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Modeling and Simulation of Doubly Fed Induction Motor (DFIM) Control using DTC and DFOC: A comparative study

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Abstract
This paper examines two control strategies of doubly fed induction motor (DFIM), the first strategy uses a Direct Torque Control (DTC); the second employs Direct Field-Oriented Control (DFOC) based on stator flux orientation. Modeling of DFIM and details of both control strategies have been presented, which an IP controller is used in speed control loop for both control methods. The performances in terms of torque tracking, accuracy and robustness of both control techniques under normal and various speed and load conditions have been shown and compared. Analysis and comparative study between Direct Torque Control (DTC); the second employs Direct Field-Oriented Control (DFOC)are presented in this paper

Keywords: Double Feed Induction Machine (DFIM), Direct Torque Control (DTC), Direct Field-Oriented Control (DFOC), comparative study.

INTRODUCTION

Electrical motor constitute a great part in industry The doubly fed induction machine (DFIM) is a very attractive solution for variable-speed applications such as electric vehicles and wind turbine systems. Obviously, the required variable-speed domain and the desired performances depend on the application. The use of a DFIM offers the opportunity to modulate power flow into and out the rotor winding. In general, when the rotor is fed through a cycloconverter, the power range can reach the order of megawatts [1]. The DFIM has some distinct advantages compared to the conventional squirrel-cage machine. The DFIM can be fed and controlled statoror rotor by various possible combinations. Indeed, the inputs controls are done by means of four precise degrees of control freedom relatively to the squirrel cage induction machine where its control appears quite simpler. The flux orientation strategy can transform the nonlinear and coupled DFIM mathematical model to a linear model conducting to one attractive solution as well as under generating ormotoring operations [2]. The performance of field-oriented controlledinduction motor drive systems is directly related tothe performance of current control. Therefore, decoupling the control scheme is required by compensation of the coupling effect between q-axis and d-axis current dynamics [3].

With the field orientation control (FOC) method, induction machine drives are becoming a major candidatein high-performance motion control applications, where servo quality operation is required. Fasttransient response is made possible by decoupledtorque and flux control [4].

The direct torque control technique (DTC) proposed by: I. Takahashi [5] and M. Depenbrock [6] has been recognized to be a viable solution to achieve these requirements [5], [7]. The scheme, as the name indicates, is the direct control of torque and stator flux of a drive by inverter voltage space vector selection through a lookup table [6, 8].

In this study, a comprehensive assessment of the effectiveness of Direct Torque Control (DTC) and Direct Field-Oriented Control (DFOC) applied on doubly fed induction motor DFIM are discussed, which a comparative study is carried out.

MODEL OF DFIM

Its dynamic model expressed in the synchronous reference frame is given by voltage equations [2]:

$$\begin{cases} V_{sd} = R_s I_{sd} \\ V_{sq} = R_s I_{sq} + \omega_s \phi_{sd} \\ V_{rd} = R_r I_{rd} - \omega_r \phi_{rq} \\ V_{rq} = R_r I_{rq} + \omega_r \phi_{rd} \end{cases} \quad (1)$$

$$\begin{cases} \phi_{sq} = 0 \;\Rightarrow \mathrm{I}_{sq} = -\dfrac{M}{Ls} I_{rq} \\ \mathrm{I}_{sd} = 0 \\ \mathrm{I}_{rd} = \dfrac{\phi_s^*}{M} \end{cases} \quad (2)$$

Flux equations:

$$\phi_{sd} = L_s I_{sd} + M I_{rd} \Rightarrow I_{sd} = \frac{1}{Ls}\left(\phi_{sd} - M I_{rd}\right) \quad (3)$$

$$\phi_{sq} = L_s I_{sq} + M I_{rq} \Rightarrow I_{sq} = \frac{1}{Ls}\left(\phi_{sq} - M I_{rq}\right) \quad (4)$$

$$\phi_{rd} = \sigma L_r I_{rd} + \frac{M}{L_s}\phi_{sd} \quad (5)$$

$$\phi_{rq} = \sigma L_r I_{rq} + \frac{M}{L_s}\phi_{sq} \quad (6)$$

The electromagnetic torque is done as:

$$C_{em} = -\frac{pM}{L_s}\phi_s I_{rq} \quad (7)$$

and its associated motion equation is:

