Comparative Analysis of Field-Oriented Control and Direct Torque Control For Induction Motor Drives

Omid moradi[1], Mohammad Reza Alizadeh Pahlavani[2], Iman Soltani[3]

[1]Department of Electrical Engineering, Izeh Branch, Islamic Azad University, Izeh, Iran
[2]Faculty of Electrical Engineering, Malek-Ashtar University of Technology (MUT) Tehran, Iran
[3]Department of Electrical Engineering, Firoozkooh Branch, Islamic Azad University, Firoozkooh, Iran

Abstract: This paper studies and compares two of the most commonly used electric driving methods of induction motors (IM).Indirect field oriented control (IFOC) and direct torque control (DTC) have been widely commercialized in induction motor drives, with each being favored by its supporters. In this paper, the dynamic performance of these drives for an electric vehicle application is examined, and sensitivities to parameter variations affecting this dynamic performance are explored by Jacobian matrix in which the sensitivities of torque, speed, and other desired variables or outputs are estimated relative to change in motor parameters. Key performance measures include torque and speed transients. The switching Scheme of these drives are hysteretic control and a switching table. The dynamic performance of DTC is superior under this comparison. Both the overshoot and the settling time of DTC are much smaller than for IFOC.

Keywords: Field oriented control; direct torque control; Induction motor; sensitivity; dynamic response

1. Introduction

The application of induction motors in traction systems, including electric vehicles, requires comparison of available drives for traction. Indirect field-oriented control (IFOC) and direct torque control (DTC) are often employed to act as torque transducers. IFOC, initiated in the 1970s, requires no flux estimation while DTC [1], [2], developed in the mid-1980s, does. These methods have several common aspects, such as torque and flux commands, fast torque response, and sensitivity to certain motor parameters. The flux command in conventional IFOC is the direct-axis rotor flux in the synchronous frame, while that of DTC is the stator flux in the synchronous frame. Available comparisons target field oriented control (FOC) and DTC without specifically considering IFOC. IFOC avoids the need for a flux estimator. The literature mainly focuses on steady-state performance of drives by comparing torque and current ripple, motor power losses, tracking command quantities, etc. The comparison of these drives has been associated with specific switching schemes, such as hysteresis current control with IFOC, as shown in Fig. 1, and a switching table with DTC, as shown in Fig. 2. In fact, the switching scheme can be decoupled from the drive control method itself. For example, both IFOC and DTC can use space-vector pulse-width modulation (SVPWM). With such an arrangement, direct comparison becomes possible. In this paper, the dynamic performance of IFOC and DTC is studied based on hysteretic control for both. Sensitivities to errors in motor parameters are considered. The magnetizing inductance, rotor resistance, and rotor inductance become relevant in IFOC, while the stator resistance plays a key role in DTC.

2. LITERATURE REVIEW

Direct comparisons of dynamic responses of IFOC and DTC do not appear to be available in the literature. Existing analyses of parameter sensitivities do not quantize the effect of parameter variations or errors on transient responses. Most of the literature deals with steady-state performance measures [3], [4], [5], [6], while [4], [5], [6], [7] provide some comparisons of dynamic responses. A detailed comparison of different induction motor drives is given in [3], including volts per hertz control (V/Hz), FOC, DTC, direct self control (DSC), and DTC with space vector modulation (DTC-SVM). This comparison mentions advantages and disadvantages relative to steady-state measures, such as phase current peaks, current and torque harmonics, and switching frequency variation. Structural measures, such as the need for flux observers, and decoupling of torque and flux commands are also presented. In [4], classical DTC and DTC-SVM, but not IFOC, are compared. The authors in [4] try to match the switching scheme with the drive in order to have similar switching frequencies, but DTC is used with a switching table tha results in variable switching frequencies, while DTC-SVM is used with fixed-frequency SVM. The speed and torque dynamic responses, including settling time and overshoot are compared. Tripathi et al. [8] propose a modified DTC

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which uses the stator flux to control the torque. No clear comparisons are made between DTC, DTC-

