Rotor Flux and Electromagnetic Torque Regulation of DFIG using Dual PI Controllers

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Abstract-This paper presents a novel direct torque command (DTC) of the doubly-fed induction generator (DFIG)-based wind power systems (WPSs) using new linear controllers to improve the current quality. The designed DTC employs a dual proportional-integral (DPI) controller to directly calculate the required rotor command voltage to eliminate the instantaneous errors of rotor and torque without involving any synchronous coordinate transformations. Thus, no extra current command loops are required, thereby simplifying the DFIG-WPS design and enhancing the transient performance. The proposed strategy is characterized by simplicity, outstanding performance, quick dynamic response, and ease of implementation. The proposed strategy is applied to the rotor side converter of DFIG in order to improve the quality of current and power while using a grid side converter with an uncontrolled inverter (diodes) to simplify the system and reduce its cost. Modified space vector modulation is used to generate the pulses needed to operate the generator inverter, which eases the designs of the AC harmonic filter and the power converter. Simulation results on a 1.5 MW DFIG-WPS are provided and compared with those of the traditional DTC strategy and DTC-DPI technique. The designed DTC-DPI provides enhanced transient performance similar to the traditional DTC technique and keeps the steady-state error at the same level as the DTC technique. The proposed strategy reduced the THD of current by an estimated 28.57% compared to the traditional strategy.

Keywords: Steady-state error, direct torque command, dual proportional-integral, doubly-fed induction generator, modified space vector modulation.

1. Introduction

Direct torque command (DTC) is one of the most popular techniques in the field of controlling AC machines because of its simplicity and ease of control [1]. The DTC strategy is considered one of the linear strategies that have a very fast dynamic response, as this strategy depends on estimating distinct values or quantities to control the inverter. This strategy was used to command the asynchronous motor [2], doubly-fed induction generator (DFIG) [3], permanent magnet synchronous generator [4], brushless DC machine [5], and the synchronous motor [6]. In principle, idea, and structure, the DTC strategy is similar to the Direct Power Command (DPC) strategy, but the difference between them lies only in the amounts controlled. The DTC strategy controls both torque and flux, while the DPC strategy controls active and reactive power. In its principle, the DTC strategy relies on the use of both a switching table and a hysteresis comparator in order to control electrical machines. The switching table is used to generate the pulses needed to operate the inverter, and the hysteresis comparator is used to control torque and flux.

Compared to field-oriented command (FOC), DTC is easy to apply and command in complex systems such as a 7-phase motor. In the DTC strategy, a switching table with six sectors is used to control the machine inverter, and three-level hysteresis comparators (HCs) are used to regulate the machine torque [7]. The DTC strategy contains a small number of gains, which makes it one of the easiest strategies to adjust the dynamic response compared to several existing controls in the field of control, such as backstepping control or vector control. The downside of this strategy is that there are ripples in both flow and torque, which creates several problems and contributes to reducing the life of the machine and the system as a whole [8]. Also, it is noted that the value of total harmonic distortion (THD) of the current is relatively high, which makes the quality of the current low, which is undesirable. Another negative of this strategy is the use of estimation of both torque and flux, which makes it affected in the event of a malfunction in the system, as the rate of ripples increases significantly with a decrease in the quality of the current, which is undesirable in the field of control. These problems and defects in the DTC strategy can be traced back to the use of the hysteresis comparator unit. Several strategies have been suggested to overcome DTC technique defects and problems such as using fuzzy logic [9], neural networks [10], super-twisting algorithm (STA) [11], multi-level inverter [12], sliding mode control (SMC) [13], and high-order SMC [14]. The use of these strategies increases the complexity of the technique and makes it difficult to implement it in practice, and this thing is undesirable. In most of these proposed solutions, traditional controllers are replaced in order to improve performance and increase durability. However, the problem of ripples and low quality always remains, especially in the event of a malfunction in the system.

