Interior permanent magnet motors with non-overlapping concentrated windings or with integral slot windings for traction application

Abstract. These interior permanent magnet machines using integral slot windings or non-overlapping concentrated windings are designed for traction applications. Four direct drive traction motors are analyzed: two 25 kW motors and two 100 kW motors at rated speed of 1000 min⁻¹. Analytical computations are verified by finite element analysis utilizing Cedrat’s Flux2D. Concentrated tooth coil winding machines can be used also as traction motors and they can be designed to produce reluctance torque. The integral slot wound 25 kW motor has been built and measured.

Streszczenie. W pracy przeanalizowano cztery typy silników elektrycznych dla napędów trakcyjnych: dwa - 25 kW i dwa – 100 kW z prędkością znaniową 1000 min⁻¹. Obliczenia analityczne zostały zeryfikowane poprzez symulację komputerową za pomocą pakietu Cedrat Flux 2D. Silnik o mocy 25 kW został wykonany i pomierzony. (Silniki z wewnętrznym magnesem trwałym z nienachodzącymi na siebie uzwojeniami koncentrycznymi dla zastosowań trakcyjnych)

Keywords: non-overlapping concentrated winding, tooth coil, traction motor, reluctance torque.

Introduction

In this paper, interior permanent magnet machines using integral slot windings or non-overlapping concentrated tooth coil windings are designed and analyzed for traction applications. Nowadays, Permanent Magnet (PM) motors are often used in traction applications despite the slight difficulties to control the stator flux in the field weakening operation. A permanent magnet motor may be called also as synchronous reluctance motor because a PM motor can produce a significant amount of reluctance torque. This reluctance torque is produced due to the inductance difference between the direct and quadrature axes inductances and the stator current linkage. Power density is increased when adding interior permanent magnets to the reluctance machine. It was in the authors’ interest to study if the reluctance torque can be beneficial also when using non-overlapping concentrated windings.

Two 25 kW motors were designed in the same frame as rated speed was fixed to 1000 min⁻¹ for direct drive applications. Both motors should give at least 2 p.u. torques at low speed and approximately 0.6 p.u. at double speed. Analytical computations are verified by finite element analysis utilizing Cedrat’s Flux2D. A non-overlapping concentrated winding machine can be designed to have a large field weakening range and to produce a significant amount of reluctance torque. The integral slot 25 kW, 240 Nm motor has been built and measured, and, therefore, the theoretical computations are verified by real measurements. Another computation case was to build a traction motor for 100 kW. This traction motor has also the rated speed of 1000 min⁻¹, with the rated torque being appr. 1000 Nm. For this application also a concentrated wound and integral slot wound solution are presented and analyzed. In this paper the comparison and analysis of these four motors are discussed. [1-2].

Traction Motor Designs

Traction motor needs to produce a different amount of torque depending on the speed and, therefore, one should compute the loading through the speed area in which the field weakening occurs. A principal figure of the desired torque and power as a function of speed for a traction application is presented in Fig. 1 in per unit values. The supply voltage increases up to the rated voltage at speed of 1 p.u. and after that it will remain constant. The field weakening area can be found as the speed is higher than 1 p.u.

Fig. 1. Desired torque, available supply voltage and desired power as a function of speed.

At the lowest speed the torque needed is very high and the machine can benefit of its capability of producing reluctance torque. At the high speed range, to achieve a large field weakening, large enough p.u. inductances are needed to be capable of diminishing the stator flux linkage. [3-4]. Analytical calculation was based on the machine d-q axis model and the vector presentation. The results are verified by finite element analysis utilizing Cedrat’s Flux2D and also practical measurements of the prototype. The machine parameters are given in table I.

