COMPARISON OF TWO TARQUE CONTROL METHODS FOR INDUCTION MOTORS

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ABSTRACT

In this paper, the static as well as the dynamic operations of the field-oriented control (FOC) and direct torque control (DTC) methods for induction machines are compared. For this purpose, an induction motor with ratings of 50^{HP}, 460^{V} and 60^{HZ} is considered. The simulink models of both methods are obtained and the simulation results show the advantages and disadvantages of each method.

I. INTRODUCTION

The most widespread electromechanical systems are based on the induction motors. From the point view of control, they represent a complex multivariable nonlinear control problem. On the other hand, implementation of the induction motor control system to achieve a high dynamical performance, efficiency, robustness is an important practical task [1].

With the apparition of the FOC, induction motor drives have become a major candidate in high performance motion control applications. With the complex machine dynamics, the decoupling technique permits independent control of the torque and field. The concepts of decoupling using both flux and torque components in the FOC method enables an easier control of induction motors. To drive the motor with the resulting current control signals the currents are transformed to the stator current components, which are then generated using pulse width modulation [2].

Various techniques are used for controlling torque induction motors. Among those are, the DTC technique, which is a convenient and relatively easy to implement. In fact, the DTC is a combination of the FOC and direct self-control techniques. It operates based on the measured voltage and current. The DTC technique may be implemented with or without speed sensors, depending on the method used to estimate the stator flux. Generally, in the design of the drive, an attempt has been made to reduce the required input data, to decrease the computational time and update the system dynamic equations [3]. Ever since the first developments of the DTC method, it has been used in many AC drive applications. This is due to the fast torque response and robustness against machine parameters variations. Its simple structure is due to using hysteresis comparators and switching vector tables for flux and torque control [4].

II. THE BASIC THEAORY OF THE FOC AND DTC TECHINQUES

A. Field Oriented Control

Blascke (1972) first developed the field orientation method. This is a torque-flux decoupling technique applied to induction machine control [1]. The FOC technique is a well-established and widely used applied control technique in dealing with high performance induction motor drives. In Fig.1, the block diagram of the FOC control technique for induction motors is shown.

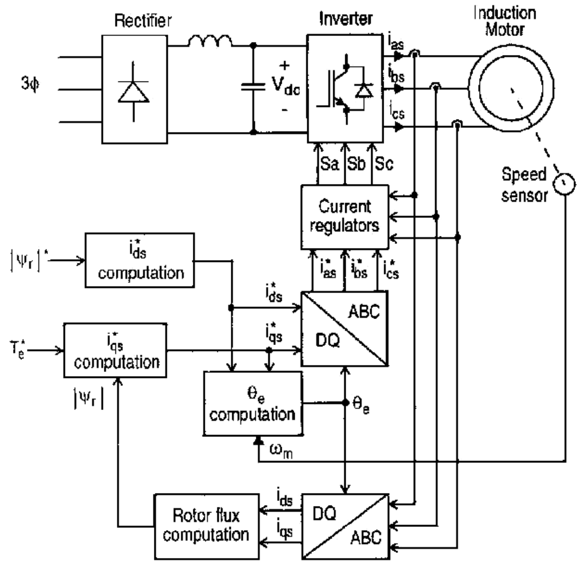

Fig 1: Block diagram of the FOC technique

To achieve a filed orientation the current components supplied to the machine should be oriented as such that to

isolate the component of the stator current, thus producing a flux.
The q-axis component of the stator reference current, i^*_{qs}, may be computed using the reference input torque (T^*_e) as:

$$i^*_{qs} = \frac{2}{3}\cdot\frac{2}{p}\cdot\frac{L_r}{L_m}\cdot\frac{T_e^*}{|\psi_r|_{est}} \tag{1}$$

where $|\psi_r|_{est}$ the estimated flux of the rotor, is given by:

$$|\psi_r|_{est} = \frac{L_m i_{ds}}{1+\tau_r s} \tag{2}$$

with L_m and τ_r are the magnetization inductance, rotor time constance, respectively.
The d-axis component of the stator reference current, i^*_{ds}, also may be obtained by using the reference input flux ($|\psi_r|^*$) as:

$$i^*_{ds} = \frac{|\Psi_r|^*}{L_m} \tag{3}$$

By using the rotor speed, ω_m, and the slip frequency given by equation (4):

$$\omega_{s1} = \frac{L_m}{|\Psi_r|_{est}}\cdot\frac{R_r}{L_r}\cdot i^*_{qs} \tag{4}$$

The angle of the rotor flux may be evaluated using the equation (5):

$$\theta_e = \int(\omega_m+\omega_{s1})dt \tag{5}$$

where R_r and L_r are the rotor resistance and inductance respectively.
The reference currents of the stator i^*_{ds} and i^*_{qs} after transferring to phase currents (i^*_a, i^*_b and i^*_c) are entered to current regulators section. The current regulators section produces the patterns of the switches of the inverter (S_a, S_b and S_c).

