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Including Core Losses in Induction Motors Dynamic Model

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Abstract—Energy efficiency improvement is the main target of many recent studies in various domains, especially for electrical drives which constitute the core of industrial applications. The simulation of induction motors is based on static and dynamic models that allow the study of their mechanical performances, as well as their power consumption and losses. However, the commonly used dynamic model doesn't take into consideration the core losses in the motor, which have a significant impact on its energy efficiency. The purpose of this paper is to present two methods for including core losses in the dynamic model of squirrel-cage induction motors (IM) in addition to the copper and mechanical losses that are already taken into consideration in the commonly used model. Core losses are introduced as an equivalent torque reduction in the mechanical equation, or as an equivalent resistor in the model's equations. The proposed model is essential for future studies aiming to improve the energy efficiency of the motor. Both methods are analyzed and simulated using Matlab/Simulink and the obtained results are experimentally validated. The performances of these proposed methods are compared in order to find the best suitable method for future applications and induction motor studies.

Index Terms—Squirrel-cage induction motor, core losses, dynamic model, energy efficiency.

I. INTRODUCTION

Nowadays, several studies are being conducted in order to improve the energy efficiency. Indeed, this constitutes an essential part of the Energy Efficiency Directive of the European Union, aiming to improve 20% of this efficiency by 2020, at all stages of the energy chain from its production to its final consumption.

Electrical drives constitute a main element of the energy chain in all industrial applications, hence the importance of assessing their efficiency. These studies require the modeling of the motor drive and its losses, in the highest possible accuracy, in order to simulate their performance and therefore analyze the efficiency behavior. In squirrel-cage induction motors, dynamic models don't usually include the core losses, whereas copper and mechanical losses are taken into

consideration [1-2]. This approximation impacts on the simulation of the motor's performance and the results in terms of input power, losses and energy efficiency.

Several studies use the basic dynamic model to simulate the motor's performance and apply new controls. For example, in [1], motor manufacturer's data is used to calculate the parameters and performance factors, using the traditional model. However, the obtained results might lack accuracy because the effect of the core losses is not shown in the model. The same issue is found in [2] where a simulation file is built, using the same model without core losses, for an induction motor fed by an inverter, to analyze the input voltage effect on the performance. In that case, the deficiency appears in the simulated input power which doesn't include the core losses, thus giving inaccurate efficiency values. A minimum settling time controller applied to an induction motor with load perturbation is studied in [3], also based on the same IM model. Simulations show the effect of the introduced controller on the motor's settling time and steady state error. However, slight differences can be observed with experimental results because core losses are not taken into consideration in the model.

Further studies introduce new methods for estimating the motor's parameters according to factors affecting its operation. For instance, the motor parameters are computed in [4] by a neural network system that is updated online according to the motor speed. The adjusted parameters are those of the basic motor model and omit the core losses. Therefore, it doesn't give an accurate representation of power and losses. Another model is proposed in [5], and includes variable parameters that take into consideration temperature and skin effect. Similarly, in [6], a new model is proposed, including the skin effect. However, core losses are not taken into consideration in these studies, which might lead to inaccurate results of temperature in the simulations.

Therefore, it is essential to include the core, copper and mechanical losses in the dynamic model of the IM. The introduction of these main losses leads to accurate values of the power input and power losses in order to make a good estimation of the energy efficiency.

In this paper, the commonly used static and dynamic models of the IM are detailed, in section II, along with the parameters which are measured through a series of experiments. The introduction of the core losses in the dynamic model of the IM is proposed in section III. In a first approach, through an equivalent torque that is introduced in the mechanical equation of the motor, and in a second approach, through an equivalent resistor introduced in the dynamic model's electrical equations. Both structures are compared in terms of accuracy and complexity. A simulation of the proposed IM dynamic model is conducted, and the main losses in the system are estimated and shown in section IV. Experimental results are also compared to simulated ones and validate the losses accurate estimation. Finally, conclusions are drawn.

II. INDUCTION MOTOR MODELS AND PARAMETERS

The squirrel-cage induction motor is commonly represented by two models, according to the purpose of the study and to the working conditions: the equivalent circuit, which is used to represent the steady state of the IM, and the dynamic model, used to simulate its operation in transient state. Both models are based on motor parameters that are measured through series of experiments. However, the equivalent circuit takes into consideration the core losses in the motor through an equivalent resistor, whereas the dynamic model neglects these losses in spite of their effect on the energy efficiency.

