Performance Evaluation of Synchronous Reluctance Motors With and Without Permanent Magnets

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***Abstract*— Nowadays, a growing interest in the efficiency and the cost of electrical machines has been noticed. Therefore, Synchronous Reluctance Motors (SynRMs) have become more attractive, thanks to their higher efficiency and nevertheless acceptable cost compared to induction machines. The rotor design of SynRMs with or without permanent magnets (PMs) has a huge effect on the motor efficiency, torque density and power factor. This paper introduces an evaluation for the performance of SynRMs with and without PMs in terms of efficiency, torque and power factor maps. Three different rotor designs for the same machine have been compared. For one machine, the experimental measurements have been obtained and the validation of the simulation results have been confirmed.**

Index Terms*—*PM, Synchronous Reluctance Motors, Design, FEM, sensitivity analysis, flux-barriers.

I. Nomenclature

i_d, i_q	Direct and quadrature axis stator current respectively, A
L_d, L_q	Direct and quadrature axis stator inductance of SynRM respectively, H
P	Number of pole pairs
p	Differential operator (d/dt)
R_s	Stator resistance of the motor, Ω
T_e	Electromagnetic torque of the motor, N.m
V_d, V_q	Direct and quadrature component of stator voltage respectively, V
V_m	Maximum input voltage of the motor, V
λ_s	Stator flux linkage of the motor, V. sec
I_m	Maximum input current of the motor, A
δ, α	Load angle and current angle, rad
ω_r	Mechanical speed of the rotor, rad/s
θ_r	Rotor position, Deg.

II. Introduction

Recently, Synchronous Reluctance Motors (SynRMs) with or without permanent-Magnets (PMs) are becoming attractive machines for industrial application especially electrical vehicles [1]. This is thanks to their merits of wide constant power speed range and high torque density. The power factor and efficiency are good compared to induction machines [2], [3].

Several papers studied the SynRMs and PMaSynRMs[1], [11]. For example, in [1], SynRM design suitable for electric vehicles has presented. In addition, a comparison between different flux-barrier design for the same stator is investigated. The effect of four different steel grade on the performance of SynRMs is studied in [2]. It is noticed that the lower thickness steel grade has the higher efficiency, however it has not the higher output torque. In [4], the design characteristics of SynRM with ferrite magnets and stator skew has investigated. In addition, mechanical stress and demagnetization of ferrite has studied as well.

This paper investigates the performance evaluation of SynRMs and PMaSynRMs. The modelling of PMaSynRM is introduced in Section III. Performance evaluation of SynRMs is investigated in Section IV. Experimental results are implemented to validate the simulation results as depicted in Section V. At the end, conclusions are figured out in Section VI.

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III. PMaSynRM Modelling

A. *Mathematical dq model of PMaSynRM*

The *dq* model of PMaSynRM can be represented in the rotor reference frame [2], [5], [6]. The *dq*-axis reference frame rotates at ω_r, so that the voltage equations are represented by:

$$V_d = R_s i_d + p\lambda_d(i_d, i_q) - \omega_r P\lambda_q(i_d, i_q) + \omega_r P\lambda_{pm} \quad (1)$$

$$V_q = R_s i_q + p\lambda_q(i_d, i_q) + \omega_r P\lambda_d(i_d, i_q) \quad (2)$$

The *dq*-axis flux-linkage relations are given by:

$$\lambda_d(i_d, i_q) = L_d(i_d, i_q)i_d,\ \lambda_q(i_d, i_q) = L_q(i_d, i_q)i_q \quad (3)$$

The electromagnetic torque can be calculated as follows:

$$T_e = \frac{3}{2}P(\lambda_d(i_d, i_q)i_q - \lambda_q(i_d, i_q)i_d + \lambda_{pm} i_d) \quad (4)$$

The *dq*-axis currents can be performed as a function of the current angle (α), which is the angle of the stator current space vector with respect to the *d*-axis of the motor as described in Fig.1.

$$i_d = I_m \cos(\alpha),\ i_q = I_m \sin(\alpha) \quad (5)$$

The *dq*-axis supply voltage can be obtained as follows:

$$V_d = -V_m \sin(\delta),\ V_q = V_m \cos(\delta) \quad (6)$$

where δ is the machine load angle as shown in Fig. 1.