B. Direct Torque Control

In addition to vector control systems, instantaneous torque control yielding fast torque response may also be obtained by employing DTC method. The DTC was developed more than a decade ago by Japanese and German researchers (Takahashi and Noguchi 1984, 1985; Depenborck 1985) [5]. The basic idea in the DTC control, whit block diagram shown in Fig. 2, is to choose the optimal vector voltage, for which the generated rotated flux produces the desired torque [4]. The DTC technique is based on the theory of the FCO induction motor and direct self control method. The core of the DTC consists of hysteresis controllers of the torque and flux; optimal switching logic; precise motor model.
The space vector of the stator flux ($\overline{\psi_S}$) is calculated by using:

$$\overline{\Psi}_S = \int(\overline{V}_s - R_s\overline{I}_s)dt \tag{6}$$

With the vector quantities stator voltage ($\overline{V}_S$) and current $\overline{I}_s$ are being obtained using equations (7) and (8) respectively.

$$\overline{V}_S = \frac{2V_{dc}}{3}\left[S_a + S_b e^{j\frac{2\pi}{3}} + S_c e^{j\frac{4\pi}{3}}\right] \tag{7}$$

$$\overline{I}_S = \frac{2}{3}\left[i_a + i_b e^{j\frac{2\pi}{3}} + i_c e^{j\frac{4\pi}{3}}\right] \tag{8}$$

where V_{dc}, S_i and i_k (i, k = a,b,c) are DC voltage, the signals of the gats of the inverter and the stator measured currents, respectively.
Finally, the electromagnetic torque T_e may be calculated using:

$$T_e = \frac{3}{2}\frac{P}{2}(\overline{I}_s \cdot j\overline{\psi}_S) \tag{9}$$

The motor model calculates the torque, stator flux and shaft speed based on the measurements of two-phase current and the circuit dc voltage. Torque and flux references are compared with these values, and control signals are produced using a two level hysteresis. The optimal switching logic defines the best vector voltage based on the torque and flux references [6].

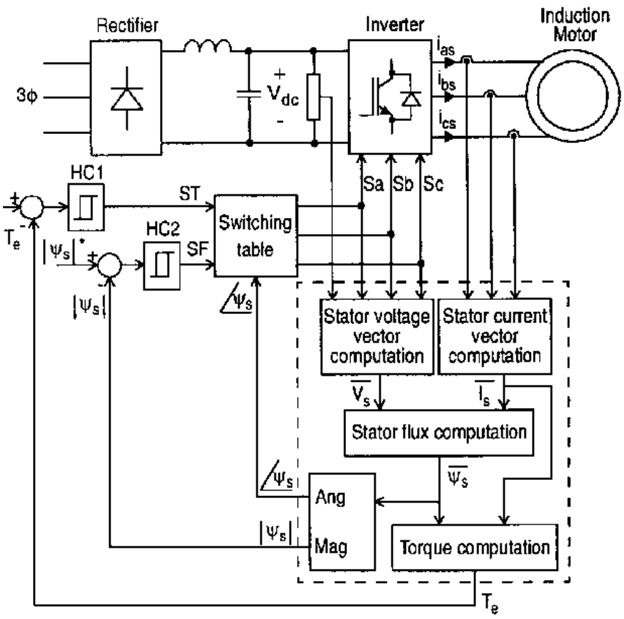

Fig 2: Block diagram of the DTC technique

III. THE SIMULATION RESULTS

Simulations of the FOC and DTC techniques have been performed for a 50^{PH} induction motor, with data being listed in the appendix. In each case, a three-phase inverter feeds the induction motor. The frequency switching for both cases are different, and depend to hysteresis controllers. However, the parameters are chosen as such that the frequency range is the same.

