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Modelling and Analysis of Dual Three-phase Induction Machine

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***Abstract*— this paper deals with the modeling and the analysis of a dual-stator winding induction motor (DSIM). The later has two sets of three-phase stator winding windings with a 30° electrical angle shift. The machine model has been developed in a synchronous reference frame. The chosen model was supplied by two voltage source inverters which are controlled using the Pulse Width Modulation PWM technique.**

To illustrate system performances evolution, this synthetized model was been implemented and simulated using matlab/Simulink.

***Keywords*— Dual-stator winding induction motor (DSIM), Modeling, Analysis, Inverter, PWM.**

I. Introduction

With the development of power electronics frequency converters the use of multiphase induction motor drives has been increased, especially for high-power applications [1].

Advantages span from power segmentation, higher reliability, lower torque ripple, less rotor harmonic and reduced harmonic content of the DC- link current. There for multiphase machine are used in specialized applications where higher reliability is demanded such as electric vehicles and ship population, aerospace applications [1]

Dual Stator Induction Motor (DSIM) has two sets of three-phase stator winding with a 30° electrical angle shift sharing the same rotor, as shown in Fig.1, is currently used specially for higher power application [2].

This paper presents a motor's mathematical model under the (d-q) reference frame. This DSIM drives was supplied by two voltage source inverters using the Pulse Width Modulation PWM.

In fact, the spatial reperation of the windings and the complex structure of this machine make the model difficult to be realized in the original reference frame. For this reason, some assumptions must be considered in order to have a simplified model [3].

This paper is organized as follows. The mathematical model of DSIM and the PWM voltage source inverters have been presented in Section II. The simulation results are discussed in Section III. The conclusion is drawn in Section V.

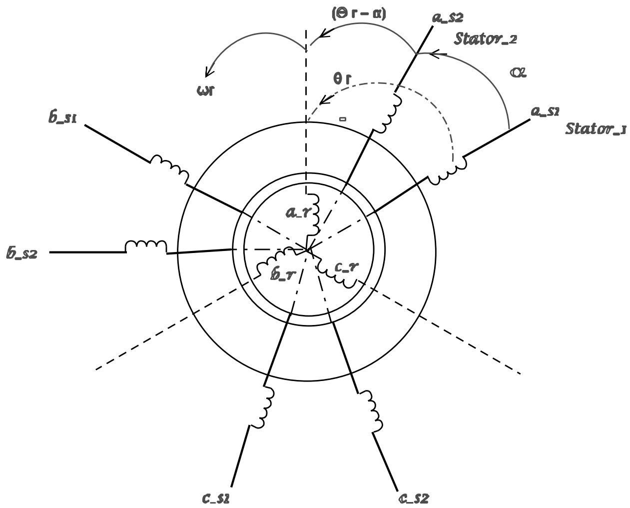

Fig.1 Dual-stator winding induction machine.

II. SYSTEM MODELING

A. Modelling of Dual-stator induction motor

The DSIM is modeled under the (d-q) reference frame. Its specifications are listed in Table1.The two sets of phase winding which are 30° shift between other can be marked as (a_s1, b_s1, c_s1) and (a_s2, b_s2, c_s2).The windings of each three-phase set are uniformly distributed and spaced by 120 electrical degrees. The three-phase rotor windings (a_r, b_r, c_r) are also sinusoidally distributed and the axes system displaced by 120 electrical degrees.

To model the Dual stator induction motor some assumptions have been taked into consideration to obtain a simplified model [4]:

- The windings are sinusoidally distributed and the rotor cage is equivalent to a six-phase wound rotor.
- The magnetic saturation, the mutual leakage inductances and the core losses are neglected.