In the field of control, several scientific works have proposed an alternative and appropriate solution to overcome the problems of the traditional strategy in order to increase the quality of the current and overcome the problem of ripples. In the work [15], the author proposed using the strategy of direct vector control (DVC) based on a modified sliding mode controller (MSMC) for 1.5 MW DFIG controller. The latter is present in the multi-rotor wind turbine system, where the proposed energy system is characterized by high performance and great durability. The proposed strategy was verified in the Matlab environment, comparing the results obtained with the traditional strategy and some new strategies for DTC in terms of reducing the ripple rates of both current and torque. Also in terms of THD of current. The proposed strategy provided very satisfactory results compared to the traditional strategy and some existing controls, and this is demonstrated by the graphical and numerical results and even the comparison achieved. Three strategies were proposed in the work [16] to control the DFIG-based wind turbine system, where DPC, neural DPC (NDPC), and backstepping control were used for this purpose. These three strategies were used to control the rotor side converter of 1.5 kW DFIG, where the Dspace 1104 was used to implement them and verify their behavior in various tests. A variable wind speed was used. These strategies were first verified using the Matlab environment, where the results obtained from the simulation showed the superiority of the NDPC strategy over other types in terms of improving the characteristics of the proposed energy system. In addition, the experimental results confirm the simulation results and prove that the ripples and the THD of current are lower when using the NDPC strategy compared to other strategies. In [17], the author improved the performance of the DTC strategy of 1.5 MW DFIG by using two different strategies for the fractional-order high-order sliding mode controller (FOHOSMC), and these strategies were applied to the RSC of DFIG. As for the grid side converter (GSC), it was used with an uncontrolled inverter to simplify the system and demonstrate the superiority of the proposed controls in terms of reducing torque and current ripples and improving the dynamic response of powers. The Matlab environment was used for this purpose, where several different tests were used to compare strategies and study the performance and durability of the proposed energy system. The results obtained demonstrate that the proposed strategies are significantly superior to the traditional strategy in terms of increasing the robustness and performance of the studied system. A new strategy for DPC of DFIG was proposed in [18] based on the use of neural networks and was used to overcome the problem of low current and power quality. In this strategy, neural networks were used to replace traditional controllers (Proportional-integral (PI) controller) in order to control the powers, where voltage reference values are generated based on the errors in the powers. Therefore, the power estimate is used to calculate the power error. The proposed strategy is simple and easy and can be implemented experimentally with ease. Also, the proposed strategy is not related to the mathematical model of the system, which increases its robustness in the event of a malfunction in the machine. The proposed strategy was implemented in a Matlab environment using a variable wind speed, with a comparison with the traditional strategy and some existing controls. The results obtained demonstrate the superiority of the proposed strategy in terms of improving the system characteristics and increasing its robustness. The high-order SMC strategy was combined with the smart strategy represented by particle swarm optimization in order to overcome the problems of the FOC of 1.5 MW DFIG-based wind turbine system [19]. The proposed nonlinear strategy is characterized by complexity, its connection to the mathematical model of the machine, and the presence of a significant number of gains, which makes it difficult to adjust the dynamic response compared to the DTC strategy. This proposed strategy was applied to the RSC of DFIG, where the PWM strategy was used for this purpose. Despite the complexity, the proposed strategy provided very satisfactory results in terms of torque and current ripples compared to several existing strategies, and this is evident from the comparison completed. However, the problem of power quality remains, especially in the case of durability testing, where an increase in the THD of current and ripple values for power, current, and torque is observed, which is undesirable. In [20], the neural STA strategy was used to overcome the drawbacks of the DPC strategy and compensate for the use of undesirable traditional controls. The proposed strategy is characterized by simplicity, low cost, high durability, outstanding performance, small number of gains, and does not use the mathematical model of the system, which makes it not greatly affected by changing machine parameters. This strategy was applied to the RSC of DFIG only, where the GSC was used by an uncontrolled inverter to simplify the system and reduce its cost. The PWM strategy was used to generate the control pulses needed to operate the RSC of DFIG, as this strategy is characterized by ease of implementation and simplicity compared to the space vector modulation strategy. Wind speed was used to study the behavior of this proposed strategy