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On the Performances Investigation of Different Surface Mounted Permanent Magnet Machines

Mansouri Ali, Msaddek Hejra, Trabelsi Hafedh
Laboratory of Computer, Electronics & Smart Engineering Systems Design, Engineering School of Sfax, Sfax, Tunisia

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ABSTRACT

In recent years, permanent magnet machines have become a common choice in many industrial applications. Therefore, several structures have been developed, and the choice of a topology designed for a specified application requires the knowledge of the advantages and disadvantages of different topologies. The present work deals with the evaluation of the performances of different radial flux surface-mounted permanent magnet motors designed for an electric vehicle motor application. The objective of this survey is to show the effect of the rotor position (inner or outer) and the magnets segmentation on the machine output torque and iron losses. In this context, four machines with: (i) inner rotor, (ii) inner rotor segmented magnets, (iii) outer rotor and (iv) outer rotor segmented magnets have been designed and studied. All these machines have the same geometrical dimensions and current loading. The main idea is to develop a machine with smoothness torque, lower torque ondulation, lower iron losses, and which is mechanically robust. Firstly, the output torque of the different structure is computed. Secondly, by means of an improved analytical model coupled with 2 dimensional transient finite element analysis (FEA), the machines iron losses are predicted.

Corresponding Author:

Mansouri Ali,
Departement of Computer Engineering,
Higher Institute of Applied Science and Technology of Gafsa (ISSAT Gafsa),
Campus Universitaire - Sidi Ahmed Zarrouk - 2112 Gafsa, Tunisia.
Email: mansouriali2002@yahoo.fr

1. INTRODUCTION

Due to their higher performances, synchronous permanent magnet machines are become a very attractive solution in several applications such as electric and hybrid vehicle traction [1], [2] and wind power generation [3]. In the literature, numerous permanent magnet machines were proposed [4]-[5]. From these machines, the most recognized are those with radial flux and surface mounted permanent magnets [6]. The radial flux configuration is the first permanent magnet machine emerged in the industry. This machine is one of the most classic, easiest to construct and the most commonly used topology [6]. Depending on the rotor arrangement, two configurations may be encountered: inner rotor machines and those in which the rotor is mounted on the outside. When designing a permanent magnet machine, several parameters should be considered, essentially the cogging torque, the electromagnetic torque ripple and the iron losses. Generally, these parameters depend on the rotor disposition and the magnets shape. In order to meet the required performances, it is necessary to study these parameters

In permanent magnet machines, a severe problem generally encountered, is the iron losses, which form a larger portion of the total losses than in induction machines. This is, essentially, due to the rotating magnetic field. It was shown, that the iron losses under rotating magnetic field is generally significantly larger than that from alternating ones. Therefore, it is imperative to evaluate these losses accurately and take them into consideration during the motor design process.

The present work deals with the design of a permanent magnet motor for an electric vehicle application. The main purpose, is to have a design with smoothness torque, lower torque ondulation and mechanically robust. To meet this goal, the performances of four surface mounted permanent magnet topologies are investigated. In each case, the electromagnetic torque and the iron losses are computed. The computation of the iron losses is based on the transient finite element analysis coupled with adequate analytical model.

2. IRON LOSSES MODELLING

In permanent magnet machines, the magnetic field is generally distorted and nonsinusoidal. As a result the estimation of the iron losses in these machines is a very complicated task. One of the first iron loss models is the Steinmetz formula [7], in which the time average power loss per unit volume $P_v(t)$ v is expressed by:

$$\overline{P_v(t)} = K.f^{\alpha}\hat{B}^{\beta} \tag{1}$$

Where f, $\hat{B}$, K and α are respectively the frequency, the peak value of magnetic flux and the loss coefficients.

