21st IMEKO TC4 International Symposium and
19th International Workshop on ADC Modelling and Testing
Understanding the World through Electrical and Electronic Measurement
Budapest, Hungary, September 7-9, 2016

Characterization of interior permanent magnet synchronous motors for loss model algorithm identification

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***Abstract* – The paper provides the results of a detailed experimental study on the variations of the characteristics of an interior permanent magnet synchronous motor, when load, speed and/or magnetization conditions vary. In particular, the characterization is carried out by assessing, for several working conditions, the motor parameters that influence its efficiency. From the knowledge of the variability of these parameters, it is possible to develop a dynamic model of the motor, which accurately describes its behaviour and allows estimating the power losses for whatever speed and load. In order to validate the model, the values of the power losses obtained by using the model are compared with the values measured with experimental tests.**

The study shows that it is possible to maximize the motor efficiency just acting on the direct axis current component, and therefore, it can be considered a first step towards the definition of a loss model algorithm for a control drive system able to minimize in real-time the power losses of the motor.

***Keywords* – interior permanent magnet synchronous motors, power loss minimization, speed control drive systems.**

I. INTRODUCTION

The interior permanent magnet synchronous motors (IPMSMs) are more and more employed in several low/medium power industrial drive applications. Their wide spread is due to their better performances with respect to the traditional synchronous and asynchronous motors; in particular the IPMSMs have higher power factor, higher torque/weight ratio and higher power/current ratio. Moreover, these good performances continuously increase thanks to several implementations of new speed and torque control strategies.

Some of these strategies take into account the power losses minimization of the motor and, consequentially, the maximization of its efficiency for different working conditions. The most diffused losses minimization approaches presented in the literature can be classified in two main categories [1-8]: the “loss model control” and the “search control”. The first strategy involves the energy losses estimation from a mathematical model during the operation of the motor, while the second strategy consists of a step-by-step change of a control variable and a real-time measurement of the active power of the motor. However, most of these algorithms discussed in literature do not take into account all of the possible variations of the parameters of the IPMSM model [9-13].

This paper presents an experimental characterization of an IPMSM finalized to build an accurate dynamic model of the motor, which allows estimating the power losses for whatever speed and load, taking into account the variation of the motor parameters that influence its efficiency.

To perform the task, we carried out a series of experiments, measuring, for several working settings, the motor parameters that have an impact on its power losses. In particular, we evaluated the direct and quadrature axis inductances, the flux generated by the permanent magnets, the armature resistance and the resistance that symbolises the iron losses.

In a second stage of measurement, we directly measured the power losses varying load, speed and magnetization conditions. The comparison of the results of these measurements with the values of the power losses obtained by using the model was used to validate the proposed approach.

II. DESCRIPTION OF THE METHOD

The starting point of our study is a well-known IPMSM model presented in several literature studies as a “circuital approach” [14–18].

The model is based on the hypothesis of linearity and isotropy of the magnetic material (stator and rotor iron), sinusoidal distribution of the magneto-motive force in the air gap and negligible eddy currents. By referring to a d−q coordinate system, the equations that describe the IPMSM dynamic model are:

$$v_d = Ri_d + L_d \frac{di_d}{dt} - p\omega L_q i_q \tag{1}$$

$$v_q = Ri_q + L_q \frac{di_q}{dt} + p\omega L_d i_d + p\omega \psi_{PM} \tag{2}$$

$$T_m = T_m + F\omega + J\frac{d\omega}{dt} \tag{3}$$

$$T_m = \frac{3}{2} p[\psi_{PM} i_q + (L_d - L_q) i_d i_q] \tag{4}$$

where:

- v_d and v_q are the direct and quadrature axis components of the stator phase voltages;
- i_d and i_q are the direct and quadrature axis components of the stator phase currents;
- p is the number of pole pairs;
- ω_m is the angular speed of the motor;
- Ψ_{PM} is the flux generated by the permanent magnets;
- R is the resistance of the three-phase stator winding;
- L_d and L_q are the direct and quadrature axis inductances;
- T_r is the load torque;
- F is the coefficient of viscous friction;
- J is the moment of inertia of the rotating parts.

