Research Journal of Engineering Technology and Medical Sciences (ISSN: 2582-6212), Volume 05, Issue 04, December-2022
Available at `www.rjetm.in`

Efficient Field-Orientation Control Technique for Induction Motor based Applications

Gulshan Kumar [1], Varsha Mehar [2],
[1,2]Department of Electrical Engineering,
RKDF University, Bhopal, India

Abstract

The Induction motors and their types have been widely applied in industries and are considered as the best component for electrical vehicle applications due to its advantages such as: fundamental design, ruggedness, and easy maintenance. Three induction motor control algorithms (field orientation control, conventional direct torque control, and stator flux orientated sensorless direct torque control) are introduced in this paper and a specific comparison is given among three of them. The main focus of this work is to design an induction motor control system using the three algorithms, to analyze the performances of different control methods, and to validate these algorithms experimentally, comparing the simulation and experimental results.

Keywords: Induction Motor, Field-Oriented Control, Direct Torque Control, Modeling, Inverted Control.

1 Introduction

An induction motor also known as asynchronous motor is basically an AC type electric motor in them, electric current in the rotor is required to generate torque which is acquired by electromagnetic induction cause by the magnetic field of the stator winding [1]. Therefore, an induction motor can be constructed without using electrical connections to the rotor. A rotor of induction motor can either be a squirrel-cage type of wound. A cross-sectional view of induction motor is presented in Figure 1.

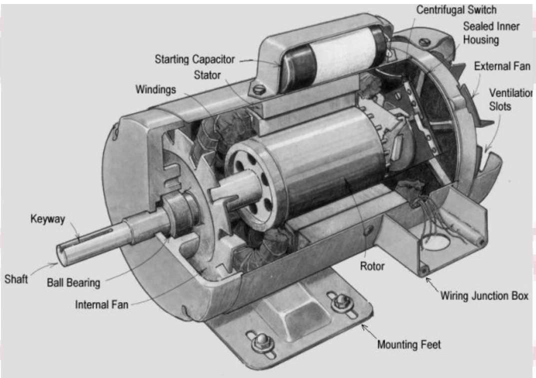

Figure 1: Induction Motor Cross-Section

The induction motors of 3-phase squirrel-cage are most extensively applied in industrial drives due to their cost, self-starting property, and reliability. Single-phase induction motors are used extensively for smaller loads, such as household appliances like fans [2]. Although traditionally used in fixed-speed service, induction motors are increasingly being used with variable-frequency drives (VFD) in variable-speed service. VFDs offer especially important energy savings opportunities for existing and prospective induction motors in variable-torque centrifugal fan, pump and compressor load applications. Squirrel-cage induction motors are very widely used in both fixed-speed and variable-frequency drive applications [3, 4].

2 Related Work

2.1 Discrete–Time Modeling and Control Based on Field Orientation for Induction Motors

Dominguez *et al.* [5] presented the sampled dynamics for induction motors when oriented to the field and both discrete-time, direct and indirect field oriented controllers were designed similarly to the continuous–time counterpart. The easiness of designing decoupled controllers with simple PI control loops was put in evidence. With the help of numerical simulations it was demonstrated that the IM motor performed well with both controllers even when the sampling period was increased. For comparison purposes, discretized continuous-time field-oriented control (FOC) controllers (direct and indirect) were also simulated, where the performance of the closed-loop IM starts to deteriorate when the sampling period increases. Real-time experiments were carried out in order to sustain the simulation study. With the realized experiments, a good output tracking performance was verified. In addition, the consistent relationship between the profiles for the stator currents, and rotor velocity and load torque, were put in evidence. In particular, the proposed "Discrete-Time Indirect Field Oriented Control (DTIFOC)" yields to smoother responses with respect to the proposed DTDFOC that can be attributable to the absence of a rotor flux observer.

2.2 Speed Control of a Three-Phase Induction Motor Based on Robust Optimal Preview Control Theory

Negm *et al.* proposed a synthesized method for speed control of a three-phase induction motor based on the optimal preview control theory. The vector method is adopted in the control law to simplify the controlled system analysis. The preview feed-forward steps are introduced in the control law to improve the transient response. The robustness of the controlled system is indicated by changing the rotor resistance and the load torque. A maximum torque is obtained over the whole control range by equating the β-axis component of the stator space flux to zero. Coincidental results between the desired signals and their responses are achieved. A space vector PWM control technique for voltage source-fed induction motor is prepared for microprocessor-based control. Spectral analysis of the output voltage of the SVM technique indicated improvements of the dynamic performance of induction motor. The proposed technique is found to be suitable for optimal preview control of induction motor. Extensive simulation results are made for speed control, field orientation control, and constant flux control. The experimental results indicate the applicability and robustness of the proposed optimal preview control system.