The power factor (*PF*) of the PMaSynRM can be calculated by:

$$PF = \cos(\phi) = \frac{V_d \cos(\alpha) + V_q \sin(\alpha)}{\sqrt{V_d^{\,2} + V_q^{\,2}}} \tag{7}$$

The torque ripple can be determined as follows:

$$T_{ripple} = \frac{\max(T_e) - \min(T_e)}{avg(T_e)} \tag{8}$$

where *max*, *min* and *avg* are the maximum, the minimum and the average values of the electromagnetic torque respectively.

The SynRM model can be obtained by inserting λ_{pm}=0 in the previous equations.

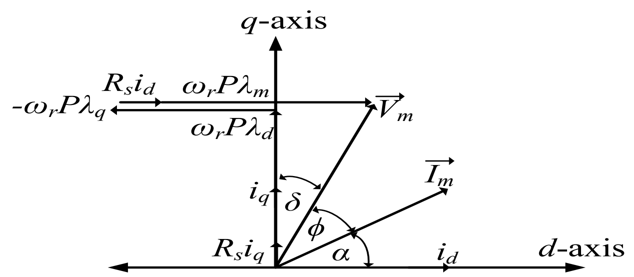

Fig. 1. Vector diagram of PMaSynRM

The iron losses of the SynRM are calculated based on the statistical losses theory of Bertotti. The theory depends on the separation of the losses into hysteresis (hy), classical (cl) and excess (ex) losses [2], [7].

$$\begin{cases} P_{hy.} = a_m B_p^{\alpha_m} f \\ P_{cl.}(t) = b_m \left| \frac{dB}{dt} \right|^2 \\ P_{ex.}(t) = c_m \left(\sqrt{1 + d_m \left| \frac{dB}{dt} \right|} - 1 \right) \left| \frac{dB}{dt} \right| \\ P_{iron} = (P_{hy.} + P_{cl.} + P_{ex.})\sigma \end{cases} \tag{9}$$

where a_m, α_m, b_m, c_m, d_m and σ are material dependent parameters, and f is the frequency of the applied field.

On the other hand, the SynRM copper losses can be easily computed using the measured phase resistance as follows:

$$P_{copper} = 3 I_{Ph}^2 R_{ph} \tag{10}$$

The efficiency of the motor can be obtained by :

$$\eta = \frac{P_o}{P_o + P_{copper} + P_{iron}} \tag{11}$$

where P_o is the mechanical output power of the motor calculated using the computed torque from the FEM model by:

$$P_o = T_e \omega_r \tag{12}$$

IV. Performance Evaluation of SynRMs and PMaSynRMs

Three different rotors with the same stator and other geometrical and electromagnetic parameters have been considered. On the one hand, the stator has 36 slots and 15 turns/slot with conventional star-connected windings. The stator design is similar to that of induction machines. Several specifications for the stator of the machine are listed in table I. On the other hand, all the rotors have 3-flux-barriers per pole as seen in Figs. 2 and 3. The first rotor has been designed by a manufacturing company. This motor is called a reference SynRM and it is the motor for which the experimental validation has been done. The geometrical rotor parameters of the reference motor are shown in table I. The second rotor has been optimized by a conventional optimization technique with 2D FEM for the twelve rotor parameters, depicted in Fig. 2. This motor is called an optimal SynRM and its rotor parameters are given in table II. The final rotor has been obtained by filling all the three flux-barriers of the optimized rotor (second one) with ferrite PMs. The ferrite PM is selected due to the lower cost and the availability in the market. In addition, it can withstand higher temperature [8]. The adopted ferrite PM properties are shown in [8]. This motor is called a PMaSynRM.