Table 1. Traction Machine Parameters

<table>
<thead>
<tr>
<th>Slots per pole and phase, q</th>
<th>1</th>
<th>0.5</th>
<th>1</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator slots, (\Psi)</td>
<td>48</td>
<td>24</td>
<td>42</td>
<td>24</td>
</tr>
<tr>
<td>Poles, (2p)</td>
<td>16</td>
<td>16</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>Power, (P) [kW]</td>
<td>25</td>
<td>25</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Frequency at 1000 (\text{min}^{-1}), (f) [Hz]</td>
<td>133</td>
<td>133</td>
<td>117</td>
<td>133</td>
</tr>
<tr>
<td>Length of the stator stack, (L_{s}) [mm]</td>
<td>65</td>
<td>65</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Stator outer diameter, (D_{sa}) [mm]</td>
<td>380</td>
<td>380</td>
<td>430</td>
<td>430</td>
</tr>
<tr>
<td>Stator inner diameter, (D_{si}) [mm]</td>
<td>287</td>
<td>287</td>
<td>330</td>
<td>330</td>
</tr>
<tr>
<td>q-axis inductance, (L_{q}) [p.u.]</td>
<td>0.4</td>
<td>0.33</td>
<td>0.3</td>
<td>0.47</td>
</tr>
<tr>
<td>d-axis inductance, (L_{d}) [p.u.]</td>
<td>0.3</td>
<td>0.28</td>
<td>0.24</td>
<td>0.4</td>
</tr>
<tr>
<td>Inductance ratio (L_{d}/L_{q})</td>
<td>1.3</td>
<td>1.2</td>
<td>1.3</td>
<td>1.2</td>
</tr>
</tbody>
</table>
The mechanical structures are shown in Fig. 2: a) the integral slot motor and b) the non-overlapping concentrated winding motor. The inductance parameters, shown in Table I, are computed with finite element analysis at the rated speed and at the rated current of 100 A and 160 A. The structure with two magnets was selected because of the strict mass limit of the machine. The big amount of poles and the double straight permanent magnet placement instead of a V-positioning result in some reluctance torque and as small stator and rotor yokes as possible. In case of 100 kW motor designs, only one magnet per pole is utilized in order to save manufacturing costs. Large dimensions result in large amount of materials and, therefore, saving must be done. The permanent magnet material has remanent flux density of 1.2 T, permeability of 1.05 and coercive force of 980 kA/m. The isotropic resistivity of permanent magnet is set to $1.5 \times 10^{-6}$ $\Omega$m. The steel material used is M270-35A.

![Fig. 2. a) Integral slot 25 kW motor with 48 slots and 16 poles, b) 25 kW tooth winding motor with 24 slots and 16 poles, c) 100 kW integral slot motor with 42 slots and 14 poles, and d) 100 kW tooth winding motor with 24 slots, 16 poles and open slots.](image)

The open slot in Fig. 2 d) for the non-overlapping concentrated wound motor yields to easier manufacturing and gives possibility to use pre-fabricated tooth coils and thereby aims to economical series production. When the non-overlapping concentrated wound motor is designed to have open slots, there will be a large dip in the flux density distribution as it can be seen in Fig. 3. The desired flux density and torque are sufficient regardless of this dip. It has been earlier noticed that high peak torque can be obtained also with open slots and embedded magnets [4-6].

![Fig. 3. Flux density in the air gap for concentrated wound motor having 24 slots and 16 poles (motor d in Fig 2).](image)

**Computation results**

A set of finite element analyses was performed to evaluate the characters of the motors. Finite element method has been used to get accurate computed values in the field weakening area in where the nonlinear effects may happen. The currents, inductances, losses and torques should be calculated as accurately as possible over the wide speed range. The torques are computed as a function of load angle at a low speed of 500 min$^{-1}$, at the rated speed 1000 min$^{-1}$ and at a high speed 2000 min$^{-1}$. The finite element computations are based on Cedrat’s Flux2D program package using transient analysis and magneto static computations.

