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Transverse flux machines as an alternative to radial flux machines in an in-wheel motor

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Abstract

This paper considers the use of Transverse Flux Machines (TFMs) as an alternative to Radial Flux Machines (RFMs) in an in-wheel application for an electric vehicle. The base motor is an existing outer rotor surface mounted permanent magnet machine with fractional slot concentrated windings and liquid cooling.

Two topologies of TFM are compared against this base machine. The first topology is a Mutual Flux-path (TFM-MP) while the second is a claw pole machine (TFM-CP). Firstly, the proposed TFM topologies are studied using FEA to understand the torque capability of both topologies. Secondly, a comparison between two different pole numbers of each topology is compared with the performance of the Benchmarking machine (BMM). The machines will be compared in terms of torque density, losses, efficiency and power factor. Lastly it is presented a comparison on the torque capabilities when constraining the magnet mass.

It is shown that the Transverse Flux Machines selected can deliver higher torques than the base motor during continuous operation, but have failed to deliver the required overload torque. Furthermore, low power factor and low efficiency makes these machines unsuitable for the application of this in-wheel traction motor.

1 Introduction

In-wheel motors have been developed for the automotive market because they can provide a direct drive transmission system. As the motor is mounted directly in the wheel, gears, drive shafts and differentials are all eliminated, see Figure 1 the reduction in rotating parts can contribute to an increase in reliability. Although the in-wheel motor increases the vehicle unsprung mass, this causes minimal steering and handling issues if the suspension system is designed to suit, whilst the removal of other components gives overall efficiency, weight and complexity gains. Control using true torque vectoring at each wheel, electronic differential, traction control and more efficient regeneration braking are inherent and usually software controlled. In addition, the integration of motor and inverter into the wheel also frees up extra space in the vehicle to be used in other ways.

Figure 1: Protean integrated drive

This work is focused on the increase of torque density of the in-wheel motor. Previous work on this machine has been related to cost reduction [1], demagnetization analysis [2] and fault tolerant performance [3]. This paper considers replacing the existing design with a Transverse Flux Machine (TFM), a topology well known for high torque-density at low speed [4].

In recent years, several researchers have considered the use of TFMs for direct drive or in-wheel applications using analytical and FEA methods[5]–[7]. In this paper, results were obtained from 3D FEA.

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The paper describes two types of TFM which have been developed during this work. One of the topologies uses traditional stator teeth and is described as a modulated pole TFM (TFM-MP), while the second uses claw poles (TFM-CP).

2 Benchmarking machine

The benchmark design is an existing outer rotor surface mounted permanent magnet machine [1]. This machine has been manufactured and extensively tested on both dynamometers and in road vehicles. Hence it is well characterised. Per unit values of torque are scaled to this machine. The benchmark machine produces very high torque density, but it is insightful to investigate whether other topologies can be even more torque dense. Two critical points of operation have been chosen for design comparison: continuous steady state and short term overload.

Dimensions of the proposed machines are constrained by the stator inner diameter and rotor outer diameter of the actual benchmarking machine as well as the overall stack length. In a TFM there are no end windings in the axial direction, so the active axial length of this topology has been increased to give the same total length in both cases. Design constraints can be seen in Table 1.

Table 1: Design Constrains

Design Constrains	
Continuous DC voltage supply [V]	320
Discontinuous DC voltage supply [V]	400
Base speed [rpm]	800
Top speed [rpm]	1600
Axial length [mm]	71
Outer diameter [mm]	386
Inner diameter [mm]	302
Continuous Current Density (RMS) [A/mm^2]	19.4
Discontinuous Current Density (RMS) [A/mm^2]	51

The Benchmarking machine operates at a nominal speed of 800 rpm with a maximum speed of 1600 rpm. The machine operates at a rated current of 19.4 A rms with an overload operation point at 51 A rms. Maximum torque at overload condition is double that at continuous operation.

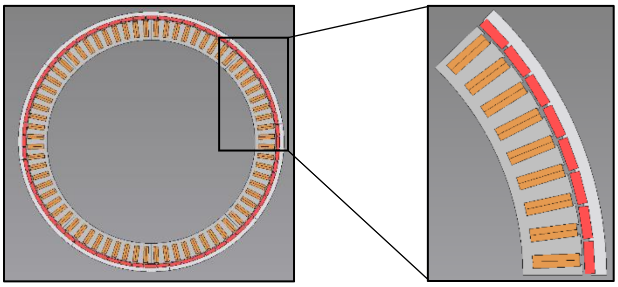

Figure 2: 2D model of the Benchmarking machine

This paper will investigate the proposed TFM topologies and compare their torque capability against the benchmarking machine, which will be subsequently referred to as the BMM.