2.3 Direct Field Oriented Control of Linear Induction Motors

Pucci [6] proposed and discusses some issues about direct field oriented control (FOC) of linear induction motor (LIM) drives. After elaborating the inductor and induced part space-vector equations of the LIM in several reference frames, some induced part flux models taking into consideration the end effects are presented. In particular, the so called "voltage model" based on the inductor equations in the inductor reference frame and the "current model" based on induced part equations in both the inductor and induced part flux linkage reference frames are deduced and compared to the rotational induction machine counterpart. Afterwards, after a proper tuning of such models based on both finite element analysis (FEA), some simulation and experiments have been performed. Simulation and experimental results show the improvements in terms of dynamic performance achievable with the proposed flux models taking into considerations the LIM end effects. Moreover, experimental results show a better behaviour of the current model with respect to the voltage model, in particular in the low speed region.

2.4 Deadbeat Controller Applied to Induction Motor Direct Torque Control with Low-Speed Operation

Altuna *et al.* [7] proposed a controller for deadbeat direct torque control (DTC) as an alternative to DTCs already existing in the literature. To achieve this goal, we used the discretized dynamic mathematical model of induction motor using flux vectors and stator current, and deadbeat control theory. The space vector modulation was used due to its operation with fixed switching frequency, facilitating the design of filters and also allowing better use of the voltage of the DC link inverter. This type of controller allows the system to achieve the fastest possible response with no errors for the system being controlled. The controller requires no adjustments of gains due to using induction motor discretized dynamic model, which makes it very attractive. Deadbeat DTC had satisfactory performance for the presented experimental results, including testing at low speed, which demonstrates the great potential of such proposal. Thus, this controller can be successfully used in IM operation.

2.5 Direct Field Oriented Neural Control of a Three Phase Induction Motor

Baruch *et al.* [8] proposed a complete neural solution to the direct vector control of three phase induction motor including real-time trained neural controllers for velocity, flux and torque, which permitted the speed up reaction to the variable load. The basic equations and elements of the direct field oriented control scheme are given. The control scheme is realized by nine feedforward and recurrent neural networks learned by Levenberg-Marquardt or real-time back propagation algorithms with data taken by PI-control simulations. The graphical results of modelling shows a better performance of the neural network control system with respect to the PI controlled system realizing the same general control scheme.

2.6 Indirect Field Oriented Control for Three-Phase Induction Motor Drive Using DSP Controller

Banerjee and Bera [9] proposed Indirect Field Oriented Control (IFOC) based Voltage Source Inverter based-Induction Motor Drives (VSI-IM) which performs satisfactorily both in transient and steady state. From the feedback information of current, speed and calculation of θ and other IFOC equations by the microcontroller is also quite accurate. The gate driver used is compatible with the microcontroller and no fault occurred. The selection of modulation scheme is also done properly otherwise there could have been excessive waveform distortion in the stator current, harmonic generation and torque pulsation.

3 Proposed Field-Orientation Control

Field-orientation control (FOC) is introduced by Blaschke [10], and is a milestone in AC motor control field. It is also commonly known as vector control because it controls both the magnitude and direction of the variables. The distinguishing characteristic of field orientation control is to decouple the torque and flux. This method imitates the separately-excited DC motor which operates with separated torque and flux. Since the high order and nonlinear system nature make AC induction motors hard to control precisely, following this well developed DC motor control technique became a popular trend.

