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Direct Torque Control of Dual Star Induction Motor

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Abstract- This paper describes a direct torque control (DTC) of dual star induction motor (DSIM). This machine possesses several advantages over conventional three-phase machine and is also known as the six-phase induction machine. The research has been underway for the last two decades to investigate the various issues related to the use of six-phase machine as a potential alternative to the conventional three-phase machine. Though six-phase machines have existed for some time, in the literature very few papers discuss DTC for six-phase motors. Therefore, in this work an investigation is reserved to the application of this type of control to the DSIM. The DTC uses the instantaneous values of voltage vector where each reference voltage vector is computed with a simple DTC algorithm. Finally, simulations results obtained from MatLab/Simulink are presented followed by a discussion.

Keywords- DSIM, DTC, modelling, drive, simulation.

1. Introduction

The Multi-phase machines could be an interesting alternative for the speed variable control [1, 2] because are possess several advantages over conventional three-phase machine [3, 4]. In a multi-phase machine drive system, more than three-phase windings are housed in the same stator of the electric machine and the current per phase in the machine is thereby reduced. In the most common of such structures, two sets of three-phase windings are spatially phase shifted by 30° electrical. However, the modelling and control techniques are found in abundance in the recent literature but very few papers discuss DTC for six-phase motors. Therefore, in this work an investigation is reserved, to the strategy of direct torque control (DTC) of dual-stator induction machine (DSIM) as well as adjusting its speed. These machines require a double tree-phase supply and have many has been used in many applications for their advantages [5].

The DTC is a control technique used in AC drive systems to obtain high performances to provide a very fast torque and flux control. The DTC is known to have a simple control structure with comparable performance to that of the field-oriented control (FOC) techniques developed by Blaschke [6]. The DTC method was proposed by I.Takahashi [7]. It is based on the errors between the reference and the estimated values of torque and flux for to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits [8, 9]. To this end, it uses tables to select the switching procedure based on the inverter states [10] and reduces the influence of the parameter variation during the operation [11]. The DTC drive contains a pair of hysterisis comparators, a flux, torque estimator and a voltage vector selection table. The torque and flux are controlled simultaneously by applying suitable voltage vectors and by limiting these quantities within their hysteresis bands [12].

In the last decade high performance drives based on the spatial position of the flux and on space vector theory have been developed and industrially applied, consequently, several papers provide sensorless control of induction motor that are based on the variable structure technique. The speed estimation is affected by parameter variations especially the stator resistance due to temperature which particularly appear at low speeds. However, it is necessary to compensate these parameters in order to improve their high performances. For this, the speed control is used and the obtained performances are analyzed.

2. Machine Modelling

The windings (a_{s1}, b_{s1}, c_{s1}) of the first stator and (a_{s2}, b_{s2}, c_{s2}) of the second stator of DSIM are represented in Fig.1, whose magnetic axes are displaced by α =30◦ electrical angle. The rotor windings (a_r, b_r, c_r) are sinusoidally distributed and have axes that are displaced apart by 120° [13].

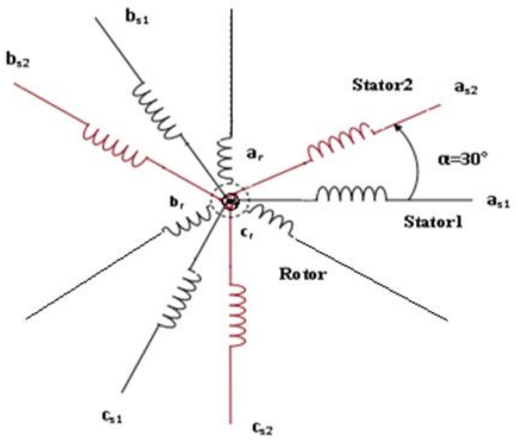

Fig. 1. Windings scheme of DSIM

In the synchronous reference frame (d, q), the equations of the DSIM are given by following system [14, 15]:

$$\begin{cases} \dot{\Phi}_{ds1} = V_{ds1} - R_{s1} i_{ds1} + \omega_e \Phi_{qs1} \\ \dot{\Phi}_{qs1} = V_{qs1} - R_{s1} i_{qs1} - \omega_e \Phi_{ds1} \\ \dot{\Phi}_{ds2} = V_{ds2} - R_{s2} i_{ds2} + \omega_e \Phi_{qs2} \\ \dot{\Phi}_{qs2} = V_{qs2} - R_{s2} i_{qs2} - \omega_e \Phi_{ds2} \\ \dot{\Phi}_{dr} = V_{dr} - R_r i_{dr} + (\omega_e - \omega_r)\Phi_{qr} = 0 \\ \dot{\Phi}_{qr} = V_{qr} - R_r i_{qr} - (\omega_e - \omega_r)\Phi_{dr} = 0 \end{cases} \quad (1)$$