TABLE I
PROTOTYPE SYNRM PARAMETERS

Parameter	Value	Parameter	Value
Number of rotor flux barriers per pole	3	**Rotor shaft diameter**	35 mm
Number of pole pairs	4	**Axial length**	140 mm
Number of stator slots	36	**Air gap length**	0.3 mm
Number of phases	3	**Rated speed**	6000 RPM
Stator outer diameter	180 mm	**Rated frequency**	200 Hz
Stator inner diameter	110 mm	**Rated current**	22 A
Rotor outer diameter	109.4 mm	**Material grade**	M400-50A
$\boldsymbol{\theta_1}$	7.5°	$\boldsymbol{W_1}$	6 mm
$\boldsymbol{\theta_2}$	20.5°	$\boldsymbol{W_2}$	4 mm
$\boldsymbol{\theta_3}$	33.5°	$\boldsymbol{W_3}$	3 mm
$\boldsymbol{L_1}$	25 mm	$\boldsymbol{p_1}$	23.5 mm
$\boldsymbol{L_2}$	19 mm	$\boldsymbol{p_2}$	36 mm
$\boldsymbol{L_3}$	12 mm	$\boldsymbol{p_3}$	46 mm

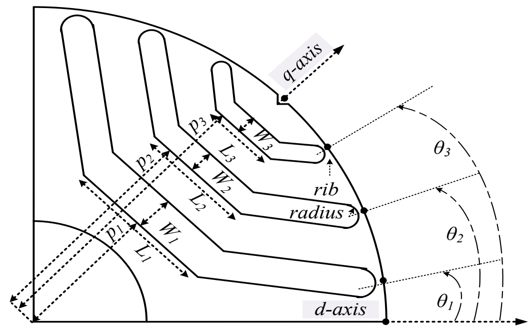

Fig. 2. Quarter rotor geometry of SynRM

The following results have been obtained by 2D-FEM at the same conditions. In FEM, only one pole of the considered four-poles machine needs to be simulated. Sinusoidal currents are injected in the machine windings at different speeds up to the rated value (6000 r/min). The currents have different values up to the rated value (I_m=30 A) at fixed current angle α=56.5°. The selected value of the current angle (56.5°) is the angle at which the machine can give approximately the maximum output power, for the different currents and speeds.

The FEM field pattern of the reference motor for quarter geometry at rated conditions, is depicted in Fig. 3. It can be noticed that there are some iron regions having higher flux level (red color). These regions are called flux-barrier tangential ribs. The thickness of these ribs has a big influence on the SynRM performance.

TABLE II
OPTIMAL SYNRM ROTOR GEOMETRICAL PARAMETERS

Parameter	Value	Parameter	Value
θ_1	8.08°	W_1	5.5 mm
θ_2	16.43°	W_2	3.5 mm
θ_3	28.4°	W_3	3.5 mm
L_1	28.85 mm	p_1	22.75 mm
L_2	28 mm	p_2	35.5 mm
L_3	13.5 mm	p_3	44.2 mm

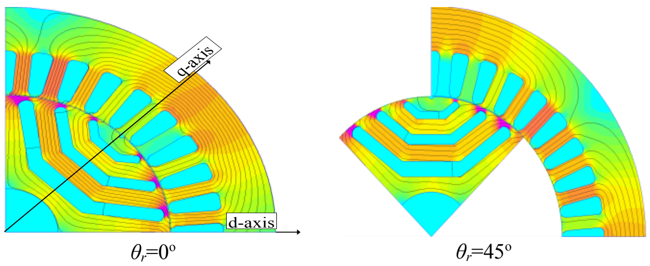

Fig. 3. Flux paths for the reference SynRM using FEM for a quarter geometry for two rotor positions