From these equations, it is possible to calculate the power losses ΔP_{tot}. However, in order to carry out an accurate estimation, it is necessary to take into account the variation of the motor parameters that influence its efficiency. In particular, the direct and quadrature axis inductances, L_d and L_q, and the flux of the rotor magnets Ψ_{PM} depend on the magnetic saturation, mainly in the motors with little air-gap and high magnetic flux [11,19,20]. The variation of these parameters is generated by the armature reaction and, therefore, its effect is bigger for high value of angular speed and load.

In order to make our model more accurate, we took into account also the variability of the resistance R_C representing the iron losses, which depends on the rotor speed. As regards the armature resistance R, which depends on its temperature, it is possible to neglect its variability, if we consider the stator in a thermal steady state.

III. TESTS FOR THE MEASUREMENT OF THE MOTOR PARAMETERS

To carry out the measurement of the aforementioned parameters, we set up a test bench (fig. 1) composed of:

- a three-phase, six-pole brushless machine (Magnetic S.r.l., type BLQ-40), with SmCo permanent magnets (HITACHI Inc., type H-18B, with maximum specific energy equal to 143 kJ/m3). The stator winding is a three-phase, double-layer, shortened pitch, located into 27 slots. Table I reports the main rated values and parameters of the machine under test;

Table 1. Rated values and parameters of the IPMSM under test

Voltage	132 V
Current	3.6 A
Speed	4000 rpm
Torque	1.8 N·m
Number of pole pairs	3
Average stator resistance R	2.20 Ω
Direct-axis inductance L_d	7.50 mH
Quadrature-axis inductance L_q	11.00 mH
PMs flux Ψ_{PM}	0.084 Wb
Coefficient of viscous friction F	0.001 N·m·s
Inertia moment J	0.001 kg·m^2

- a DPS 30-A power converter (Automotion Inc.), directly connected to the electrical grid;
- a dSPACE® rapid prototyping control board, in order to drive the IGBT bridge of the converter;
- a HD-715 hysteresis brake (Magtrol Inc.), which allows to perform experimental tests at different load conditions
- a DSP6001 high-speed programmable dynamometer controller (Magtrol Inc.), used to drive the brake;
- a PZ 4000 three-phase power analyzer (Yokogawa Inc), used to measure the electrical quantities in the various working conditions of the motor;
- an ARTUS resolver (type 26SM19 U452), which is connected to the motor shaft in order to measure the motor speed;
- a variable auto-transformer (Variac Inc.), used for the measurement of the stator winding parameters;
- a PC with the dSPACE®-based electrical drive user interface, which allows to perform the real-time control and the supervision of the main electrical and mechanical quantities of the proposed system.

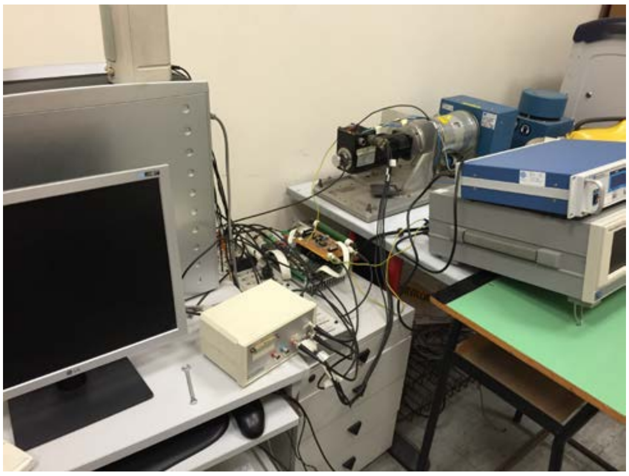

Fig. 1. IPMSM test bench

The direct and quadrature axis inductances were evaluated by means of blocked rotor tests. We measured the L_d for various i_d values, blocking the rotor at the 0° position, and the L_q for various i_d values, blocking the rotor at the 90° electrical position. Fig. 2 shows how the stator windings are connected to the measurement system.