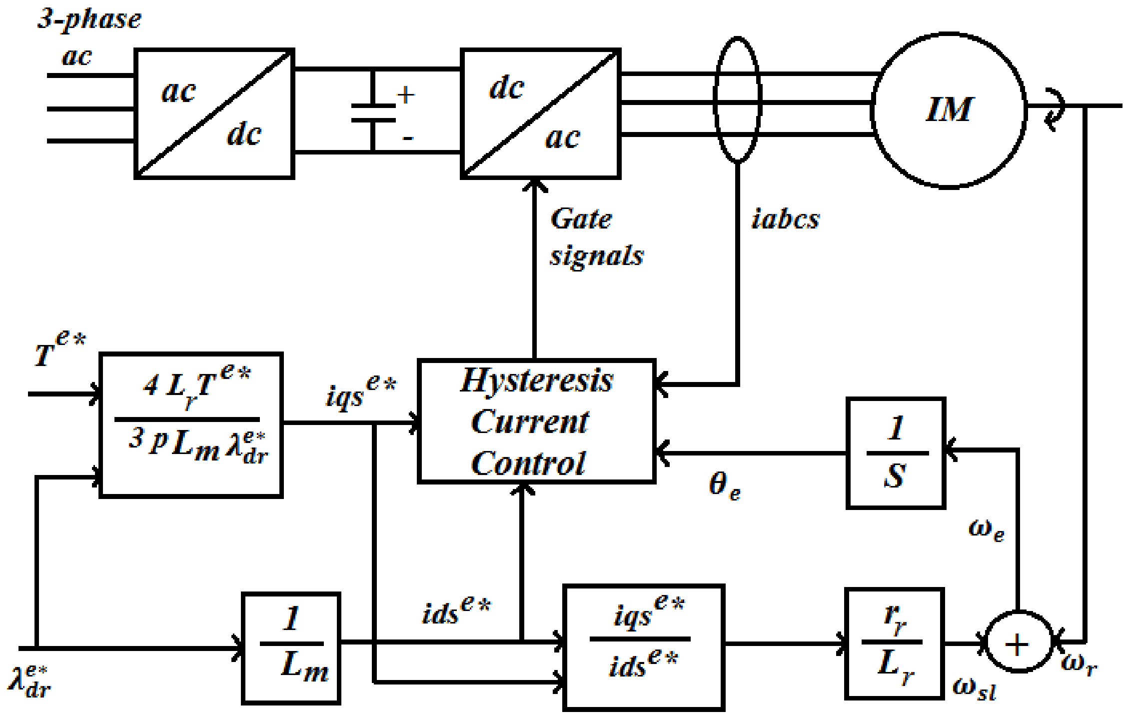

Fig. 1. IFOC block diagram for hysteresis current control.

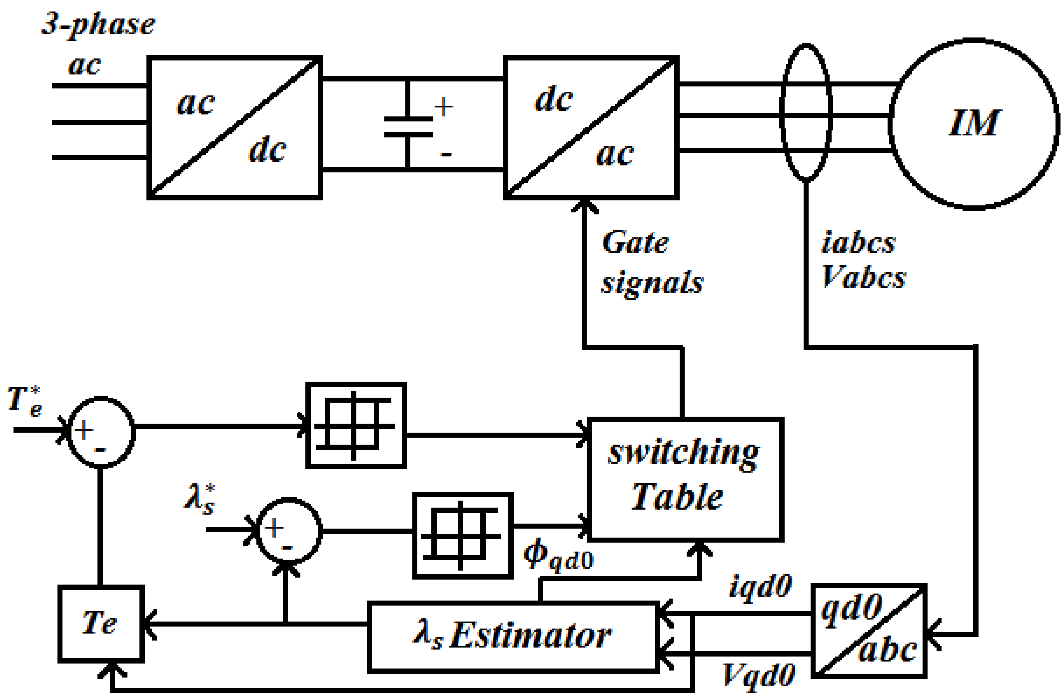

Fig. 2. DTC block diagram based on a sector switching table.