Figure 4 shows the output torque of the reference, optimal and PM assisted SynRMs at different speeds and currents up to the rated values. On the one hand, for the same current and speed, the output torque of the machine depends on the rotor design which is affected strongly by the design of the twelve rotor parameters, shown in Fig. 2. Therefore, an optimized rotor geometry for the SynRMs is necessary and unavoidable to maximize the machine performance. The SynRM performance mainly depends on the direct (d) and quadrature (q) inductances that depend on the rotor flux-barrier geometrical design. On the other hand, when comparing the subfigs. of optimal SynRM and PMaSynRM, it can be noticed that adding ferrite PM in the optimized rotor of the SynRM leads to an increase of about 25% in the motor torque. This is because of the effect of PMs on the q-axis inductance of the SynRM. The PMs saturate the tangential ribs (see: Fig. 2) of the motor. By consequence, reduce the q-axis inductance, this leads to a higher output torque.

Figure 5 shows the computed losses (iron and copper) of the reference, optimal and PM SynRMs for different currents and speeds up to the rated values. The copper losses are constant for all the machines due to the same stator windings and currents. The iron losses depend on the material properties, the currents and the geometry design of the machine. Only, the rotor design is different between the reference, optimal and PM SynRMs. The variation of the flux-barrier parameters, shown in Fig. 2, has a notable effect on the machine iron losses. This is due to the variation of the saturation regions of the iron especially, the stator teeth and rotor tangential ribs. This can be observed in fig. 5, by comparing the subfigs. (reference, optimal and PMaSynRM). For the same current and speed, the iron losses increases for the PMaSynRM that has the higher output torque (Fig. 4) compared to the others. In addition, for one machine as expected, the iron losses increases with increasing the speed and current, approximately in proportional way.