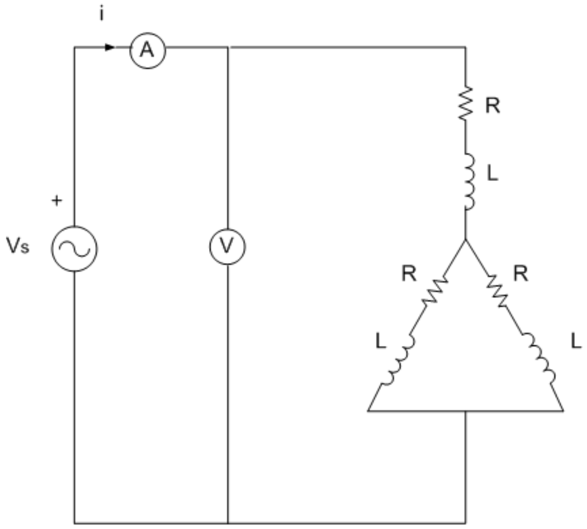

Fig. 2. Schematic for the measurement of L_d and L_q

The L values were calculated by means of Eq. (5).

$$L = \frac{2}{3}\frac{\sqrt{Z^2 - R^2}}{2\pi f} \tag{5}$$

In fig. 3 and in fig. 4, the direct and quadrature axis inductances, as functions of i_d and i_q respectively, are reported.

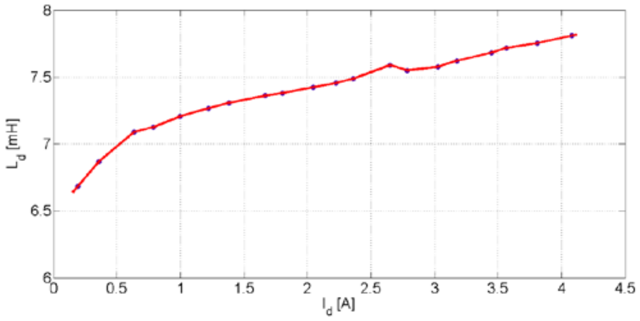

Fig. 3. Direct axis inductance as a function of i_d

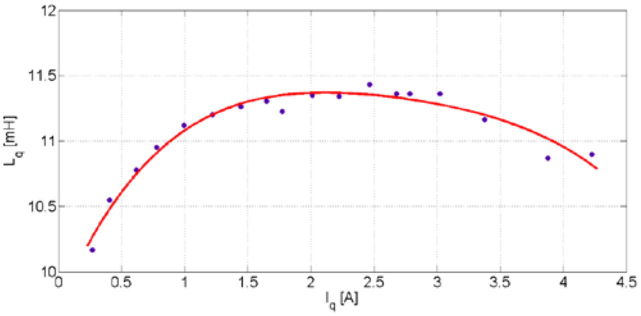

Fig. 4. Quadrature axis inductance as a function of i_q

In order to evaluate the magnetic flux variability, we performed other blocked rotor tests, fixing the rotor position at the 90° electrical position and, therefore, setting $i_d = 0$. The torque T_m was measured by means of the dynamometer for various i_q values. Starting from Eq. (4), the flux value is given by:

$$\psi_{pm} = \frac{2}{3}\frac{T_m}{p i_q} \tag{6}$$

The fig. 5 reports the magnetic flux trend versus i_q.

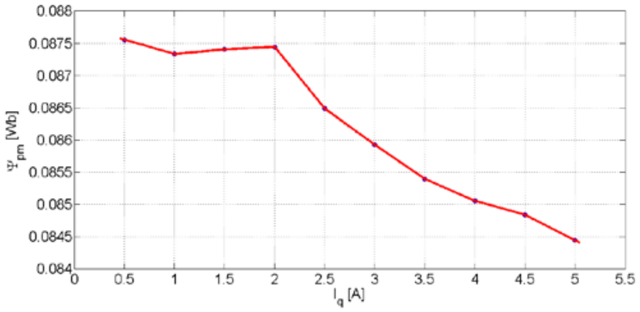

Fig. 5. Magnetic flux as a function of i_q

The assessment of the resistance R_C representing the iron losses was carried out by means of no-load tests, varying the motor speed. In these conditions, the motor power consumption P_{tot} is:

$$P_{tot} = \Delta P_{fe} + \Delta P_{cu} + \Delta P_m + \Delta P_{add} \quad (7)$$

where:

- ΔP_{fe} are the losses in the stator and rotor iron;
- ΔP_{cu} are the joule losses in the stator winding that were calculated as $3RI$ where R is the armature resistance and I is the current of each stator winding;
- ΔP_m are the mechanical losses (friction and ventilation) that were evaluated by means of a deceleration test;
- ΔP_{add} are the additional losses, which, in this context, can be neglected.