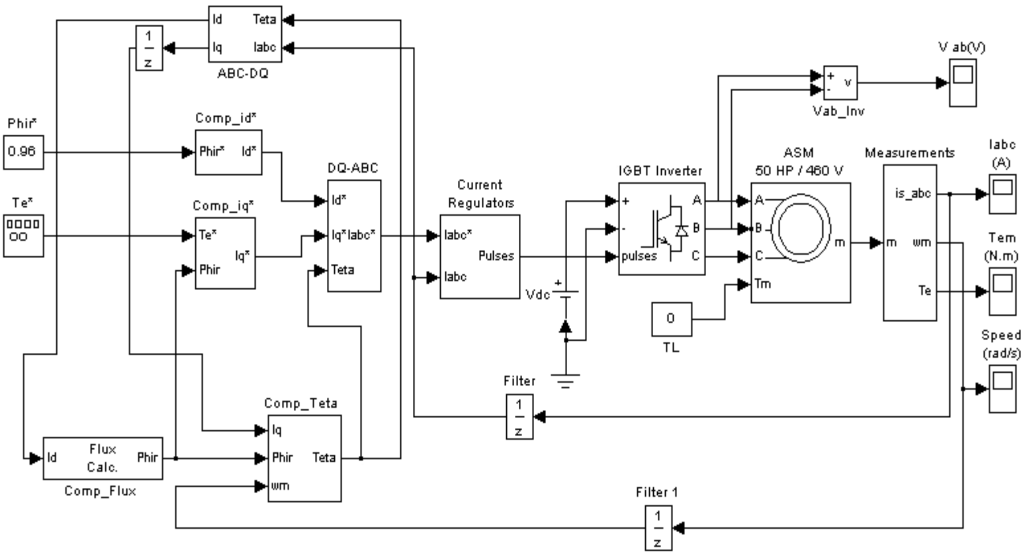

Fig. 3: The simulink model for FCO technique

Using FOC technique, the band of the hysteresis current controller is 10^{A}, and using DTC, the bands of the hysteresis flux and torque controllers are 0.2^{Wb} and $40^{N.m}$, respectively.

To investigate the dynamic operation of the torque, a square wave with amplitude $200^{N.m}$ is applied to the torque while the reference of the flux being fixed at rating value. The motor operates with low speed, and the switching time is approximately 0.5^{ms}.

To investigate the operation of the flux, we decrease the input control flux to be 0.75 percent of the rating value, while keeping of the torque fixed.

Next, we first describe the simulation for both of methods and then provide the simulation results.

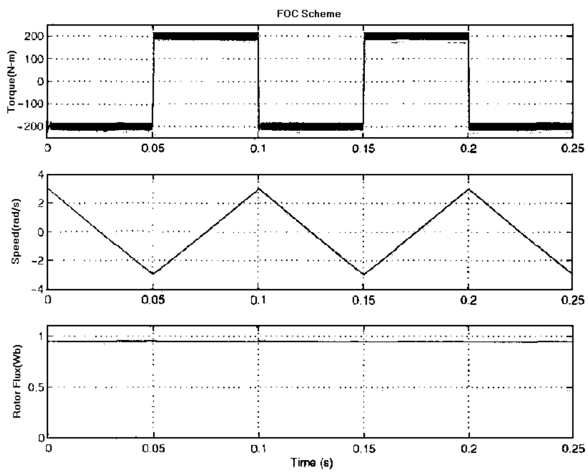

Fig. 4: The step response of the torque control in FOC technique

A. The FOC method

Fig. 3 shows the simulink model of the FOC technique, where the *q*-axis component of the stator current is being considered. Therefore, the operation of the control system depends on the stator currents regulators. Due to the fast response, the hysteresis controllers are used. Therefore, the switching frequency of the inverter will be variable and will depend on the operation conditions. The variation of the torque is proportional to the variation of the *q*-axis component of the stator current:

$$\frac{\Delta T_e}{\Delta t} = \frac{3}{2} \cdot \frac{P}{2} \cdot \frac{L_m}{L_r} \cdot |\psi_r| \cdot \frac{\Delta i_{qs}}{\Delta t} \tag{10}$$

Figs. 4 and 5 show the simulation results for the FOC technique.

At FOC technique, as the Fig. 5 shows the stator and rotor flux's change with the time constance equal to the rotor time constance (in this case τ_r=0.156^{S}).

