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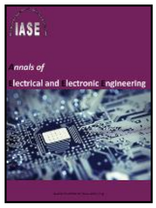

On the mathematical saturated models of dual stator squirrel-cage induction machine

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ABSTRACT

In this research, the mathematical saturated models of dual stator squirrel-cage induction machine are presented, which are formulated in both phase coordinate system and in general transformed space vector form. The two types of models of dual stator induction motor are considered. The proposed model takes into account the effect of magnetic saturation, the stator mutual leakage inductance between two stars and the skin effect. Some preliminary simulation and experimental test results, carried out on a prototype of dual star induction machine operating as generator and supplying various loads under different conditions, are presented and discussed.

1. Introduction

The general theory of electric machines provides sufficient means for dealing with the mathematical representation of an induction machine with an arbitrary number of phases on both stator and rotor. It can also effectively model machines with sinusoidally distributed windings and with concentrated windings, where one has to account for the higher spatial harmonics of the magneto-motive force. Probably, the most comprehensive treatment of the modeling procedure at a general level is available in Basak and Chakraborty (2015). More recently, detailed modeling of an n-phase induction machine, including the higher spatial harmonics, has been reported in Levi et al. (2007), whereas specific case of a five-phase induction machine has been investigated in detail in Levi et al. (2007). Transformations of the phase-variable model are performed using appropriate real or complex matrix transformations, resulting in corresponding real or space vector models of the multiphase machine.

The double stator induction machine needs a double three phase supply which has the many advantages (Guizani and Ben Ammar, 2013). It minimize the torque pulsations and uses power electronics components which allow a higher commutation frequency compared to the simple machines. However the double stator Induction machines supplied by a source inverter generate harmonics which result in supplementary losses (Levi, 2008). The double star induction machine is not a simple system, because a number of complicated phenomena which appear in its function, as saturation (Ammar and Guizani, 2008; Singh et al., 2001; Andriamalala et al., 2008).

Among the different multiphase drive solutions, one of the most interesting and widely applied is the dual three-phase stator winding squirrel cage induction motor. The dual stator induction motor (DSIM) has two separate three-phase stator windings, sharing the same machine core and the common squirrel cage rotor winding. According to the layout of the stator windings in the motor core the dual stator induction motors can be divided into two basic groups. The first one comprises the construction in which two separate three-phase stator windings are located sequentially along the stator core. In this case there is no magnetic coupling between the stator windings, but each of stator windings is magnetically coupled with the rotor cage winding (Khlifi et al., 2016; Aroquiadassou et al., 2006; Khedher and Mimouni, 2010; Abdel-Khalik et al., 2012).

The presence of the mutual leakage inductance between two stars is due to the fact their windings share the same slots Levy (1986) and Razik (2003), and are, therefore, mutually coupled. The mutual leakage coupling has an important effect on the harmonic coupling between the two stator winding sets and depends on the winding pitch and the displacement angle between the two stator winding sets. Nevertheless, there have been studies where the stator mutual leakage coupling has been neglected (Yazdani et al., 2009; Slimene et al., 2013, 2015).

2. Saturated model dual stator winding IM

In the mathematical description of dual stator induction motor it is assumed that the DSIM motor is considered as an electromechanical system consisting of two three-phase stator windings, denoted as stator 1 and stator 2 and the common squirrel-cage rotor winding. The cage rotor winding is replaced by an equivalent three-phase winding. Fig. 1 shows the representation of the stator and rotor windings of dual stator induction motor. A common type of multiphase machine is the dual stator induction machine (DSIM), where two sets of three-phase windings, spatially phase shifted by 30 electrical degrees, share a common stator magnetic core. The voltage equations of the dual stator induction machine using decomposition vector space are as follow. For the stator circuit we can write:

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$$\begin{cases} V_{ds1} = R_s . i_{ds1} + \frac{d\lambda_{ds1}}{dt} - w_a \lambda_{qs1} \\ V_{qs1} = R_s . i_{qs1} + \frac{d\lambda_{qs1}}{dt} + w_a \lambda_{ds1} \\ V_{ds2} = R_s . i_{ds2} + \frac{d\lambda_{ds2}}{dt} - w_a \lambda_{qs2} \\ V_{qs2} = R_s . i_{qs2} + \frac{d\lambda_{qs2}}{dt} + w_a \lambda_{ds2} \end{cases} \tag{1}$$

and for the rotor circuit we have:

$$\begin{cases} 0 = R_r . i_{dr} + \frac{d\lambda_{dr}}{dt} - (w_a - w)\lambda_{qr} \\ 0 = R_r . i_{qr} + \frac{d\lambda_{qr}}{dt} + (w_a - w)\lambda_{dr} \end{cases} \tag{2}$$

where w_a is the speed of the reference frame.

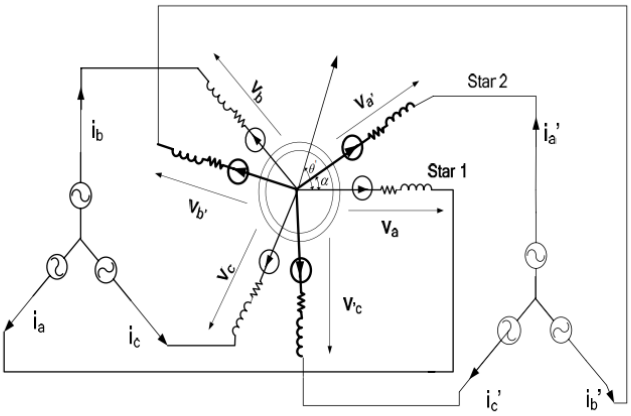

Fig. 1. Equivalent DSIM scheme.

The expressions of stator and rotor flux linkages are:

$$\begin{cases} \lambda_{ds1} = (l_s + l_{sm} + L_{dm}) i_{ds1} + (l_{sm} + L_{dm}) i_{ds2} + L_{dm} i_{dr} \\ \lambda_{qs1} = (l_s + l_{sm} + L_{qm}) i_{qs1} + (l_{sm} + L_{qm}) i_{qs2} + L_{qm} i_{qr} \\ \lambda_{ds2} = (l_s + L_{dm}) i_{ds1} + (l_s + l_{sm} + L_{dm}) i_{ds2} + L_{dm} i_{dr} \\ \lambda_{qs2} = (l_{sm} + L_{qm}) i_{qs1} + (l_s + l_{sm} + L_{qm}) i_{qs2} + L_{qm} i_{dr} \\ \lambda_{dr} = L_{dm} i_{ds1} + L_{dm} i_{ds1} + (l_r + L_{dm}) i_{dr} \\ \lambda_{qr} = L_{qm} i_{qs1} + L_{qm} i_{qs2} + (l_r + L_{qm}) i_{qr} \end{cases} \tag{3}$$

such us l_{sm} is the common mutual leakage inductance between the two sets of stators windings, L_m is the mutual inductance between stator and rotor, l_s and l_r are the stator and rotor leakage inductance respectively. Where:

$$\begin{cases} L_s = l_s + l_{sm} + L_m \\ L_r = l_r + L_m \\ L_{ps} = l_{sm} + L_m \\ M = L_m \end{cases} \tag{4}$$

with

$$\begin{cases} \frac{d\lambda_{dm}}{dt} = \frac{d\lambda_{dm}}{di_{dm}} \frac{di_{dm}}{dt} = L_{dmdy} \frac{d}{dt}(i_{ds1} + i_{ds2} + i_{dr}) \\ \frac{d\lambda_{qm}}{dt} = \frac{d\lambda_{qm}}{di_{qm}} \frac{di_{qm}}{dt} = L_{qmdy} \frac{d}{dt}(i_{qs1} + i_{qs2} + i_{qr}) \end{cases} \tag{5}$$

the writing matrix of flux is characterized by the following relationship:

$$\begin{cases} [V] = [A][\dot{X}] + [B][X] \\ [V] = [V_{ds1} \quad V_{qs1} \quad V_{ds2} \quad V_{qs2} \quad 0 \quad 0]^t \\ [X] = [i_{ds1} \quad i_{qs1} \quad i_{ds2} \quad i_{qs2} \quad i_{dr} \quad i_{qr}]^t \end{cases} \tag{6}$$

$$[A] = \begin{bmatrix} l_s + l_{sm} + L_{dmdy} & 0 & l_{sm} + L_{dmdy} & 0 & L_{dmdy} & 0 \\ 0 & l_s + l_{sm} + L_{qmdy} & 0 & l_{sm} + L_{qmdy} & 0 & L_{qmdy} \\ l_{sm} + L_{dmdy} & 0 & l_s + l_{sm} + L_{dmdy} & 0 & L_{dmdy} & 0 \\ 0 & l_{sm} + L_{qmdy} & 0 & l_s + l_{sm} + L_{qmdy} & 0 & L_{qmdy} \\ L_{dmdy} & 0 & L_{dmdy} & 0 & l_r + L_{dmdy} & 0 \\ 0 & L_{qmdy} & 0 & L_{qmdy} & 0 & l_r + L_{qmdy} \end{bmatrix}$$

$$[B] = \begin{bmatrix} R_s & 0 & 0 & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 & 0 & 0 \\ 0 & 0 & R_s & 0 & 0 & 0 \\ 0 & 0 & 0 & R_s & 0 & 0 \\ 0 & L_{qm} \ w_e & 0 & L_{qm} \ w_e & R_r & (l_r + L_{qm}) \ w_e \\ -L_{dm} \ w_e & 0 & -L_{dm} \ w_e & 0 & -(l_r + L_{dm}) \ w_e & R_r \end{bmatrix}$$

The analytical d- model has been developed in a general reference frame and can be used to analyze the behavior of induction machine in any reference frame.

These equations suggest the equivalent circuit as shown in Fig. 2. The common mutual leakage inductance represents the fact that the two sets of stator windings occupy the same slots and are, therefore, mutually coupled by a component of leakage flux.

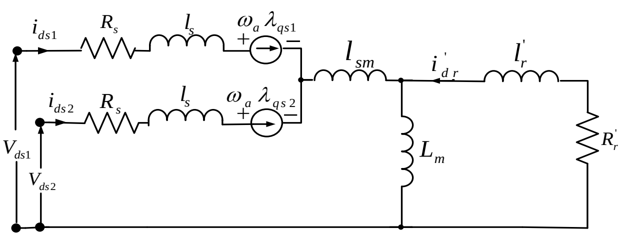

Fig. 2. d-axis equivalent circuit of a DSIM in arbitrary reference frame.

The electromagnetic torque and dynamic equations can be expressed as:

$$C_{em} = n_p \frac{M}{L_r} [(i_{qs1} + i_{qs2})\lambda_{dr} - (i_{ds1} + i_{ds2})\lambda_{qr}] \tag{7}$$

$$J \frac{dw}{dt} + K_f w = n_p (C_{em} - C_r) \tag{8}$$

3. Steady state analysis of DSIM features

The characteristic of the electromagnetic torque as function of the speed for different cases of stator mutual leakage inductance between two stars is illustrated in Figs. 3 and 4, for both types of power. The curves of three models present a different starting torques. Indeed, the starting torque developed by the machine of high power, for model 3, is quite important, up to double that of model 1. Great influence which is clearly and primarily in the transient than in the static.

The influence of the stator mutual leakage inductance on the electrical and mechanical performances is less significant. Indeed, if the mutual leakage inductance is neglected compared to the full model, the torque variation is about 9%. This variation is about 4.5% if the mutual leakage inductance is included as a self-leakage inductance.

Stator current change, compared to model 1, is about 2.23% for model 2 and it is around 4.5% for the model 3. In addition, a stator current increase is observed if the mutual leakage inductance is neglected. This allows us to note that performances obtained with model 2, if mutual leakage is included as a self-inductance, are more acceptable in static mode operation.