The electrical equations of dual-stator induction machine under the (d-q) reference frame are given by [1-5].

$$\begin{cases} V_{ds1} = r_1 i_{ds1} - \omega_e \Phi_{qs1} + p\Phi_{ds1} \\ V_{qs1} = r_1 i_{qs1} + \omega_e \Phi_{ds1} + p\Phi_{qs1} \\ V_{ds2} = r_2 i_{ds2} - \omega_e \Phi_{qs2} + p\Phi_{ds2} \\ V_{qs2} = r_2 i_{qs2} + \omega_e \Phi_{ds2} + p\Phi_{qs2} \\ V_{dr} = 0 = r_r i_{dr} - \left[\omega_e - \omega_r\right]\Phi_{qr} + p\Phi_{dr} \\ V_{qr} = 0 = r_r i_{qr} + \left[\omega_e - \omega_r\right]\Phi_{dr} + p\Phi_{qr} \end{cases} \quad (1)$$

V_{ds1}, V_{ds2} , i_{ds1} , i_{ds2} and Φ_{ds1} , Φ_{ds2} are respectively the "d" component of the stator voltages, currents and flux linkage; V_{qs1} , V_{qs2} , i_{qs1} , i_{qs2} and Φ_{qs1} , Φ_{qs2} are respectively the "q" components of the stator voltages, currents and flux linkage; V_{dr} , i_{dr} and Φ_{dr} are respectively the "d" components of the rotor voltage, current and flux linkage; V_{qr} , i_{qr} and Φ_{qr} are respectively the "q" components of the rotor voltage, current and flux linkage; r_1 , r_2 and r_r are respectively the per phase stator resistance and the per phase rotor resistance; ω_e is the speed of the reference frame; ω_r is the rotor electrical angular speed and p denotes differentiation .

The expressions for stator and rotor flux linkages are [1-5]:

$$\begin{cases} \Phi_{ds1} = l_{s1} i_{ds1} + L_m \left[i_{ds1} + i_{ds2} + i_{dr} \right] \\ \Phi_{qs1} = l_{s1} i_{qs1} + L_m \left[i_{qs1} + i_{qs2} + i_{qr} \right] \\ \Phi_{ds2} = l_{s2} i_{ds2} + L_m \left[i_{ds1} + i_{ds2} + i_{dr} \right] \\ \Phi_{qs2} = l_{s2} i_{qs2} + L_m \left[i_{qs1} + i_{qs2} + i_{qr} \right] \\ \Phi_{dr} = l_r i_{dr} + L_m \left[i_{ds1} + i_{ds2} + i_{dr} \right] \\ \Phi_{qr} = l_r i_{qr} + L_m \left[i_{qs1} + i_{qs2} + i_{qr} \right] \end{cases} \quad (2)$$

Where l_{s1} , l_{s2} and l_r are respectively the stator and rotor inductances and L_m is the mutual inductance.

The mechanical dynamic equation is given by:

$$J.\frac{d\Omega_m}{dt} = T_{em} - T_r - f.\Omega_m \quad (3)$$

Where J , f , Ω_m and T_r are respectively the moment of inertia, the coefficient of friction, the mechanical speed and the load torque.

The electromagnetic torque is evaluated as:

$$T_{em} = \frac{3p}{2}.\frac{L_m}{L_m + l_r}\left[\left[i_{qs1} + i_{qs2} \right]\Phi_{dr} - \left[i_{ds1} + i_{ds2} \right]\Phi_{qr}\right] \quad (4)$$

The total flux magnetizing Φ_m is the sum of Φ_{md} and Φ_{mq} and that can be written by [6]:

$$\Phi_m = \sqrt{\Phi_{md}^{\ 2} + \Phi_{mq}^{\ 2}} \quad (5)$$

Where the equations of the flux are:

$$\begin{cases} \Phi_{md} = L_m \left[i_{ds1} + i_{ds2} + i_{dr} \right] \\ \Phi_{mq} = L_m \left[i_{qs1} + i_{qs2} + i_{qr} \right] \end{cases} \quad (6)$$

B. *Modelling of the PWM Voltage Source Inverter*

The dual–stator induction motor has two sets of windings. Therefore, it will be supplied by two PWM source voltage inverters shifted by 30°.