$$C_e - C_r = j\frac{d\Omega}{dt} \quad (8)$$

DIRECT STATOR FLUX ORIENTATION CONTROL

In this section, the DFIM model can be described by the following state equations in the synchronous reference frame whose axis d is aligned with the stator flux vector [9, 10]:

$$V_{rd} = R_r I_{rd} + \sigma L_r \frac{dI_{rd}}{dt} + \frac{M}{L_s}V_{sd} - (\omega_s - \omega)\sigma L_r I_{rq} \quad (09)$$

$$V_{rq} = \left(R_r + \frac{M^2}{L_s T_s}\right) I_{rq} + \sigma L_r \frac{dI_{rq}}{dt} + \frac{M}{L_s}V_{sq} - \frac{M}{L_s}\omega\phi_{sd} + (\omega_s - \omega)\sigma L_r I_{rd} \quad (10)$$

The flux estimator can be obtained by the following equations [11]:

$$\phi_{sd} = L_s I_{sd} + M I_{rd} \quad (11)$$

$$\phi_{sq} = L_s I_{sq} + M I_{rq} \quad (12)$$

The position stator flux is calculated by the following equations

$$\theta_r = \theta_s - \theta$$

In which:

$$\theta_s = \int \omega_s dt, \quad \theta = \int \omega\, dt, \quad \omega = P.\Omega \quad (13)$$

Where:

θ_s is the electrical stator position,

θ is the electrical rotor position

Figure. 1 shows the block diagram of speed control using IP (Integral Proportional) regulator.

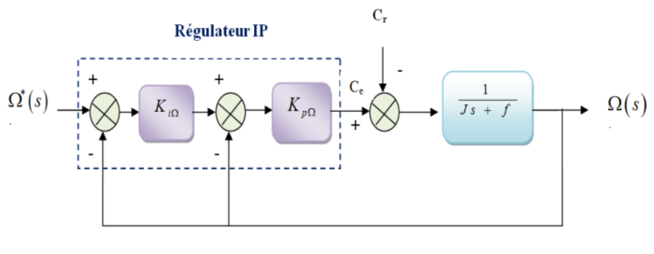

Figure 1: Block diagram of speed control using IP regulator.

The closed-loop speed transfer function is given by:

$$\frac{\Omega(s)}{\Omega^*(s)} = \frac{1}{1 + \frac{K_{p\Omega} + f}{K_{p\Omega}K_{i\Omega}}s + \frac{J}{K_{p\Omega}K_{i\Omega}}s^2} \quad (14)$$

Where $\mathbf{k_p}$ and $\mathbf{k_i}$ denote proportional and integral gains of IP speed controller

It can be seen that the motor speed is represented by second order differential equation:

$$\omega_n^2 + 2\xi\omega_n S + S^2 = 0 \quad (15)$$

By identification, we obtain the following parameter:

$$\begin{cases} \frac{J}{K_{p\Omega}K_{i\Omega}} = \frac{1}{\omega_n^2} \\ \frac{K_{p\Omega} + f}{K_{p\Omega}K_{i\Omega}} = \frac{2\xi}{\omega_n} \end{cases} \quad (16)$$

k_p and k_i are calculated by

$$K_{p\Omega} = 2J\xi\omega_n - f$$
$$K_{i\Omega} = \frac{J\omega_n^2}{K_{p\Omega}} \quad (17)$$

DIRECT TORQUE CONTROL

A Direct Torque and Flux Control (DTC) for a double feed Induction Machine (DFIM). This method has become one of the high performance control strategies for AC machine due to its very fast torque and flux control. The performance of DTC strongly depends on the quality of the estimated actual stator flux and torque.

The mathematical model for the electrical parts is written as a set of equations:

$$\frac{dX}{dt} = \dot{X} = AX + BU$$

Where X is the state variable and U is control variable:

The matrices A and B are given by:

$$A = \begin{bmatrix} \frac{-1}{T_s'\delta} & \omega_r & \frac{1-\delta}{\delta M T_s} & \frac{1-\delta}{\delta M}\omega_r \\ -\omega_r & \frac{-1}{T_s'\delta} & -\frac{1-\delta}{\delta M}\omega_r & \frac{1-\delta}{\delta M T_s} \\ \frac{M}{T_s} & 0 & -\frac{1}{T_s} & 0 \\ 0 & \frac{M}{T_s} & 0 & -\frac{1}{T_s} \end{bmatrix} ; B = \begin{bmatrix} -\frac{1-\delta}{\delta M} & 0 & \frac{1}{L_r\delta} & 0 \\ 0 & -\frac{1-\delta}{\delta M} & 0 & \frac{1}{L_r\delta} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