Where the expressions for stator and rotor flux are:

$$\begin{cases} \Phi_{ds1} = L_{s1} i_{ds1} + L_m (i_{ds1} + i_{ds2} + i_{dr}) \\ \Phi_{qs1} = L_{s1} i_{qs1} + L_m (i_{qs1} + i_{qs2} + i_{qr}) \\ \Phi_{ds2} = L_{s2} i_{ds2} + L_m (i_{ds1} + i_{ds2} + i_{dr}) \\ \Phi_{qs2} = L_{s2} i_{qs2} + L_m (i_{qs1} + i_{qs2} + i_{qr}) \\ \Phi_{dr} = L_r i_{dr} + L_m (i_{ds1} + i_{ds2} + i_{dr}) \\ \Phi_{qr} = L_r i_{qr} + L_m (i_{qs1} + i_{qs2} + i_{qr}) \end{cases} \quad (2)$$

Where V_{ds1}, V_{qs1}, V_{ds2}, V_{qs2} are the stator voltages components; i_{ds1}, i_{qs1}, i_{ds2}, i_{qs2} are the stator currents components; V_{dr} and V_{qr} are the rotor voltages components ; i_{dr} and i_{qr} are the rotor currents components; Φ_{ds1}, Φ_{qs1}, Φ_{ds2}, Φ_{qs2} are the stator flux components; Φ_{dr} and Φ_{qr} are the rotor flux components; R_{s1}, R_{s2} and R_r are respectively the stator and rotor resistance; ω_e is the speed of the synchronous reference frame; ω_r is the rotor electrical angular speed.

The mechanical equation is given by (3), where the equation of the electromagnetic torque is calculated with the expression (4):

$$J\dot{\Omega} = T_{em} - T_l - k_f\ \Omega \quad (3)$$

$$T_{em} = \frac{pL_m}{(L_m + L_r)\left(\Phi_{dr}(i_{qs1} + i_{qs2}) + \Phi_{qr}(i_{ds1} + i_{ds2})\right)} \quad (4)$$

Where, J is the moment of inertia of the DSIM Ω is mechanical speed; T_{em} is the electromagnetic torque; T_l is the load torque and K_f is friction coefficient.

3. Direct Torque Control

3.1. Direct Torque Control

The DTC based on hysteresis comparators and switching tables provides a fast torque response. However, in steady state the torque has large ripples due to the switching frequency of the inverter caused by the hysteresis bands. DTC requires accurate knowledge of the amplitude and angular position of the controlled flux with respect to the stationary stator axis in addition to the angular velocity for the torque control purpose [16]. The principle of DTC operation can also be explained by analyzing the stator voltage equation in the stator flux reference frame [17].

$$\vec{u}_s = R_s \dot{i} + \frac{d\vec{\phi}}{dt} + j\omega_s \vec{\phi}_s \quad (5)$$

If this expression is separated into the direct (α) and the quadrature component (β) of the stator voltage, the following expression can be obtained:

$$u_{s\alpha} = R_s i_{s\alpha} + \frac{d\phi_{s\alpha}}{dt} \quad (6)$$

$$u_{s\beta} = R_s i_{s\beta} + \frac{d\phi_{s\beta}}{dt} \tag{7}$$

The torque expression is :

$$T_{em} = \frac{3.p.\phi_{s\alpha}}{2.R_s}(u_{s\beta} - \omega_s \phi_{s\alpha}) \tag{8}$$

Electromagnetic torque can be controlled by means of the component of the stator voltage, under adequate decoupling of the stator flux. DTC requires the estimation of stator flux and torque, which can be performed by means of two different phase currents, the state of the VSI and the voltage level in the DC voltage bus. This work uses a DTC schemes for an induction motor fed by two-level voltage source inverter. The flux estimation is based in the following equations:

$$\frac{d\varphi_{drest}}{dt} = \frac{R_r.L_m}{L_r.L_m}(i_{ds1} + i_{ds2}) - \frac{Rr}{Lr + Lm}\varphi_{drest} + \omega_{sl}.\varphi_{qrest}$$
$$\frac{d\varphi_{qrest}}{dt} = \frac{R_r.L_m}{L_r.L_m}(i_{qs1} + i_{qs2}) - \frac{Rr}{Lr + Lm}\varphi_{qrest} - \omega_{sl}.\varphi_{drest} \tag{9}$$

Hence, the modulus of the estimated rotor flux is:

$$\varphi_{rest} = \sqrt{\varphi_{qret}^2 + \varphi_{drest}^2} \tag{10}$$

The following table gives the control vectors according to the outputs of the flux and torque regulators for the sixth sectors considered and dedicated to the control of dual star induction machine. The switching table to select the appropriate inverter switching state is presented as follows.