compared to the traditional strategy, and the Matlab environment was used for this purpose. The value of the torque and current ripples is very low if the proposed strategy is used compared to the traditional strategy. Also the same with the THD of current value. However, this strategy has a negative side, which is the estimation of capabilities, which makes it affected if the machine parameter values change, which is an undesirable matter that contributes to reducing the quality of the current. Another strategy for STA proposed in [21] relies on the use of fractional-order control to overcome the drawbacks of the FOC technique of the DFIG-based wind turbine. Five fractional-order STA controllers were used for this purpose, with the PWM strategy used to generate the pulses necessary to operate the RSC of 1.5 MW DFIG. Compared to the DTC strategy, the proposed strategy is complex and difficult to implement, as it is very expensive. It is also characterized by the presence of a significant number of gains, which makes it difficult to adjust and determine the best dynamic response to power. In addition, this proposed strategy relies on estimating capabilities, which is a negative thing that contributes to increasing the ripples and reducing the quality of the current if the system parameters change. This proposed strategy has been verified for its properties compared to the proposed strategy using the Matlab environment using several tests for this purpose. The results obtained demonstrate the high performance and robustness of the proposed strategy compared to the traditional strategy. However the problem of energy waves remains present, especially in the durability test in which the machine parameters are changed. In [22], three strategies were used together in order to obtain one strategy characterized by high robustness to overcome the defects of the FOC of the DFIG strategy, where the STA technique, PI controller, and fractional-order control were used. The resulting strategy is characterized by complexity and a significant number of gains, which makes it difficult to implement and control the dynamic response compared to the traditional strategy. In addition, four proposed controllers were used to control the power, which makes the control complicated and expensive experimentally, which is undesirable. The proposed strategy was implemented in the Matlab environment, where various tests were used to study the behavior of the proposed strategy. The simulation results prove that the proposed strategy has outstanding performance and great robustness despite its complexity and number of gains. However, the proposed strategy has a negative aspect in estimating capabilities, which made it affected in the robustness test, where an increase in the value of THD of current and power ripples was observed, which is undesirable. A new strategy for FOC of DFIG is proposed using nonlinear strategies to overcome problems and defects such as ripples and low current quality [23]. In this proposed strategy, traditional controllers were replaced with nonlinear strategies to increase durability and performance. The PWM strategy was used in addition to these nonlinear strategies in order to control the RSC of DFIG. The use of these nonlinear strategies increases the complexity of the FOC strategy and the difficulty of achieving it experimentally, which is an undesirable negative. Also, there are a significant number of gains compared to the traditional or DTC strategies. The capacity estimation process is used, which increases the impact of the proposed strategy on changing machine parameters and gives unsatisfactory results. This proposed strategy was implemented in the Matlab environment, with the obtained results compared to the results of the traditional strategy in terms of current quality, dynamic response, and overshoot. Results show the superiority of the proposed strategy in terms of improving system characteristics and increasing its robustness compared to the traditional strategy. However, it was noted that the quality of the current decreased significantly in the durability test, which is not desirable. In [24], a third-order sliding mode controller (TOSMC) was used to improve the performance of both the strategy DVC of DFIG and the maximum power point tracking (MPPT) technique of wind turbine. This proposed strategy is characterized by high performance and ease of implementation, as it has a small number of gains, which makes it easy to adjust compared to several other strategies such as backstepping control. Also, the use of the TOSMC strategy is not linked to the mathematical model of the machine, which allows it to give good results compared to the traditional strategy. DVC-TOSMC is a different strategy from the traditional strategy, as the traditional controllers are replaced by TOSMC to control the distinct amounts. In the proposed MPPT strategy, TOSMC was used instead of traditional controllers in order to increase the performance and energy gained from the wind. The proposed power system is characterized by great durability as a result of using the TOSMC strategy to control power. This is evident through high reduction rates for response time, ripples, THD of current, overshoot, and steady-state error of DFIG power. The negativity of the proposed control is to rely on the mathematical model of the system and to use power estimation in order to calculate the error power, which makes there ripples and a decrease in the quality of the current in the event of a malfunction in the system.