Therefore, by measuring the motor input electric power and rearranging the Eq. (7), it is possible to calculate the iron losses for various motor speeds. The values of the resistance R_C representing the iron losses were obtained from Eq. (8):

$$R_C = \frac{V^2}{\Delta P_{fe}} \quad (8)$$

The fig. 6 shows the R_C trend as a function of the rotor speed ω_m.

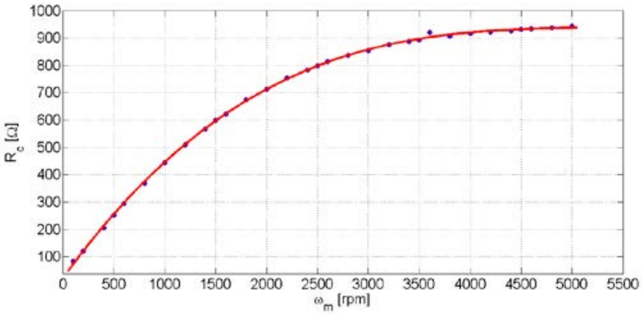

Fig. 6. R_C as a function of the rotor speed

Considering the variability of these four parameters and by means of the dynamic model of the motor, it is possible to evaluate the power losses for whatever speed and load.

IV. TESTS FOR THE DIRECT MEASUREMENT OF THE MOTOR LOSSES

In order to validate the model, the values of the power losses ΔP_{tot} obtained by using the model (with both constant and variable parameters) were compared with the values obtained by experimental tests measuring the power losses as difference between the electrical input power and the mechanical output power [21-22]. The losses were measured for 1000 different working conditions, varying: the motor speed in the range 500 ÷ 4000 rpm with steps of 500 rpm; the load in the range 0 % ÷ 100 % of rated load with steps of 25 %; the i_d value in the range -2.4 ÷ 2.4 A with steps of 0.2 A. The expanded uncertainty (k = 2) of the ΔP_{tot} measurements is 1.2 % [23].

For instance, fig. 7, 8 and 9 show this comparison in three different working conditions, reporting the losses evaluated with the constant parameters model (blue lines), the losses evaluated with the variable parameters model (red lines) and the losses measured with the experimental tests (black lines).

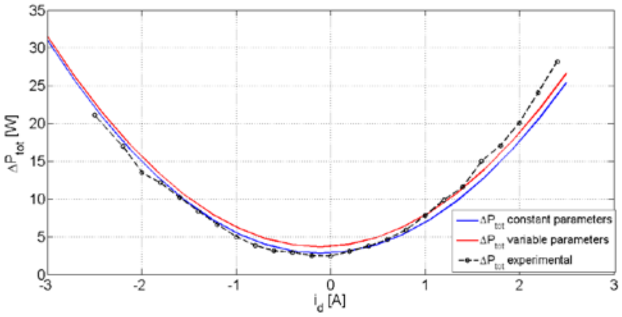

Fig. 7. Comparison between the losses evaluated with the model and the measured losses (1500 rpm; no-load)

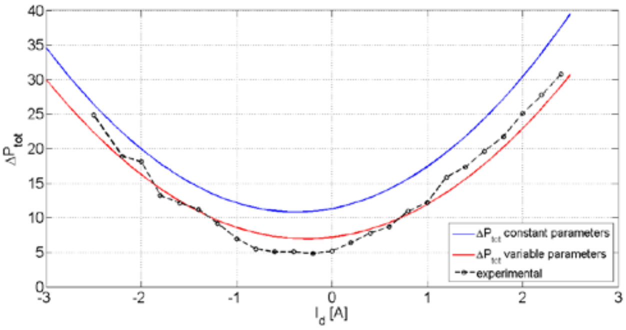

Fig. 8. Comparison between the losses evaluated with the model and the measured losses (3000 rpm; no-load)

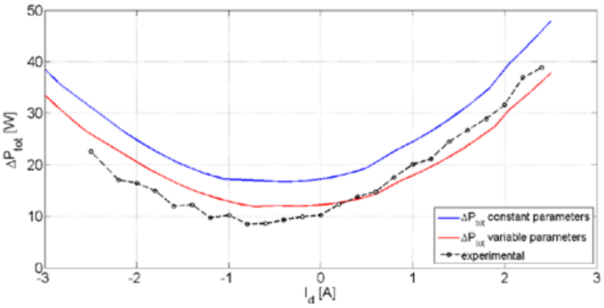

Fig. 9. Comparison between the losses evaluated with the model and the measured losses (3000 rpm; 50 % load)

It is possible to notice that considering the variability of the motor parameters leads to a more accurate assessment of the motor losses rather than using a constant parameters model. As could be expected, the differences gets bigger, as the motor speed and/or load increase.