Table 1. Switching table

Flux	1			0		
Torque	1	0	-1	1	0	-1
Sector 1	V_2	V_1	V_6	V_3	V_4	V_5
Sector 2	V_3	V_2	V_1	V_4	V_5	V_6
Sector 3	V_4	V_3	V_2	V_5	V_6	V_1
Sector 4	V_5	V_4	V_3	V_6	V_1	V_2
Sector 5	V_6	V_5	V_4	V_1	V_2	V_3
Sector 6	V_1	V_6	V_5	V_2	V_3	V_4

Where : V_1(100), V_2(110), V_3(010), V_4(011), V_5(001), V_6(101).

Table 1 shows the sequences corresponding to each position, knowing that

the error between the reference flux and the estimated flux is introduced into a hysteresis comparator at two levels, which 1 if the error is positive and 0 if negative. Similarly, the error (ζ) between the reference and the estimated torques is fed with to three levels hysteresis comparator: 1 if ζ>0 , 0 if ζ =0 and -1 if ζ<0.

The speed regulation schema by direct torque control of dual star induction motor drive is given in Fig.2.

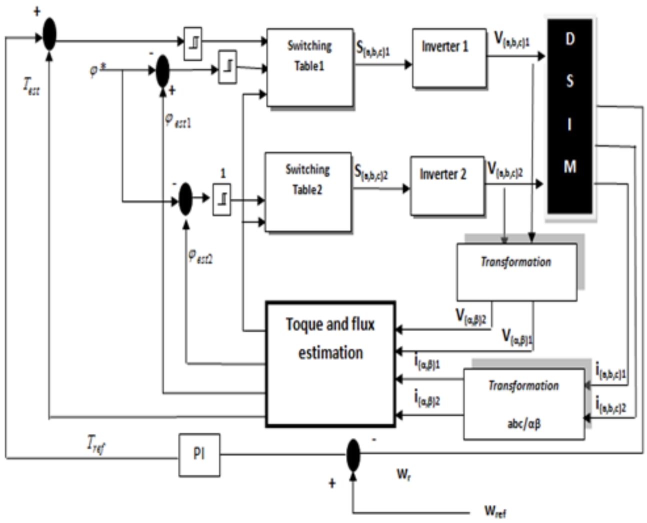

Fig. 2. Speed control bloc diagram

4. Simulation results

The simulation results are presented in figures 3, 4, 5 and 6. These results are obtained with simulation under Matlab/ Simulink. Fig.3 shows that the speed reaches its reference speed (100rd/s) after 0.4s when the load torque is zero. At 2s, we changed the value of load torque to T_l=10Nm, we note that the speed stabilized with speed static error. Fig.4 presents the behaviour of the electromagnetic torque. Fig .5 shows that the flux in Concordia plan (α, β) is circular with a radius equal to the reference flux. Finally, Fig. 6 shows the temporal evolution of the flux where it is important to note, that the flux and torque can be controlled independently. In fact, after the fast flux response, it retains its value despite the variation of the torque.