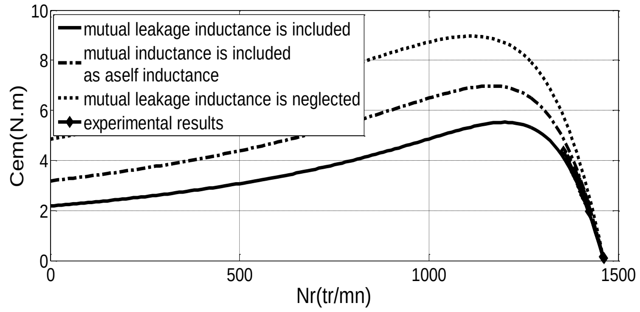

Fig. 3. Characteristic of the electromagnetic torque.

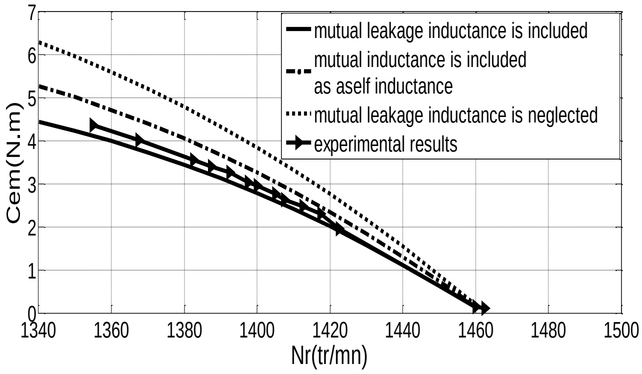

Fig. 4. Zoom characteristic of the electromagnetic torque with speed.

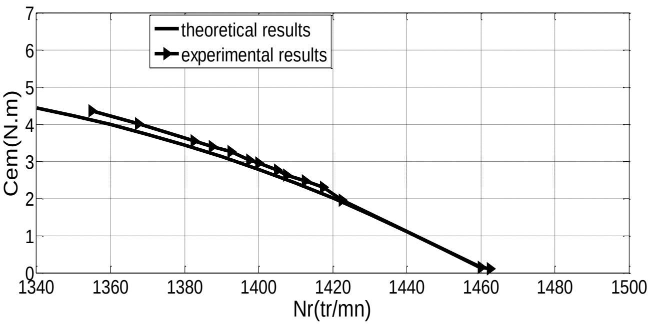

Fig. 5. Estimation of the torque error.

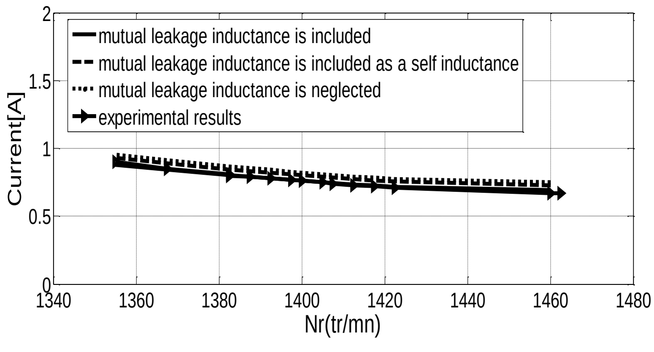

Fig. 6. Characteristic of current with speed.

We note that the effect of stator mutual leakage inductance is no longer negligible for high power machines and it is significant for all characteristics. The results of model where the mutual leakage is neglected are almost equal to twice of model where the mutual leakage is included as a self-inductance. As consequence, the effect of mutual inductance is more pronounced on high power machines than low power. Hence the mutual impact increases in parallel with the increasing power of the dual star asynchronous machine.

4. Dynamic characteristics Of DSIM

The first scenario was carried out to compare online start-up of the saturated DSIM with three methods where the mutual is included and neglected and included as a self-inductance. Figs. 7 and 8 show the speed (rad/s) and electromagnetic torque (Nm) of the saturated DSIM with and without mutual leakage inductance.