In order to describe the basic concept of field orientation control, we need to finish the third coordinate transformation: from synchronous rotating frame to rotor flux oriented reference frame. This transformation is done to fix the d-axis of the synchronous rotating frame with the rotor flux direction of AC induction motor. Since the d-axis is aligned with the rotor flux direction, the flux d and q components can be rewritten as:

$$\Psi_{\mathrm{dr}} = L_r i_{\mathrm{dr}} + L_m i_{\mathrm{ds}} \tag{1}$$

$$\Psi_{\mathrm{qr}} = L_r i_{\mathrm{qr}} + L_m i_{\mathrm{qs}} \tag{2}$$

Substituting Equation 1 and 2 to simplify the rotor voltage equations, it can have:

$$L_m P i_{\mathrm{ds}} + (R_r + L_r p) i_{\mathrm{dr}} = 0 \tag{3}$$

$$(\omega_e - \omega_r) L_m i_{\mathrm{ds}} + (\omega_e - \omega_r) L_r i_{\mathrm{dr}} + R_r i_{\mathrm{qr}} = 0 \tag{4}$$

Combining the stator equations, the rotor flux oriented voltage equations can be rewritten in matrix form as:

$$\begin{pmatrix} u_{\mathrm{ds}} \\ u_{\mathrm{qs}} \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} (R_s + L_s p) & -L_s \omega_e & L_m p & -L_m \omega_e \\ L_s \omega_e & (R_s + L_s p) & L_m \omega_e & L_m p \\ L_m p & 0 & (R_r + L_r p) & 0 \\ L_m(\omega_e - \omega_r) & 0 & L_r(\omega_e - \omega_r) & R_r \end{pmatrix} \cdot \begin{pmatrix} i_{\mathrm{ds}} \\ i_{\mathrm{qs}} \\ i_{\mathrm{dr}} \\ i_{\mathrm{qr}} \end{pmatrix} \tag{5}$$

In the matrix equation, the difference between the synchronous speed ω_e and rotor speed ω_r is the motor slip speed ω_{sl} .

$$\omega_{\mathrm{sl}} = \omega_e - \omega_r \tag{6}$$

From the torque equation $T_e = K_6 i_{\mathrm{qs}} \Psi_r \times I_s$, one can have:

$$T_e = K_6 (i_{\mathrm{qs}} \omega_{\mathrm{dr}} - i_{\mathrm{ds}} \omega_{\mathrm{qr}}) \tag{7}$$

Substituting the rotor flux Equation 2 $\Psi_{\mathrm{qr}} = 0$ into Equation 7, it becomes:

$$T_e = K_6 \cdot i_{\mathrm{qs}} \Psi_{\mathrm{dr}} \tag{8}$$

Equation 8 shows another important feature: when the flux level Ψ_{dr} is a constant, the electromagnetic torque is determined by i_{qs} , which is completely decoupled form i_{ds}.

From Equation 1 and 2, it can be:

$$i_{\mathrm{qr}} = \frac{-L_m i_{\mathrm{qs}}}{L_r} \tag{9}$$

$$i_{\mathrm{dr}} = \frac{\Psi_{\mathrm{dr}} - L_m i_{\mathrm{ds}}}{L_r} \tag{10}$$

From the rotor voltage Equation 3, and flux Equation 4, it can have:

$$R_r i_{\mathrm{dr}} + p\Psi_{\mathrm{dr}} = 0 \tag{11}$$

Substituting Equation 10 into Equation 11, it can have:

$$R_r \frac{\Psi_{\mathrm{dr}} - L_m i_{\mathrm{dr}}}{L_r} + \Psi_{\mathrm{dr}} = 0 \tag{12}$$

$$(1 + T_r p)\Psi_{\mathrm{dr}} = L_m i_{\mathrm{dr}} \tag{13}$$

Consider Equation as a transfer function $G(p)$ as represented in Figure 2, and substitute it into Equation $T_e = K_6 \cdot i_{\mathrm{qs}} \Psi_{\mathrm{dr}}$ one can finally have the torque equation as:

$$T_e = K_6 \cdot i_{\mathrm{qs}} \cdot \frac{L_m i_{\mathrm{ds}}}{(1 + T_r p)} \tag{14}$$

In field orientation control, there are two kinds of coordinate transformations: three phase to two phase (Clarke transformation), and stationary to rotation (Park transformation). To accomplish the rotating transformation, the flux angle θ_e must be known precisely. The Figure 3 represents the electromagnetic torque which is directly controlled by two decoupled currents.