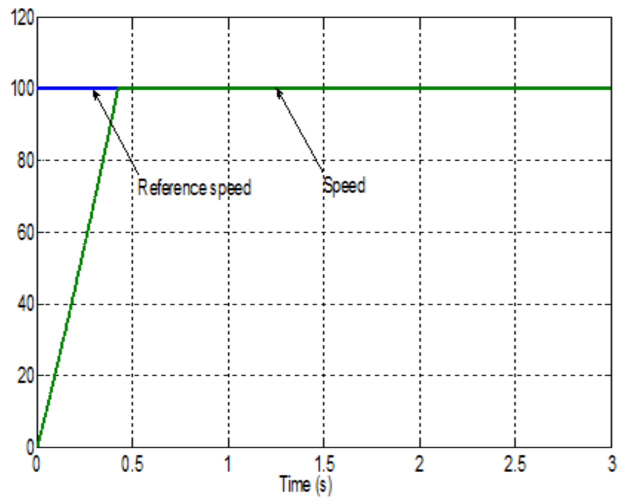

Fig. 3. Real and reference speeds

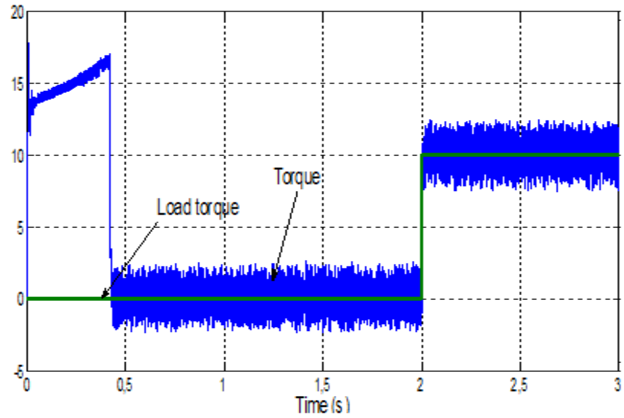

Fig. 4. Machine and load torques

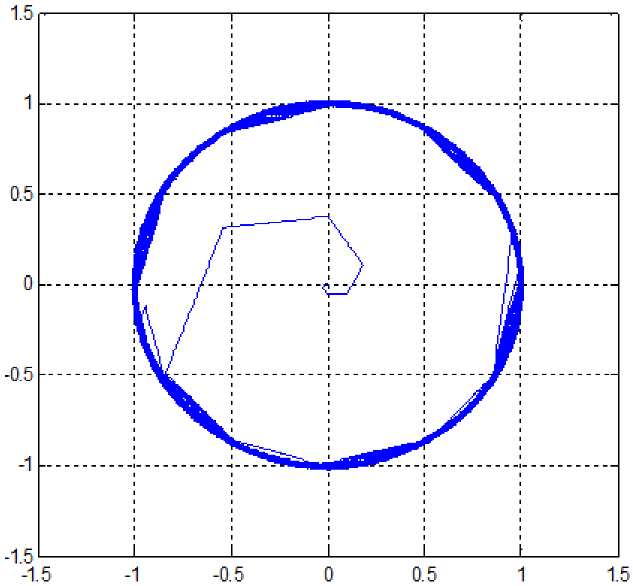

Fig. 5. Flux machine Concordia plan

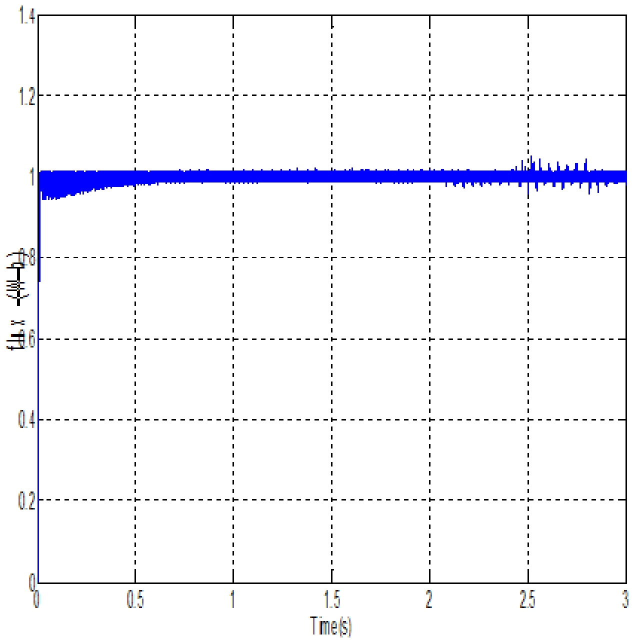

Fig. 6. Flux machine

Table 2. Simulation data

L_m: Mutual inductance	0.3672H
L_r : Rotor inductance	0.006H
$L_{s1}= L_{s2}$: Stator inductances	0.022H
$R_{s1},= R_{s2}$: Stator resistances	3.72Ω
R_r: Rotor resistance	2.12Ω
K_f: Friction coefficient	0.001
p : Number of pole pairs	1
J : Moment of inertia	0.0662Kg.m2
V_n: Nominal voltage	220V
P_n: Nominal power	4,5Kw

5. Conclusion

In this work, the principle and a several characteristics of direct torque control for a double star induction motors drive are studied by simulation. This machine has many advantages to offer over conventional. The DTC was introduced to give a fast dynamic torque and flux. The study bloc has been simulated and the obtained results simulations show acceptable performances. However, two major problems associated with DTC drive: electromagnetic torque ripple and variable switching frequency.

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