Fig. 7 shows the comparison between three method results of rotor speed in transient regime at startup on load operation. We also note that at start-up, the rotor speed of the DSIM, if taking into account the saturation is closer to the rotor speed measured than if ignored. We can confirm that the impact of the saturation model is clearer in transient regime and especially at start-up.

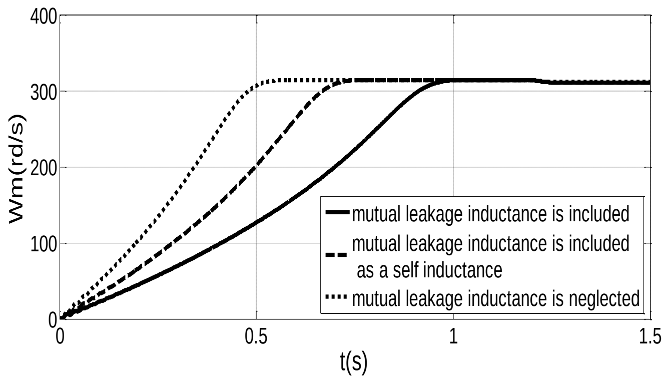

Fig. 7. Ttransient rotor speed characteristics.

The torque peak- values computed from model with saturation and skin effect is higher than computed values using conventional model. Moreover, the time taken to reach the steady state for accurate model is about to the same for experimental results. Based on these results, we can conclude then, that the starting torque developed by the machine where we take into account main flux saturation is closer to the measurement result that the linear regime.

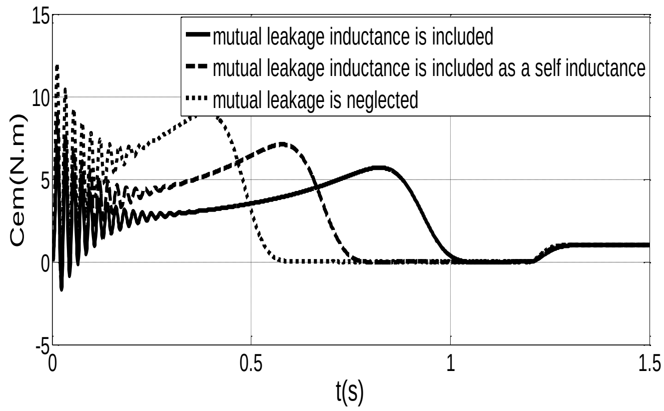

Fig. 8. Transient electromagnetic torque of DSIM.

Fig. 9 presents the waveform of current is1 of the DSIM for tree cases of stator mutual leakage inductance between two stars. It has been simulated that the reference current at first rises linear versus time, then has the constant value and after that is reversing. The performed simulation confirms that the model included the mutual inductance is performed.

Fig. 10 presents the waveforms of magnetic flux components. The obtained simulation results confirm also with the three equivalent circuit models selected showed the influence of the stator mutual leakage inductance between two windings of the two stator stars. It was proven that neglecting the stator mutual leakage inductance, or including it as a self-leakage inductance, or taking it into account can influence the magnetic, electrical and mechanical characteristics and consequently the performance of the machine.

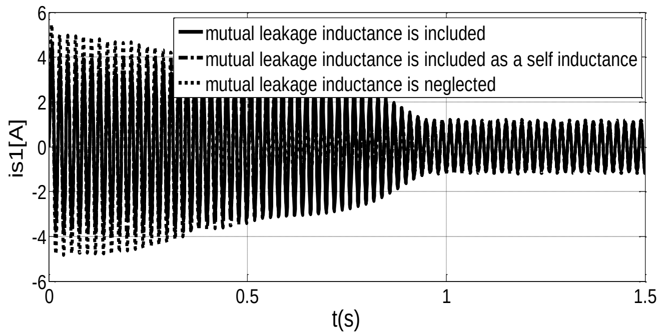

Fig. 9. The time waveforms of current is1 of the DSIM.