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SVM, and FOC, even though a vector diagram showing the dynamic operation of FOC and DTC is presented. Sikorski et al. [9] compare linear DTC-SVM to nonlinear DTC methods, DTC-δ, DTC-2x2, and DTFC-3A, using steady-state performance metrics while keeping the average switching frequency the same.Cruz et al. [5] compare FOC, DTC and input-output linearization based on steady-state torque ripple, current peak, and switching frequency. They conclude that FOC and DTC are “good” in dynamic response, and that the parameter sensitivities are “low” and “medium” in DTC and FOC, respectively. Wolbank et al. [7] compare low and zero-speed applications of DTC and sensorless FOC. They study steadystate stability and speed overshoot, where FOC shows slower dynamics but better steady-state tracking compared to DTC. As both FOC and DTC have drawbacks, an interesting combination of DTC and FOC is presented in [10]. The resulting direct torque and stator flux control method (DTFC) uses no voltage modulation, current regulation loops, coordinate transformations, or voltage decoupling. Casadei et al. [11] evaluate standard DTC and DFOC and present a unique scheme, discrete space vector modulation (DSVM), which is a variation of the standard SVM. Performance criteria are steady-state current and torque ripples, and dynamic response due to a torque step.

Comparisons of other drives focus on steady-state response. Thomas et al. [12] propose and experimentally validate geometric sliding mode/limit cycle control. Three different inverter modes, asynchronous, synchronous, and square wave, are analyzed. Industrial control objectives such as stator and rotor flux regulation, torque, speed, and position control, minimal energy and harmonics criteria, and optimization of torque pulsations are evaluated. Refs. [13] and [14] discuss formal validation of DTC, from a singular perturbation and a geometric control perspective, respectively. In [13], the controls for DTC are established independent of the inverter, and it is shown that the DTC approach can be decoupled from the switching scheme.

The comparison of FOC and DTC (but not IFOC) provided in [6] is perhaps the most thorough in the literature. There, dynamic performance of both controls is compared and sensitivity analyses are done with respect to stator resistance for DTC and rotor-time constant for FOC. The main drawback is the lack of quantization of torque and flux dynamics, and parameter sensitivities. Vasudevan et al. [15] compare IFOC to DFOC, along with classical DTC-SVM and direct torque neuro-fuzzy control, using MATLAB/Simulink. Stator voltages and currents, angular velocity, torque, and flux responses to a change in torque or angular velocity, are compared. The effect of parameter variation such as stator resistance variation due to temperature increases is also discussed in relation to the DTC control method. Ref. [16] presents an interesting approach targeting the operation of DFOC, DTC with PWM and DTC-SVM under a driving cycle of an electric vehicle. However, the authors do not compare IFOC and DTC.

3. Simulation of Direct Torque Control

The block diagram for a hysteretic DTC motor drive is shown in Figure 2. The typical use of DTC in an industrial setting, where a motor is connected to the electric grid via an inverter and rectifier pair. The ac/dc block in Figure 2 stands for the rectifier, while the dc/ac block represents the inverter. Between the two is a dc link which can vary from a few volts to well into the kV range. The induction motor in the block diagram is represented by the labeled circle. As described earlier, the inputs from the user in this motor drive are the electrical torque, T^{e*}, and the stator flux, λ_s^*, which are given by equations (1) and (2), respectively.

$$T^{e*} = \frac{3}{2}\frac{P}{2}L_M\left(\lambda_{qr}\, i_{dr}^{'} - \lambda_{dr}\, i_{qr}^{'}\right) \tag{1}$$

$$\lambda_s^* = \sqrt{\lambda_{qs}^2 + \lambda_{ds}^2} \tag{2}$$

They are compared against the calculated torque and stator flux, respectively. The difference, or error, is sent through the hysteresis block for each signal. The output from these blocks is a -1, 0, or 1, where -1 represents a negative error, 0 no error, and 1 a positive error. In practice, it is very unlikely that there will be no error, so the 0 output is neglected. The output for both the torque and the flux signals is sent into the switching table, which decides what gate signals should be set to the inverter by exploiting a simple look-up table. The other input to the look-up table is the stator flux angle,ρ_s, given by Equation (3).

$$\rho_s = tan^{-1}\left(\frac{\lambda_{qs}}{\lambda_{ds}}\right) \tag{3}$$

The other important signals are the voltage and current measurements taken from the motor. Combined, the stator current and voltages are transformed into the stator qd0 reference frame, and used to create the stator flux magnitude estimate. The stator flux is then used along with the transformed currents to come up with the torque estimate. These two estimates,$\hat{T}_e$ and $\hat{\lambda}_s$, are then compared against the commanded value given by the user.

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4. Simulation of Indirect Field-Oriented Control

The block diagram for an IFOC motor drive with current hysteresis as the switching scheme is shown in Figure 1. This combination is by far the most common higher-performance drive used in industry. The commanded signals are the torque,T^{e*} , and direct axis rotor flux,λ_{dr}^{e*}, which differs from the DTC motor controller that uses the absolute value of the total stator flux. The torque and rotor flux commands are converted into the quadrature and direct stator current variables and then compared to the measured induction motor currents that are fed back. The induction motor in the block diagram is represented by the circle with the label "IM".

