Influence of Slot Wedge Material on Permanent Magnet Losses in a Traction Motor with Tooth Coil Windings

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Abstract. Permanent magnet (PM) machines with tooth coil windings are designed and analyzed. We study how the slot wedge material affects the behavior of PM losses when using tooth coil windings, which generate a significant air gap flux density harmonic content. The losses and cogging torques of a surface permanent magnet rotor and an interior permanent magnet rotor are compared in no-load and load situations. A finite element analysis applying Cedrat’s Flux2D is made. Motors of this size can have high permanent magnet eddy current losses, and therefore, segmented magnets are often preferred even though interior magnets and semi-magnetic wedge material are used. The study shows that tooth coil windings may benefit from using semi magnetic material as a wedge material as it decreases the stator iron losses and, especially, losses in the permanent magnets.

Keywords: Interior permanent magnet machines, concentrated winding

1. Introduction

Permanent magnet (PM) synchronous motors are widely used in traction applications because they offer high efficiency, high power density, and an opportunity to control the stator flux in the field weakening operation. Field weakening is obtained by suitably selecting the direct axis inductance. Tooth coil windings are preferred, especially in several mobile applications because of their compactness, easy and low-cost manufacturability [1, 2]. In this study, the tooth coil windings under investigation are of the type that has the number of slots per pole and phase \( q \) equal to 0.5. In the literature, these windings are also called concentrated non-overlapping windings or fractional slot windings [1]. In principle, such windings are possible only in machines having very low conductivity rotors. After the winding work, motor slots are usually closed for instance with some glass-fiber-based wedge material, in order to prevent falling of the coils or interference caused by the air gap or the rotor. Glass-fiber wedges have been used for several years, and it has several advantages: it is mechanically strong enough, its relative permeability is equal to one, and it does not cause heat or other losses. Some other materials tested in closing of the slot opening are Magnoval, Somaloy and soft magnetic composite (SMC) materials [3,4]. The permeability of Magnoval varies between 2 or 3, and it depends on the amount of flux density. Magnoval is made of glass cloth, iron powder, and a high temperature resistant epoxy resin. SMC materials have a permeability even up to 850. [3,4] Hence, from the machine design perspective, these materials are advantageous as they can provide a path for the main flux. If SMC is used as slot wedge material an increased leakage flux will result. Consequently, the increased leakage flux (q-axis inductance) results in an increase in the reluctance torque. Because the d/q ratio determines the torque production capability of the machine, this also increases the maximum torque of the machine.

Donato et. al have investigated slot wedges in a \((q = 1)\) rotor surface magnet 10 kW axial flux machine in [5, 6]. They noticed that thick soft magnetic composite wedges (with a permeability of 500) produce high wedge losses and thereby increase the total losses of the machine, even though the PM losses are remarkably lower than those of open slot designs. Rotor losses of tooth-coil-wound PM motors have been studied in [7], including measurement verifications for a 12-slot-10-pole 1 kW axial flux surface PM machine. According to the study, the wedges with a higher permeability produce worse results as far as the rotor loss reduction is concerned (in the study, the permeabilities of 20 and 500 were tested).

There are several studies of PM losses in surface magnet machines [5-10], usually axial flux machine applications, but less of analytical computation methods for radial flux interior magnet motor. A comprehensive study of IPM vehicle rotor iron losses and eddy current losses is given in [11] in which also a fractional slot wound machine is studied in different driving conditions. A computation method for rotor losses is presented in [12]. A genetic algorithm is introduced in [13] to optimize a 4.5 kW IPM machine. For traction application it was in the authors need to have an interior permanent magnet motor and therefore some computations of slot behavior was needed. Our investigation focuses on a 110 kW radial flux motor losses when using an open slot design with or without Magnoval wedges. The
Magnoval material was chosen because of its low permeability (producing low leakage) and good mechanical properties.

2. Concentrated Non-Overlapping Winding PM Motor

A CNW machine provides high power density, high efficiency, short end windings, and a low cogging torque. In contrast, the end windings of a traditionally wound machine need more space leading to a larger copper volume and mass, and are less reliable because coils of different phases cross each other causing a higher risk of a short circuit fault. In addition, in a concentrated non-overlapping winding, the number of slots per pole and phase \( q \) is a fractional number. In a distributed winding, the fraction must be higher than 0.5, but in CNW machines, \( q \) can be equal to or less than 0.5, which leads to a large amount of spatial harmonics compared with rotating field windings with \( q > 1 \). In addition, CNWs can be arranged as single- or double-layer windings. In the latter case, the windings produce a lower spatial harmonic content [8]. Good performance is expected with embedded magnets, when the number of slots per pole and phase \( q \) is chosen close to 0.5. There is a correlation between the pull-out torque and \( q \) in the case of CNWs having permanent magnets. This method is introduced by [14]. In the author's previous investigations, it has been shown that most of the studied rotors with embedded permanent magnets give higher efficiencies than the rotors with surface magnets.