Fig. 10 reports the IPMSM efficiency parametrized for different speeds, as function of i_d with an applied load fixed at 25 % of the rated one. The maximum efficiency is obtained for negative values of i_d. In addition, by increasing the speed, the related peak is detected for higher negative values of i_d.

Fig. 11 reports the IPMSM efficiency parametrized for different loads, as function of i_d when the motor is rotating at 2000 rpm. The maximum efficiency is obtained when the motor works between 25% and 50% of the full load.

It is possible to notice that, for each operating condition of the motor, it is always possible to determine a specified i_d value that maximizes the IPMSM efficiency without decreasing the dynamic performances of the drive.

The good agreement of the two graphs validates both the exactness of the model and the measurement accuracy of the motor parameters.

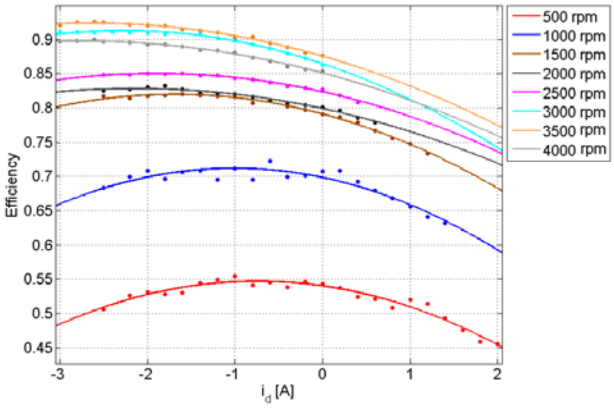

Fig. 10. IPMSM efficiency as a function of i_d (25 % of rated load)

V. NOVELTIES IN THE PAPER

Several loss model algorithms were presented in literature. However, most of them do not completely consider the variations in terms of frequency and saturation of all the parameters involved in the dynamic model of the machine.

In this paper, the variability of all parameters, which have an impact on the power losses of the motor, is considered. In addition, the variability of these parameters is studied also for demagnetizing values of the direct-axis current component. Therefore, the proposed loss model algorithm allows a more accurate detection of the minimum point of the IPMSM power losses, both in terms of ΔP and i_d values.

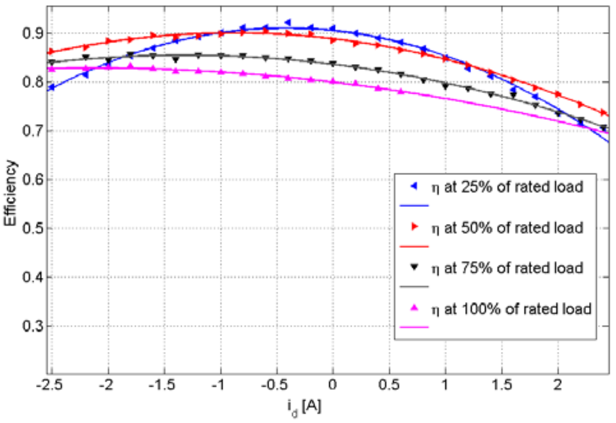

Fig. 11. IPMSM efficiency as a function of i_d (2000 rpm)

VI. CONCLUSIONS

This paper presented an experimental study on the efficiency of an IPMSM at different working and magnetization conditions.

Starting from a well-known dynamic model of the motor, the variability of the model parameters, on which the power losses depend, was studied and evaluated. By taking into account these variabilities, it was possible to sharp the dynamic model and to obtain a more accurate estimate of the power losses of the motor.

The validity of the model was proved by comparing the power loss estimates with the loss values obtained from experimental tests, directly measuring the power losses as difference between the electrical input power and the mechanical output power.

The results of the study demonstrate that the motor efficiency can be maximized for any IPMSM working condition by simply acting on the direct axis current and without decreasing the dynamic performances of the electrical drive.

Because of its high flexibility, the proposed approach is applicable to several typologies of brushless motors and their related applications.

VII. ACKNOWLEDGMENT

This work was realized with SDESLab - University of Palermo.

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