Dimensioning of a permanent magnets motor with double rotor for electric vehicle

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Abstract – The applications of the electric motors in transport require a broad range of operation at constant power. To answer this requirement, we have studied a structure of machine with double rotor. Indeed, the total torque delivered is the sum of torques supplied by the two rotors. This article describes, then a design methodology of a permanent magnets motor with double rotor, radial flux and strong starting torque for electric vehicles. This work consists, of the analytical dimensioning of the motor by taking into account several constraints of operation followed by a modelling by the finite element method and a Comparison between a motor with double rotor and a motor with one rotor.

Key words: permanent magnet, electric motor, dimensioning, electric vehicle

INTRODUCTION

Among the range of the electric motors, the choice a motor of the traction for electric vehicle is vast and delicate task. A wide range of motors exists with their intrinsic qualities and defects such as: the asynchronous motor, the synchronous motor, the variable reluctance motor and the permanent magnets motors. In electric motors application related to electric vehicle, fundamental selection criteria are considered: the power-to-weight ratio, the efficiency and the production cost. Our choice has focused on the permanent magnets motor with double rotor, guided not only by these criteria but also by reduced bulk and by the strong starting torque developed. The main objective of this work is the sizing of the strong starting torque motor by the analytical method and by the finite elements method.

1. Analytical dimensioning of the motor

1.1. Configuration

The motor with double rotor is composed of two stators and two rotors. Each stator contains four poles pairs and six main teeth. Between two main teeth an inserted tooth is added to improve the waveform and reduce the flux leakages. Each phase winding is made up of four coils diametrically opposed.

The configuration of the motor is characterized by a relation ship between the number of teeth and the number of poles pairs directly bound to the space percentage occupied by the slots compared to that occupied by the inserted tooth. The figure (1) represents a permanent magnets motor with double rotor.

Figure 1. Configuration of permanent magnets motor with double rotor

Three design ratios define the motor’s structure [1]:
The first coefficient is the ratio $\beta$ of the angular width of a magnet $L_a$ by the pole path $L_p$

$$\beta = \frac{L_a}{L_p}$$

The second coefficient is the ratio $R_{ldla}$ of the main tooth angular width $A_{tooth}$ by the angular width of a magnet.

$$R_{ldla} = \frac{A_{tooth}}{L_a}$$

It adjusts the size of the main tooth and has a strong influence on the electromagnetic force.

The last coefficient $R_{did}$ is the ratio of the inserted tooth $A_{toothi}$ by a main tooth $A_{tooth}$. It fixes the inserted tooth size.

$$R_{did} = \frac{A_{toothi}}{A_{tooth}}$$

The size of the inserted tooth is optimised by the finite element method in order to reduce leakage flux and ripple torque [2,3,4].

1.2. Analytical estimate of the electromagnetic force related to a stator and a rotor.

The electromagnetic force is deduced from the flux derivative, its necessary then to be able to express the flux in versus magnets position. [5,6]

The flux leakage between the air-gap and the stator is neglected and the Magnetic induction is supposed to be perfectly rectangular on the air-gap.

With these assumptions, for a stator, the in coning flux in a coil can be put in the following form: [7]

$$\varphi_b = \int \frac{Be(\theta)}{2} d\theta = \int \frac{Be(\theta)}{2} d\theta$$

Where $Be$, in the magnetic induction in the air-gap.

The electromagnetic force can be given by the following equation [8]:

$$\text{emf} = \sum_{1}^{n} b_n \sin\left(2\pi\frac{\theta}{T}\right)$$

with: $b_n = \frac{4}{T} \int_{00}^{T/2} E(\theta) \sin\left(2\pi\frac{\theta}{T}\right) d\theta$

and $\theta = \frac{L_a - A_{tooth}}{2}$

The first harmonic of the electromagnetic force in a stator deduced and expressed as follows:

$$\text{emf}(t) = \frac{8}{\pi} N_{sph} L_m D_m B_e \sin\left(\frac{\pi}{2} \beta \right)$$

$$\sin\left(\frac{\pi}{2} \beta \frac{R_{ldla}}{\Omega} \sin\left(p \Omega_t t\right)$$

With:

- $L_m$, motor length
- $D_m$, Stator diameter
- $N_{sph}$, number of spire per phase
- $P$, number of pole pairs

The total electromagnetic force of the motor is then expressed as follows:

$$\text{emf}(t) =$$

$$+ \frac{8}{\pi} N_{sph2} L_m D_m B_e \sin\left(\frac{\pi}{2} \beta \right)$$

$$+ \frac{8}{\pi} N_{sph2} L_m D_m B_e \sin\left(\frac{\pi}{2} \beta \right) \Omega_n \sin\left(p \Omega_n t\right)$$

The motor electric constant is deduced and given by the following expression:

$$K_e = \frac{12}{\pi} N_{sph1} L_m D_m B_e \sin\left(\frac{\pi}{2} \beta \right)$$

$$+ \frac{12}{\pi} N_{sph2} L_m D_m B_e \sin\left(\frac{\pi}{2} \beta \right) \frac{R_{ldla}}{\Omega_n}$$

1.3. The motor dimensioning

The magnet height fixes the flux density level in the air-gap. This parameter is given by applying the ampere law for a maximal covering a magnet and a main tooth. The flux created by magnets is composed of the leakage flux between magnets and the flux in stator and rotor.