A. Equivalent Circuit of the Induction Motor

The induction motor equivalent circuit that is commonly used [7] to represent its performance in steady-state is shown in Fig.1 with:

| | |
|--------|--|
| R_1 | resistance of a stator phase winding |
| X'_L | global leakage impedance referred to the stator |
| R_c | core losses equivalent resistor |
| X_m | magnetizing impedance |
| R'_2 | resistance of a rotor phase winding referred to the stator |
| s | slip of the IM |

The parameters of this circuit are measured on the studied IM through classic experiments:

- The stator phase winding resistance is obtained by applying a DC test.

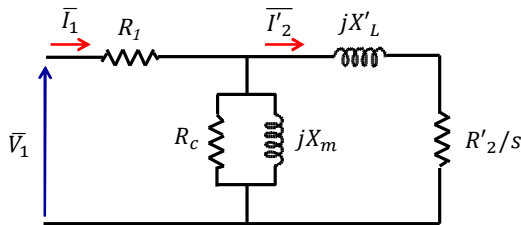


Fig. 1. IM equivalent circuit in steady state

- A no-load rotating test is then conducted, at rated voltage. Current and absorbed power are measured, to compute the core losses equivalent resistor and the magnetizing impedance.
- A short-circuit blocked-rotor test is done by blocking the rotor's rotation and feeding the motor while insuring that the rated current is not exceeded; this leads to the calculation of the global leakage impedance and the rotor phase winding resistance.

Having all the necessary parameters, the motor's performances can be predicted through the equivalent circuit at steady state.

B. Commonly used IM dynamic model

The induction motor is commonly modelled for simulation by a dynamic model based on electrical, flux and mechanical equations [6], to predict the motor's performances in variable and steady state. This model requires the knowledge of the following parameters:

| | |
|----------|--|
| R_s | resistance of a stator phase winding |
| R_r | rotor resistance referred to the stator |
| L_s | self inductance of a stator phase winding |
| L_r | rotor self inductance referred to the stator |
| M_{sr} | stator-rotor mutual inductance referred to the stator |
| σ | motor dispersion coefficient $\sigma = 1 - \frac{M_{sr}^2}{L_s L_r}$ |
| p | number of pole pairs of the motor |
| J | total motor load inertia |
| f_v | viscous friction coefficient |
| T_0 | dry friction torque |

The values of the above parameters are obtained from those of the equivalent circuit [8-9] by the relations in (1) where ω_n represents the rated stator voltage angular frequency.

$$\begin{cases} R_s = R_1 \\ R_r = R'_2 \\ L_s = L_r = \frac{X'_L}{2\omega_n} + \frac{X_m}{\omega_n} \\ M_{sr} = \frac{X_m}{\omega_n} \end{cases} \quad (1)$$

The number of pole pairs and motor inertia are taken from the manufacturer's datasheet, as for the values of the viscous friction coefficient and the dry friction torque, an additional experiment is conducted. The motor is driven at rated speed, then is decelerated with zero load; the speed results lead to the requested mechanical parameters.

Having all the necessary parameters, the commonly used dynamic model for squirrel-cage induction motors in the stationary reference frame is given in (2) to (10). It simulates the performance of the motor in variable and steady state operation. However, this model is based on an approximation

that omits the core losses and doesn't include its equivalent resistor, as in the equivalent circuit in Fig. 1.

- Stator and rotor flux equations:

$$\Phi_{s\alpha}(t) = L_s i_{s\alpha}(t) + M_{sr} i_{r\alpha}(t) \quad (2)$$

$$\Phi_{s\beta}(t) = L_s i_{s\beta}(t) + M_{sr} i_{r\beta}(t) \quad (3)$$

$$\Phi_{r\alpha}(t) = L_r i_{r\alpha}(t) + M_{sr} i_{s\alpha}(t) \quad (4)$$

$$\Phi_{r\beta}(t) = L_r i_{r\beta}(t) + M_{sr} i_{s\beta}(t) \quad (5)$$

Where Φ and i represent respectively the flux and current variables. s and r subscripts correspond to the stator and rotor of the IM, and α and β refer to the stationary reference frame's axes.