The three-phase inverter consists of three independent arms, represented in Fig.2. Each one includes two pairs of switches which are complementary and controlled by the Pulse Width Modulation PWM.

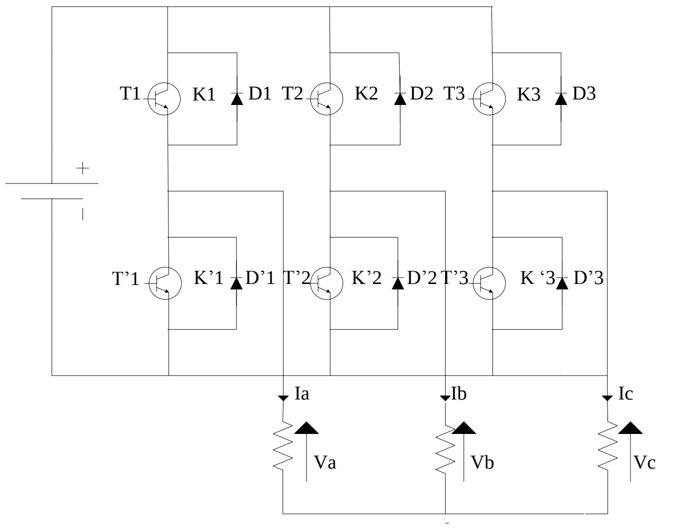

Fig.2 Model of a three-phase inverter.

The voltage inverters can be controlled by several strategies. Pulse Width Modulation PWM is the most common and popular technique of digital pure sine wave generation. The PWM wave is generated by comparing a sinusoidal wave with a triangular carrier wave.

This technique is characterized by the following two parameters m and r :

- The parameter m is the ratio of the carrier frequency (f_p) on the reference frequency (f).
- The parameter r is the ratio of the reference amplitude (V) on the carrier frequency (V_p).

The induction stator voltages $(V_{sa1}, V_{sb1}, V_{sc1})$ and $(V_{sa2}, V_{sb2}, V_{sc2})$ are expressed in terms of the upper switches as follows:

$$\begin{bmatrix} V_{sa1} \\ V_{sb1} \\ V_{sc1} \end{bmatrix} = \frac{U_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} . \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} \qquad (7)$$

$$\begin{bmatrix} V_{sa2} \\ V_{sb2} \\ V_{sc2} \end{bmatrix} = \frac{U_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} . \begin{bmatrix} f_4 \\ f_5 \\ f_6 \end{bmatrix} \qquad (8)$$

U_{dc} : the voltage of DC bus.

$f_i = (i = 1:6)$ are the controller signals applied to the switches.

The modulating wave is a sinusoidal signal expressed by:

Stator 1

$$V_{ref1} = \begin{cases} V_{refa1} = V_m \sin \ 2\pi ft \\ V_{refb1} = V_m \sin\left(2\pi ft - \frac{2\pi}{3}\right) \\ V_{refc1} = V_m \sin\left(2\pi ft + \frac{2\pi}{3}\right) \end{cases} \qquad (9)$$

Stator 2

$$V_{ref2} = \begin{cases} V_{refa2} = V_m \sin \ 2\pi ft - \alpha \\ V_{refb2} = V_m \sin\left(2\pi ft - \frac{2\pi}{3} - \alpha\right) \\ V_{refc2} = V_m \sin\left(2\pi ft + \frac{2\pi}{3} - \alpha\right) \end{cases} \qquad (10)$$

Where $V_m = \sqrt{2}.V_{eff}$.

$\alpha = 30°$

The dual stator induction machine connected with both inverters is shown in Fig.3.