3. Methods

As a basis of all computations, generally known analytical computation methods and d-q-vector analyses are used. A set of finite element analyses were performed to evaluate the characteristics of several motor designs. The motor designs with surface-mounted magnets and interior permanent magnets. The machine is designed as a traction machine, where the torque demand in the low speed area can be 2–3 times the rated torque, and in the high speed area, field weakening is used. The wedge materials tested were glass fiber and Magnoval with permeability of 3 and 30. Glass-fiber non-magnetic wedge is used as reference wedge material: its relative permeability is equal to 1, and it does not cause heat or other losses, hence, the resistivity may be assumed to be infinite. Some other materials in closing of the slot opening are magnetic wedge with permeability from 1 to 850. Magnetic wedges having a permeability from 1 to 7 (e.g. Magnoval) are generally made of glass cloth (5-10%), iron powder (75%), and a high temperature resistant epoxy resin (15-20%). Their permeability depends on the flux density. Magnetic wedge material with as high permeability values as above 200 are called as soft magnetic composite (SMC) materials. In SMCs material the iron powder particles are separated with electrically insulated layer. These wedges have given maximum permeability’s as high as 850. [4] The advantages of magnetic wedges, when compared with nonmagnetic wedges, are lower stator temperature rise and reduced core losses, slightly higher motor efficiency, reduced inrush current and reduced noise level. The major disadvantage of magnetic wedges is that they are more susceptible to failure when compared with nonmagnetic wedges. Hence they are more brittle due to the high percentage of iron powder. In addition, for reciprocating-type loads, the magnetic wedges are subject to cyclic mechanical forces and fretting can occur, and the movement will slowly increase until wedge failure occurs. [15,16]

Dynamic computations were performed Cedrat’s 2D finite element method to get accurate computed values in the field weakening area, where nonlinear effects may take place [17]. In the dynamic computation, voltage sources were placed to the circuit model and time-stepping analyses were performed with several load angles. The eddy current losses in permanent magnets and iron losses were computed over one time period (during which the dynamic state stabilized) to obtain accurate results. There are simplified analytical models to compute the rotor losses; see for instance [18]. The rotor losses depend both on the specific wavelength and the harmonic order. It was shown in [18] that when the harmonic order number increases, the wavelength decreases, and therefore, it is not easy to determine the order of the current linkage harmonic, which causes the highest rotor losses. Analytical and finite element methods were combined in [8] in order to solve the rotor eddy-current losses of an axial flux rotor.

Calculations were performed for a 24 slot radial flux machine having 16 poles as shown in Fig. 1. This machine has an output power of 110 kW, and its speed range is up to 3000 min\(^{-1}\). The slot opening width is 60 % from the slot pitch. Solutions with interior and surface magnets (same amount of magnet material) are given in Figs. 1a and b, respectively. The wedge height is 0.07 of the stator yoke height, and the slot height is 0.65 of the stator yoke height. 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 the permanent magnet is set to \(1.5 \times 10^{-9} \text{ Ohm}\cdot\text{m}\). The steel material used is M270-35A.
Fig. 1 Geometries of the radial flux 110 kW traction motor. The motor design has 24 slots and 16 poles with a) interior magnets and b) surface magnets. The wedge material is indicated by the black diagonal lines. Interior magnet rotor geometry can’t be shown more detailed, because the work is for a company.

The harmonic content of these tooth-coil-wound machines is studied in detail to determine which losses may be generated as a result of harmonics. The harmonic content in the load situation consists of harmonics caused by the magnets, slots, armature, and the interaction of these all harmonics. Rotor based harmonics are explained in detail in [18]. The harmonics in the magnetic field can be computed according to [19] by

\[ i = (2n-1)p \]

where \( n \) is 1, 2, 3, … and \( p \) is the pole pair number. The harmonics in the armature reaction are obtained by

\[ j = nt \]

where \( t \) is the greatest common divider of the number of stator slots \( N_s \) and pole pairs \( p \). According to (1) and (2), the main harmonics for the 24 slot 16 pole machine are as given in Table 1. The slot harmonics may also be computed as

\[ k = N_s / 2pm \quad (m = 0, \pm 1, \pm 2, \pm 3, \ldots) \]

according to [20]. The control method will also generate its own amount of harmonics. Non-sinusoidal currents may increase losses of the machine [21]. Especially the permanent magnet losses are practically caused by the switching frequency and therefore not present in these FEA based computations.