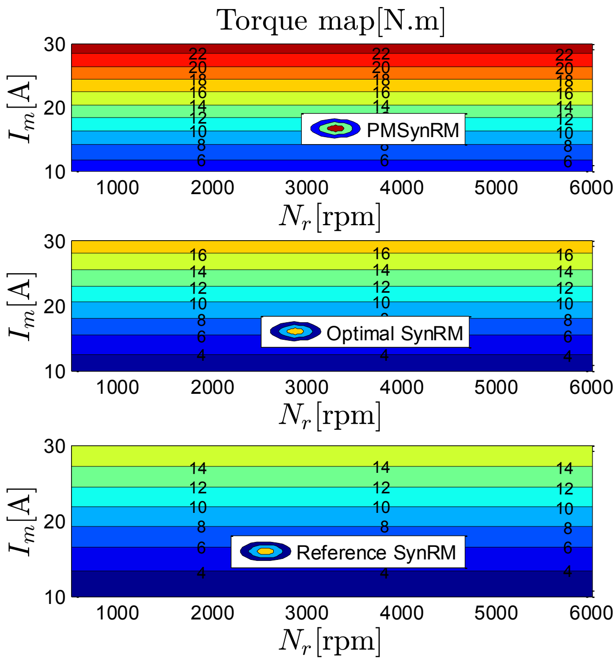

Fig. 4. Motor torque maps for different rotor designs

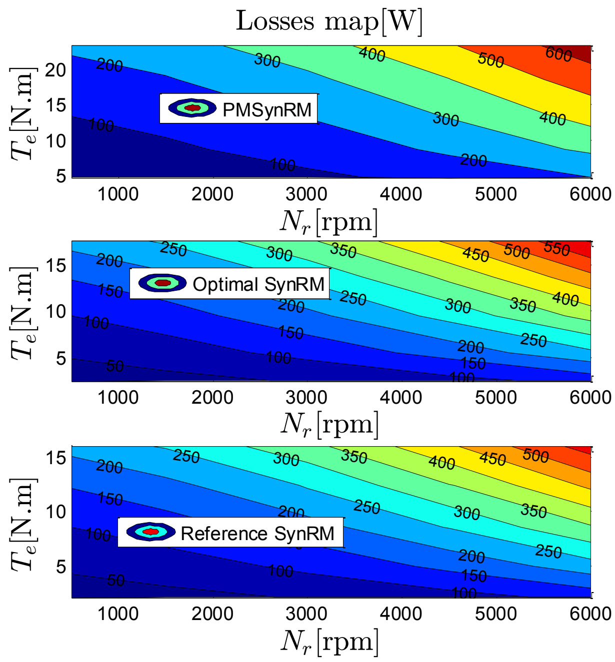

Fig. 5. Motor power losses maps for different rotor designs

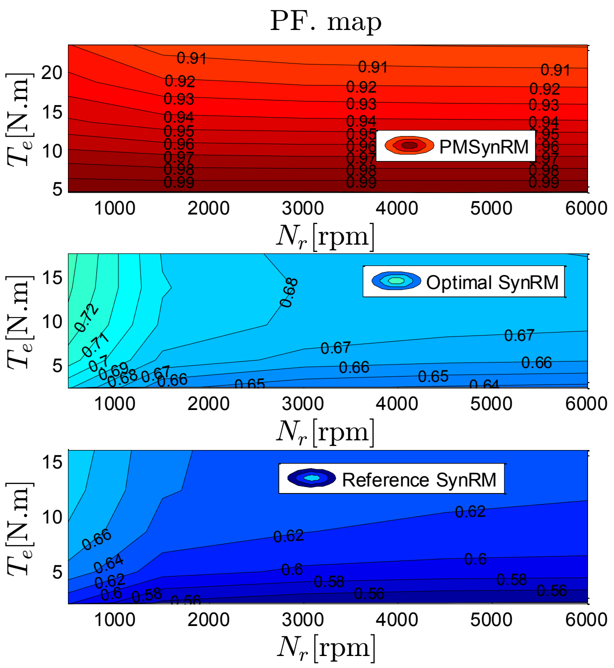

Fig. 6. Motor power factor maps for different rotor designs

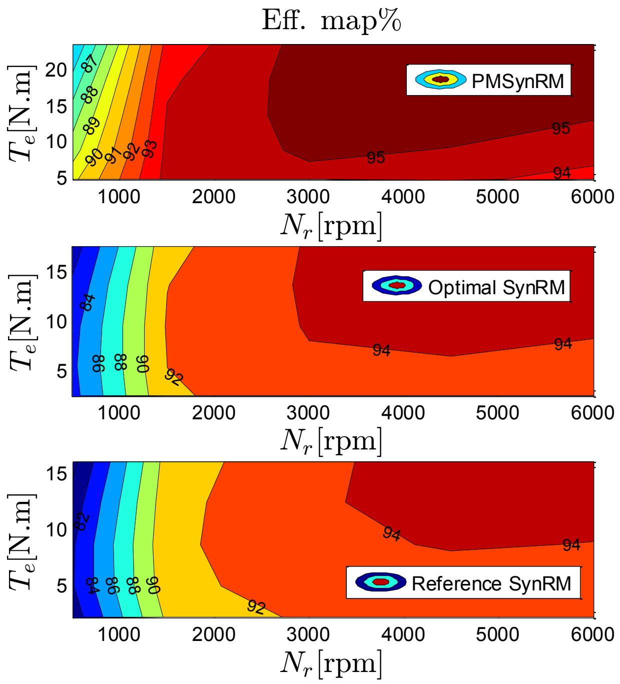

Fig. 7. Motor efficiency maps for different rotor designs

The power factor of the SynRMs depends on the saliency ratio (L_d/L_q) which is affected by the rotor design. As the optimal SynRM has the higher saliency ratio than the reference motor, then it has higher power factor. However, although the SynRM rotor is optimized, the power factor is still low about 0.68 at the rated conditions. Hence, adding PM in the optimized rotor reduces the phase angle between the voltage and current as seen in Fig.1 hence, increases the power factor. The power factor is increased to about 0.91 at the rated conditions as observed in Fig .6 (PMaSynRM). This is good indication for PMaSynRM to be attractive motor for industrial applications. Moreover, the efficiency of SynRMs is better than induction motors [3] and is inferior compared to the permanent synchronous motors [9] as deduced in Fig. 7. As the output power and total losses were affected with the rotor design, the efficiency of the machine depends on the rotor design as well (Fig. 7). The efficiency of the PMaSynRM can reach 95% for half rated conditions.