In this work, an easy-to-implement, simple, and robust DTC strategy is proposed, whereby a switching table and two hysteresis comparators are dispensed with and replaced by a proposed dual proportional-integral (DPI) controller and PWM technique. The PWM strategy is used to generate the pulses necessary to operate the rotor side converter. This strategy was relied upon to simplify control and reduce cost. The paper's contribution is the use of a DPI controller to control the flux and torque of the DFIG-based energy system. The proposed strategy is characterized by simplicity, ease of implementation, low cost, fast dynamic response, and few gains, which makes it easy to adjust and change the dynamic response. Matlab software is used to verify the DTC-DPI strategy compared to the DTC-PI in terms of reference tracks, ripple reduction, and current quality. The simulation results demonstrated the efficacy and effectiveness of the DTC-DPI in improving the characteristics of the DFIG. The objectives achieved by this work can be defined in the following points:

- Significantly improving the performance of the PI controller.
- Reduced torque and flux ripples compared to the traditional strategy.
- Raise the amplitude of the signal fundamental (50 Hz) of current.
- Increase the robustness of the DTC strategy.

- Underestimating the THD of current compared to the DTC-PI technique.

The article was divided into the following main sections: The second section deals with the mathematical model of the machine used to generate electrical energy, where the electrical and mechanical equations necessary to create the proposed energy system in the Matlab environment were given. In the third section, the proposed strategy used to control the RSC of DFIG was discussed, where the pros and cons were mentioned. The mathematical model of the proposed controller was also given. The fourth section discusses the results obtained from the proposed strategy, comparing the results with the traditional strategy and some existing controls in terms of the THD of current value. Finally, the article ends with the conclusions obtained, which are included in the fifth section.

2. DFIG Model

DFIG is the most used generator in the case of variable wind speeds because of its durability [3]. Also, this generator is characterized by low cost, ease of control, and low maintenance, which makes it the most suitable in the field of renewable energies. In this type of generator, the moving part feed is used to command the rotational speed of the generator. To give the DFIG a mathematical shape, the Park transformation is used. Equations (1) to (5) represent the mathematical form used in this work.

$$\begin{cases} \psi_{dr} = L_r I_{dr} + M I_{dr} \\ \psi_{qr} = L_r I_{qr} + M I_{qr} \\ V_{dr} = R_r I_{dr} + \dfrac{d}{dt}\psi_{dr} - \omega_r \psi_{qr} \\ V_{qr} = R_r I_{qr} + \dfrac{d}{dt}\psi_{qr} + \omega_r \psi_{dr} \end{cases} \tag{1}$$

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

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

The DFIG power are shown in Equation (3).

$$\begin{cases} P_s = \dfrac{3}{2}(V_{ds} I_{ds} + V_{qs} I_{qs}) \\ Q_s = \dfrac{3}{2}(V_{qs} I_{ds} - V_{ds} I_{qs}) \end{cases} \tag{3}$$

The generator torque is written as:

$$T_e = \frac{3}{2} p \frac{M}{L_r}(I_{dr}.\psi_{qs} - I_{qr}.\psi_{ds}) \tag{4}$$

Equation (5) represents the relationship of velocity development in terms of torque.

$$T_e - T_r = J \cdot \frac{d\Omega}{dt} + f \cdot \Omega \tag{5}$$

where, T_r is the load torque, Ω is the mechanical rotor speed, J is the inertia, f is the viscous tneiciffeoc noitcirf.

Using Equation (5), the operating state of the DFIG can be controlled, as it can be operated as a generator or a motor, depending on the speed development. The latter is related to the difference between the torques of the machine and the turbine.

3. Proposed DTC-DPI Strategy

In this part, a concept of the DTC-DPI technique of DFIG-based wind turbine system technique is given with its pros and cons. The proposed DTC-DPI technique is a modification of the DTC strategy, where the hysteresis comparator is compensated by a DPI controller and the switching table is compensated by PWM technique. In this way, the simplicity and ease of achievement are preserved, and the strength of the DTC technique is raised. This proposed strategy is characterized by a significant number of gains and has the same structure as the traditional strategy, as it uses estimation of both torque and flux. In this proposed strategy, the same estimation equations found in the traditional strategy are used. Fig. 1 represents the proposed DTC-DPI strategy for controlling the DFIG-based wind turbine system, where the proposed technique is used to control the RSC of DFIG. In this proposed strategy, two DPI controllers are used to regulate flux and torque of the DFIG. DPI controllers are used to calculate voltage reference values based on the error in capabilities. Voltage reference values are used by the PWM strategy to generate the pulses needed to operate the RSC.

