A Comparative Study of Two Permanent Magnet Motors Structures with Interior and Exterior Rotor

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Abstract
Currently, the permanent magnet motors PMM represent an attractive solution in the electric traction field, thanks to their higher performances than other electric motors. In this context, this work represents an analytical study and validation by the finite element method of two configurations, the radial flux permanent magnet synchronous motors with exterior rotor PMSMER and with interior rotor PMSMIR. This paper is divided into two sections: In the first section, we represent the analytical study based on electromagnetic law of the two structures PMSMER and PMSMIR. In the second section, we represent a comparative study of the two structure performances.

Keywords
permanent magnet motors design, radial flux, finite element method, modelling, performance

1. INTRODUCTION
Considering the large variety of electric motors, such as asynchronous motors, synchronous motors with variable reluctances, permanent magnet motors with radial or axial flux, the committed firms try to find the best choice of the motor conceived for electric vehicle field.

There are different criteria of selection in order to solve this problem such as the power-to-weight ratio, the efficiency and the price. The traction electric motor is specified by several qualities, such as the flexibility, reliability, cleanliness, facility of maintenance, silence etc. Moreover, it must satisfy several requirements, for example the possession of a high torque and an important efficiency [Zire et al., 2003; Gasc, 2004; Chan, 2004].

In this context, The PMM is characterized by a high efficiency, very important torque, and power-to-weight, so it becomes very interesting for electric traction. The rotor of the PMM supports several configurations interesting for the magnets mounted on surface.

In the intension, to ensure the most suitable and judicious choice, we start by a comparative study between the two structures, then, we implement a methodology of design based on an analytical modelling and on the electromagnetism laws.

2. MODELLING OF THE TWO PMM STRUCTURES
2.1 Structural data
The motors structure allowing the determination of the studied geometry is based on three relationships. The ratio $\beta$ is the relationship between the magnet angular width $L_{a}$ and the pole-pitch $L_{p}$.

$$\beta = \frac{L_{a}}{L_{p}}$$  \hspace{1cm} (1)

$L_{p} = \frac{\pi}{P}$  \hspace{1cm} (2)

The ratio $R_{ld}$ is the relationship between the principal tooth angular width $L_{a}$ and the inserted tooth angular width $A_{dent}$. This relationship fixes the inserted tooth size.

$$R_{ld} = \frac{A_{dent}}{L_{a}}$$  \hspace{1cm} (3)

The $R_{did}$ ratio is the relationship between the principal tooth angular width and the inserted tooth angular width $A_{dent}$. This relationship fixes the inserted tooth size.

$$R_{did} = \frac{A_{dent}}{L_{a}}$$  \hspace{1cm} (4)
2.2 Geometrical structures of the PMSMIR and the PMSMER
This part is devoted to an analytical sizing allowing calculation of geometrical sizes of the two PMM configurations which are the PMSMER and the PMSMIR. Figure 1 represents the PMSMER and the PMSMIR with the number of pole pairs is 4 and a number of principal teeth is 6, between two principal teeth, an inserted tooth is added to improve the form of wave and to reduce the leakage flux [Hadj et al., 2007]. The slots are right and open in order to facilitate the insertion of coils and to reduce the production cost. The type of winding is concentric; each winding of phase is made up of two diametrically opposite coils [Magnussen et al., 2005; Bianchi et al., 2003; Libert and Soulard, 2004].