The electromagnetic torque is given by:

$$C_{em} = \frac{3pM}{2L_s}(\Phi_{s\alpha}I_{r\beta} - \Phi_{s\beta}I_{r\alpha}) \quad (18)$$

Direct torque control is based on the flux orientation, using the instantaneous values of voltage vector. An inverter provide eight voltage vector, among which two are zeros.This vector are chosen from a switching table according to the flux and torque errors as well as the stator flux vector position. In this technique, we don't need the rotor position in order to choose the voltage vector. This particularity defines the DTC as an adapted control technique of AC machines and is inherently a motion sensorless control method [11], [12].

The block diagram for the direct torque and flux control applied to the double feed induction motor shown in figure2.The stator flux $Øs_{ref}$ and the torque Cem_{ref} are compared with respective estimated values and errors are processed through hysteresis-band controllers.

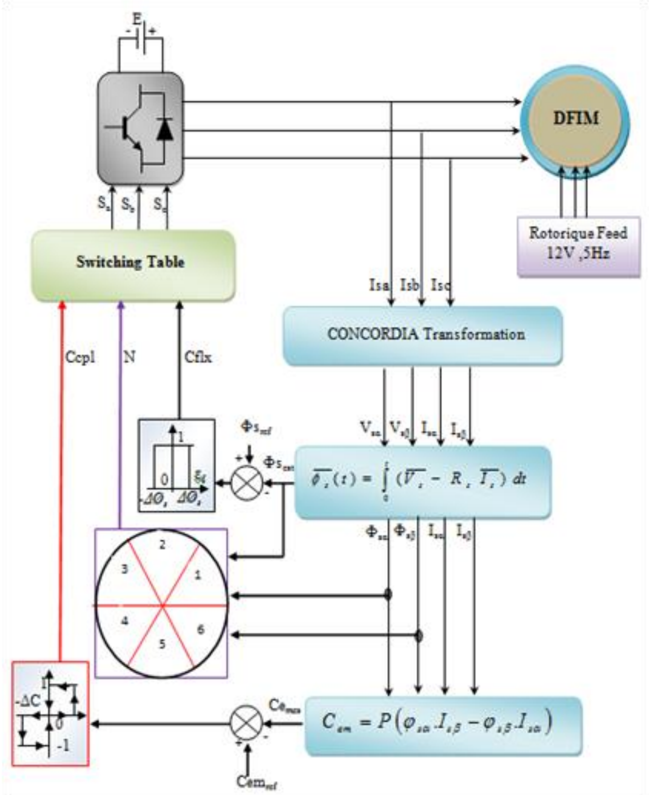

Figure 2: DTC applied to double feed induction machine (DTC_DFIM)

The eight possible voltage vector switching configuration is shown in Table 1:

Table 1: Control Strategy with hysteresis comparator at three levels.

Flux	*Couple*	$N = 1$	$N = 2$	$N = 3$	$N = 4$	$N = 5$	$N = 6$	*corrector*
	Ccpl=1	V_3	V_4	V_5	V_6	V_1	V_2	*2* levels
Cflx=0	*Ccpl=0*	V_0	V_7	V_0	V_7	V_0	V_7	
	Ccpl=-1	V_5	V_6	V_1	V_2	V_3	V_4	*3* levels
	Ccpl=1	V_2	V_3	V_4	V_5	V_6	V_1	*2* levels
Cflx=1	*Ccpl=0*	V_7	V_0	V_7	V_0	V_7	V_0	
	Ccpl=-1	V_6	V_1	V_2	V_3	V_4	V_5	*3* levels

SIMULATIONRESULTS

Simulation Results of Direct Stator Flux Orientation Control

The simulation resultsfor both control strategies have tested using 0.8 kW DFIM, which parameters are listed in appendix.