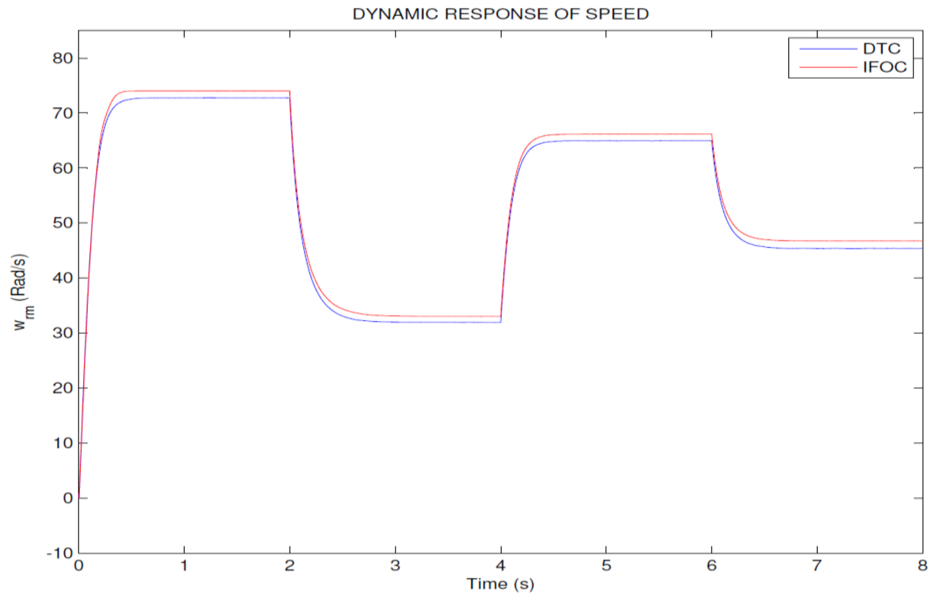

Fig. 3. Speed response during a driving cycle.

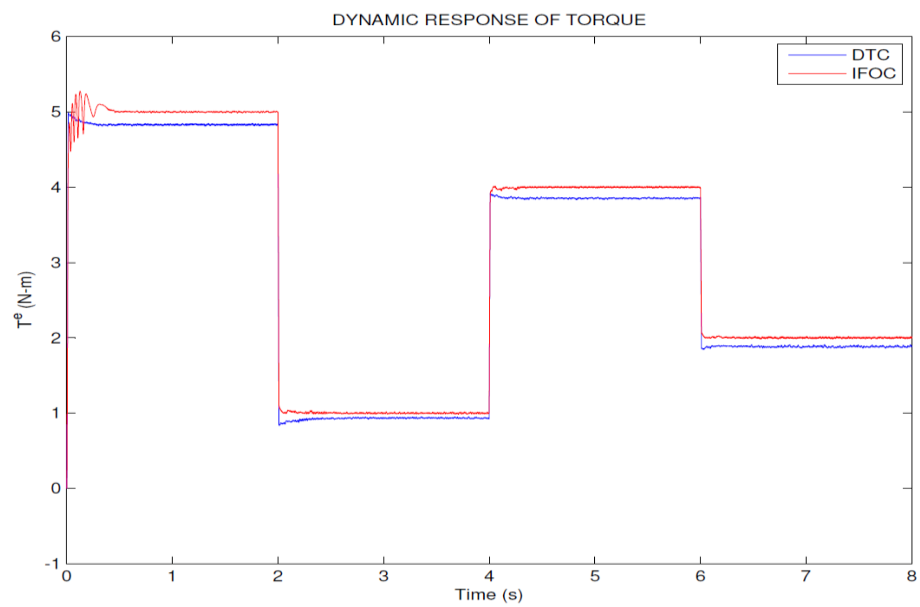

Fig. 4. Torque response during a driving cycle.