2.3 Analytical sizing of the two motors structures
The analytical study of motor sizing is based on the schedules conditions parameters, the constant characterizing materials, the expert data and the configuration of the two motors. This Sizing motor approach is represented as follows:

2.3.1 The schedules data conditions
- Electric vehicle mass \( M = 1000 \) kg
- Angle of starting \( a_d = 3^\circ \)
- Time of starting \( t_d = 4 \) s
- Outside temperature \( t_{ext} = 40 \) °C
- Maximum motor power \( P_{mmax} = 21,635 \) kW
- Winding temperature \( t_w = 95 \) °C
- Base speed of the vehicle \( V_b = 30 \) km/h
- Maximum Speed of the vehicle \( V_{max} = 100 \) km/h
- Load factor of the slots \( k_r = 0,44 \)
- Acceptable density of current in the slots \( \delta = 7 \) A/mm²

2.3.2 Constants specific to materials
The motor is composed by a diversity of materials specified as follows:
- Remanent magnetic induction of the magnets \( B_m = 1,175 \) T
- Induction of demagnetization \( B_c = 0,383 \) T
- Magnetic induction in teeth data base \( B_{cs} = 0,9 \) T
- Relative permeability of the magnets \( \mu_a = 1,05 \) H/m
- Coefficient of mechanical losses \( k_m = 1 \% \)
- Resistivity of copper with \( 95 \) °C \( R_{cu} = 17,2 \times 10^{-9} \) Ωm
- Coefficient of variation of the copper resistivity \( \alpha = 0,004 \)
- Density of the electrical sheets \( M_{el} = 7850 \) kg
- Density of magnets \( M_{va} = 7400 \) kg
- Density of copper \( M_{vc} = 8950 \) kg
- Coefficient of quality of the sheets \( Q = 1,100 \)
- Density of copper \( M_{vc} = 8950 \) kg

2.3.3 Expert data
The expert data are practically represented by three sizes which are, the magnetic induction in the air gap \( B_e \), the magnetic induction in the stator yoke \( B_{cs} \) and the magnetic induction in the rotor yoke \( B_{cr} \). It should be noted that the zone of variation of these three parameters varies between 0,2 to 1,6 T [Hadj et al., 2007].
2.3.4 Structural data
For the two configurations, we adopted the same number of pole pairs $P = 4$, with an air gap thickness equivalent to 2mm, With a relationship $\beta$ equal to 0.667 and $R_{ldla}$ equal to 1.2.

2.3.5 Data identified by the finite element method
$K_{fu}$ is the flux leakage coefficient of the PMSMIR which is fixed to 0.95 whereas for the PMSMER, $K_{fu}$ is equal to 0.98. Between the principal tooth angular width $A_{dent}$ and the inserted tooth angular width $A_{denti}$, we define a ratio $R_{didi}$ equal to 0.2.

2.4 Geometrical sizes
Geometrical parameters of the two structures motors are defined in Figure 3.

2.4.1 Stator geometrical sizes of the PMSMIR
The slot average width: $L_{enc}$

$$ L_{enc} = \frac{D_m + e + H_d}{2} A_{enc} $$  \hspace{1cm} (5)

The principal tooth section: $S_d$

$$ S_d = \frac{D_m + e}{2} A_{denti} L_m $$  \hspace{1cm} (6)

The inserted tooth section: $S_{di}$

$$ S_{di} = \frac{D_m + e}{2} A_{denti} L_m $$  \hspace{1cm} (7)

The slot section: $S_e$

$$ S_e = A_{enc} \frac{D_m + e}{2} L_m = \frac{1}{2} \left[ \frac{2\pi}{N_d} A_{dent} - A_{denti} \right] \frac{D_m + e}{2} L_m $$  \hspace{1cm} (8)

2.4.2 Stator geometrical sizes of the PMSMER
The slot average width: $L_{enc}$

$$ L_{enc} = \frac{D_m - e - H_d}{2} A_{enc} $$  \hspace{1cm} (9)

The principal tooth section: $S_d$

$$ S_d = \frac{D_m - e}{2} A_{enc} L_m $$  \hspace{1cm} (10)

The inserted tooth section: $S_{di}$

$$ S_{di} = \frac{D_m + e}{2} A_{denti} L_m $$  \hspace{1cm} (11)

The slot section: $S_e$

$$ S_e = A_{enc} \frac{D_m - e}{2} L_m = \frac{1}{2} \left[ \frac{2\pi}{N_d} A_{dent} - A_{denti} \right] \frac{D_m - e}{2} L_m $$  \hspace{1cm} (12)

with $L_m$ is the motor length.