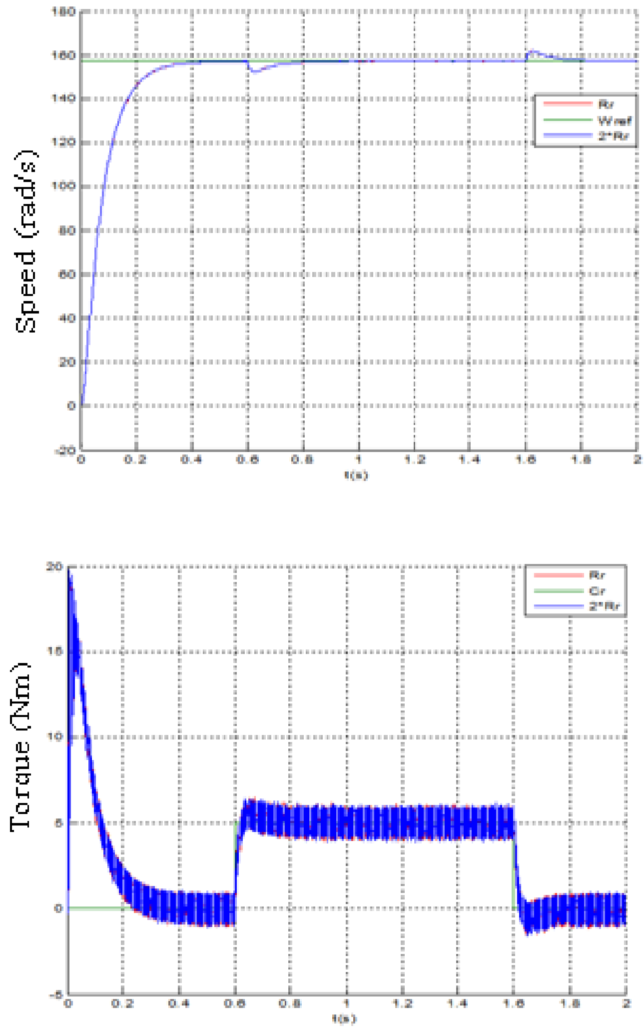

Figure 3: Results of speed controlusing DFOCbased IP controlle; (a) speed, (b) torque

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The motor is operated at 157 rad/s under no loadand a load disturbance torque (5 Nm) is suddenlyapplied at t=0.6s and eliminated at t=1.6s,. In these tests, the IP controller rejects the load disturbance

Simulation Results of Direct Torque Control

The Figure 4 shows in order, the variation in magnitude of the following quantities, speed, flux and electromagnetic torque obtained while starting up the induction motor initially under no load then connecting the nominal load. As can be seen during the starting up with no load the speed reaches rapidly its reference value without overtaking, however when the nominal load is applied a little overtaking is noticed and the command reject the disturbance. The excellent dynamic performance of torque and flux control is evident.

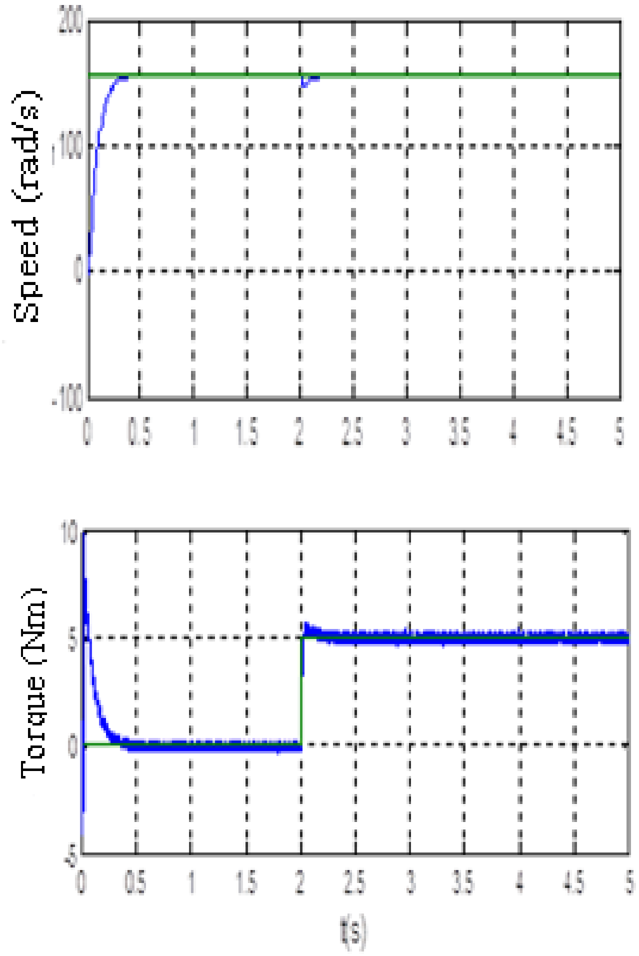
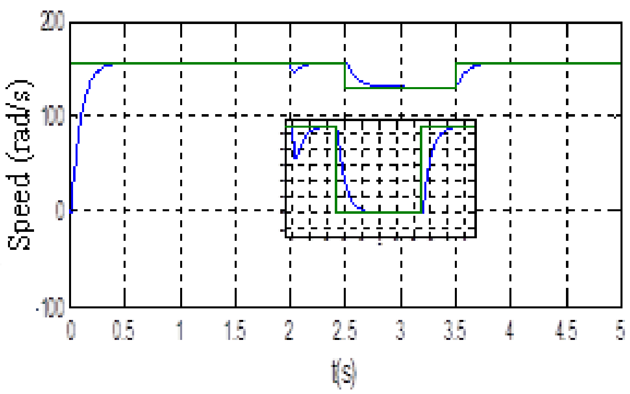