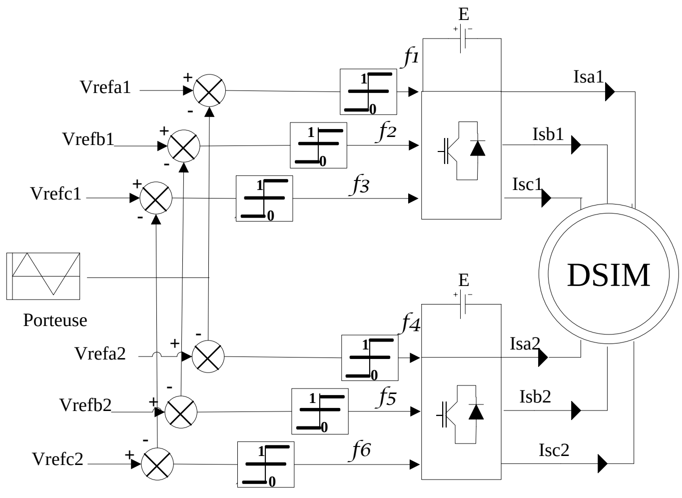

Fig. 3 Dual stator induction motor supplied by two three-phase inverters.

III. SIMULATION RESULTS

The proposed system has been implemented with Matlab/Simulink in order to evaluate its performances.

Firstly, the DSIM is supplied directly by two sinusoidal sources expressed as follows:

Stator 1

$$\begin{cases} V_{sa1} = V_m \sin \ 2\pi ft \\ V_{sb1} = V_m \sin\left(2\pi ft - \frac{2\pi}{3}\right) \\ V_{sc1} = V_m \sin\left(2\pi ft + \frac{2\pi}{3}\right) \end{cases} \qquad (11)$$

Stator 2

$$\begin{cases} V_{sa2} = V_m \sin \ 2\pi ft - \alpha \\ V_{sb2} = V_m \sin\left(2\pi ft - \frac{2\pi}{3} - \alpha\right) \\ V_{sc2} = V_m \sin\left(2\pi ft + \frac{2\pi}{3} - \alpha\right) \end{cases} \qquad (12)$$

Where $V_m = \sqrt{2}.V_{eff}$.

The two figures below Fig.4 and Fig.5 illustrate the evolution of the DSIM characteristics, in case where a resistive torque $T_r = 14N.m$ was applied at t = 2s.

We can note here that the speed evolves linearly until reaching the nominal speed. At startup the DSIM supplied a maximum torque, which decreases linearly to stabilize at a minimum value.

The stator current shown in Fig. 5 has or shows many fluctuations inducing high current draw, which are about 4 times the rated current. But they disappear leading to a sinusoidal wave with constant magnitude.

By applying the load torque $T_r = 14\ N.m$ at t=2s, the speed decreases but the torque and the stator currents increase.