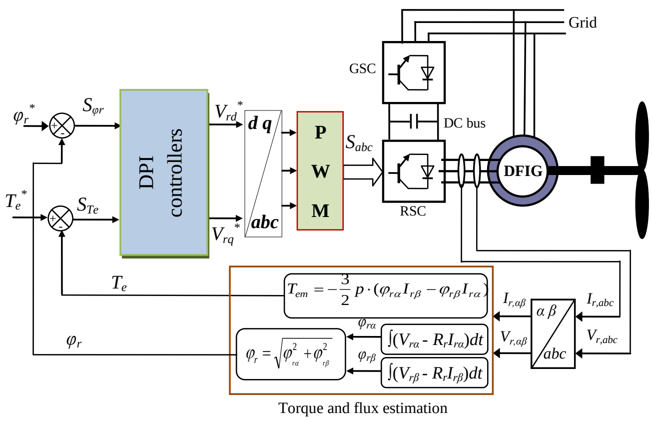

Fig. 1 The DTC-DPI technique of the DFIG.

In the proposed strategy, torque and flux are estimated according to Equations (6) to (9). The measured values are used to calculate the error in flux and torque [3, 25].

$$\psi_{r\alpha} = \int_0^t (V_{r\alpha} - R_r i_{r\alpha}) d \quad (6)$$

$$\psi_{r\beta} = \int_0^t (V_{r\beta} - R_r i_{r\beta}) d \quad (7)$$

With:

$$\psi_r = \sqrt{\psi_{r\alpha}^2 + \psi_{r\beta}^2} \quad (8)$$

Equation (9) represents the measured torque, where its value is related to current.

$$T_e = \frac{3}{2} p \frac{M}{L_r} (I_{dr} . \psi_{qs} - I_{qr} . \psi_{ds}) \quad (9)$$

PI regulator is one of the simplest controllers that have been used in the field of control because of the ease of programming and implementation, as it is used in this work to command the DFIG power in the form of a DPI controller. Equation (10) represents the PI controller, where Ki and Kp are the response tuning parameters for the PI controller [26]. Particle swarm optimization or genetic algorithms can be used to calculate the PI controller parameter.

$$u = K_p . e + K_i \int e . dt \quad (10)$$

DPI technique is two PI controllers in parallel as shown in Fig. 2. In this way, we get a more robust controller compared to the traditional controller. This proposed controller is simple, can be programmed easily, and applied to complex systems easily. To calculate the DPI controller parameter, genetic algorithms can be used. The disadvantage of this controller is the presence of several parameters, which makes it difficult to calculate.

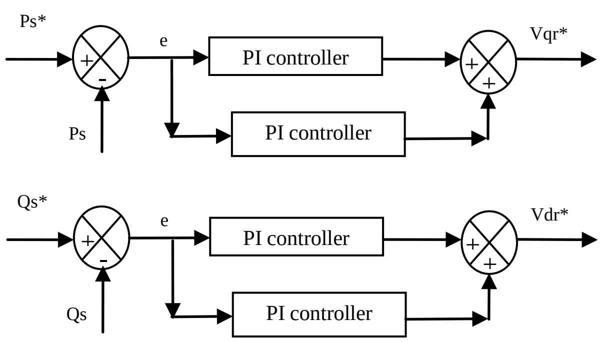

Fig. 2 Proposed DPI controller of active/reactive power.

The DPI controller is used to calculate each of the reference rotor voltage values according to the following two equations:

$$V_{qr}^* = (K_1 . S_{Te} + K_2 \frac{d\, S_{Te}(t)}{dt}) + (1 + K_3 . S_{Te} + K_4 . \int_0^t S_{Te} . dt) \quad (11)$$

$$V_{dr}^* = (K_1 . S_{\psi s} + K_2 \frac{d\, S_{\psi s}(t)}{dt}) + (1 + K_3 . S_{\psi s} + K_4 . \int_0^t S_{\psi s} . dt) \quad (12)$$

where, S_{Te} is the torque error ($S_{Te} = T_{e\_ref} - T_e$) and $S_{\psi r}$ is the rotor flux error ($S_{\psi r} = \psi_{r\_ref} - \psi_r$)

4. Results

The DTC-DPI technique is achieved using Matlab, and the obtained results are compared with the results of the traditional strategy. The generator parameters are as follows: 50 Hz, 1.5 MW, L_m = 0.0135 H, L_s = 0.0137 H, R_r = 0.021 Ω, 380/696 V, R_s = 0.012 Ω, L_r = 0.0136 H, J = 1000 kg.m^2, p=2, and f_r = 0.0024 Nm/s [27, 28].