It was shown, that under sinusoidal magnetic field, this model gives accurate results [7]. Nevertheless, the magnetic field in permanent magnet machine is highly distorted and nonsinusoidal. This is way this model was improved to meet this non-sinusoidal variation. As a result a modified Steinmetz model was proposed in [8, 9]. In this model, the time average power loss per unit volume, $P_v(t)$ are expressed as follows:

$$P_v(t) = K.f_{eq}{}^{\alpha\ 1}\hat{B}^{\beta}f_r \tag{2}$$

f_r is the remagnetization frequency and f_{eq} is an equivalent frequency derived from the rate of change of the flux density.

In spite of this improvement, it was shown in [8, 9] that the use of this model in the iron loss estimation in permanent magnet machines causes inaccurate results. To overcome this inconvenient, other improvement were introduced in the model proposed by [9]. In that model, the iron loss per unit volume is expressed as a function of the flux density B(t) and its rate of change (dB/dt):

$$\overline{P_v} = \frac{1}{T}\int_0^T K_1 \cdot \left|\frac{dB}{dt}\right|^{\alpha} |B|^{\beta\ \alpha}\,dt \tag{3}$$

Where K_1 is coefficient deduced from K, α and β.

Despite all the improvements made on the Steinmetz model, it remains limited to the sinusoidal non distorted magnetic fields. In the same context, Bertotti in 1988 was found that the total iron losses P_t can be separated into three terms namely: hysteresis losses P_h, classical eddy current losses P_c and excess losses P_e [10] which can be expressed as follows:

$$P_t = P_h + P_c + P_e \tag{4}$$

$$P_h = C_0\hat{B}^2 f \tag{5}$$

$$P_c = \frac{\pi^2\sigma(2d)^2}{6}\left(\hat{B}f\right)^2 \tag{6}$$

$$P_e = C_1\left(B_{max}f\right)^{\frac{3}{2}} \tag{7}$$

Where C_0, 2d, σ and C_1 denotes respectively: the hysteresis loss coefficient, the steel sheet thickness, the electrical conductivity and the excess loss coefficient.

The Bertotti model was then applied in numerous surveys. Based on such model, an analytical expression of the three iron loss components in the stator teeth and yoke was developed in [11].

In order to improve the estimation of the iron losses in rotating machines, a model considering the effect of the minor hysteresis loops was developed in [12]. The obtained analytical results give good agreements with the measured ones. The use of all the flux density harmonics in the iron losses computation was proposed in [13]. But it has shown that this approach is not enough accurate. Another approach using the two orthogonal components of the flux density were applied to estimate the iron losses in [14]. The research to improve the iron losses estimation in electrical machines continues to attract the attention of several authors. In our work, we evaluate the machine iron losses by using the FEA and a three components model. In this case, the instantaneous iron losses are calculated using the following formulations [15]:

$$p_v(t) = p_h(t) + p_c(t) + p_e(t) \tag{8}$$

$$p_h(t) = \left(\left| H_x \frac{dB_x}{dt} \right|^{\frac{2}{\beta}} + \left| H_y \frac{dB_y}{dt} \right|^{\frac{2}{\beta}} \right)^{\frac{\beta}{2}} \tag{9}$$

$$p_c(t) = K_c \left(\left(\frac{dB_x}{dt} \right)^2 + \left(\frac{dB_y}{dt} \right)^2 \right) \tag{10}$$

$$p_e(t) = K_e \left(\left(\frac{dB_x}{dt} \right)^2 + \left(\frac{dB_y}{dt} \right)^2 \right)^{\frac{3}{4}} \tag{11}$$

β, k_c and k_e are respectively the Steinmetz, the classical eddy current and the excess losses coefficients.

