was about 33.33%.

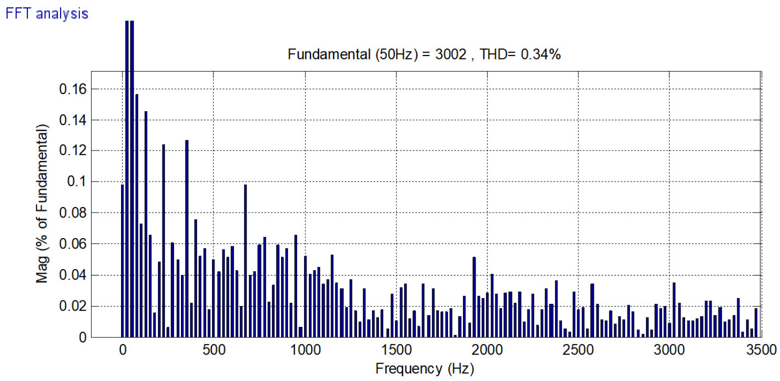

Fig. 20 THD value of stator current (DTC-FPI)

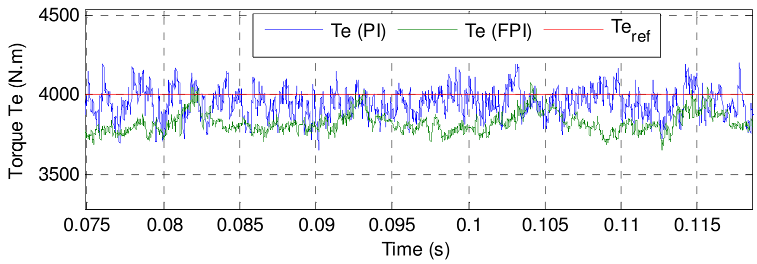

Fig. 21 Zoom in the torque

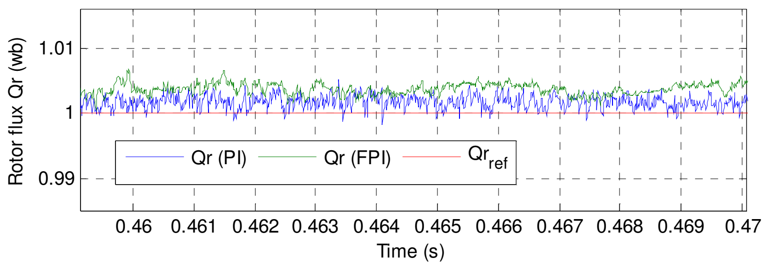

Fig. 22 Zoom in the flux

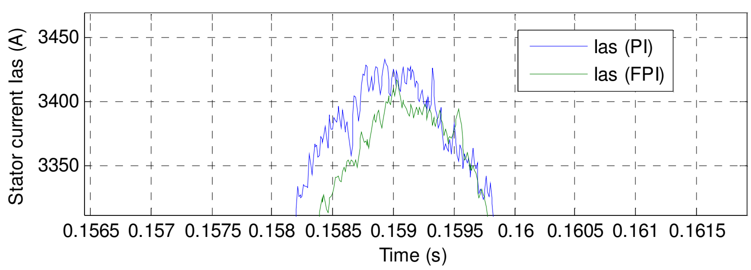

Fig. 23 Zoom in the stator current

Table 4 presents the current ripples, electromagnetic torque ripples, and rotor flux ripples of both strategies, as well as the rate of improvement in current, electromagnetic torque, and flux-ripple reduction controlled by the proposed DTC-FPI technique compared to the traditional DTC strategy. As shown in this table, the ripples of current, electromagnetic torque, and rotor flux are important in the studied system controlled by the traditional DTC technique compared to the proposed DTC-FPI technique. However, they were less with the traditional DTC strategy. Therefore, the reduction rate of ripples was very significant in the case of the proposed DTC-FPI technique. The average rate of improvement in torque-ripple reduction controlled by the proposed DTC-FPI technique compared to the traditional DTC strategy was 29.82%. The average rate of improvement in current-ripple reduction controlled by the proposed DTC-FPI technique compared to the traditional DTC strategy was 55.55%. On the other hand, the average rate of rotor flux-ripple reduction controlled by the proposed DTC-FPI technique compared to the traditional DTC strategy was 20%. These results confirmed the high performance of the proposed DTC-FPI technique over the traditional DTC strategy.

