Comparison Study of Permanent Magnet Transverse Flux Motors (PMTFMs)
For In-Wheel Applications

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Abstract—This paper investigates the existing structures of transverse flux machines (TFMs) that can be constructed as an outer rotor in-wheel motor which is suitable for low speed applications. As the main characteristic of TFM is providing the best torque density at low speeds, it would be a suitable choice and having a great future for low speed mobile platforms. Different structures of TFM are re-designed as outer rotor motors with the same diameter, axial length and pole number and they undergo a comparison study through the use of three dimensional (3D) finite element method (FEM). The simulations have been done via Flux3D software from Cedrat. An analytical study of the TFMs is done in terms of highest torque production capability and design optimisation.

Keywords—Transverse flux machine; in-wheel motor; U-core; I-core; twisted core; flux concentrated; surface permanent magnet

I. INTRODUCTION

Designing and developing more efficient and reliable electric motors that are directly mounted inside the wheels as so-called in-wheel motors, is becoming a target of electric vehicle researchers. The in-wheel motor itself is mainly considered to be of a higher efficiency compared to the conventional motor due to the riddance of transmission, drive shafts, differential gears or other complex mechanical components. Moreover, integrating motors into the wheels will improve the vehicle stability since each wheel will be driven independently and such integration save as well masses of space and weight, which offer improvement possibilities in terms of the body design of the vehicle.

Different types of electric motors have already been designed and optimised for in-wheel applications. Some of them are designed for high speed applications, e.g. electric vehicles and others for low speed employments such as small passenger electric cars [1-3]. An axial flux in-wheel PM motor for solar-powered electric vehicle has been designed in order to produce 1800 W at mean speed of 1060 RPM and with peak torque of 50.2 Nm [4]. An optimal design of an axial-flux permanent magnet (PM) brushless dc motor that is suitable for direct-driven wheel applications appears in [5]. The motor serves a low rated speed of 500 RPM for a rated torque of 30 Nm. A salient pole axial-gap PM motor has been patented for in-wheel applications, which applied to a direct coupling type drum washing machine in [6].

Permanent magnet TFM is claimed to exhibit a higher torque density compared to induction motor, switched reluctance motor, brushless dc motor and normal PM synchronous motor. The main attractive characteristic of TFM is its high torque density capability at low speeds. In TFM, the flux enters segments of stator core in transverse i.e. perpendicular to the direction of rotor movement in the cross section plane, therefore, it is called transverse flux machine. Fig. 1 illustrates the idea of the TFM operation that can be classified into two well-known categories, surface permanent magnet, SPM-TFM and flux concentrated permanent magnet, FCPM construction. In SPM-TFM, the PMs are radially magnetised with alternating polarities and are placed near each other on a surface of soft magnetic material as obviously identified in Fig. 1.a. The FCPM-TFM has PMs, which are circumferentially magnetised with alternative polarities too and their flux is concentrated via soft magnetic poles placed between the PMs. Fig. 1.b demonstrates the flux concentration topology.

The incorporation of TFM as an in-wheel motor has become more in focus from the researchers as more sophisticated development of high speed power electronic devices came to the market. Many researchers are currently involved in the design of PMTFM based propulsion systems [7]. A 3-phase TFM with SMC materials is designed to work...
as an outer rotor of rated torque 3.67 Nm and at high rated speed of 1800 RPM [8]. A prototype of transverse flux permanent magnet motor wheel drive is reported in Italy [9], where increase in total torque is achieved through implementing an optimised C-form arrangement. Different design criteria have been exploited in [10] to propose a new configuration approach that improves the torque of FCPM-TFM in order to achieve a compact radial structure. Two-phase in-wheel TFM has been designed based on flux concentrated topology for a lawn mower of a low transport speed of 143 RPM and a nominal torque of 150 Nm. Only one phase has been constructed of this machine [11].

This paper evaluates four different structures of TFM that are designed as outer rotor in-wheel motors for low speed vehicles. Two of these constructions belong to surface permanent magnets topology [12]. Another two structures associated with flux concentrated topology [13-15]. The reason behind the chosen structures is, because they have already been documented as built machines to give high torque values at low speed and they are considered to be the simplest from construction point of view for TFMs [15].