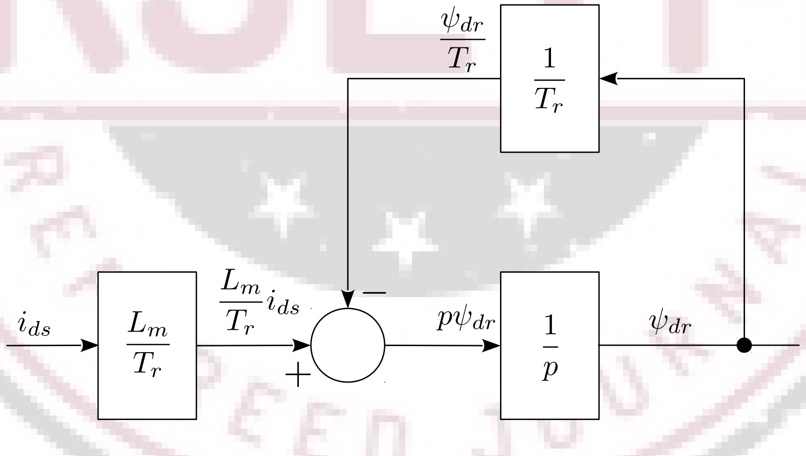

Figure 2: The Transfer Function $G(p)$

There are two basic ways to obtain the angle information: one is direct measurement,another is indirect estimation. Therefore, we end up having two types of field orientation control: Direct Field Orientation Control (DFOC) and Indirect Field Orientation Control (IFOC).

4 Simulation Result

Simulations for both steady state and dynamic condition were carried out to validate the theories in the previous chapters. It is very necessary to test the feasibility of control strategies using simulation before practicing them in

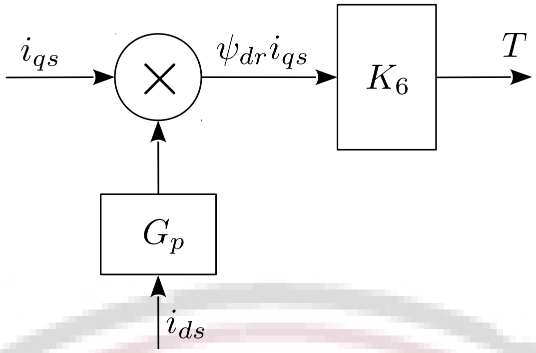

Figure 3: The Electromagnetic Torque Directly Controlled by Two Decoupled Currents

hardware. Thus, simulation models of FOC, conventional DTC and Sensorless DTC were built respectively. A 5-hp induction motor is used, and the parameters of this motor are given in the table below. Simulations scripts were written using MATLAB M-script, and simulation models were built using Simulink toolboxes and blocks.

Table 1: Induction Motor Parameters for Simulation

S.No.	**Parameter**	**Value**
1.	Nominal Power	14800 W
2.	Rotor Resistance	0.1645 Ω
3.	Voltage (line-line)	460 V
4.	Rotor Inductance	0.002891 H
5.	Frequency	60 Hz
6.	Mutual Inductance	0.1062 H
7.	Stator Resistance	0.2761 Ω
8.	Stator Inductance	0.002891 H
9.	Inertia	0.1 J(kg $\times$ m^2)
10.	Polar Number	2

Table 1 represents the simulation parameters for induction motor. Both steady state and dynamic performance are important to the system design engineers no matter what controller is being used. So for any given application, evaluation of the system performance should be considered in both aspects.

4.1 Result Analysis:(Torque verses Constant Speed)

First of all, it is important to analyze the starting performance. During this starting period, the electric motor needs to produce a relatively high torque in a very short time to accelerate itself. The investigation here is focused on speed response time, fluctuations as well as three phase currents of induction motor.

Then, when the vehicle is running at a constant speed for example in cruise mode, the load on the motor can vary abruptly because of the change of the road conditions. At this kind of state, the vehicle also needs a precise average torque and stable response from the electric motor. Therefore, the investigation is focused on torque fluctuations and current ripples. In the scenario 1, the speed command and torque command are given in Figure 4 and 5 respectively.