The obtained results are represented in Figs. 3 to 10. Through these figures, torque and flux follow the references well with ripples and preference for the DTC-DPI technique in terms of dynamic response (see Figs. 3 and 4). Fig. 4 represents an electric current, where the evolution of the current takes the form of the evolution of the torque. Also, the electric current has a sinusoidal shape with fewer ripples in the case of the DTC-DPI technique.

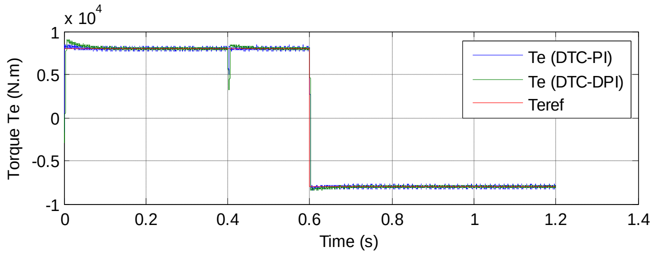

Fig. 3 Torque

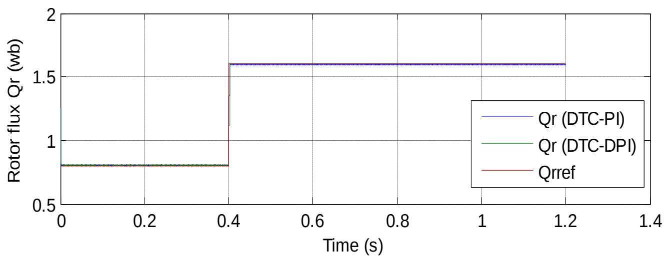

Fig. 4 Rotor flux

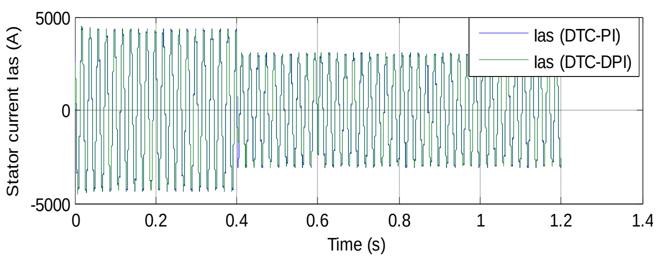

Fig. 5 Stator current

The THD value of the current is shown in Figs. 6 and 7 for each of the DTC-DPI and DTC techniques, respectively, where the THD value of the DTC-DPI technique is 0.30% and 0.42% for the DTC-PI technique. So the designed DTC-

DPI technique gave less THD value than the DTC-PI technique. Therefore, the designed DTC-DPI technique minimized the THD value by an estimated 28.57% compared to the DTC-PI technique. Through this ratio, it can be said that the designed DTC-DPI technique has an advantage in improving the quality of the current compared to the DTC-PI technique. It is also noted from Figs. 6 and 7 that the proposed strategy provided a better value for the amplitude of the fundamental signal (50 Hz) of current compared to the traditional strategy, as the amplitude was 3019 A and 3020 A for DTC-PI and DTC-DPI, respectively.