- Stator and rotor electrical equations:

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

$$v_{s\beta} = R_s i_{s\beta} + \frac{d\Phi_{s\beta}}{dt} \quad (7)$$

$$0 = \frac{d\Phi_{r\alpha}}{dt} + \omega \Phi_{r\beta} + R_r i_{r\alpha} \quad (8)$$

$$0 = \frac{d\Phi_{r\beta}}{dt} - \omega \Phi_{r\alpha} + R_r i_{r\beta} \quad (9)$$

Where variable v represents the voltage and ω the electrical speed of the rotor of the IM.

- Mechanical equation:

$$J \frac{d\Omega}{dt} = T_{em} - f_v \Omega - T_0 \text{sign}(\Omega) - T_L \quad (10)$$

Where $\Omega = \omega/p$, T_{em} and T_L represent respectively the mechanical speed, electromagnetic torque and load torque of the IM.

The electrical equations of this dynamic model are represented by the circuit shown in Fig. 2.

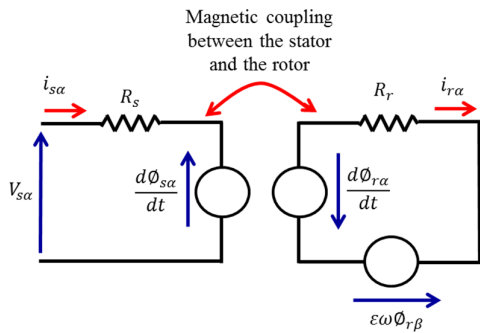


Fig. 2. α -axis simplified IM representation, with $\epsilon = 1$. The β -axis representation is obtained by replacing α components by β components of the same variable and v.v. with $\epsilon = -1$.

III. CORE LOSSES INTRODUCTION

The commonly used dynamic model represents the squirrel-cage induction motor, and allows the study of its performance while taking into consideration both copper losses through the resistors R_s and R_r , and mechanical losses through f_v and T_0 . However, the core losses are not taken into consideration.

Therefore, once the core losses equivalent resistor R_c is measured, the idea is to introduce it in the IM dynamic model in order to consider the effect of these losses in the simulation in order to evaluate the performance of the motor.

In a primary approach, the resistive torque, which is caused by the core losses, is computed and introduced in the mechanical equation (10), and in another approach, the current variation due to these losses is included in the electrical equations of the model, using the core losses equivalent resistor. These approaches consider only the power reduction aspects induced by the core losses, without any additional distortion or harmonics associated with these losses.

A. Core losses equivalent torque

The core losses equivalent resistive torque is obtained by computing the ratio of the core losses and the motor speed. In the simulation, core losses are calculated according to (11), where v_s and i_s represent respectively the instantaneous stator phase voltage and line current in each phase, according to the phases subscripts, a, b and c.

$$P_c(t) = \frac{(v_{sa}(t) - R_s i_{sa}(t))^2}{R_c} + \frac{(v_{sb}(t) - R_s i_{sb}(t))^2}{R_c} + \frac{(v_{sc}(t) - R_s i_{sc}(t))^2}{R_c} \quad (11)$$

The resistive torque $T_c = P_c/\Omega$ equivalent to these losses is deducted from the electromagnetic torque in the mechanical equation (10), which becomes as in (12).

$$J \frac{d\Omega}{dt} = T_{em} - f_v \Omega - T_0 \text{sign}(\Omega) - T_L - T_c \quad (12)$$

The obtained model simulates the performance of the IM and its power losses while taking into consideration the core losses and their effect, in addition to the copper and mechanical losses that were already included in the commonly used model.

B. Core losses equivalent resistor

In a second approach, core losses are directly introduced in the model through the equivalent resistor R_c , as in [10] and [11], that is represented schematically in a parallel branch as shown in Fig. 3, similar to its representation in the IM equivalent circuit in Fig. 1.

The effect of this resistor on the dynamic model appears in the current flowing through the stator inductance, which becomes $i_{2s\alpha}$ instead of $i_{s\alpha}$ (respectively $i_{2s\beta}$ instead of $i_{s\beta}$). The relation between these currents is given in (13):

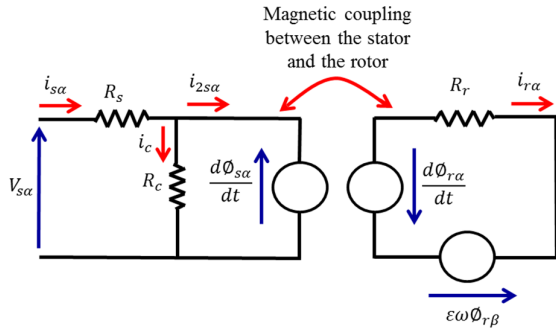


Fig. 3. α -axis IM representation with core losses resistor. The β -axis representation is obtained by replacing α components by β components of the same variable and v.v. with $\varepsilon = -1$.

