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# An improved Dynamic Model for Induction Motors Including Core Losses

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**Abstract**—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. The purpose of this paper is to present an improved dynamic model for squirrel-cage induction motors (IM) which includes the core losses in addition to the copper and mechanical losses that are already taken into consideration in the commonly used models. The goal of this model is to compute accurate efficiency values in order to build a control system of the IM, aiming to improve the energy efficiency. Therefore, core losses are computed using the Bertotti model, which is a function of the magnetic field and the frequency. These losses are then included in the induction motor dynamic equations through a variable resistor that depends mainly on the magnetic field and frequency. The proposed model is simulated using Matlab/Simulink and the obtained results are experimentally validated. Then, energy efficiency equations are obtained using an improved model, taking into consideration the main losses in the machine. Energy efficiency contours are drawn, in order to track the best efficiency zone according to flux, speed and load torque.

## I. INTRODUCTION

Nowadays, the development of control systems for electrical drives is based on energy efficiency analysis. These studies require the modeling of the motor drive and its losses 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, as in [1] and [2]. This approximation impacts on the simulation of the motor performance and the results in terms of input power, losses and energy efficiency.

Several studies use the basic dynamic model to simulate the motor performance and apply new controls. For example, in [3], motor manufacturer 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 [4] 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 [5], also based on the same IM model. Simulations show the effect of the introduced controller on the motor 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 parameters according to factors affecting its operation. For instance, the motor parameters are computed, in [6], 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 [7], and includes variable parameters that take into consideration temperature and skin effect. Similarly, in [8], 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 and skin effect in the simulations.

The main scope of this study is to build an accurate control system based on energy efficiency computation. Therefore, it is essential to clearly include the main losses, including the core, copper and mechanical losses of the IM, in the motor through a model, which gives accurate values of the input power and losses in order to make a good estimation of the energy efficiency. In this paper, core losses are included in the dynamic model of the IM as a function of the frequency and the magnetic field according to the Bertotti equation [9]. During the simulation, the main losses in the system are estimated. This leads to an accurate computation of the motor efficiency.

This paper presents, in section II, an improved model of the squirrel-cage induction motor, in non-saturated operating conditions, in both stationary and rotating reference frames, which includes copper, mechanical and core losses that vary according to the system parameters. To the best knowledge of the authors, this model has not been used yet in literature. In

section III, energy efficiency equations are established, taking the core losses into consideration, in order to track the best efficiency operating point according to the user requirements. Experimental results are also compared to simulated ones and validate the efficiency accurate estimation. Finally, conclusions are drawn.

## II. INDUCTION MOTOR MODELING

The induction motor model usually used for simulation is based on electrical, flux and mechanical equations [8], and requires the knowledge of the following parameters:

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

The values of these parameters are obtained through experiments, and used in the dynamic model of the studied IM. The commonly used model for the squirrel-cage induction motors, in the stationary reference frame, is based on an approximation that omits the core losses. The equivalent circuit of the induction machine is shown in Fig. 1, and the equations defining the model are given below:

- Stator and rotor flux equations:

$$\Phi_{s\alpha}(t) = L_s i_{s\alpha}(t) + M_{sr} i_{r\alpha}(t) \quad (1)$$

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

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

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

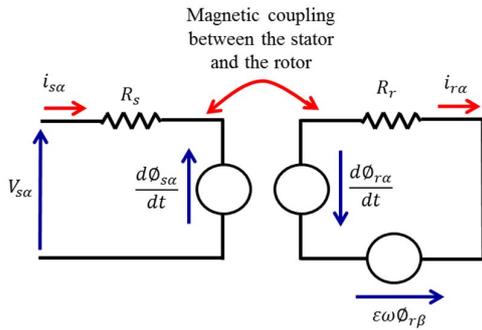


Fig. 1.  $\alpha$ -axis simplified IM representation, with  $\varepsilon = 1$ . The  $\beta$ -axis representation is obtained by replacing  $\alpha$  components by  $\beta$  components of the same variable and v.v. with  $\varepsilon = -1$ .