<table>
<thead>
<tr>
<th>Slots per pole and phase, $q$</th>
<th>1</th>
<th>0.5</th>
<th>1</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>The amount of Copper, [kg]</td>
<td>10</td>
<td>6.5</td>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>The amount of Permanent Magnets, [kg]</td>
<td>4.7</td>
<td>4.7</td>
<td>7.4</td>
<td>8.2</td>
</tr>
<tr>
<td>Max. Flux density in teeth, [T]</td>
<td>1.65</td>
<td>1.9</td>
<td>1.9</td>
<td>1.65</td>
</tr>
<tr>
<td>Max. Flux density in yoke, [T]</td>
<td>1.5</td>
<td>1.3</td>
<td>1.3</td>
<td>1.15</td>
</tr>
<tr>
<td>Power, [kW]</td>
<td>25</td>
<td>25</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Peak Torque, [p.u.]</td>
<td>2.0</td>
<td>1.9</td>
<td>2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>3fIR losses, [kW]</td>
<td>0.7</td>
<td>0.6</td>
<td>2.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Iron losses, [kW]</td>
<td>0.24</td>
<td>0.25</td>
<td>1.1</td>
<td>0.6</td>
</tr>
<tr>
<td>PM losses, [kW]</td>
<td>0.05</td>
<td>0.4</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Additional losses, [kW]</td>
<td>0.4</td>
<td>0.4</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Efficiency (at rated point)</td>
<td>0.945</td>
<td>0.935</td>
<td>0.96</td>
<td>0.964</td>
</tr>
<tr>
<td>Tangential stress, [kPa]</td>
<td>30</td>
<td>30</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>

The 25 kW motors achieve 2.5 p.u. and the 100 kW motors 2 p.u. peak torques at 300 A current. The difference is because the 100 kW motors are designed to higher tangential stresses of 40 kPa and the 25 kW ones to 30 kPa. The material amount of the $q = 1$ motors is slightly higher than with $q = 0.5$ motors. Small savings of material can be made by suitable designing. The manufacturing cost of the 100 kW $q = 0.5$ motor makes it more interesting as it can utilize pre-fabricated tooth coils. [7].

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The iron losses were about the same range with the integral slot windings and with the concentrated windings. The $3 I^2R$ losses show some benefit for the concentrated windings having very short end windings. The $3 I^2R$ losses are dominating at the low speed range.

**Permanent magnet losses:** Losses in permanent magnets are caused by the eddy currents flowing through them. Eddy currents are caused both by permeance and stator harmonics. Therefore, at no load situation the magnet losses computed with finite element method are significantly smaller than the PM losses calculated under load, especially, when dealing with non-overlapping concentrated windings that produce large stator harmonics. In non-overlapping concentrated wound PM machines the magnets suffer from the eddy current losses due to the large amount of stator winding created harmonics. This is often solved neatly by using segmented magnets. [8-9]. The 25 kW integral slot wound motor has 50 W losses in the permanent magnets as the 25 kW concentrated wound motor has 400 W with similar bulky magnets. In the 100 kW machine with tooth windings the magnets are constructed of 10 segments – thereby the PM losses are about at the same level as when using integral slot windings and semi closed slots.

**Losses:** Fig 4. shows the torque and current values as function of speed for the non-overlapping concentrated wound 100 kW motor. Fig. 4 b) shows the iron losses, $3 I^2R$ losses and losses in the permanent magnets. These values are computed utilizing Flux 2D. Fig. 5 shows the torque and current values as function of speed for the 100 kW integral slot winding motor with 42 slots and 14 poles.

![Fig. 4.  a) Torque and current versus speed. b) Efficiency and loss distribution of the 100 kW integral slot winding motor with 42 slots and 14 poles.](image)

![Fig. 5.  a) Torque and current versus speed b) Efficiency and loss distribution of the 100 kW integral slot winding motor with 42 slots and 14 poles.](image)

The integral slot winding 25 kW traction motor was built and tested. Fig. 6 illustrates the test set up of the machine.

![Fig. 6. Test set up in the laboratory.](image)

According to the measurements the 25 kW motor fulfills the requirements set for it. The efficiency at the rated torque of 240 Nm and speed 1000 min$^{-1}$ was 94 % as the computed value is 94.5%. At start the peak torque of 700 Nm was achieved for some seconds. Otherwise, the computational results and the measurement results match very well.

**Conclusion**

Interior PM machine producing also reluctance torque using integral slot winding was compared to interior PM motor with concentrated tooth winding. According to the
finite element analyses there was an inductance difference between the direct and quadrature axes inductances also in the case of concentrated windings, which means that there can be reluctance torque when using concentrated winding, too. It can be concluded that both machines can be driven in the field weakening utilizing their large enough inductances. A 25 kW integral slot machine has been manufactured and measured, and it fulfills the requirements at different speeds. In future, also the 100 kW concentrated tooth winding traction motor will be also built and the results will be verified also by measurements.

REFERENCES


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