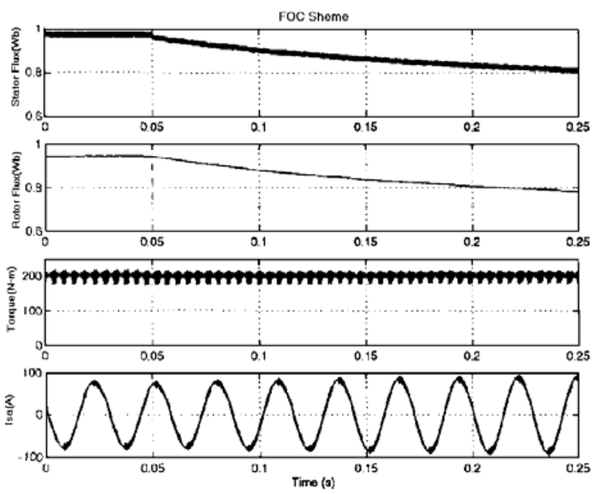

Fig. 5: The step response of the flux control in FOC technique

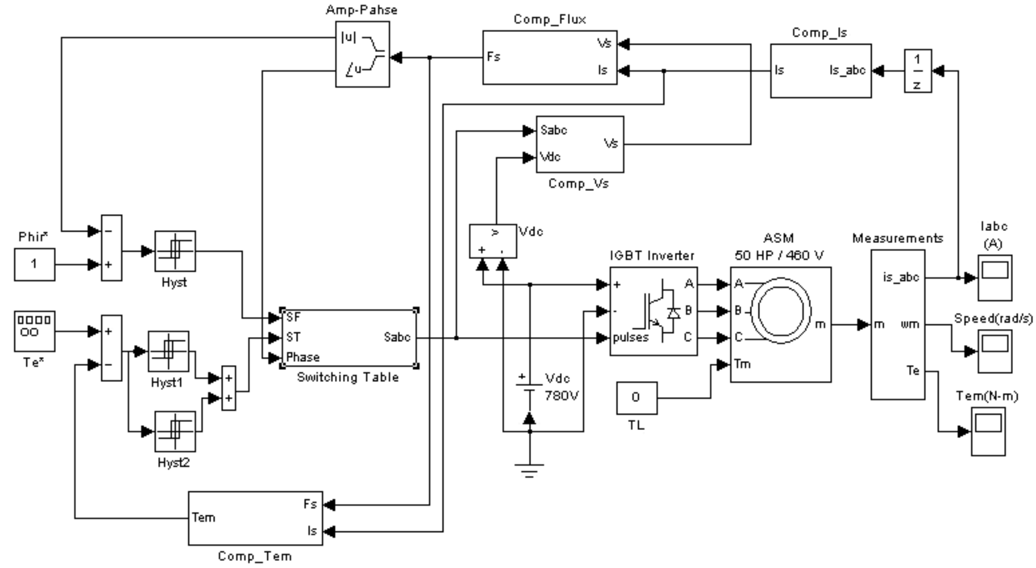

Fig. 6: The simulink model for DTC technique

B. The DTC Method

Depending on the application, electric vehicle technology needs to develop induction motor-powered converter systems with quick-response and high efficiency. Direct torque control is used in many of the new drives where the technique is usually based on the direct control of the stator flux and torque [6]. This is accomplished by sampling the supply voltage and stator current and using a hysteresis controller with simulink given in Fig. 6. By noting that the time of the torque response, depends on the angular speed slip and may be evaluated using the equation (11):

$$\omega_s(\max) = \pm \frac{2V_{dc}}{3|\psi_s|} \tag{11}$$

where $|\overline{\Psi}_S|$ is the stator flux vector.

Also, the maximum variation of the motor torque is proportional to the maximum angular speed slip:

$$\frac{\Delta T_e}{\Delta t}(\max) = \frac{3}{2}\cdot\frac{P}{2}\cdot\frac{L_m}{L_s L_r - L_m^2}\cdot|\psi_s|\cdot|\psi_r|\cdot\omega_{sle} \tag{12}$$

where ω_{sle} is given by:

$$\omega_{sle} = \omega_s(\max) - \omega_m = \pm\frac{2V_{dc}}{3|\psi_s|} - \omega_m \tag{13}$$

Thus, the flux stator may be changed fast and this is shown in Figs. 7 and 8. In this case, the time response of the stator flux is approximately 0.5^{ms}, and this ability shows the fast dynamic response of the DTC technique respect to FOC technique. At DTC method, the rotor flux follows the stator flux with time constance $\sigma\tau_r$ (in this case $\sigma\tau_r = 7^{ms}$).