Where  $\Phi$  and  $i$  represent respectively the flux and current variables. s and r subscripts corresponds to the stator and rotor of the IM, and  $\alpha$  and  $\beta$  refer to the stationary reference frame axes.

- Stator and rotor electrical equations:

$$V_{s\alpha} = R_s i_{s\alpha} + \frac{d\Phi_{s\alpha}}{dt} \quad (5)$$

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

$$0 = \frac{d\Phi_{r\alpha}}{dt} + \omega\Phi_{r\beta} + R_r i_{r\alpha} \quad (7)$$

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

Where variable  $V$  represents the voltage and  $\omega$  the electrical speed of the rotor of the IM.

- Mechanical equation:

$$J \frac{d\Omega}{dt} = T_{em} - f_v \Omega - T_0 \text{sign}(\Omega) - T_L \quad (9)$$

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

This dynamic model represents the squirrel-cage induction motor, and allows the study of his performance while taking into consideration both copper losses through the resistors  $R_s$  and  $R_r$ , and mechanical losses through  $f_v$  and  $T_0$ .

### A. Introducing the core losses in the model

The core losses are introduced in the model, as in [10] and [11], through an equivalent resistor  $R_c$ , that is represented schematically in a parallel branch as shown in Fig. 2. This resistor is experimentally measured at steady state. Its effect 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 relations between these currents are given in (10):

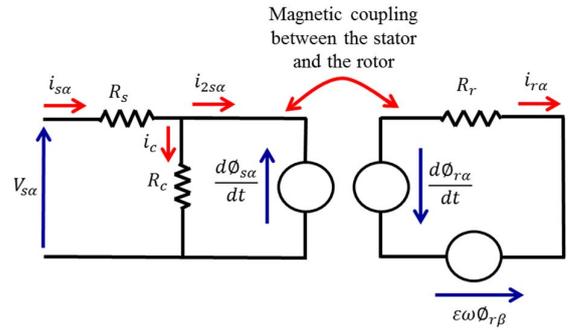


Fig. 2.  $\alpha$ -axis IM representation with core losses resistor. The  $\beta$ -axis representation is obtained by replacing  $\alpha$  components by  $\beta$  components of the same variable and v.v. with  $\varepsilon = -1$ .

$$\begin{cases} i_{2s\alpha}(t) = i_{s\alpha}(t) - \frac{1}{R_c} \frac{d\phi_{s\alpha}(t)}{dt} \\ i_{2s\beta}(t) = i_{s\beta}(t) - \frac{1}{R_c} \frac{d\phi_{s\beta}(t)}{dt} \end{cases} \quad (10)$$

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, (1) to (4), and by combining these equations to (10), the new stator and rotor flux equations become:

$$\begin{aligned} \phi_{s\alpha}(t) &= L_s i_{2s\alpha}(t) + M_{sr} i_{r\alpha}(t) \\ &= L_s i_{s\alpha}(t) - \frac{L_s}{R_c} \frac{d\phi_{s\alpha}(t)}{dt} + M_{sr} i_{r\alpha}(t) \end{aligned} \quad (11)$$

$$\begin{aligned} \phi_{s\beta}(t) &= L_s i_{2s\beta}(t) + M_{sr} i_{r\beta}(t) \\ &= L_s i_{s\beta}(t) - \frac{L_s}{R_c} \frac{d\phi_{s\beta}(t)}{dt} + M_{sr} i_{r\beta}(t) \end{aligned} \quad (12)$$

$$\begin{aligned} \phi_{r\alpha}(t) &= L_r i_{r\alpha}(t) + M_{sr} i_{2s\alpha}(t) \\ &= L_r i_{r\alpha}(t) + M_{sr} i_{s\alpha}(t) - \frac{M_{sr}}{R_c} \frac{d\phi_{s\alpha}(t)}{dt} \end{aligned} \quad (13)$$

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

The electrical and mechanical equations in the previous IM model, (5) to (9), are not modified because the current through the stator resistance is equal to the input current of the motor, in both models.

The obtained model, in the stationary reference frame, simulates the performance of the motor by taking into consideration the three main losses, copper, core and mechanical losses, which gives an accurate result for the simulated efficiency for analysis purposes.