3 Transverse Flux Machine

Transverse flux machines have already been studied as an alternative to radial machines for automotive applications, as can be seen in [4], [8]–[10].

A three phase TFM generally comprises three separate stator phases, with phases separated from each other by an axial gap and displaced 120° electrical. Due to restrictions in space for an in wheel machine, this topology is not ideal as the axial separation has to be large enough to avoid magnetic coupling and leakage flux between the phases, decreasing the space available for the active length of the machine. For this reason, a mutual flux paths topology was chosen in this work. This topology combines all three phases together, using all the axial space which is available. By combining the three phases, each of them is able to link more flux and hence offer higher torque than a separate phase machine [11], [12]. A single pole pair of a combined three phase machine is shown in Figure 3.

A parametric 3D FEA model was created using the package “JMAG”, modelling a single pole pair using the volumetric constraints. The rotor contains the magnets in a flux focusing position, with an SMC pole piece between poles.

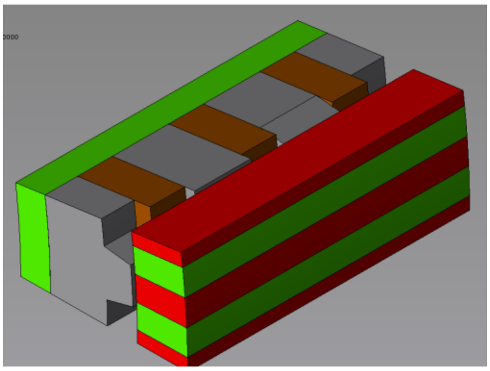

Figure 3: 3D model of the TFM-MP

For a fixed volumetric envelope, transverse flux machines offer an advantage over regular radial machines as there is no space competition between the flux path and the current carrying coil. The coil magneto motive force (MMF) is seen by all of the poles, hence an increase in pole number will lead to an increase of the electric loading. As torque is proportional to volume, magnetic loading and electric loading, an increase in electric loading and a strong magnetic loading leads to high torque densities [13]. As stated in the literature, and confirmed in the FEA predictions of Figure 4, the increase of pole number brings an increase in torque, however leakage and saturation in the teeth affect higher pole numbers / smaller pole pitches.

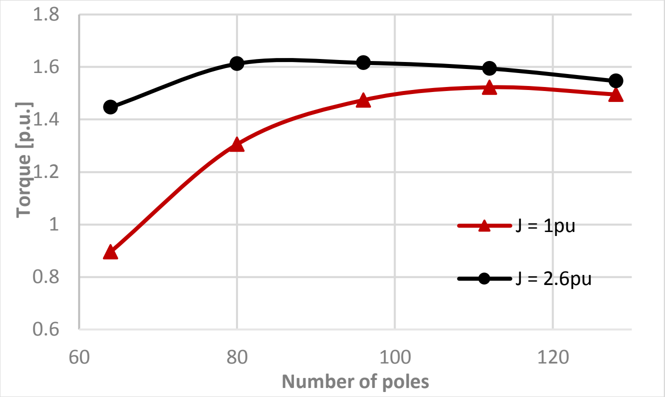

Figure 4: Peak torque for different pole number at different current densities

Figure 4 shows the predicted peak torque for machines at rated (1 per unit) and overload (2.6 per unit) current densities. When using rated current density, there is an increase in the torque with an increase in the pole number. For the same volume, the TFM-MP can deliver close to a 40% higher torque.

As the number of poles increases, the distance between rotor pole faces and the distance between stator teeth decrease, allowing a bigger amount of flux to leak to the next pole instead of following its design path. As shown in Figure 5, this reduces the increase on torque for high pole number and makes it constant (after 128 poles, torque increase per pole tends to a constant value).