5. DYNAMIC RESPONSE

Both IFOC and DTC perform as torque transducers with robust torque-tracking capabilities. The dynamic performance of both drives is usually Compared neglecting the effects of the different switching Schemes being used by each drive. To simulate an electric or hybrid-electric vehicle driving cycle, a stepping torque profile was simulated with both drives in Simulink. The simulated IFOC is from [19] while DTC is from [13]. The motor model is a 1.5 hp induction motor. The simulation is run for 8 s with torque commands of 5, 1, 4 and 2 N·m,

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changing every 2 s. Fixed stator and rotor flux commands of 0.52 V·s and 0.5 V·s are used for a 4% leakage inductance. The simulation results for IFOC [19] and DTC [13] with hysteresis control and switching table, respectively, are shown in Figs. 3 and 4. The load is modeled as quadratic in speed,

$$T_L = 1.82 \times 10^{-4} w_{rm}^2 + 1.82 \times 10^{-2} w_{rm} \quad (4)$$

In Fig. 3 under the test drive cycle, the only noticeable difference in the two control methods is the initial start-up rotational speed where in IFOC there is an overshoot of about 4% and no overshoot with DTC. From Fig. 4, there is an initial torque overshoot of about 14% with IFOC while there is none using DTC. Fig. 4 shows that IFOC takes about 1 s to reach steady-state torque at of 5 N·m, while DTC arrives in steady state in just 15 ms. The torque performance is comparably the same with response that is fast on the time scale shown. While the performance of IFOC and DTC cannot be carefully judged from such a scenario where two different switching schemes are used, the dynamic performance of DTC is superior under this comparison. Both the overshoot and the settling time of DTC are much smaller than for IFOC.

6. SENSITIVITY ANALYSIS

6.1. Overview

Variations in motor parameters are expected to result in variations in the dynamic response of the drives. When IFOC is used with current control, it is dependent on L_{lr} (or L_r), L_m, and r_r. When DTC is used with a switching table, it is only dependent on r_s.

It is possible to build a Jacobian J matrix in which the sensitivities of torque, speed, and other desired variables or outputs are estimated relative to change in motor parameters. For IFOC, the Jacobian matrix is expected to be,

$$\begin{pmatrix} \Delta T^e \\ \Delta w_{rm} \end{pmatrix} = J_{IFOC} \begin{pmatrix} \Delta L_{lr} \\ \Delta L_m \\ \Delta r_r \end{pmatrix}$$

Where

$$J_{IFOC} = \begin{pmatrix} \frac{\partial T^e}{\partial L_{lr}} & \frac{\partial T^e}{\partial L_m} & \frac{\partial T^e}{\partial r_r} \\ \frac{\partial w_{rm}}{\partial L_{lr}} & \frac{\partial w_{rm}}{\partial L_m} & \frac{\partial w_{rm}}{\partial r_r} \end{pmatrix} \quad (5)$$

For DTC with a switching table, the Jacobian would be,

$$\begin{pmatrix} \Delta T^e \\ \Delta w_{rm} \end{pmatrix} = J_{DTC-ST} [\Delta r_s]$$

Where

$$J_{DTC-ST} = \begin{pmatrix} \frac{\partial T^e}{\partial r_s} \\ \frac{\partial w_{rm}}{\partial r_s} \end{pmatrix} \quad (6)$$

It is important here to consider torque and speed ripple under switching control for both IFOC and DTC. While the sensitivity analyses would result in steady-state variations ΔT^e and Δw_{rm}, dynamic variations can also result from switching. For a given stator current under hysteretic switching, for example, the formulations of the above Jacobian matrices are not trivial. If the stator current i_s is given by $i_s = I_s + \Delta i_s$ where Δi_s is the width of the hysteresis band, the expected T^e and w_{rm} are;

$$T^e = T^e_{(offset)} + \Delta T^e_{(hys)} \quad (7)$$

$$w_{rm} = w_{rm(offset)} + \Delta w_{rm(hys)} \quad (8)$$

Denoting the time average of a variable x as $< x >$, the resulting averages would be,

$$\langle T^e \rangle = \langle T^e_{(offset)} \rangle + \langle \Delta T^e_{(hys)} \rangle \quad (9)$$

$$\langle w_{rm} \rangle = \langle w_{rm(offset)} \rangle + \langle \Delta w_{rm(hys)} \rangle \quad (10)$$

An offset will not occur if $\langle \Delta T^e_{(hys)} \rangle$ and $\langle \Delta w_{rm(hys)} \rangle$ are zero, but zero-average ripple is not guaranteed in general and must rely on integral gain in the loop controls. To understand sensitivities in (5)-(6) from an operational perspective, the simulations of IFOC, DTC were run with +25%, -25%, and nominal parameters in the controllers and estimators. These results are discussed below.