Some studies require the IM dynamic model in the rotating reference frame, obtained by applying the Park transform to the stationary reference frame model, which consists in applying a rotation to 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 below:

- Stator and rotor flux equations:

$$\phi_{sd} = L_s i_{sd} - \frac{L_s}{R_c} \left[ \frac{d\phi_{sd}}{dt} - \omega_d \phi_{sq} \right] + M_{sr} i_{rd} \quad (15)$$

$$\phi_{sq} = L_s i_{sq} - \frac{L_s}{R_c} \left[ \frac{d\phi_{sq}}{dt} + \omega_d \phi_{sd} \right] + M_{sr} i_{rq} \quad (16)$$

$$\phi_{rd} = L_r i_{rd} + M_{sr} i_{sd} - \frac{M_{sr}}{R_c} \left[ \frac{d\phi_{sd}}{dt} - \omega_d \phi_{sq} \right] \quad (17)$$

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

- Stator and rotor electrical equations:

$$V_{sd} = R_s i_{sd} + \frac{d\phi_{sd}}{dt} - \omega_d \phi_{sq} \quad (19)$$

$$V_{sq} = R_s i_{sq} + \frac{d\phi_{sq}}{dt} + \omega_d \phi_{sd} \quad (20)$$

$$0 = R_r i_{rd} + \frac{d\phi_{rd}}{dt} - (\omega_d - \omega) \phi_{rq} \quad (21)$$

$$0 = R_r i_{rq} + \frac{d\phi_{rq}}{dt} + (\omega_d - \omega) \phi_{rd} \quad (22)$$

Where  $\omega_d$  represents the angular speed of the rotating frame. This form of the IM model shall be used in further studies for efficiency calculations and IM control systems.

### B. Core losses variable model

The core losses are so far introduced in the model through a constant resistor. However, experiments and researches show that these losses vary with the frequency and the magnetic field, which means that the resistance is not always constant, but varies accordingly. Therefore, a variable core losses model should be used.

Several studies related to these losses, used a model proposed by Bertotti in order to simulate their variations and analyze the influence of various parameters. This model is used for sinusoidal applications, and divides the losses  $P_c$  into three categories according to their source: hysteresis losses  $P_H$ , eddy currents losses  $P_E$  and excess losses  $P_{ex}$ . The model is presented in (23).

$$\begin{aligned} P_c &= P_H + P_E + P_{ex} \\ &= K_H B_{max}^2 f + K_E B_{max}^2 f^2 + K_{ex} B_{max}^{1.5} f^{1.5} \end{aligned} \quad (23)$$

Where  $B_{max}$  is the peak value of the magnetic field, and  $f$  the current frequency. The coefficients  $K_H$ ,  $K_E$  and  $K_{ex}$  are rarely provided by the motor constructor. Their values are measured through a series of experiments, by applying the least squares method that minimizes the estimation error, leading to an accurate loss model compatible with the experimental results.

Moreover, knowing that in most cases the induction motor is fed by a PWM inverter that provides a non-sinusoidal voltage, another version of the model is used which takes into consideration the harmonics of the magnetic field signal, as detailed in [12] and [13]. Thus the core losses are computed according to (24).

$$\begin{aligned} P_c &= K_H B_{max}^2 f + K_E f^2 \sum_k k^2 B_k^2 \\ &\quad + K_{ex} f^{1.5} \sum_k k^{1.5} B_k^{1.5} \end{aligned} \quad (24)$$

Where  $B_k$  is the amplitude of the  $k^{th}$  magnetic field harmonic.

The use of these models leads to an accurate estimation of the core losses by taking into account their variations, affected by the magnetic field and frequency, according to the operating mode (sinusoidal or PWM stator voltage).

### C. Introduction of variable core losses in the IM model

The introduction of the core losses variations in the equivalent resistor  $R_c$  of the model proposed in A to cope with the variations depicted in B, is done by continuously computing  $R_c$  through (25), where  $v_s$  and  $i_s$  represent respectively the instantaneous stator phase voltage and line current in each phase.