V. EXPERIMENTAL VALIDATION

The FEM results have been validated by the experimental measurements. The experimental set up shown in Fig. 8, consists of:

- a three-phase induction motor as a braking load, 10 kW
- a prototype SynRM (reference design), 10 kW and 22 A
- three phase Semikron inverter, 24 A and 500 V
- torque sensor of Lorenz Messtechnik, DR-2112-R
- power analyser Tektronix, PA4000
- a dSpace platform, DS1103
- DC power supply, 17 A and 600 V

The measured and simulated validation results have been obtained at 2000 rpm and 14.14 A.

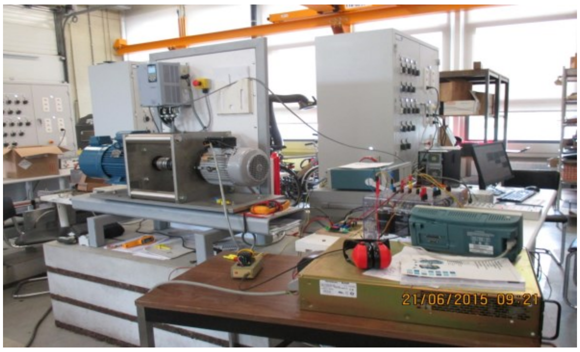

Fig. 8. Photograph of the experimental setup

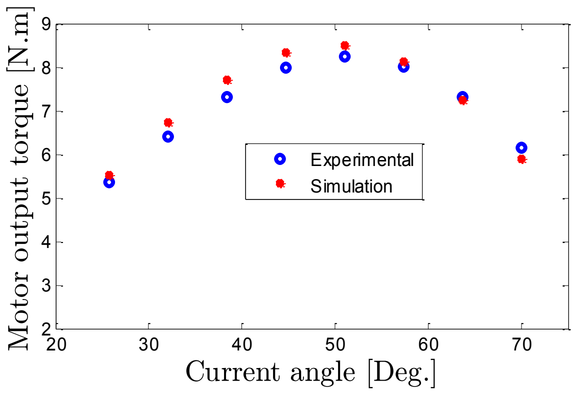

Fig. 9. Computed and measured output torque of SynRM with different current angles

Figure 9 shows the computed (FEM) and the measured output torque of the SynRM. There is a good agreement between the simulated and the measured values. However, the difference between the measured and computed results is due to different reasons: the cutting and punching effects on the steel properties, the manufacturing tolerance and the measurement error.

VI. CONCLUSION

This paper has discussed the performance evaluation of Synchronous reluctance motors (SynRMs) with and without permanent-magnets. same Three different rotors having the stator design and other geometrical and electromagnetic parameters are considered. The three rotors are reference, optimized and optimized assisted by ferrite PMs (PMaSynRMs) in its flux-barrier. Different performance indicators for the machine are computed by FEM and compared at the same conditions. The performance indicators are efficiency, torque, total losses and power factor maps. It is found that the PMaSynRMs can reach efficiency and power factor higher than 95% and 0.91 respectively at the rated conditions. This means that the PMaSynRMs are much better than both the induction machines and switched reluctance machines. In addition, they can be good competitors compared with the permanent magnet synchronous machines due to lower cost. Finally, measurements are obtained and validated FEM model.

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VIII. BIOGRAPHIES

Mohamed N. Ibrahim was born in Kafrelshiekh, Egypt on September 18, 1986. He has graduated from Faculty of Engineering, Kafrelshiekh University, Egypt on 2008. He received his MSc. degree in Electrical Power and Machines Engineering from Tanta University in 2012. Since 2012, he is working as an assistant lecturer at the Department of Electrical Engineering, Faculty of Engineering, Kafrelshiekh University, Egypt.

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