Figure 4: Simulation results using DTC with an IP regulator

Simulation Results under Variable Speed

The simulation results obtained for a speed variation for the values: (Ωref=157, 130, 157 rad/sec) with the load of 5 Nm applied at t=2s are shown in Figure5. This results show that the speed variation lead to the variation in flux and the torque. The response of the system is positive, the speed follow its reference value while the torque return to its reference value with a little error.



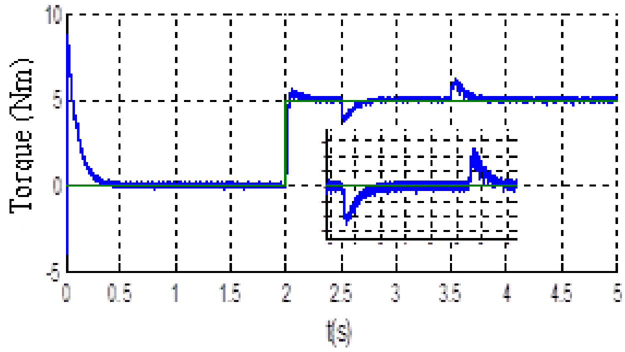


Figure 5: Robust controlusing DTC

Simulation Results under Various Load Conditions

For a load variation (Cr=3 Nm, 5 Nm), the simulation results obtained are shown in figure 6. As can be seen the speed, the torque and the flux are influated with the load variation. Indeed the torque and the speed follow their reference values.