II. COMPARISON OF SPM-TFMS

A. Structure Description

In SPM-TFM, the PMs are magnetised in a direction perpendicular to the direction of the rotor movement. Only two pole pitches, \(2\tau_p\), of two different constructions for SPM-TFMs under the study are shown in Fig. 2. In one case the stator consists of one U-core that lies over \(2\tau_p\) of the rotor. The rotor has surface back element of soft magnetic material, where four PMs of alternating polarities are fixed on it. Each two of the PMs are located opposite to each other as shown in Fig. 2.a. The other structure of SPM-TFM has U- and I-cores that are located in the stator, while the rotor back element in the rotor is split into two parts as can be seen in Fig. 2.b. The winding is toroidal and is placed inside the U-cores and circulated around the stator. The windings are not shown on the figures for simplicity.

B. Magnetostatic Study (Electromagnetic Torque)

Generally, the total torque produced in TFM is of three components: cogging, reluctance and interaction torque. Cogging torque component is the attraction force that occurs between the active PMs in the rotor and the soft magnetic parts of the stator as the stator coil is not excited. The reluctance torque component, is the force due to the attraction force between the soft magnetic parts in stator and rotor that faces the air gap i.e., due to saliency. The interaction torque component is that due to interaction force between the magnetic field of armature current and that of PMs in the rotor.

The torque simulations for the two constructions via Flux3D [16] are shown in Fig. 3. These machines can be operated as two- or three-phase, so that the machine can be set in operation. The simulations are done for one phase and plotted over one \(\tau_p\). Two different materials have been implemented for the stator cores and rotor back elements. In the first case, the permeability is set to be constant, defined as a linear magnetic material, and in the second case, non grain oriented electrical steel, M400-50A [17], is being utilized. Thirty six NdFeB magnets are used in each side of the rotor for each construction. TFM with only one U-core will give the same torque values for both the materials as shown in Fig. 3.a. Through observing the torque difference along with utilization of linear and non-linear materials, it can be deduced, when the machine will enter the saturation region. SPM-TFM with U- and I-cores will enter the saturation, when the rotor movement achieves 10% \(\tau_p\), as shown in Fig. 3.b. It is obvious that the SPM-TFM with U- and I-cores gives more torque than those
of only U-core, when both the machines are supplied with the same supply. This phenomenon can proof itself through studying the flux path route. Considering two pole pitches, the flux of the four PMs in SPM-TFM with U- and I-cores, will always be utilized as the rotor moves over the PMs, while half the number of the PMs will be useful for the torque production in SPM-TFM with one U-core over $2\tau_p$. Therefore, the cogging torque component is smaller for SPM-TFM with one U-core compared to the SPM-TFM with U- and I-cores. The reluctance torque in each case of SPM-TFM has no effect on the total torque since there are no soft magnetic poles on the rotor that face the air gap.

C. Effect of PM Height Variation

The permanent magnet height effect on torque production capability has been studied. This study is shown in Fig. 4 for the interaction and cogging torques. Based on surface magnet topology with using U-cores in the stator as shown in Fig. 4.a, the increase in the height of the permanent magnet will cause a significant increase in the interaction torque till this height reaches a limited value where any further increase will cause a reduction in the output torque. The dominant effect of the PM flux or/and the leakage flux will decide the maximum value of the output torque.

As the radial length of the PM increases, the increase of the PM flux will be dominant, therefore, the torque will rise until the leakage flux will have the dominant influence and the major part of the flux produced by the PMs rather than crossing the air gap into stator poles, it will prefer the short path from one PM to the nearby PM, then back again through the back element. Thus, a reduction in average torque will take place. It is worth to be mentioned here that the torque is a function of flux per pole, $\Phi$, the leakage factor, $K_{k_p}$, the equivalent PM current, $I_m$ and the torque angle, $\theta$, [11], which can be expressed as in (1).

$$T = \frac{p}{2} \times (p \times \Phi \times K_{k_p}) \times I_m \times \cos(\theta)$$  

(1)

where, $p$ is the number of pole pairs and $K_{k_p}$ is of a value less than one and it is defined as the ratio between the flux on the bottom bar of U-core that links all the turns of the winding and the flux per pole in the air gap.