The teeth height $H_d$ of the PMSMIR is expressed by equation 13 with $N_{ sph }$ is the number of turns per phase and $I_n$ is the rated current.

$H_d$ specific to the PMSMIR is expressed:

$$ H_d = \sqrt{\frac{N_{ sph } I_n}{N_d \delta K_e A_{enc}}} + \left( \frac{D_m + e}{2} \right)^2 - \frac{D_m + e}{2} $$  \hspace{1cm} (13)

$H_d$ specific to the PMSMER is expressed:

$$ H_d = \sqrt{\frac{N_{ sph } I_n}{N_d \delta K_e A_{enc}}} + \left( \frac{D_m - e}{2} \right)^2 - \frac{D_m - e}{2} $$  \hspace{1cm} (14)

The stator yoke thickness $H_{cs}$ is obtained by application of the flux conservation theorem.

$$ H_{cs} = \frac{B_d S_d}{2 L_m B_{cs}} $$  \hspace{1cm} (15)

Fig. 4 Application of the theorem of the flux conservation

2.4.3 The rotor geometrical sizes of the two structures
The expression of the magnet height $H_a$ is the same one in the two structures; it is obtained by the application of the Ampere theorem:

$$ \int_{contour} H dI = \Sigma n_i \Rightarrow H_h + e_h = 0 $$  \hspace{1cm} (16)

The remanent induction of the magnet $M_r(T_a)$ at $T_a$ °C is defined by:

Fig. 3 PMSMER and PMSMIR parameters
\[ H_a = \frac{\mu B_x e}{M(T_{Ta}) - \frac{B_x}{K_{Ta}}} \] (17)

\[ M(T_{Ta}) = M[1 + \alpha_{teg}(T_a - 20)] \] (18)

The rotor yoke thickness \( H_{cr} \) is defined:

\[ \Phi \alpha = \frac{B_{x}a_{H}f_{m}L_{a_{H}}}{2K_{a_{H}} L_{a_{m}} B_{cr}} \] (19)

2.4.4 Electrical sizing

The electromotive force in the two structures is expressed by:

\[ \text{EMF}(t) = \frac{8}{\pi} N_{ph} L_{a_{m}} B_{x} \sin\left(\frac{\pi}{2} \beta \right) \sin\left(\frac{\pi}{2} \beta R_{x_{a_{m}}} \right) \]

\[ \Omega_{m} \sin(\Omega_{m} t) \] (20)

The motor electric constant: \( K_e \)

\[ K_e = \frac{12}{\pi} N_{ph} L_{a_{m}} B_{x} \sin\left(\frac{\pi}{2} \beta \right) \sin\left(\frac{\pi}{2} \beta R_{x_{a_{m}}} \right) \] (21)

The electromagnetic torque: \( T_{em} \)

\[ T_{em}(t) = \frac{1}{3} \sum_{i=1}^{3} \text{EMF}(t),i(t) \] (22)

with \( \text{EMF}_i \) and \( i_i \) respectively represent the electromotive force and the current of the \( i \) phase.

The motor rated current \( I_n \) is the ratio between the electromagnetic torque and the motor electric constant

\[ I_n = \frac{T_{em}}{K_e} \] (23)

The phase resistance of the motor: \( R_{ph} \)

\[ R_{ph} = R_{ce}(T_b) \frac{N_{ph} B_{x} L_{a_{m}}}{I_n / \sqrt{2}} \] (24)

where \( R_{ce}(T_b) \) is the Resistivity of copper at the temperature of winding \( T_b \) and \( L_{a_{m}} \) is the spire average length defined as follow [Hadj et al., 2007].

\[ R_{ce}(T_b) = R_{ce}[1 + \alpha(T_b - 20)] \] (25)

\[ L_{a_{m}} = 2 \left( A_{enc} + A_{dem} \right) \left( \frac{D_{n_{m} + e + h_{d}}}{2} + I_{m} \right) \] (26)

3. COMPARATIVE STUDY BETWEEN THE TWO STRUCTURES

In this study, the validation and comparation between the two structures is based on the finite elements method using the software FEMM. The mesh in the two studied structures is given by figures 5 and 6, we make a refined mesh in the air gap to obtain a precised result [Ohyama et al., 2005].