Core losses  $P_c$  are calculated using the model shown in B, and the instantaneous values of  $R_c$  are introduced in the IM dynamic model as proposed in A.

$$P_c(t) = \frac{(v_{sa}(t) - R_s i_{sa}(t))^2}{R_c(t)} + \frac{(v_{sb}(t) - R_s i_{sb}(t))^2}{R_c(t)} + \frac{(v_{sc}(t) - R_s i_{sc}(t))^2}{R_c(t)} \quad (25)$$

The proposed dynamic model including core losses leads to the simulation of the IM performance, while taking into consideration the effect of the variation of core losses according to the operating conditions.

### D. Experimental validation

A Matlab/Simulink file has been built in order to simulate the motor with the variable core losses. The simulation continuously computes the losses and the equivalent resistance which is then included in the motor model as a variable parameter  $R_c$ .

Experiments have been carried on a 5.5kW Leroy Somer motor, operating in sinusoidal mode, at zero load. The core losses are measured, for several input voltage values, by deducting the copper and mechanical losses from the absorbed input power.

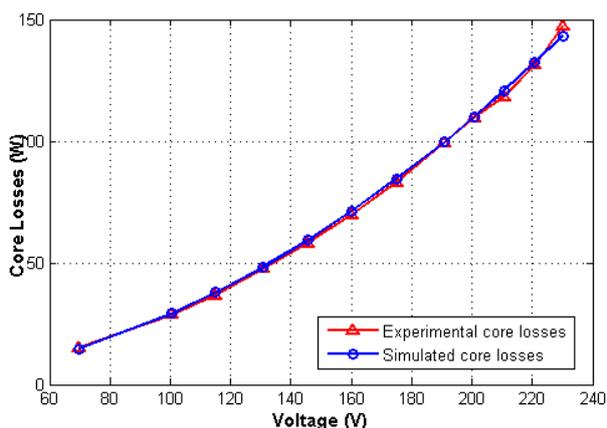


Fig. 3. Comparison of experimental and simulated core losses.

Fig. 3 shows a comparison of the experimental and simulation core losses; the results are satisfactory, with an average error of 1.84%, which allows the validation of the proposed models for the squirrel-cage induction motor.

## III. MOTOR EFFICIENCY ANALYSIS

An accurate knowledge of the motor efficiency in steady state, is a preliminary step to find the best energy efficiency operating point.

Therefore, the proposed and validated model in II, which includes the main losses in the motor, is appropriate for computing the motor efficiency accurately, in order to draw the efficiency contours according to the main parameters' variations.

The study is carried at steady state rotating sinusoidal operating mode, where the angular frequency of the reference frame  $\omega_d$  is equal to the stator angular frequency  $\omega_s$ , and thus, the following relation between the stator and rotor angular frequency  $\omega_r$  is verified:  $\omega_r = \omega_s - \omega$ .

### A. Energy efficiency equation

The efficiency is calculated using the following equation:

$$\eta = \frac{T_{em} \cdot \Omega - P_{mec}}{P_{in}} \quad (26)$$

Where,

$P_{mec}$  mechanical losses written as  $P_{mec} = f_p \Omega^2 + T_0 \Omega$   
 $P_{in}$  IM input power

Knowing that the Concordia transform, which preserves power values, is used to obtain the model in the stationary reference frame, the input power [2] is computed according to (27). Space phasors of the stator voltage and line currents in the rotating reference frame are used in the calculations.

$$P_{in} = Re(\bar{V}_s \cdot \bar{I}_s^*) \quad (27)$$

Where,

$\bar{V}_s$  stator voltage space phasor  
 $\bar{I}_s^*$  conjugate of stator line current space phasor

The electromagnetic torque of the motor is calculated as in (28).

$$T_{em} = p \cdot M_{sr} \cdot Im(\bar{I}_s \cdot \bar{I}_r^*) \quad (28)$$

Where,

$\bar{I}_r^*$  conjugate of rotor line current space phasor

In order to compute the input power and electromagnetic torque, the model equations, (15) to (22), are combined in space phasors equations, (29) to (32).