The cogging torque will increase as the PM length increases. This increase will continue until the attraction force raise has no significance on the stator poles, because the area of the PM facing the air gap area will get smaller as the PM length increases. Therefore, a compromise between low cogging and high interaction torques will guide the designer to choose the optimal height of the PM.

The effect of increasing the height of the PM on the interaction and cogging torques for SPM-TFM with U- and I-cores is shown in Fig. 4.b. This increase will lead to an increase in both torque components as in the case of TFM with only U-cores. However, a limit in PM height is reached after which constant torques start to occur. At these values, the flux still finds its closed path via crossing the stator cores and since the rotor back element is of divided segments, this will be the only way for PM flux to complete its path. The leakage flux will not cause any reduction effect. The core material used for this study in both constructions is of linear BH characteristics.

Summaries of these results are shown in Fig. 5, where the average interaction torque is plotted as a function of PM height as the machines operate in the linear region of the BH curve and as they are constructed of the material M400-50A. The plots are for 2- and 3-phase SPM-TFMs. The 3-phase average torque is naturally higher than that for 2-phase machine as can be depicted from the figure. As shown in Fig. 5.a, the average torque reaches its maximum value as the height of PM approaches 3 mm for SPM-TFM with U-cores. The constant value of average torque is seen in Fig. 5.b, for SPM-TFM with U- and I-cores. In order to make use of the PM material for the later configuration, it is recommended that the height of PM not to be more than 5 mm.

III. COMPARISON OF FCPM-TFMS

A. Structure Description

In FCPM-TFM, the PMs are magnetised in a direction parallel to the winding and the direction of the rotation. Fig. 6 shows two constructions of FCPM-TFM. Fig. 6.a. shows FCPM-TFM with U-core and two inclined I-cores located for the stator. Inclination in the stator I-cores have been done to reduce the leakage flux paths that take place between the end corners of the I-cores and the U-cores. Poles of soft magnetic
material, which are also called flux-concentrated poles, FC-poles, are inserted between each two PMs that are of alternative tangential magnetisation polarities. A combination of two PMs and two FC-poles that are placed on two layers facing each other will form $2\tau_p$ of the rotor. The PMs in each layer are of alternative polarities and the polarities of the PMs in both layers are opposite to each other.

The second construction belonging to FCPM-TFM is shown in Fig. 6.b with twisted stator U-core that covers $2\tau_p$ of the rotor. The PMs and FC-poles in the rotor are made equal to the axial length of one phase of the machine. The circular coil passes through the U- and the twisted cores in both constructions. Apparently, the coil dimensions will be limited in terms of FCPM-TFM with U- and inclined I-cores.

B. Magnetostatic Study (Electromagnetic Torque)

By comparing FCPM-TFM with twisted U-core with a TFM with U- and inclined I-cores, the TFM of twisted stator core gives the higher torque than that with U- and inclined I-cores as clearly observed in Fig. 7. That is because most of the flux will link the coil and the leakage flux will be reduced through the usage of twisted U-cores. The peak value of the phase torque, when a material of linear BH characteristics is used, for FCPM-TFM with U- and inclined I-cores as shown in Fig. 7.a is $\approx 125$ Nm while its corresponding value reaches $\approx 185$ Nm for TFM with twisted core as presented in Fig. 7.b.

Contradictory to SPM-TFM, the reluctance torque will have an effect on the total torque produced by FCPM-TFM. This torque component has a smaller effect for TFM with
twisted U-core, when the material of linear BH characteristics is used. The cogging torque waveform of TFM with twisted U-core will have as well smaller maximum value for the two implemented materials. The dimensions of the four simulated machines are shown in Table I. Note that the axial length of FCPM-TFM with twisted U-cores is less than that of FCPM-TFM with U- and inclined I-cores by ≈34.6%.

C. Effect of PM Height Variation

In a similar manner, the effect of the PM height has been studied for FCPM-TFM for the two constructions as it has been conducted for SPM-TFMs, for materials of linear and non-linear BH characteristics. The results are shown in Fig. 8. As the height of the PM increases, the average torque of FCPM-TFM with U- and inclined I-cores is of continuous increase as obtained from Fig. 8.a. for the linear case.