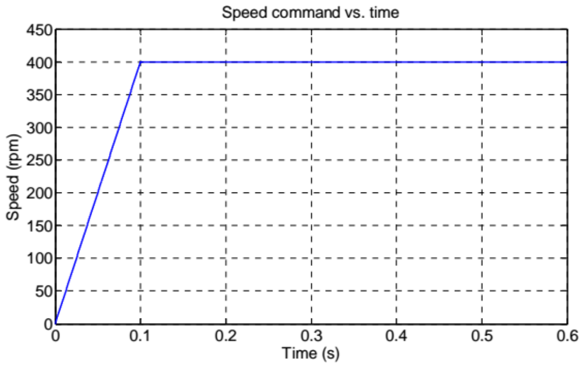

Figure 4: Speed Command vs. Time

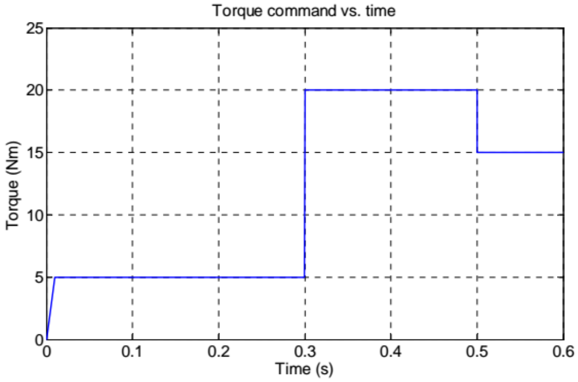

Figure 5: Torque Command vs. Time

A ramp signal is used to simulate the vehicle starting behavior, after the motor rotor speed reaches the target value of 400 rpm, it was kept as a constant. At the same time, when the motor was started from standstill with a ramp load torque from 0 to 5 Nm to the steady state speed of 400 rpm. And then, during the constant speed period, the load was changed to 20 Nm at the time $t = 0.3$ s, and changed again to 15 Nm at $t = 0.5$ s.

The speed response of field-oriented control (FOC), conventional direct torque control (DTC) and Sensorless DTC are presented in Figure 6, 7 and 8 respectively.

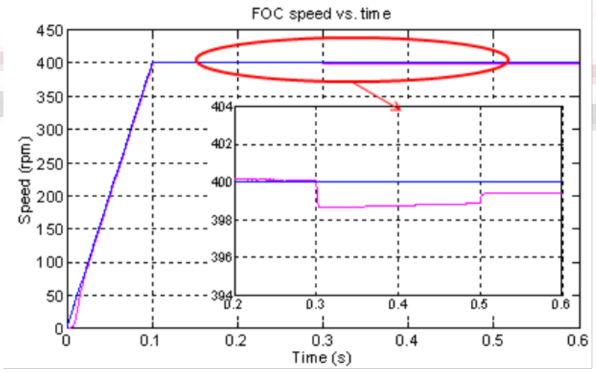

Figure 6: Speed Response of Field-Oriented Control

Generally, for FOC, conventional DTC and sensorless DTC , the speed of any of them is well regulated; there is no spike in speed response curves. It can be seen that as the load torque is suddenly changed, there is a small

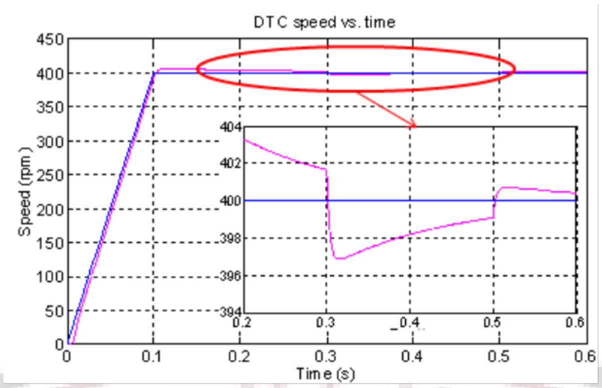

Figure 7: Speed Response of Conventional Direct Torque Control

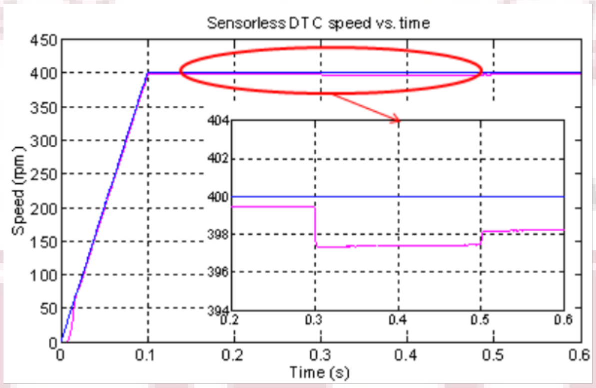

Figure 8: Speed Response of Sensorless Direct Torque Control

speed dip, but then it is restored quickly.