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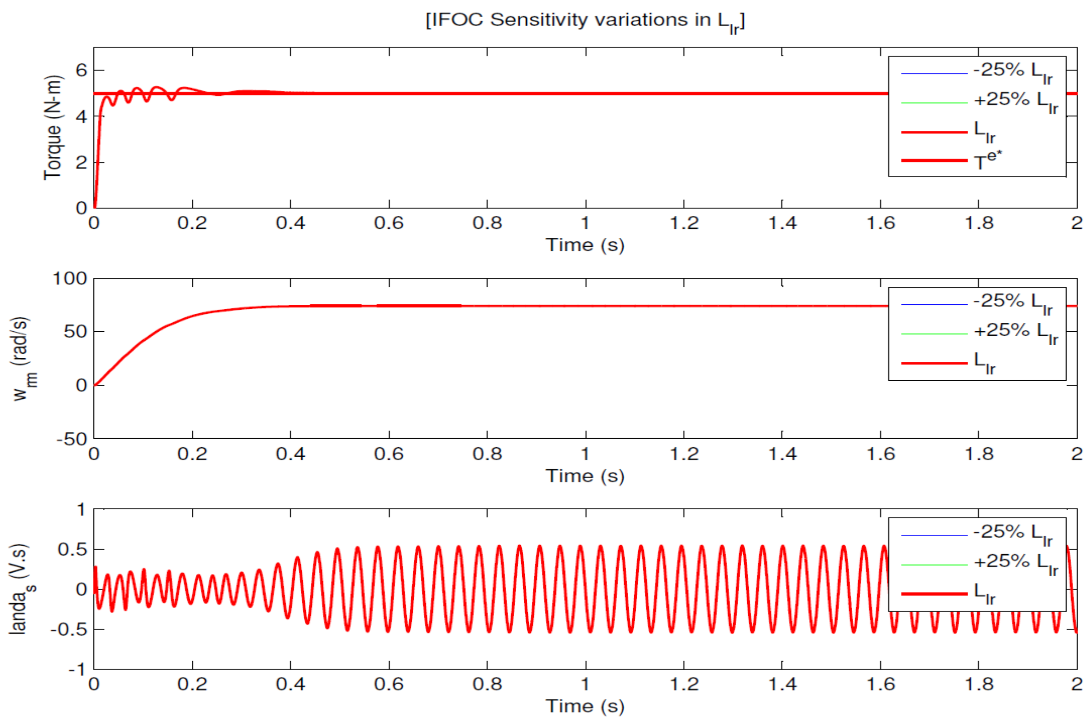

Fig. 5. IFOC sensitivity to variations in L_{lr}.

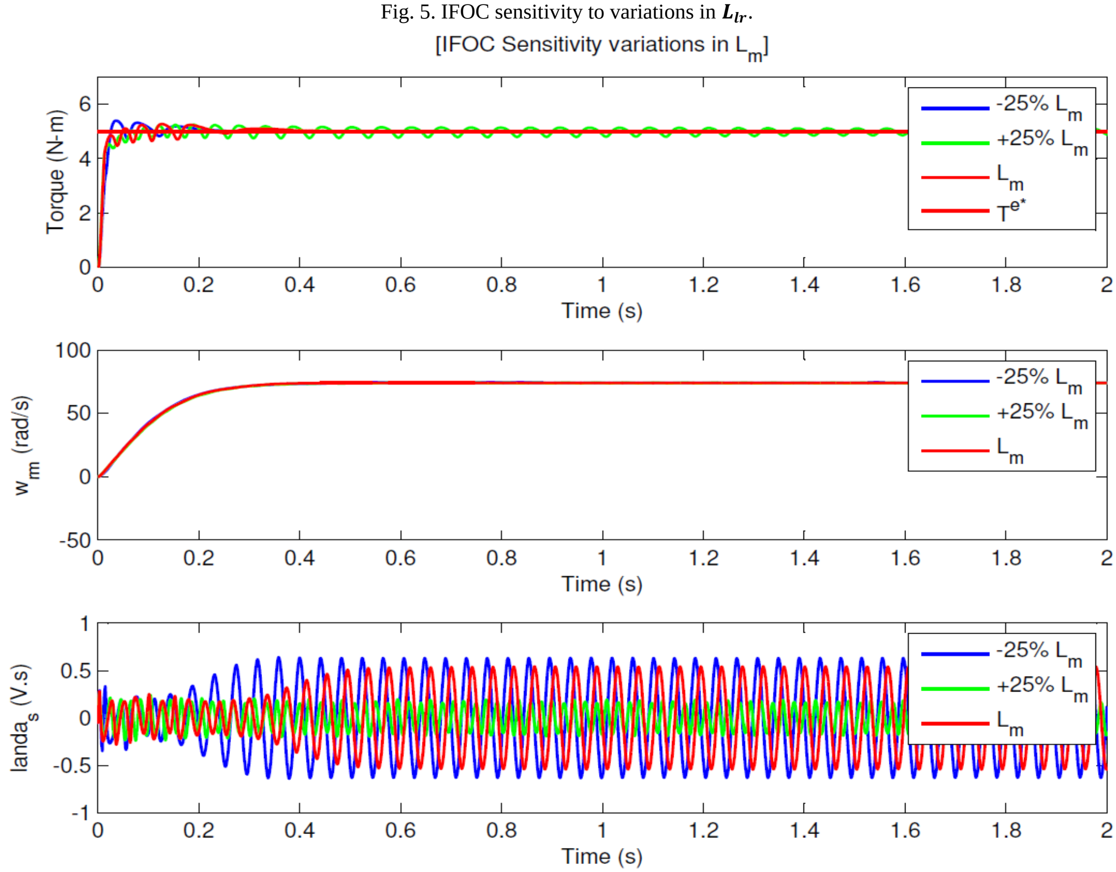

Fig. 6. IFOC sensitivity to variations in L_m.