- The stator flux equation

$$\bar{\phi}_s = L_s \bar{I}_s - j \frac{L_s}{R_c} \omega_s \bar{\phi}_s + M_{sr} \bar{I}_r \quad (29)$$

- The rotor flux equation

$$\bar{\phi}_r = L_r \bar{I}_r + M_{sr} \bar{I}_s - j \omega_s \frac{M_{sr}}{R_c} \bar{\phi}_s \quad (30)$$

- The stator electrical equation

$$\vec{V}_s = R_s \vec{I}_s + j\omega_s \vec{\Phi}_s \quad (31)$$

- The rotor electrical equation

$$0 = R_r \vec{I}_r + j\omega_r \vec{\Phi}_r \quad (32)$$

By combining the above equations, (27) to (32), the efficiency formula can be calculated as a function of the stator flux  $\Phi_s$  and the stator angular frequency  $\omega_s$  which are two of the main parameters that affect the efficiency variation.

However, in order to obtain efficiency values from (26), angular frequency of the rotor,  $\omega_r$ , which depends on the load torque required, should be calculated.

The flux and stator angular frequency are provided by the user or control system, according to the operating conditions required, whereas the resistive torque depends on the load.

Therefore, the angular frequency  $\omega_r$  is obtained by resolving the motor torque equation (33), at steady state, when the electromagnetic torque should cope with both the load demand and the mechanical losses.

$$T_{em} = f_v \Omega + T_0 + T_L \quad (33)$$

Having all the necessary data, the IM input power  $P_{in}$  and the electromagnetic torque  $T_{em}$  are computed, which allows the calculation of the motor energy efficiency.

### B. Simulation Results

A Matlab/Simulink file has been used to draw the efficiency contours as a function of the flux, stator frequency and load torque references, according to the above equations and calculations. Simulations are done for the same studied 5.5kW motor of a 36.1N.m rated torque. Fig. 4, 5 and 6 show the best efficiency zone in the flux-speed plan, which varies according to the load requirement of the motor.

The results confirm that the best efficiency zone of the squirrel-cage induction motor, while considering all its main losses, is not always at rated operating conditions and varies according to the load requirement, especially for small torque values. These results are essential for any further study of a motor control, based on the best efficiency point tracking.

### C. Experimental validation

Energy efficiency results obtained in the experiments are compared to simulation results obtained in the same working conditions. However, the rated power of the DC motor used to create the load torque is 3.9kW. As a result, it was impossible to test all the simulated cases of load torque, especially the case of rated load torque, because of the mismatch between motors rated power. Therefore, experimental results of efficiency are compared in Table I with simulation results, computed in the same conditions of the tests.

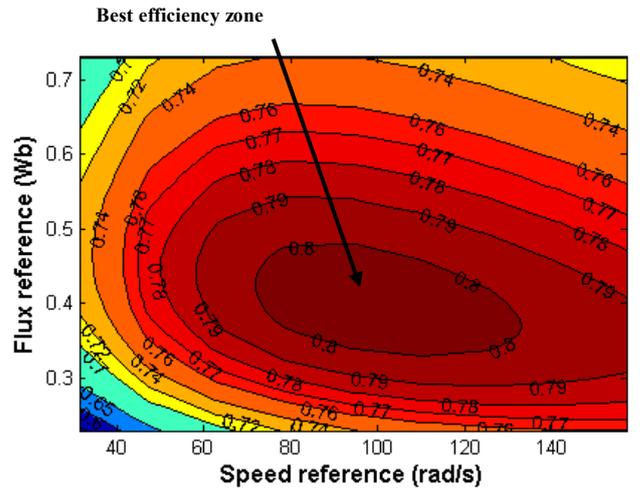


Fig. 4. Efficiency contours at 5Nm load.