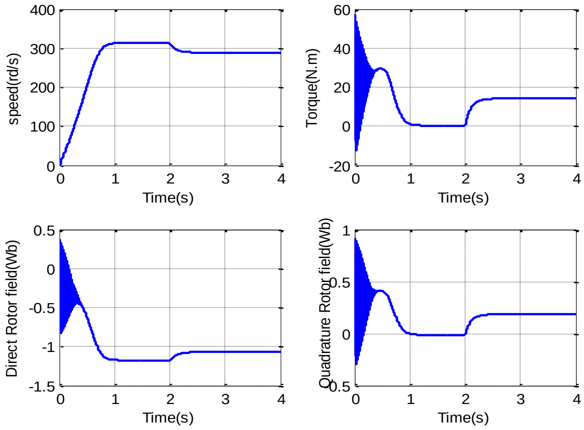

Fig. 4. Speed, torque and dq rotor flux responses

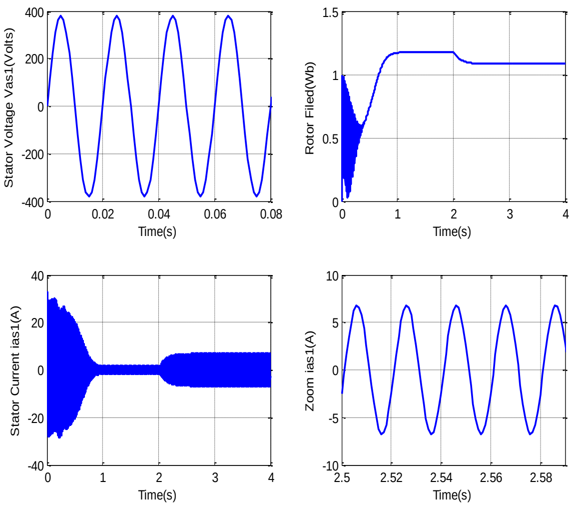

Fig. 5. Stator voltage, Stator current (i_{as1}), and rotor flux responses

Then the dual–stator induction motor windings will be supplied by two PWM source voltage inverters, followed by the application of the load torque $T_r = 14N.m$.

The simulation results shown in Fig.6 and Fig.7 are approximately similar to those obtained by direct power shown by figures Fig.4 and Fig.5 above. However, these curves have increased ripples mainly due to harmonics issued by the inverter and which mainly affect the electromagnetic torque.

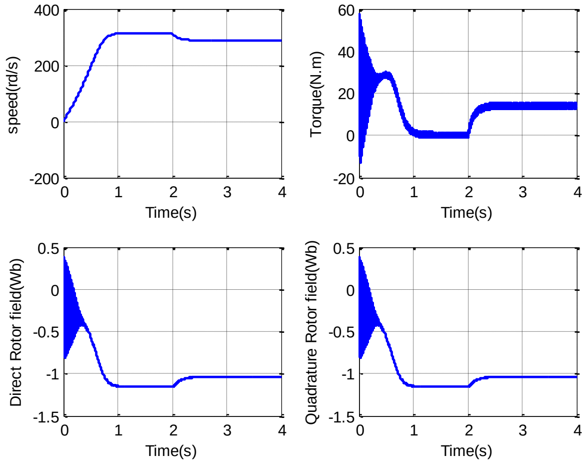

Fig. 6 Speed, torque and dq rotor flux responses

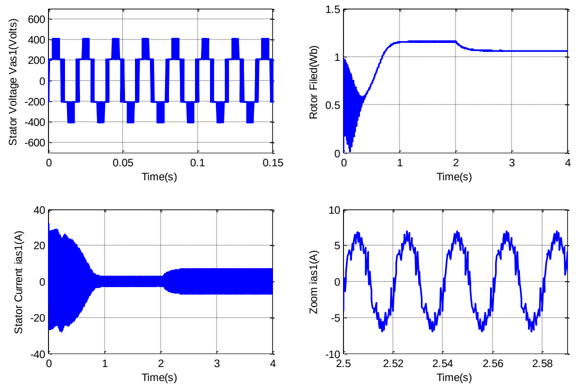

Fig. 7. Stator voltage, Stator current (i_{as1}), and rotor flux responses

IV. CONCLUSIONS

In the present paper, mathematical model of a Dual–stator induction motor based on electrical and mechanical equations has been investigated, adopting some simplifying assumptions. Firstly, the DSIM is supplied directly by two sinusoidal sources then by two PWM voltages source inverters.

The simulation results show that: the proposed model has good performances. The speed torque is different; it has some oscillations. The inverter role is driving motor by varying its output voltage.

Some assumptions have been tacked into consideration in the modelling. Consequently, this model should be improved in order to detect the defects machine.

ANNEXES

TABLE I : MACHINE PARAMETERS

Rated power	4.5 KW
Nominal voltage	400 V
Nominal speed	288 rd/s
Rated torque	14 N.m
Frequency	50 Hz
Resistance of the stator 1	3.72 Ω
Resistance of the stator 2	3.72 Ω
Resistance of the rotor	2.12 Ω
leakage inductance of the stator1	22 mH
leakage inductance of the stator2	22 mH
leakage inductance of the rotor	6 mH
Mutual inductance	0.3672 H
Machine inertia	0.0625 kg/m^2
Coefficient of friction	0.001
Pole pair	1

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