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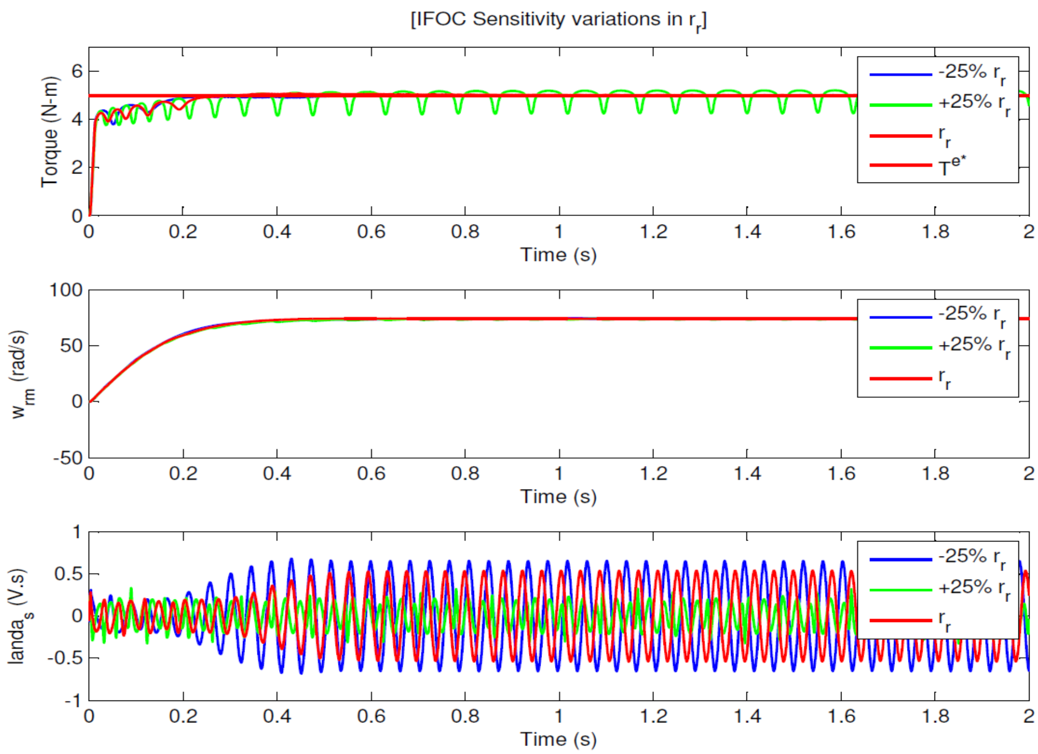

Fig. 7. IFOC sensitivity to variations in r_r.