| Harmonics of the 24-16 machines. Harmonics in the magnet field are denoted by \( i \), harmonics in the armature reaction by \( j \), and slot harmonics by \( k \). |
|---|---|---|---|---|---|---|---|---|---|
| \( i \) | 8 | 24 | 40 | 56 | 72 | 88 | 104 | 120 | 136 |
| \( j \) | 8 | 16 | 24 | 32 | 40 | 48 | 56 | 64 | 80 | 88 | 96 | 104 | 112 | 120 | 128 | 136 |
| \( k \) | 8 | 16 | 32 | 40 | 56 | 64 | 80 | 88 | 104 | 112 | 128 | 136 |

4. Computation results

To study the effect of slot wedges, a set of finite element analyses were performed for the radial flux machine. The comparison was carried out between the machine with an ordinary wedge material, like glass fiber, with a permeability of 1 and with the Magnoval wedge material. The material with permeability of 1 treated as it would be air in finite element computations. In addition, two different alternatives to mount the magnets were taken into consideration in the study; interior and surface mounting. The study was made for no-load and load cases, and the machine cogging torque and losses were analyzed.

**No-load:** The cogging torque calculated for the machine is presented in Fig 2. The figure shows that with the Magnoval wedges it is possible to achieve a lower cogging torque than with the ordinary wedge material. Similar results have been reported in [22].
The losses in the no-load case are presented in Table 2. The results in Table 2 show that the highest losses occur when using surface magnets with ordinary wedges, while the losses are lowest when using interior magnets with Magnoval wedges. The surface magnet loss level was expected, as the magnets are easily influenced by the stator harmonics i.e. winding and slot harmonics. The Magnoval material can reduce these losses. Instead, with air as the slot wedge material, the losses caused by permanent magnets are twice as high compared with the losses when Magnoval wedges are used. However, it is emphasized here that these results are obtained by finite element 2D computations, which may differ slightly from 3D computations (and actual measurements.) [23].

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Interior</th>
<th>Interior</th>
<th>Surface</th>
<th>Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wedge</td>
<td>Magnoval</td>
<td>Air</td>
<td>Magnoval</td>
<td>Air</td>
</tr>
<tr>
<td>Magnet losses, W</td>
<td>220</td>
<td>570</td>
<td>4900</td>
<td>12200</td>
</tr>
<tr>
<td>Stator iron losses, W</td>
<td>590</td>
<td>590</td>
<td>920</td>
<td>840</td>
</tr>
<tr>
<td>Rotor iron losses, W</td>
<td>290</td>
<td>350</td>
<td>30</td>
<td>300</td>
</tr>
<tr>
<td>Induced voltage, V</td>
<td>246</td>
<td>244</td>
<td>262</td>
<td>236</td>
</tr>
</tbody>
</table>

**Load:** The losses in the rated point of traction motors are presented in Table 3. This rated point is assumed to be at the speed of 1 p.u. and at 1 p.u. torque production as the shaft power is 110 kW. As one may predict, the PM losses are higher with the motor having no Magnoval wedges. Interior PM solutions have lower PM losses than surface magnets. Because the surface magnets caused as high losses as 11 kW at rated load, there was no reason to compute them with 2D at higher speeds, because such losses are out of real utilization. The permanent magnets in this study are bulky magnets, and not segmented. However for practical application or in future for the prototype motor segmented magnets may be utilized in order to get high efficiency. Magnets that are buried inside the rotor are better protected against harmonics [23,24]. PM losses can be minimized for instance by burying the magnets deeper as in the V-magnet shape rotor or by segmenting the magnets. In this case the iron losses in the stator and rotor of the interior and surface structures are approximately the same; the only difference is that they are divided differently into the rotor and stator areas as can be seen from Table 3.