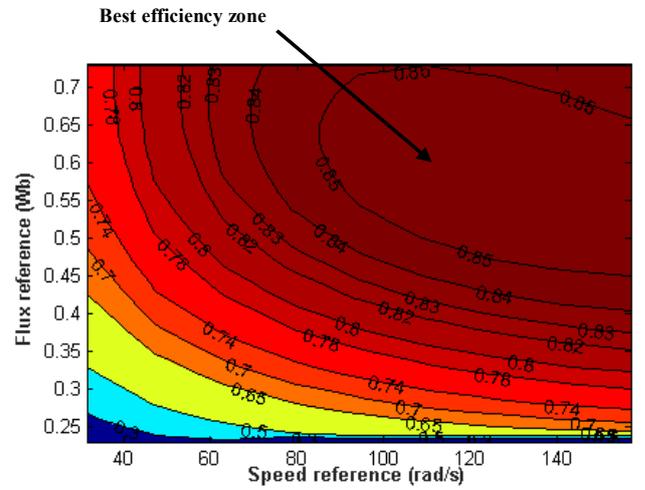


Fig. 5. Efficiency contours at 12.6Nm load.

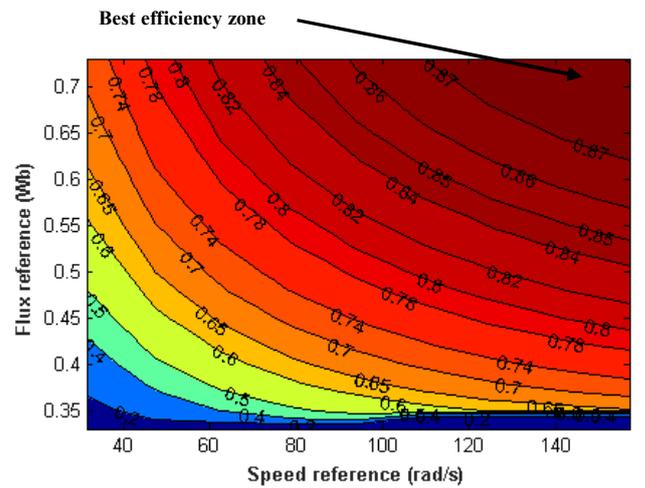


Fig. 6. Efficiency contours at 27.6N.m load.

TABLE I  
Efficiency Results Experimental Validation

Load Torque (N.m)	Experimental efficiency	Simulated efficiency	Error (%)
27.6	0.878	0.880	0.33
25.7	0.875	0.880	0.57
20.6	0.863	0.873	1.25
15.4	0.846	0.857	1.29
12.6	0.830	0.841	1.36

The error values are satisfactory and allow to validate the simulation results, and therefore to validate the proposed efficiency equations, which makes it reliable for any further efficiency analysis study.

#### IV. CONCLUSION

This study presented an improved squirrel-cage induction motor model that takes into consideration the core losses which form an essential part of the losses in electrical machines. These losses were introduced in the model through a resistor, which varies with the magnetic field and the stator frequency. Consequently, the dynamic model simulates the motor performance, the most accurately possible. Simulation results were experimentally validated.

This model was first used to establish energy efficiency equations, in order to analyze the efficiency variations according to flux, speed and load variables. The results, that were experimentally validated, show a variation of the best efficiency zone according to the load requirement. These results may contribute in tracking the best energy efficiency point of the motor, in the operating conditions, in order to enhance its performance.

Future studies will use the models and results obtained to implement a control system aiming to reduce the losses and increase the efficiency of a 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.

#### V. APPENDIX: MOTORS CHARACTERISTICS

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

$$\begin{aligned} U_n &= 400V & L_s &= 163mH \\ I_n &= 11.9A & L_r &= 163mH \\ N_n &= 1500Rpm & M_{sr} &= 157mH \\ T_n &= 36.1N.m & J &= 0.0157 kg.m^2 \\ p &= 2 & f_v &= 0.002928kg.m^2.s^{-1} \\ R_s &= 0.86\Omega & T_0 &= 0.2471N.m \\ R_r &= 0.83\Omega & & \end{aligned}$$

The characteristics of the 3.9kW Leroy Somer DC motor used to create the load torque are:

$$\begin{aligned} U_n &= 260V & N_n &= 1450Rpm \\ I_n &= 17.6A & J &= 0.05 kg.m^2 \end{aligned}$$

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