$H_{a1}$ and $H_{a2}$ represent the magnet height of the interior and external rotor.

$$H_{a1} = \frac{\mu_a B_{a1}}{K_{fu}}$$

and

$$H_{a2} = \frac{\mu_a B_{a2}}{K_{fu}}$$

With

- $\mu_a$ is the magnet relative permeability
- $B_{a1}$ is the magnets remanent induction
- $K_{fu}$ is coefficient of flux leakages
- $e$ is the air-gap thickness
- $H_{enc1}$ and $H_{enc2}$ represent respectively the slot height of the interior stator and the exterior stator.
\[
H_{enc1} = \frac{N_{sph1} I_n}{2N_d \delta K \varepsilon L_{enc1}} \\
H_{enc2} = \frac{N_{sph2} I_n}{2N_d \delta K \varepsilon L_{enc2}}
\]

Where
- \(N_d\) is the number main teeth
- \(K_\varepsilon\) is the filling coefficient of slots
- \(L_{enc}\) is the slots width

\[
\text{Figure 2. The motor heights of various constituting elements}
\]

To avoid the demagnetisation, the current of phase must be below \(I_{max}\)
\[
I_{max1} = \frac{P}{3 \mu_0 N_{sph1}} \left[ (B_{m1} + (1 + \alpha_m(t_a - 20)) - B_{c1})H_{a1} - \frac{B_{c1} \varepsilon_l \varepsilon_c}{\mu_0} \right] \\
I_{max2} = \frac{P}{3 \mu_0 N_{sph2}} \left[ (B_{m2} + (1 + \alpha_m(t_a - 20)) - B_{c2})H_{a2} - \frac{B_{c2} \varepsilon_l \varepsilon_c}{\mu_0} \right]
\]

With \(B_{c}\) is the minimum flux density allowed in the magnet and \(\mu_0\) is the permeability of the air

1.4. Diameter of the motor

The external diameter of the motor is expressed by the following formula:
\[
D_{ex} = D_{m1} + e_1 + 2(h_{c1} + h_{a1} + h_{c2} + h_{a2} + e_2 + h_{c2} + h_{a2})
\]

With:
- \(H_{ex}\) and \(H_{a}\) are respectively the stator yoke thickness and rotor yoke thickness
- \(h_{a}\) is the magnet height
- \(H_{c}\) is the main tooth height.
- \(e_{c}\) is the vacuum between rotor one and stator two

1.5. Power-to-weight ratio of the motor

The power-to-weight ratio of the motor \(P_m\) (W/Kg) is defined by the ratio of the electric power by the total mass:
\[
P_m = \frac{P_{em}}{M_{tot}}
\]

The total mass of the motor \(M_{tot}\) is the sum of masses of the statoric teeth \((M_{dt})\), of the inserted teeth \((M_{di})\), of the stator yoke \((M_{ct})\), of the copper \((M_{cu})\), of the magnets \((M_{am})\) and of the rotor yoke \((M_{cr})\):
\[
M_{tot} = M_{dt1} + M_{dt2} + M_{di1} + M_{di2} + M_{ct1} + M_{ct2} + M_{am1} + M_{am2} + M_{cr1} + M_{cr2}
\]

\(M_{dt1}\) and \(M_{dt2}\) represent respectively the teeth mass of the interior stator and the exterior stator.
\[
M_{dt1} = \frac{A_{tooth}}{2} \left[ \left( \frac{D_{m1} - e_1}{2} \right)^2 - \left( \frac{D_{m1} - e_1}{2} - H_{a1} \right)^2 \right] L_{m} M_{ct}
\]

\(M_{dt2} = \frac{A_{tooth}}{2} \left[ \left( \frac{D_{m2} - e_2}{2} \right)^2 - \left( \frac{D_{m2} - e_2}{2} - H_{a2} \right)^2 \right] L_{m} M_{ct}
\]

With:
- \(N_d\) is the total number of main teeth.
- \(M_{ct}\) is the density of metal sheets
\(M_{ct1}\) and \(M_{ct2}\) represent respectively the mass of the interior and exterior stator yoke.
\[
M_{ct1} = \frac{3 I_n}{\sqrt{2}} N_{sph1} L_{sp} M_{ct}
\]
\[
M_{ct2} = \frac{3 I_n}{\sqrt{2}} N_{sph2} L_{sp} M_{ct}
\]

Where:
- \(L_{sp}\) is the average length of a spire
- \(\delta\) is the current density admissible in the notches
- \(I_{n}\) is the rated current of the motor
- \(M_{ec}\) is the copper density