B_x, B_y, H_x, H_y are the two orthogonal components of the flux density and the magnetic intensity both in the stator yoke and teeth are calculated in each finite element from the 2-D transient FEA simulations. The computation of the total iron losses per length unit for periodic variable magnetic fields is described in the following four steps [16]:

1. Meshing the machine stator into N_e finite element mesh
2. Devising the time domain into N steps denoted t_j,
3. Integrating the previous equations over one period,
4. Summing the equations obtained in step 3 over the total number of elements

$$P_h(e) = \frac{1}{T} \sum_{j=0}^{j=N-1} \int_{t_j}^{t_{j+1}} \left(\left| H_{ex,t_j} \frac{dB_{ex,t_j}}{dt} \right|^{\frac{2}{\beta}} + \left| H_{ey,t_j} \frac{dB_{ey,t_j}}{dt} \right|^{\frac{2}{\beta}} \right)^{\frac{\beta}{2}} A_e dt \tag{12}$$

$$P_c(e) = K_c \frac{1}{T} \sum_{j=0}^{j=N-1} \int_{t_j}^{t_{j+1}} \left(\left(\frac{dB_{ex,t_j}}{dt} \right)^2 + \left(\frac{dB_{ey,t_j}}{dt} \right)^2 \right) A_e dt \tag{13}$$

$$P_e(e) = K_e \frac{1}{T} \sum_{j=0}^{j=N-1} \int_{t_j}^{t_{j+1}} \left(\left(\frac{dB_{ex,t_j}}{dt} \right)^2 + \left(\frac{dB_{ey,t_j}}{dt} \right)^2 \right)^{\frac{3}{4}} A_e dt \tag{14}$$

Here $B_{ex,tj}$, $B_{ey,tj}$, and $H_{ex,tj}$, $H_{ey,tj}$ denote the two orthogonal components of the flux density B and intensity H in the finite element e at the time step t_j . A_e and p are respectively the finite elment area and the machine pair pole number.

Three coefficients (β, k_c and k_e) used in the previous iron loss model have to be identified. These coefficients are derived from the information supplied by the lamination manufacturers.

3. STUDIED TOPOLOGIES

The studied topologies are all of 3-phase, 4-pole, and 48-slots. The different configurations are shown in Figure 1. The stator is made up of a laminated iron core ((MA800-65A) and a three phase armature windings fed by three phase sinusoidal current. The rotor is made up of iron core on which are mounted, in opposite direction the magnets which are NdFeB rare-earth. The major machines parameters and features are respectively provided in Tables 1 and 2.

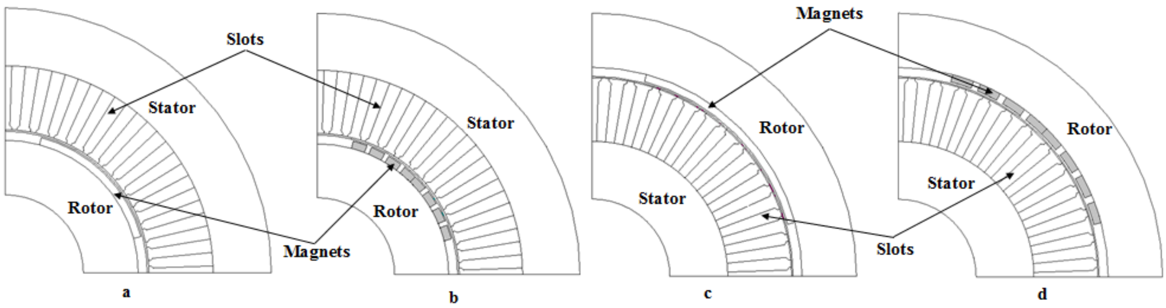

Figure 1. Studied topologies; (a): inner rotor, (b): inner rotor segmented magnet, (c): outer rotor segmented magnet, (d): outer rotor segmented magnet

Table 1. Characteristics of the studied topology

Characteristic	Value
Nominal output power	9.42 kw
Nominal speed	1500 rpm
Maximum speed	4500 rpm
Nominal torque	60 N.m

Table 2. Machine's dimensions

Variable	Value	Variable	Value
outer stator diameter	170 mm	shaft diameter	50 mm
inner stator diameter	91.8 mm	rotor core diameter	85 mm
active machine length	160 mm	stator tooth width	4.8 mm
airgap length	1 mm	slot opening angle	30º
half pole angle	60 º	rotor yoke height	17.5 mm
stator slot pitch	11.9 mm	magnet thickness	2.4 mm

4. RESULTS AND ANALYSIS

Owing to the symmetries and the periodicities in the studied structures, our studies are limited to the fourth of the machines. In our survey we use a dynamic modeling; so we need to ensure the continuity of the FEA model when the rotor moves. For this reason, we have used an interpolation technique consisting of equalizing the potential vector A in the airgap. This technique requires the division of the airgap into two parts: the stator half and the rotor one. Then we define equality constraints between coincident nodes.