From speed response, it can be observe that at the time $t = 0.1$ s, the speed response of FOC follows the command very closely, the overshoot is almost 0, for DTC, the overshoot at $t = 0.1$ s is about 5 rpm, and for sensorlees DTC, the error is less than 1 rpm. At the time $t = 0.3$ s when the torque changes, the change of FOC speed response is about 2 rpm while the DTC's is around 6 rpm and sensorless DTC's is around 3 rpm. From this analysis it can be summarized that FOC has the best speed following characteristic among three of them, and sensorless DTC has a better one than the conventional DTC.

The torque response of FOC, conventional DTC and Sensorless DTC are presented in Figure 9, 10 and 11 respectively.

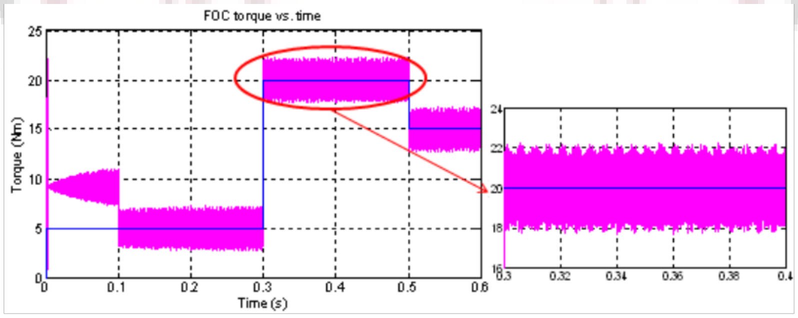

Figure 9: Torque response of FOC

For the torque responses, at the first stage, a large torque is generated to accelerate the motor. After reaching the target speed, the torque output follows the command closely. In DTC family, either conventional DTC or

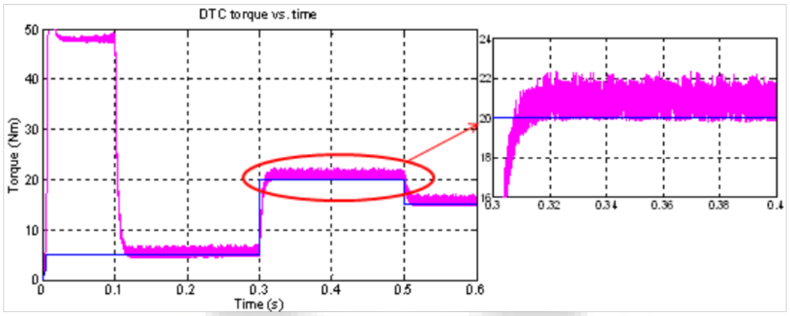

Figure 10: Torque response of conventional DTC

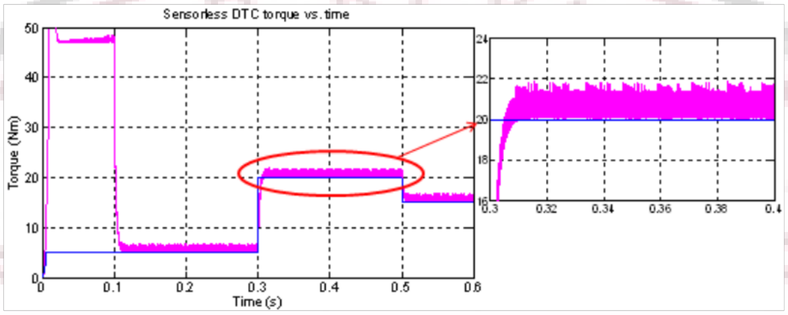

Figure 11: Torque response of SFO-Sensorless DTC

sensorless DTC, the torque is controlled by a hysteresis controller. By properly adjusting the positive band and negative band of this hysteresis controller, a satisfied torque response will be achieved. From the simulation result presented above, it is clear to see that the torque response is decent and fast.

5 Conclusion

The results from the simulations have clearly shows that FOC has the best steady performance and best speed following characteristic while conventional DTC and sensorless DTC have a better dynamic performance. At the same time, stator flux oriented sensorless DTC combines the advantages of FOC and conventional DTC, and results in a control method which maintains a good dynamic response as well as a decent steady state performance.

The parameters of the induction motor used in this test bench still need to be estimated. Some parameters are not precisely known and some parameters may vary with different operating conditions. Compensations regarding the motor parameters need to be further considered in the software program.

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