$$\begin{cases} i_{2s\alpha}(t) = i_{s\alpha}(t) - \frac{1}{R_c} \frac{d\phi_{s\alpha}(t)}{dt} \\ i_{2s\beta}(t) = i_{s\beta}(t) - \frac{1}{R_c} \frac{d\phi_{s\beta}(t)}{dt} \end{cases} \quad (13)$$

By replacing $i_{s\alpha}$ and $i_{s\beta}$ respectively by $i_{2s\alpha}$ and $i_{2s\beta}$ in the flux equations of the common model, (2) to (5), and by combining these equations to (13), the new stator and rotor flux equations become:

$$\begin{aligned} \phi_{s\alpha}(t) &= L_s i_{2s\alpha}(t) + M_{sr} i_{r\alpha}(t) \\ &= L_s i_{s\alpha}(t) - \frac{L_s}{R_c} \frac{d\phi_{s\alpha}(t)}{dt} + M_{sr} i_{r\alpha}(t) \end{aligned} \quad (14)$$

$$\begin{aligned} \phi_{s\beta}(t) &= L_s i_{2s\beta}(t) + M_{sr} i_{r\beta}(t) \\ &= L_s i_{s\beta}(t) - \frac{L_s}{R_c} \frac{d\phi_{s\beta}(t)}{dt} + M_{sr} i_{r\beta}(t) \end{aligned} \quad (15)$$

$$\begin{aligned} \phi_{r\alpha}(t) &= L_r i_{r\alpha}(t) + M_{sr} i_{2s\alpha}(t) \\ &= L_r i_{r\alpha}(t) + M_{sr} i_{s\alpha}(t) - \frac{M_{sr}}{R_c} \frac{d\phi_{s\alpha}(t)}{dt} \end{aligned} \quad (16)$$

$$\begin{aligned} \phi_{r\beta}(t) &= L_r i_{r\beta}(t) + M_{sr} i_{2s\beta}(t) \\ &= L_r i_{r\beta}(t) + M_{sr} i_{s\beta}(t) - \frac{M_{sr}}{R_c} \frac{d\phi_{s\beta}(t)}{dt} \end{aligned} \quad (17)$$

The electrical and mechanical equations in the commonly used IM dynamic model, (6) to (10), are not modified because the current through the stator resistance is equal to the input current of the motor, in both models.

In a similar way to the previous model using the core losses equivalent torque, this proposed model, simulates the performance of the motor, in the stationary reference frame, by taking into consideration the three main losses, copper, core and mechanical losses, which gives accurate results in terms of losses for the simulated efficiency for analysis purposes.

In addition to the above results, the IM dynamic model is required in some studies in the rotating reference frame. It is obtained by applying the Park transform to the stationary reference frame model. This transform consists in a rotation of

the reference frame to meet a particular condition, usually chosen to best suit the purpose of the needed control. The equations of the proposed model of the IM including the core losses, in the rotating reference frame, are given in (18) to (25).

- Stator and rotor flux equations:

$$\phi_{sd} = L_s i_{sd} - \frac{L_s}{R_c} \left[\frac{d\phi_{sd}}{dt} - \omega_d \phi_{sq} \right] + M_{sr} i_{rd} \quad (18)$$

$$\phi_{sq} = L_s i_{sq} - \frac{L_s}{R_c} \left[\frac{d\phi_{sq}}{dt} + \omega_d \phi_{sd} \right] + M_{sr} i_{rq} \quad (19)$$

$$\phi_{rd} = L_r i_{rd} + M_{sr} i_{sd} - \frac{M_{sr}}{R_c} \left[\frac{d\phi_{sd}}{dt} - \omega_d \phi_{sq} \right] \quad (20)$$

$$\phi_{rq} = L_r i_{rq} + M_{sr} i_{sq} - \frac{M_{sr}}{R_c} \left[\frac{d\phi_{sq}}{dt} + \omega_d \phi_{sd} \right] \quad (21)$$