4.1. Electromagnetic Torque

In order to show the influence of the rotor disposition and the magnet segmentation on the output torque of the studied machines on the output torque of the studied topology, several FEA investigations were carried out. The obtained results are illustrated in Figure 2.

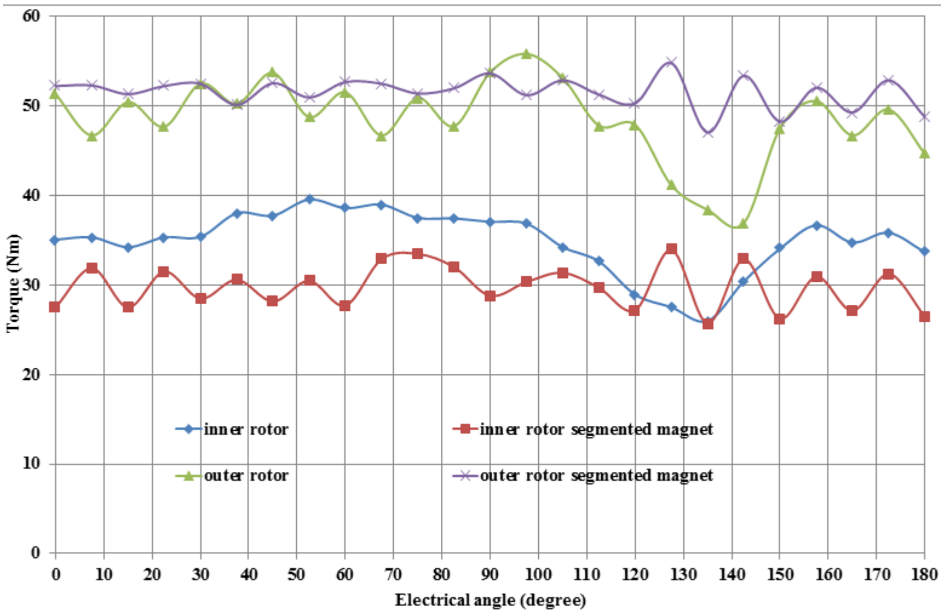

Figure 2. Output torque versus electrical angle

Based on the results related to the electromagnetic torque variation of the different studied topologies, we can deduce the toque peak value and ondulation corresponding to each topology. This result is illustrated in Table 3.

Table 3. Torque ondulation and peak value

Topology	Torque ondulation (%)	Peak value
Inner rotor	34	39,552
Inner rotor segmented magnet	24	33,92
Outer rotor	33	55,808
Outer rotor segmented magnet	14	54,784

According to the previous results, we can deduce:

- The outer rotor machine has a higher electromagnetic torque than the inner rotor one. This is essentially due to the higher airgap diameter in the outer rotor topology. The output torque reaches 55.8 Nm for the outer rotor machine that is about 1.5 times greater than for the inner rotor machine.
- The non-segmented magnets machine has the highest torque ondulation. This ondulation is caused by the so called cogging toque. In this context, it was shown in [17] that the magnets segmentation is one of the most used techniques to considerably reduce the cogging torque in permanent magnet machines. For the non-segmented magnets machine, the torque ondulation exceeds 33% in both cases of outer and inner rotor machines.

Referring to figure 2, and compared to the results obtained in [16], we can deduce that inverting the rotor position leads to doubling the machine output toque.