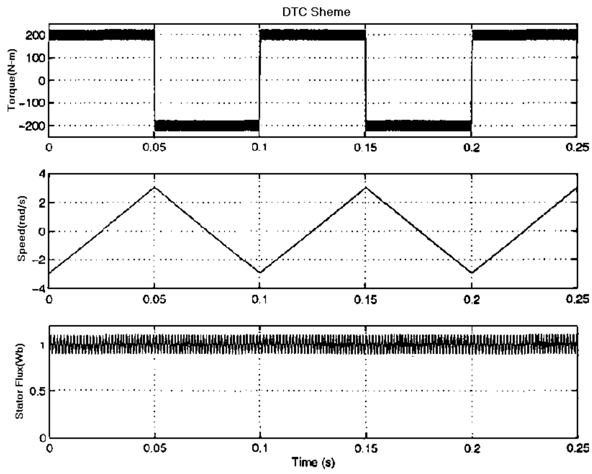

Fig. 7: The step response of the torque control in DTC technique

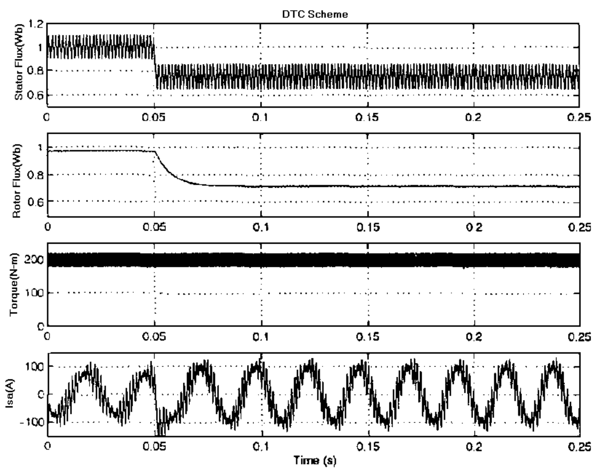

Fig. 8: The step response of the flux control in DTC technique

However, a direct torque controlled motor suffers from great torque ripple due to the fast response of the torque. The most important characteristic of DTC is its fast torque response. When a proper vector is applied to motor, the stator flux vector rotates very fast and the angle between the stator flux and rotor flux is increased [4]. Direct torque control (DTC) is used to control the motor. In this control strategy, efficiency is optimized by adjusting the magnetic flux of the motor [6].

The important characteristics of the DTC method are:

- Direct control of stator flux and electromagnetic torque and indirect control of stator currents and voltages;
- Almost sinusoidal stator fluxes and currents;
- Reduced torque oscillations;
- Excellent torque dynamics;
- Inverter switching frequency depending on flux and torque hysteresis bands.

The main advantages of the DTC method are:

- Absence of coordinated transformations (which are required in most of the vector-controlled drive implementations), separate voltage modulation block (required in vector drives) and voltage decoupling circuits (required in voltage-source inverter-fed vector drives);
- Reduced number of controllers
- Determination of the actual flux-linkage vector position is not necessary only the sector where the flux linkage is located.

The main disadvantages of a conventional DTC method are:

- Starting, low-speed operation and torque changes could be of some concern.
- The flux-linkage and electromagnetic torque estimator are needed.
- Variable switching frequency [5].

IV. CONCLUSIONS

In this paper, two methods namely FOC and DTC for controlling the induction motors are considered. Implementation of the FOC method requires having a sinusoidal reference signal, while on the contrary, due to the use of stationary reference, the DTC method does not necessitates having a sinusoidal reference signal. Finally, it can be shown that the DTC algorithm provides much faster response than FOC.

Appendix: Induction motor data

Rated power	50PHP
Rated voltage	460V
Rated frequency	60Hz
Number of poles	4
Stator resistance	R_s=0.087Ω
Stator inductance	L_s=0.8mH
Magnetization inductance	L_m=34.7mH
Rotor resistance	R_r=0.228Ω
Rotor inductance	L_r=0.8mH

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