- Stator and rotor electrical equations:

$$v_{sd} = R_s i_{sd} + \frac{d\phi_{sd}}{dt} - \omega_d \phi_{sq} \quad (22)$$

$$v_{sq} = R_s i_{sq} + \frac{d\phi_{sq}}{dt} + \omega_d \phi_{sd} \quad (23)$$

$$0 = R_r i_{rd} + \frac{d\phi_{rd}}{dt} - (\omega_d - \omega) \phi_{rq} \quad (24)$$

$$0 = R_r i_{rq} + \frac{d\phi_{rq}}{dt} + (\omega_d - \omega) \phi_{rd} \quad (25)$$

Where ω_d represents the angular speed of the rotating frame. This form of the IM model shall be used in further studies, for example in efficiency calculations and IM control strategies.

C. Comparison of the two proposed methods

The proposed methods for introducing core losses in the IM dynamic model are based on the same equivalent resistor R_c which is measured through tests on the motor. Therefore, both methods simulate the core losses in the machine without any difference in terms of input power and power loss. However, the difference appears through the technique of taking these core losses into consideration in the motor, whereas the equivalent torque is introduced through the mechanical equation, and R_c is directly used in the electrical equations of the model.

It is obvious that the representation of core losses through a resistor is closer to reality than the use of the equivalent torque, because these losses appear in the motor as current loss in the magnetic circuit of the stator and the rotor. This should cause differences in the simulation of the currents, in the case of equivalent torque use, because the currents' losses would be indirectly simulated through this equivalent torque, and through its effect on motor speed, in the mechanical equation.

On the other hand, the introduction of R_c in the electrical equations of the models complicates the calculations because of implicit equations created in the simulation, whereas the use of the equivalent torque is a simpler way that doesn't involve simulation problems.

IV. SIMULATION RESULTS AND EXPERIMENTAL VALIDATION

A Matlab/Simulink file has been built in order to simulate the motor introducing the core losses according to the methods explained above. The induction motor is simulated in a direct start-up operation at zero load rotation in sinusoidal supply.

Zero load experiments were also carried on a 5.5kW Leroy Somer motor, operating in sinusoidal mode, where power input and losses were measured at steady state for several input voltage values.

Fig. 4 shows the core losses simulated results obtained by the two methods explained in section III, using in the first approach, an equivalent torque included in the mechanical equation of the IM dynamic model, and in the second approach, an equivalent fixed resistor included in the electrical equations of the IM dynamic model.

The graph shows an identical behavior of the core losses in both cases, which confirms that the use of either methods gives similar results in terms of simulated core losses in the motor. Moreover, experiments performed in the same conditions of the simulation indicate results of 147.2W for core losses at steady state, compared to 148.3W obtained in the simulation, which corresponds to an acceptable error of 0.75%.

The motor input power was also simulated in the cases shown in Fig. 5, in order to analyze the effect of introducing the core losses as an equivalent torque or resistor. The behavior of the simulated input power is similar in both cases, with a difference for the case excluding core losses, which appears in Fig. 6 showing the steady state zone. This difference is due to the core losses that were taken into account, which increased the simulated input power by 147W, corresponding to the core losses value at steady state in the same operating conditions. The graph shows that both methods of introducing core losses give the same value of input power.

Experimental results confirm the simulations with 314W for the input power at steady state, which is similar to the simulated results of 312W, with an acceptable 0.64% error.

However, the difference between the two methods appears in the stator currents as mentioned in section III. Fig. 7 shows these currents simulated in the rotating reference frame in both cases of core losses introduction. The use of an equivalent

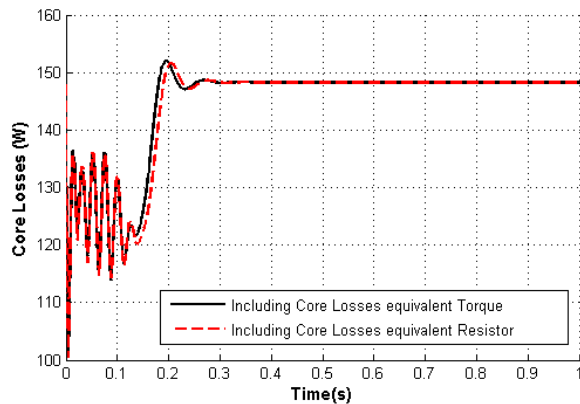


Fig. 4. Results of simulated core losses.