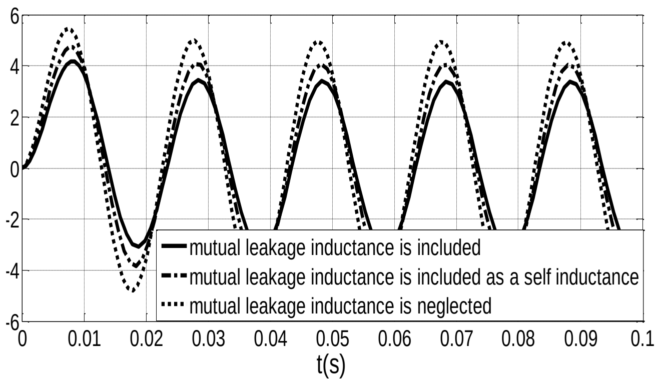

Fig. 10. Zoom of the time waveforms of current is1 of the DSIM.

In order to study the effect of the leakage mutual inductance between the stator star windings in normal operation. The following Figs. 11 and 12 illustrate the effect of the mutual leakage inductance on the magnetic flux of the dual stator induction machine.

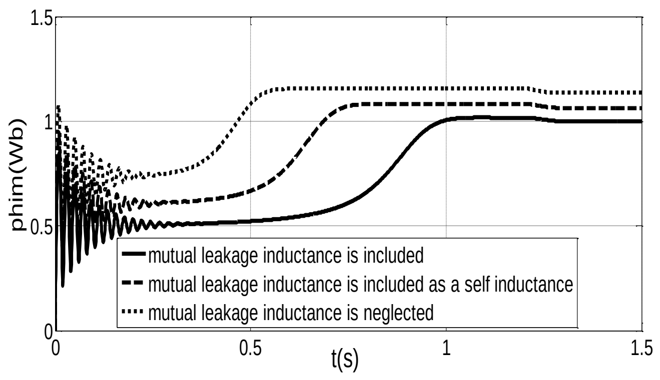

Fig. 11. Effect of the stator mutual leakage inductance on the magnetic flux.

If the mutual leakage inductance is not correctly modeled or simply ignored, important differences in pics and magnitudes of simulated variables are observed, confirming the static analysis. In addition, all dynamic and transient previous characteristics are very shifted relative to curves of the reference model including mutual leakage inductance. Consequently, model with mutual leakage inductance are by no means recommended in control systems and drives.

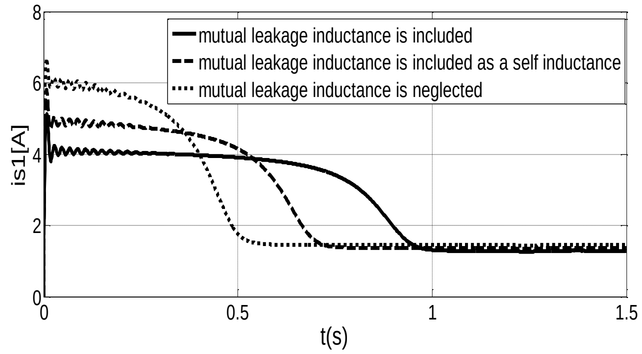

Fig. 12. Effect of the stator mutual leakage inductance on the stator current.

5. Conclusion

In this paper, the effect of the mutual leakage inductance on accuracy of DSIM models is discussed. Three different models are used to investigate the impact of such parameter, in steady state and dynamic operation. A d-q mathematical model of the dual star induction machine (DSIM) with cross saturation is presented, whatever the electrical shift between the two stator stars. The proposed model takes into account the effect of magnetic saturation. It is proven that, if the mutual leakage inductance is not suitably introduced in the modeling process a significant loss of accuracy is resulting.

A dynamic characteristic of the dual star induction machine that takes into account the magnetic saturation, the stator mutual leakage inductance between two stars are presented.

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