4.2. Iron Losses Computation

The iron losses in the stator teeth and yoke for the different studied permanent magnet machines were investigated by means of the FEA and the analytical model described in section 2. The obtained results for no load and load conditions are respectively illustrated in Tables 4 and 5.

Table 4. No load iron losses

Loss Component	Inner rotor	Inner rotor segmented magnets	Outer rotor	Outer rotor segmented magnets
Eddy current (W)	32	29	43.6	45
Hysteresis (W)	6	5.5	6.2	7.4
Excess (W)	45	35	85	80
Total (W)	83	69,5	134,8	132,4

Table 5. Load iron losses

Loss Component	Inner rotor	Inner rotor segmented magnets	Outer rotor	Outer rotor segmented magnets
Eddy current (W)	55	50	50	60
Hysteresis (W)	10	9	7.5	9.4
Excess (W)	194	147	396	378
Total (W)	259	206	453,5	447,4

As it can be noticed is Tables 4 and 5, the outer rotor machine with non-segmented magnets has the highest iron losses, whereas the inner rotor machine with magnets segmented has the lowest ones.

5. CONCLUSION

This paper is devoted to the performances evaluation of four surface mounted permanent magnet machines. This evaluation is carried out by computing the iron losses and the electromagnetic torque. Based on the obtained results, it can be affirmed that, on one hand the outer rotor topology has the smoother and the higher output torque, in fact for the inner rotor machine the torque is about 1.5 times. On the other hand, the outer rotor machine has also the highest iron losses.

The inner rotor configuration allows a very compact construction, since the rotor can be of small volume. However, this results in a low torque at small radius of the air gap. Concerning the outer rotor topology, the air gap radius must be greater than a certain minimum value, so that this configuration produces a higher torque compared to the inner rotor one. As far as the cogging torque is a severe problem degrading the machine performances, it needs to be minimized. A way to do this is the segmentation of the magnets.

Based on the obtained results, an exterior-segmented permanent magnets topology will be selected in order to br optimized and integrated in an in-wheel vehicle application. This choice is justified by the smooth out put torque of this machine.

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BIOGRAPHIES OF AUTHORS

Ali Mansouri received the B.S. degree in electromechanical engineering, the M.S. degree in electrical machine analysis and control and the Ph. D. degree in electrical engineering from Sfax Engineering School (SES), University of Sfax, Sfax, Tunisia, in 2002, 2003 and 2009 respectively. He is working in the field of electrical machine design at SES. He joined the Tunisian University, Tunisia, in 2003 as an Assistant at Gafsa Engineering Institute. Currently he is working as Associate Professor in the Higher Institute of Applied Science and Technology of Gafsa. He is a member of the Laboratory of Computer, Electronics & Smart Engineering Systems Design the University of Sfax.

Hejra Msaddek received the B.S. degree in electrical and automatic engineering, the M.S. degree in automatic and intelligent technic from Gabes Engineering School (GES), University of Gabes, Gabes, Tunisia, in 2011and 2012 respectively. She is working in the field of electrical machine design and optimization at Sfax Engineering School SES. She is a member of the CES Laboratory of Computer, Electronics & Smart Engineering Systems Design the University of Sfax.

Hafedh Trabelsi received the B.S. degree from Sfax Engineering School (SES), University of Sfax, Sfax, Tunisia, in 1989, the M.S. degree in the Central School of Lyon, France, in 1990, the Ph.D. degree from the University of Paris XI Orsay, France, in 1994 and the "Habilitation à Diriger des Recherches" (accreditation to lead research) degree from Sfax Engineering School (SES), University of Sfax, Sfax, Tunisia, in 2009 all in electrical engineering. He is working toward the Research Management Ability degree in the field of electrical machine design at SES. He joined the Tunisian University, Tunisia, in 1995 as an Assistant Professor at Gafsa Engineering Institute. He is currently a Professor of Electrical Engineering at SES. He is a member of the CES Laboratory in the University of Sfax.