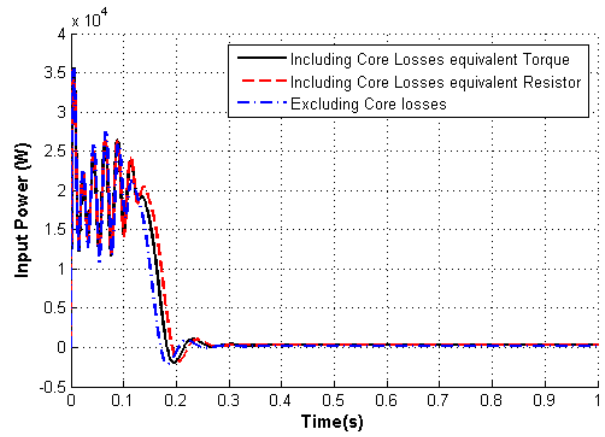


Fig. 5. Results of simulated input power.

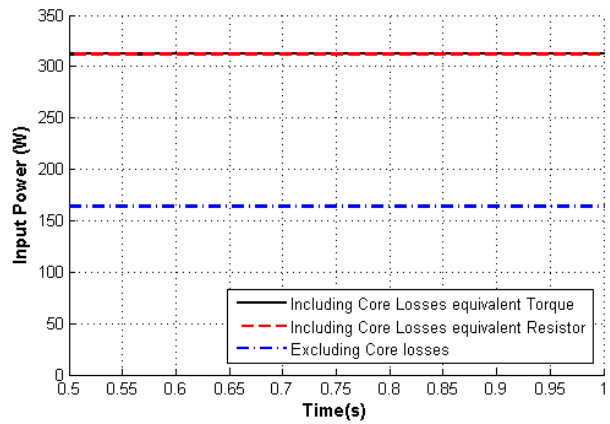


Fig. 6. Results of simulated input power at steady state.

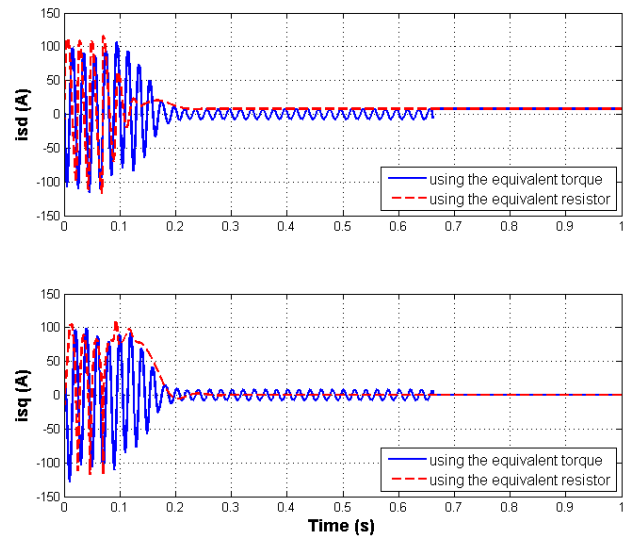


Fig. 7. Simulated stator currents in the rotating reference frame, for both cases of the study.

torque proves to be different than the other method in the transient state, and simulates currents perturbations that do not occur after the motor start-up.

This difference is due to the presence of a negative torque at the beginning of the simulation, caused by the core losses equivalent resistive torque. This does not affect the simulated steady-state zone of the motor shown in Fig. 8, where both simulated currents are similar. This leaves the choice between the two methods, according to the complexity of calculations for the equivalent resistor method, and the lack of accuracy in the transient zone for the equivalent torque approach.

V. CONCLUSION

The main scope of this study was the introduction of the core losses effect in the squirrel-cage induction motor dynamic model, in order to evaluate its energy efficiency in the most accurate way. These losses were introduced in the model through an equivalent torque in a first approach, and through an equivalent resistor in a second approach. The results obtained confirm taking into consideration the core losses in the simulated input power in both cases, which leads to the simulation of energy efficiency variation according to the operating conditions. Simulated losses and power were experimentally confirmed at steady-state, so the dynamic model simulates the motor's performance accurately in terms of power consumption. Core losses taken into consideration here are only related to the fundamental of the supply voltage. It is considered that the harmonic contribution is low.