### TABLE I. MACHINE DIMENSIONS

<table>
<thead>
<tr>
<th>General Machine Dimensions (mm)</th>
<th>Pole pairs number*</th>
<th>Air gap diameter</th>
<th>Pole pitch, τp</th>
<th>Air gap length</th>
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<tbody>
<tr>
<td></td>
<td>18</td>
<td>207</td>
<td>18.06</td>
<td>0.8</td>
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<table>
<thead>
<tr>
<th>SPM-TFMs Dimensions</th>
<th>Height (radial direction)</th>
<th>Width (circumferential)</th>
<th>Length (axial direction)</th>
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<tbody>
<tr>
<td>U-core</td>
<td>52</td>
<td>12</td>
<td>52</td>
</tr>
<tr>
<td>I-core</td>
<td>15</td>
<td>12</td>
<td>52</td>
</tr>
<tr>
<td>PM</td>
<td>4</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Yoke of U-core</td>
<td>15</td>
<td>12</td>
<td>17</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>SPM with U-core</th>
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<tbody>
<tr>
<td>Back element</td>
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<tr>
<td>Stator slot</td>
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</table>

<table>
<thead>
<tr>
<th>SPM with U- and I-cores</th>
<th>Height (radial direction)</th>
<th>Width (circumferential)</th>
<th>Length (axial direction)</th>
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<tr>
<td>Stator slot</td>
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<td>22</td>
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<table>
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<tr>
<th>FCPM-TFMs Dimensions</th>
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<tbody>
<tr>
<td>FCPM-TFM with U- and inclined I-cores</td>
</tr>
<tr>
<td>PM</td>
</tr>
<tr>
<td>Rotor pole</td>
</tr>
<tr>
<td>U- and I-core</td>
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<table>
<thead>
<tr>
<th>FCPM-TFM with twisted U-core</th>
<th>PM</th>
<th>Rotor pole</th>
<th>Yoke</th>
<th>Shoe</th>
<th>Side</th>
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<tr>
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<td>10</td>
<td>9.4</td>
<td>20</td>
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<td>44</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Pole pairs number*</td>
<td>Number of pole pairs on one side of the rotor</td>
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<td></td>
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</table>
The reluctance torque is eliminated in SPM-TFM as there are no soft magnetic poles in the rotor that face the air gap. The effect of this component of the torque is significant in FCPM-TFM due to FC-poles that faces the air gap and will be attracted to the soft magnetic poles in the stator when the machine is excited by the current. TFM with twisted U-cores will exhibit a smaller reluctance torque compared to FCPM-TFM with U- and inclined I-cores, when the machine is mainly not saturated.

The smallest cogging torque component produced in SPM-TFM with U-cores, since half of the magnets will be useful as the rotor rotates. By comparing the cogging torque of the two constructions of FCPM-TFMs, the FCPM-TFM with twisted U-cores will be of a smaller value because the total area of the soft magnetic material of the stator poles which face the air gap is smaller than that in FCPM-TFM with U- and inclined I-cores, therefore, the attraction force will be smaller and as consequence, the cogging torque will be reduced.

The height of the permanent magnets can be increased with a limit. Beyond this limit, any increase in its radial height will be a waste of the PM-material used in TFM constructions. The leakage flux has an obvious effect on the average torque production in SPM-TFM, which will limit its maximum value despite the increase of PM height. The effect of the leakage flux causes either a reduction in the average torque as in SPM-TFM with U-cores or a constant average torque as in the case of SPM-TFM with U- and I-cores, when the machine operates in the linear region of the BH curve. Moreover, the average torque will be of a constant value, when the SPM-TFM operates in the saturation region of the BH curve, as has been shown for SPM with U- and I-cores.

The increase on the height of the PM for FCPM-TFM will cause an increase in the average torque as long as the machine operates on the linear region of the BH curve of the material. Otherwise, the average torque will not change after a certain increase of the PM height. This phenomenon appears earlier with FCPM-TFM with twisted cores compared to FCPM-TFM with U- and inclined I-cores. The increase of the PM height in FCPM-TFM has the same effect of increasing the flux concentration factor that is defined as the ratio of the PM area that touches the flux concentrating pole to the area of the PM that faces the air gap, which should be of a value greater than one as this comes consistent to what has been proved in [15].

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