Table 4 Comparison of ripples derived from both techniques

	Classical DTC	Proposed DTC	Ratios
Torque ripple (N.m)	About 570	About 400	29.82%
Rotor flux ripple (wb)	About 0.01	About 0.008	20%
Stator current (A)	About 90	About 40	55.55%

7. Conclusions

In this paper, the designed feedback PI controller was used to improve the performance and effectiveness of the DTC generator control strategy. Among the advantages of this proposed DTC strategy based on feedback, PI controllers are their simplicity, durability, ease of control, and low cost compared to other methods such as field-oriented control. On the other hand, the proposed DTC strategy based on feedback PI controllers shows excellent performance for both steady-state and transient-state operations of DFIG-based wind turbines. In addition, the responses of stator power and current have been improved by regulating the rotor flux and electromagnetic torque of the DFIG at changing parameters.

The Matlab program was used to verify the effectiveness of the proposed DTC strategy based on feedback PI controllers, where the simulated results showed the robustness of the proposed DTC strategy based on feedback PI controllers compared to the traditional DTC strategy. The results obtained through this work are illustrated in the following points:

(1) The proposed DTC-FPI strategy minimizes the ripples in the flux, torque, and current by approximately 20%, 55.55%, and 29.82%, respectively.

(2) The proposed DTC-FPI strategy improved the THD value of the current compared to the classical-DTC technique, where the value was 0.25% for the proposed DTC method and 0.44% for the classical DTC method.

(3) The proposed DTC-FPI strategy improved the response dynamic compared to the classical technique.

(4) The designed fractional PI controller improved the characteristics of the DTC strategy compared to the traditional PI controller.

In future works, we intend to focus on implementing the proposed DTC-FPI strategy and applying other AI techniques.

Conflicts of Interest

The authors declare no conflict of interest.

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Appendix

Fig. A-1 represents the internal structure of the rotor side converter used to feed the generator rotor. Fig. A-2 represents the internal architecture of the SVM technique used to control the generator inverter. To control the generator inverter, pulse-width modulation (PWM) technique can be used instead of using SVM technique. Fig. A-2 represents the two-level SVM technique of the DFIG inverter.

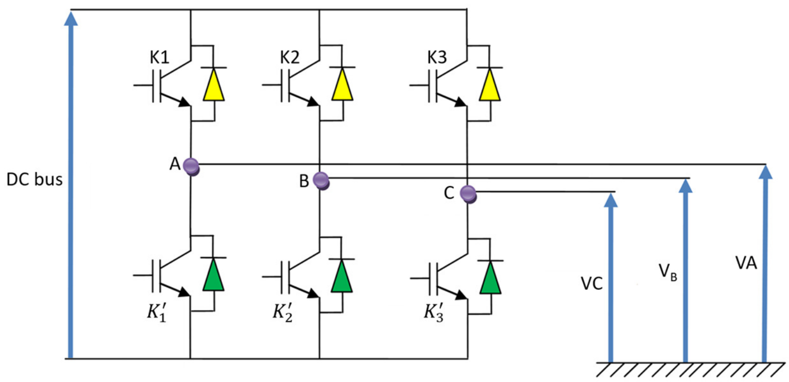

Fig. A-1 The block diagram of the rotor side converter

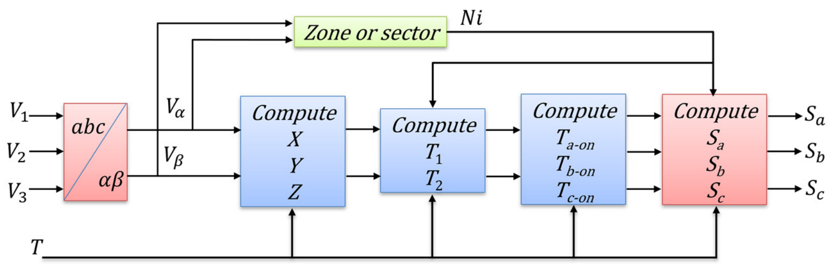

Fig. A-2 Two-level SVM technique