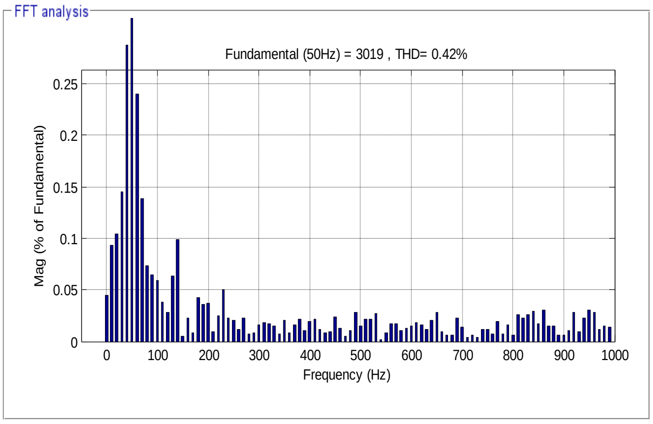

Fig. 6 THD value (DTC-PI)

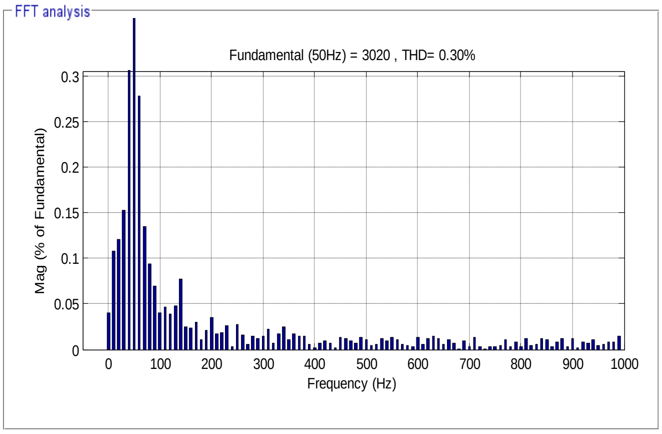

Fig. 7 THD value (DTC-DPI)

Figs. 8 through 10 represent zoom in the torque, flux, and current of the DFIG-WES. Through these forms, it can be said that the DTC-DPI technique is better than the DTC-PI technique in terms of ripples and the quality of the current, and this is a good thing.

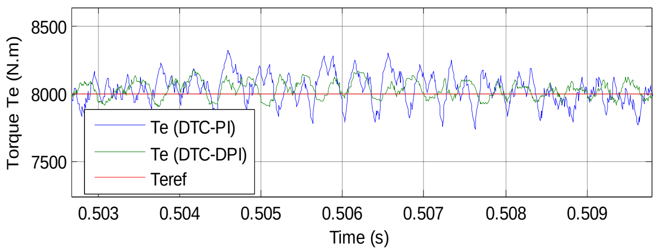

Fig. 8 Zoom in the torque

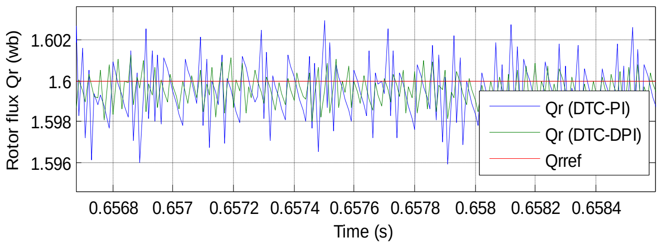

Fig. 9 Zoom in the rotor flux

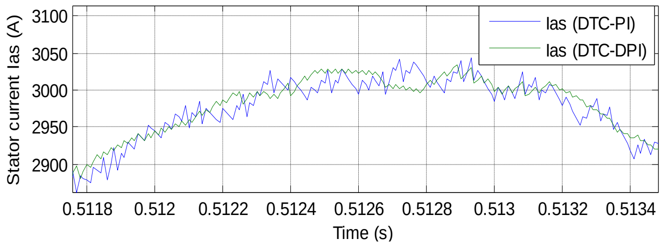

Fig. 10 Zoom in the current

5. Conclusion

This work presented a simple technique for controlling a DFIG using direct torque control based on DPI controllers. This proposed strategy was implemented using Matlab software and results obtained are discussed briefly in the above section.

The results showed that the DTC-DPI technique is more efficient and effective in reducing the flux and torque ripples. Also, a higher quality of current was obtained compared to the DTC-PI technique. Also, the results showed that the current value is highly related to the torque value. A limitation of this work is that the proposed strategy is tested in a constant wind speed condition only. In the future, the proposed strategy will be verified in different working conditions of DFIG with the use of genetic algorithms or particle swarm optimization to calculate the DPI controller parameter.

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