\(M_{dt1}\) and \(M_{dt2}\) represent the mass of the interior and external magnets.
\[
M_{dt1} = L_{m} L_{a} \left[ \left( \frac{D_{m1} + e_1}{2} + H_{a1} \right)^2 - \left( \frac{D_{m1} + e_1}{2} \right)^2 \right] M_{am}
\]
\[
M_{dt2} = p L_{m} L_{a} \left[ \left( \frac{D_{m2} + e_2}{2} + H_{a2} \right)^2 - \left( \frac{D_{m2} + e_2}{2} \right)^2 \right] M_{am}
\]

With \(M_{am}\) is the magnets density, \(M_{cr1}\) and \(M_{cr2}\) represent the mass of the interior and exterior rotor yoke.
\[ M_{di1} = \left[ \frac{D_{di1} + e_{i}}{2} + H_{di} \right] \ln M_{ri} \] (26)
\[ M_{di2} = \pi \left[ \frac{D_{di2} + e_{i}}{2} + H_{di} \right] \ln M_{ri} \] (27)

\[ M_{ds1} \text{ and } M_{ds2} \text{ represent the mass of the inserted teeth of the interior and exterior stator.} \]
\[ M_{di1} = \frac{M_{ds1} A_{di1}}{A_{dent}} \] (28)
\[ M_{di2} = \frac{M_{ds2} A_{dent}}{A_{dent}} \] (29)

2. Modelling by finite elements

The studied motor is rotated at its nominal speed at no load. In these conditions, the simple tension corresponds to the emf. The representation of the lines of field, obtained by simulation and represented on the following figure (3).

For different positions of the rotor in versus the stator, the incoming flux obtained by the machine winding is represented on the figures (4) and (5).

The figures (6) and (7) represent the electromotive forces forms at the level of the three phases followed the alimentation of the motor by a balanced current three-phase system.

\[ T_{\text{emf}}(\theta) = \frac{1}{\Omega} \sum_{i=1}^{3} E_{ii}(t) I_{i\text{ph}}(t) + \frac{1}{\Omega} \sum_{i=1}^{3} E_{2i}(t) I_{i\text{ph}}(t) \] (30)
Where, $E_i$ and $I_{phi}$ are respectively the electromotive force and a phase current.

The electromagnetic torques produced by the two rotors and the total torque of the machine are represented by the following figures.

![Figure 8. Electromagnetic torques of the interior and exterior rotor](image)

Figure 8. Electromagnetic torques of the interior and exterior rotor

![Figure 9. Electromagnetic torque of the motor](image)

Figure 9. Electromagnetic torque of the motor

The average value of the torque reaches the value fixed by analytical calculations, which validates this analytical dimensioning method.

3. Comparison between a motor with double rotor and a motor with one rotor

The following table presents the mass and the power-to-weight ratio of a motor with double rotor and a motor with one rotor for a variation of power of 19 kw to 95 kw.

<table>
<thead>
<tr>
<th></th>
<th>Power (kw)</th>
<th>Torque motor (Nm)</th>
<th>Mass (kg)</th>
<th>Power-to-weight ratio (kw/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor with double rotor</td>
<td>19</td>
<td>100</td>
<td>68.96</td>
<td>0.276</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>200</td>
<td>83.64</td>
<td>0.455</td>
</tr>
<tr>
<td></td>
<td>76</td>
<td>400</td>
<td>106.1</td>
<td>0.717</td>
</tr>
<tr>
<td></td>
<td>95</td>
<td>500</td>
<td>115.2</td>
<td>0.826</td>
</tr>
<tr>
<td>Motor with one rotor</td>
<td>19</td>
<td>100</td>
<td>40.11</td>
<td>0.474</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>200</td>
<td>67.87</td>
<td>0.561</td>
</tr>
<tr>
<td></td>
<td>76</td>
<td>400</td>
<td>122.5</td>
<td>0.621</td>
</tr>
<tr>
<td></td>
<td>95</td>
<td>500</td>
<td>149.7</td>
<td>0.636</td>
</tr>
</tbody>
</table>

If we make a comparison between the results obtained by calculation of the mass and the Power-to-weight ratio of the two motors for the same application and in identical state of use (fig 10 and fig 11)

![Figure 10. Mass of a motor with one rotor and of a motor with double rotor](image)

Figure 10. Mass of a motor with one rotor and of a motor with double rotor

![Figure 11. Power-to-weight ratio of a motor with one rotor and of a motor with double rotor](image)

Figure 11. Power-to-weight ratio of a motor with one rotor and of a motor with double rotor

We shows the advantage of a motor with double rotor compared to that with only one rotor on the level of power-to-weight ratio for the strong powers, this explains the benefit of using a motor with double rotor in the field of the electric traction.

4. Conclusion

The study consists in dimensioning a motor with double rotor of strong starting torque for an electric vehicle. Firstly an analytical sizing of the machine was carried out. Secondly a modeling by finite elements in dynamics to validate the waveform strongly depending on the machine geometry as well as the electromagnetic torque delivered by the motor. Finally a comparison between the motor with double rotor and the motor with one rotor.

REFERENCES