Figure 7 and figure 8 show respectively the flux density in the PMSMER and in the PMSMIR.

We note that the maximal induction for the motor yokes is equal to 1.4 T that proves no saturation in magnetic motor circuit.

We note the appearance of leakages flux in the motor, this requires the determination of the leakages flux co-
efficient to validate the analytical model.

3.1 Electromagnetic parameters

3.1.1 Air gap flux density

Figures 11 and 12 show the airgap induction in the PMSMER and in the PMSMIR, the maximal value is about 1 T [Pakdel, 2009].

3.1.2 Flux

Figures 13, 14, 15 and 16 illustrate the three phases flux at no-load and at full load according to the mechanical angle for the PMSMIR and PMSMER. According to the Figure 17, we can conclude that the variation of the flux at no-load and at full-load according to the rotor position is very weak, that originates the magnetic reaction.
3.1.3 Electromotive forces EMF

The form of EMF represents a very significant parameter. It is expressed by:

\[
\text{EMF} = -N_{\text{ph}} \frac{d\Phi}{dt}
\]  

(27)

Figures 18, 19, 20 and 21 give an idea on the form of the EMF at no-load and at full load according to the rotor position. This EMF is generated by the flux evolution through a coil of the stator.

and at no load of the two structures obtained by the finite element method (Zhu et al., 2006; Yee-pien et al., 2009). The obtained results validate the analytical model because the torque oscillates around the average value found analytically which is 112 Nm.

3.2 Torque and Power-to-weight ratio

3.2.1 Calculation of the torque

The instantaneous torque is expressed by equation 22. Figure 22 and 23 represent the torque at full-load and at no-load of the two structures obtained by the finite element method (Zhu et al., 2006; Yee-pien et al., 2009). The obtained results validate the analytical model because the torque oscillates around the average value found analytically which is 112 Nm.
3.3 Losses and efficiency

Table 1 represents the efficiency and the losses for the PMSMIR and the PMSMIR.

<table>
<thead>
<tr>
<th>Loss Type</th>
<th>PMSMIR</th>
<th>PMSMIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joule losses</td>
<td>557,180</td>
<td>547,089</td>
</tr>
<tr>
<td>Iron losses</td>
<td>59,662</td>
<td>32,653</td>
</tr>
<tr>
<td>Mechanical losses</td>
<td>215,755</td>
<td>216,025</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.962</td>
<td>0.964</td>
</tr>
</tbody>
</table>

We can deduce that the Joules losses and the iron losses for the PMSMIR are lower than those of the PMSMIR. Moreover, the efficiency of the PMSMIR is more interesting than the other structure. Figure 27 illustrates the total losses of the two structures.

3.2.2 Power-to-weight ratio

The power-to-weight ratio is defined by the relationship between the power and the mass of the motor active part. Figure 26 represents the power-to-weight ratio specific to the two structures according to the power.

According to this figure, we notice that the power-to-weight ratio of the PMSMIR is slightly lower than the PMSMIR, while the great motor power it is the reverse.
reached by the first structure. This type of configuration is adapted more to be exploited as a motor-wheel.

4. CONCLUSION
We choose the synchronous permanent magnet motor with radial flux. Basing on the schedule data conditions, sizing approach given by Figure 2, electromagnetic laws, an analytical modelling of two structures which are the PMSMER and the PMSMIR is carried out.

We compare efficiency, mass, torques and losses in the two structures of the PMM. In conclusion, the PMSMER is the most interesting since it is more profitable and lighter than the PMSMIR. Finally, the realization of a prototype is necessary to confirm our study.

References

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