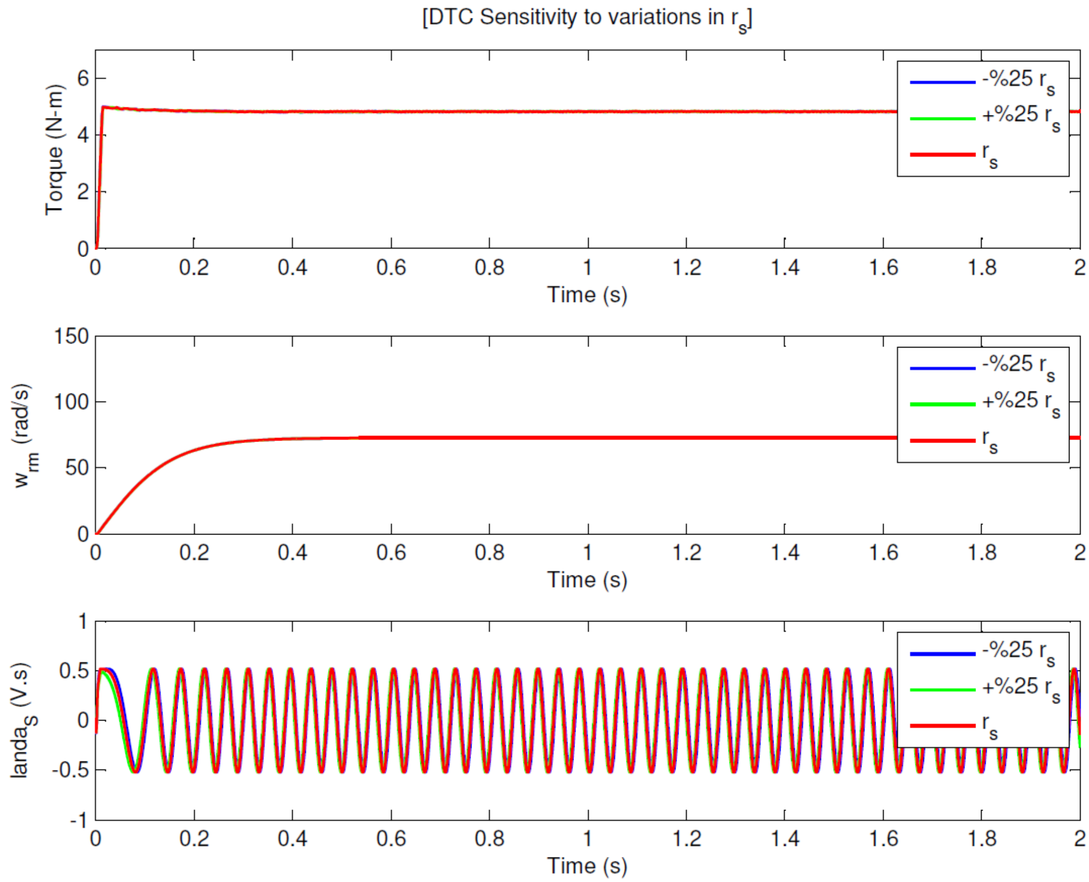

Fig. 8. DTC sensitivity to variations in $\boldsymbol{r_s}$.

6.2. IFOC and DTC

Figs. 5 through 8 show results under parameter variation for IFOC and DTC, coupled with hysteresis current control and a switching table, respectively. The torque command is set to be 5 N·m. Fig. 5 suggests that the impact of leakage inductance error on IFOC is small with minimal offset. On the other hand, Fig. 6 suggests a much larger impact of magnetizing inductance error. The time constant error implied by inaccurate rotor resistance impacts dynamic behavior, as in Fig. 7, although the impact on steady-state offset is more limited. The effects can be seen in terms of settling times, and dynamic impacts in addition to steady-state torque and speed. The shifting of the flux is implied in the IFOC sensitivity plots. In Fig. 8, suggests that DTC is relatively immune to variations in r_s, and that this parameter error has little impact on torque offset and even details of dynamics. These simulations suggest that DTC has advantages from a parameter sensitivity perspective. This is incomplete, however, until the impacts of switching scheme are included.

7. CONCLUSION

In this paper, it has become clear that drive controls must be decoupled from the switching scheme to permit comparisons of dynamic performance and parameter sensitivities. While there is a significant debate on which induction motor drive is most suitable for applications such as traction, it is important to have a common ground for these comparisons. Given choices of switching schemes that differ between IFOC and DTC, misleading conclusions can result. When the drive controls are decoupled from the switching scheme, differences are more subtle, and indeed IFOC appears to have advantages in terms of dynamic performance and immunity against parameter variations. The dynamic performance of DTC is superior under this comparison. Both the overshoot and the settling time of DTC are much smaller than for IFOC. This conclusion implies a need for examining a range of combinations of drive controls and switching schemes.

NOMENCLATURE

P: Number of poles

r_s : Stator resistance (Ω)

r_r : Rotor resistance (Ω)

L_m : Mutual inductance (H)

L_s : Stator inductance (H)

L_r : Rotor inductance (H)

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i_{qs} : Quadrature stator current (A)
i_{ds} : Direct stator current (A)
i_{abcs} : 3-phase stator current (A)
v_{qs} : Quadrature stator voltage (V)
v_{ds} : Direct stator voltage (V)
v_{abcs} : 3-phase stator voltage (V)
T_e : Electromechanical torque (N·m)
T_L : Load torque (N·m)
θ_e : Electrical angle (rad)
w_e : Electrical frequency (rad/s)
w_r : Rotor speed (rad/s)
w_{rm} : Mechanical speed (rad/s)
w_{sl} : Slip frequency (rad/s)
λ_{qs} : Quadrature stator flux linkage (V·s)
λ_{ds} : Direct stator flux linkage (V·s)
λ_{qr} : Quadrature rotor flux linkage (V·s)
λ_{dr} : Direct rotor flux linkage (V·s)
λ_s : Stator flux magnitude (V·s)
λr : Rotor flux magnitude (V·s)

The superscript "*" denotes a command input. The superscripts "*e*" and "*s*" denote variables in the synchronous and stationary reference frames, respectively.

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