The methods showed however some differences in terms of simulated stator currents, while using the equivalent torque, due to the fact that the current losses were indirectly estimated through the torque loss included in the mechanical equation of the model. The equivalent torque method proved to be reliable at steady-state, leaving the choice to the user, according to the transient zone accuracy needed, and to the calculations complexity allowed.

Future studies shall use the results obtained to analyze the energy efficiency variations according to the operating conditions. This will lead, in a further study, to establish control

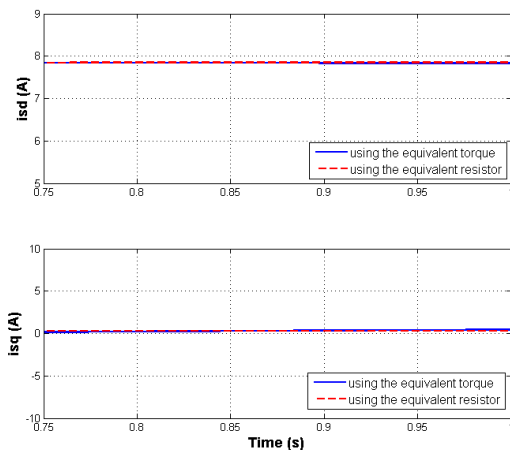


Fig. 8. Simulated stator currents in the rotating reference frame, at steady state.

systems aiming to reduce the losses and increase the efficiency of the system composed of the inverter, the motor and the control system itself, while keeping the best mechanical performances, to cope for the load demand and the needed response characteristics.

VI. APPENDIX: MOTOR PARAMETERS

The parameters of the 5.5kW Leroy Somer squirrel-cage induction motor used for the experiments are:

$$\begin{aligned}
 U_n &= 400V & L_s &= 163mH \\
 I_n &= 11.9A & L_r &= 163mH \\
 N_n &= 1500Rpm & M_{sr} &= 157mH \\
 T_n &= 36.1N.m & J &= 0.0657 kg.m^2 \\
 p &= 2 & f_v &= 0.002928kg.m^2.s^{-1} \\
 R_s &= 0.86\Omega & T_0 &= 0.2471N.m \\
 R_r &= 0.83\Omega
 \end{aligned}$$

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REFERENCES

- [1] B.K. Johnson and J. R. Willis, "Tailoring induction motor analytical models to fit known motor performance characteristics and satisfy particular study needs", IEEE Transactions on Power Systems, vol. 6, no. 3, pp. 959-965, August 1991.
- [2] A.Z. Leedy, "Simulink/MATLAB Dynamic Induction Motor Model for use in Undergraduate Electric Machines and Power Electronics Courses", Southeastcon, Proceedings of IEEE, 2013.
- [3] E. Madhuri, R. Kalpana, K. Anuradha, "Performance analysis of Inverter fed Induction Motor with minimum settling time control", IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), December 2012.
- [4] W. Pawlus, M. Choux, G. Hovland and V. K. Huynh, "Parameters Identification of Induction Motor Dynamic Model for Offshore Applications", IEEE/ASME 10th International Conference on Mechatronic and Embedded Systems and Applications (MESA), 2014.
- [5] E. R. Filho and R. M. de Souza, "Three-phase Induction Motor Dynamic Mathematical Model", IEEE International Electric Machines and Drives Conference Record, pp. MB1/2.1 - MB1/2.3, May 1997.
- [6] S. Canat, J. Faucher, "Modeling and simulation of induction machine with fractional derivative", Proceedings of the FDA'04, 1st IFAC workshop on fractional differentiation and its applications, pp. 393-399 2004.
- [7] D. O'Kelly, "Performance and control of electrical machines", McGraw-Hill UK, pp. 241-271, 1991.
- [8] J. Chatelain, "Machines électriques", Dunod, Tome 1, pp. 225-257, 1983.
- [9] P. Vas, "Parameter Estimation, Condition Monitoring and Diagnosis of Electrical Machines", Monographs in Electrical and Electronic Engineering 27, Oxford Science Publications, pp. 180-189, 1993.
- [10] G. Garcia, J. Santisteban, S. Brignone, "Iron Losses Influence on a Field-Oriented Controller", 20th International Conference on Industrial Electronics, Control and Instrumentation, IECON, pp. 633-638, 1994.
- [11] E. Levi, "Iron Core Loss Effects in Indirect Rotor Flux Oriented Induction Machines", 7th Mediterranean Electrotechnical Conference, pp.766-769, 1994