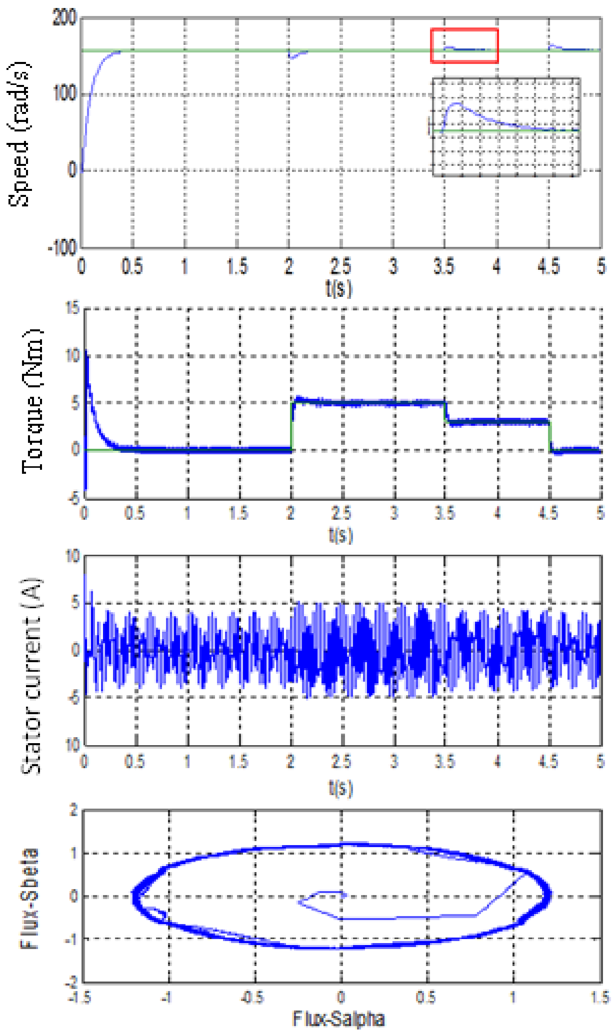


Figure 6: robust controlusing DTC under various load conditions

Simulation Results Robust Control under Stator Resistance Variation

In order to verify the robustness of the regulator under motor parameters variations we carried out a test for a variation of 50% in the value of stator resistance at tile t=2.5s. The speed is fixed at 157 rad/s and a resistant torque of 5Nm is applied at t=2s. Figure 7 shows the in order the torque response, the current, the stator flux and the speed. The results indicate that the regulator is very sensitive to the resistance change which results in the influence on the torque and the stator flux

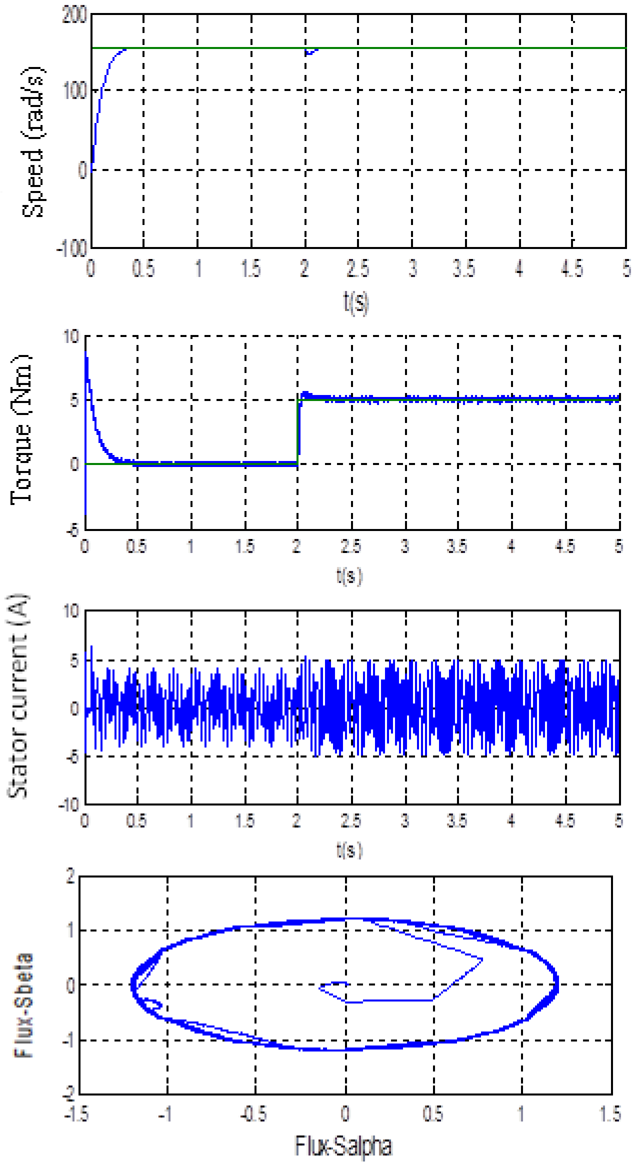


Figure 7: robust controlusing DTC under Stator Resistance Variation

CONCLUSION

In this paper, Direct Field-Oriented Control (DFOC) and Direct Torque and Flux Control (DTC) of doubly fed induction motor (DFIM) have been studied. The proposed techniques have been tested using the SIMULINK/MATLAB. The simulation results have demonstrated good performances for both control methods. However, Direct Torque Control (DTC) has provided better performances in term of response time (fast torque response), simple and robust design. Thus, theseproprieties have made it one of the popular control strategies in industrial applications.In addition, we plane in our future works to reduce the torque ripples, flux and switching number using an appropriate PI controller tuned by genetic algorithm or PSO, which many criteria can be selected in fitness function.

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APPENDIX

Double Feed Induction Machine parameters:
P_n=0.8 kW, U_n=220/380 V; F=50 Hz: I=3.8/2.2 A; Vr=3×120 V; 4.1 A; Ω=1420 tr/min; Rs=11.98 Ω; Rr=0.904 Ω: Ls=0.414 H; Lr=0.0556 H; M=0.126 H;P=2; J=0.01 kg.m^2; f=0.001 S.I