<table>
<thead>
<tr>
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<th>Surface</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Wedge</td>
<td>Magnoval</td>
<td>Air</td>
<td>Magnoval</td>
<td>Air</td>
</tr>
<tr>
<td>Magnet losses, W</td>
<td>3900</td>
<td>6600</td>
<td>6800</td>
<td>11000</td>
</tr>
<tr>
<td>Stator iron losses, W</td>
<td>850</td>
<td>870</td>
<td>1060</td>
<td>1150</td>
</tr>
<tr>
<td>Rotor iron losses, W</td>
<td>330</td>
<td>480</td>
<td>120</td>
<td>240</td>
</tr>
</tbody>
</table>

The interior PM machines were analyzed as speed varied and the torque and output power were set according to customers application demands. For the application 2.5 p.u. torque is needed at start up and 110 kW output power is
needed at speed range from 1 to 2 p.u. speed as seen in Fig. 3. Fig. 3 depicts the PM losses in interior magnet machines as a function of speed. The wedge material ($\mu = 3$) is damping these losses over the whole speed area, and at the 1 p.u. speed, the difference between the Magnoval $\mu_r = 3$ and air $\mu_r = 1$ as the wedge material is at largest. As the speed increases, the difference becomes smaller. The PM loss curves are inversely proportional to the power curve above the 1 p.u. speed (the rated voltage level is reached at the 1 p.u. speed). Losses caused by the permanent magnets are proportional to the square of frequency and currents, as explained in [23,24]. The total loss caused by the eddy-current density according to [23] is

$$P_{PM,k} = J_{0,PM,k}^2 \frac{\delta_{PM,k}}{2}$$

in where $k$ the harmonic order number, $J_{0,PM,k}$ is the current density on the surface and $\delta_{PM,k}$ the depth of penetration. The depth of penetration in permanent magnet is proportional of the frequency and may be computed as [23]

$$\delta_{PM,k} = \frac{2\rho_{PM}}{\omega_{PM} \mu_0 \mu_{r,PM}}$$

in where $\rho_{PM}$ is resistivity of magnets and $\omega_{PM}$ is angular frequency of magnets. From 0 speed to rated speed of 1 p.u. the losses due to permanent magnets are increasing. Reasons for this behavior are: The needed current is high at low speed, the supply voltage (integral of flux linkage) is increasing from 0 to rated voltage as speed increases from 0 to 1 p.u. speed and also the frequency is increasing too. The currents are presented as a function of speed in Fig. 4. The iron losses are also smaller when using this wedge material, as can be seen in Fig. 5.
When looking at the flux density waves, depicted along the air gap radius (Fig. 6 and Fig. 7) in the load situation, we can see the difference between the Magnoval and air wedges. Fig. 6 shows the flux density waves of the interior motor at the 1 p.u. speed and 110 kW power with the wedge materials having permeability of 3 and permeability of 30, and with no wedge (air). There are deep dips in the flux density waves caused by the slot openings. The dip is deeper with slots having no wedge material. One may notice that wedge material with permeability of 30 will decrease useful flux. That is, why this material would cause too low torque in real motor. In Fig. 7 the waves are shown at the speed of 2.7 p.u., where the PM losses have a smaller difference. The base harmonic, the harmonic number 1 (for the 24 slot 16 pole machine), has a flux density normal component of 0.77 T at the speed of 1 p.u. and 0.52 T at the speed of 2.7 p.u.
Winding, armature reaction, and slot harmonics can be seen from the spectrum taken from the flux density distribution (Fig. 8 and Fig. 9). The flux density normal component is calculated along the air gap, and spectral analyses are performed. From the rated load flux pattern presented in Fig. 8, we can see the base harmonic 8 and several harmonics, of which the slot harmonics (in Table I, \( k \) is 8, -16, 32, -40, 56, -64, 80, -88, ...) can be seen to be present. The amplitude of the flux density normal component is clearly lower with the Magnoval wedges than with the machine with open slots, when the \( j \) and \( k \) harmonics are present; that is, 16, 32, 64, 80, 96, 112, and 128.

Fig. 8 Flux density harmonics at the rated load at the speed of 1500 min\(^{-1}\).

Fig. 9 depicts the spectral analysis of the 24 slot 16 pole machine with open slots (permeability 1 in the slot opening). A special finite element computation from [9] was performed to solve the winding harmonic content. In this computation, \( B_r \) of the magnets is set equal to zero and the machine is rotated at the rated speed. Thereby the winding-harmonics-caused and permeance-harmonics-caused can be studied separately even though this approach may also lead to erroneous result because different harmonic components may either strengthen or weaken or even cancel each other. [9] The spectral analysis shows that the winding harmonics are higher than the load harmonics at the numbers of 16, 88, 104, 120, and so on.
density analysis showed that the Magnova material damped the flux variation caused by the slot opening. The flux material decreased the iron losses and losses caused by permanent magnets especially around the rated speed. The flux density analysis showed that the Magnova material damped the flux variation caused by the slot opening.

5. Conclusion

It was shown that tooth-coil-wound traction motors benefit from using the Magnova wedge material. The wedge material decreased the iron losses and losses caused by permanent magnets especially around the rated speed. The flux density analysis showed that the Magnova material damped the flux variation caused by the slot opening.

References