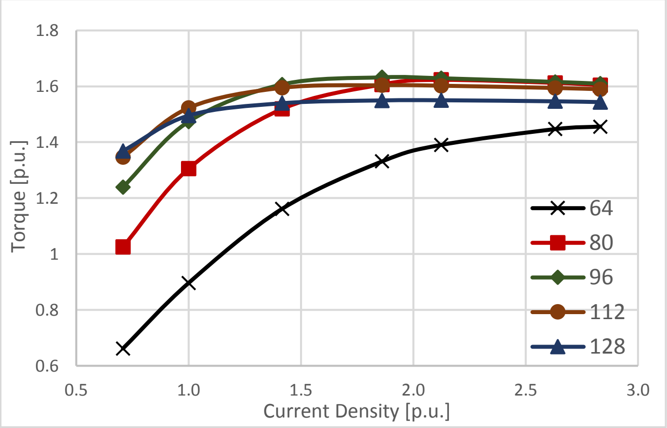

Figure 5: Peak torque against current density for different pole number

For the same pole number, increasing the current density increases the torque until saturation occurs. Higher pole numbers tend to give greater torque at low current density, but offer no improvement at higher current density. This is because they have more leakage flux and saturate at a much lower electric loading

4 Claw pole machine

As previous results showed, the TFM-MP can deliver higher torque than the BMM machine during steady state operation, but not during overload. Due to the volume constraints, it is not possible to simply increase the size of the laminations to increase the torque. One solution to overcome this problem is to attempt to reduce the leakage flux using a Claw Pole topology.

Claw pole machines are widely used in the automotive industry as the preferred topology for alternators and have previously been proposed in Transverse flux machines as seen in [14], [15], [16].

Unlike the TFM-MP, the phases of this machine are separated by a small gap big enough to avoid unwanted coupling between the phases. The same flux focusing rotor as in the TFM-MP was used, as shown in Figure 6.

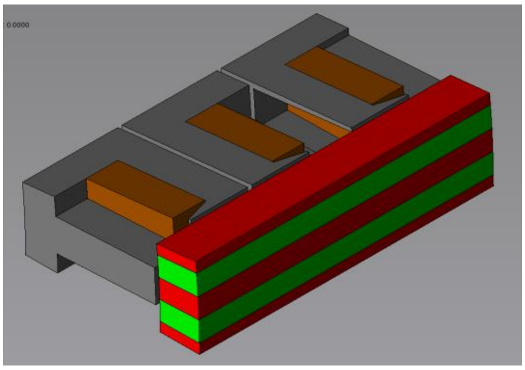

Figure 6: Claw Pole Transverse Flux machine 3D model

The same study performed in the TFM-MP was repeated for the TFM-CP. A similar behaviour can be observed, however higher peak torque was achieved.

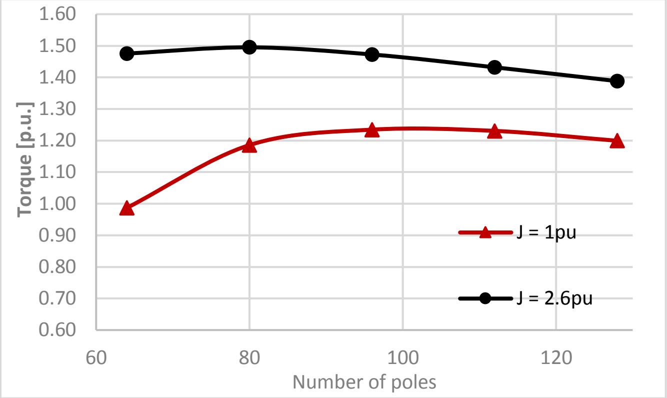

Figure 7: Peak torque for different pole number at different current densities in TFM-CP

At low pole numbers the topology shows greater torque at all current densities, with less saturation than in the TFM-MP. However as poles increase leakage becomes more present and lower torques than in the TFM-MP are observed.

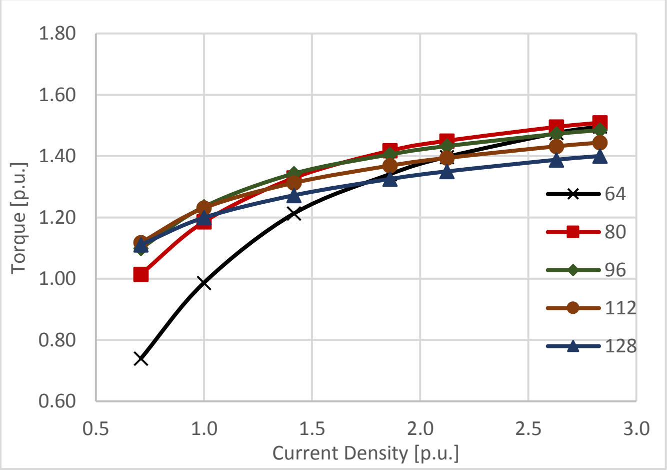

Figure 8: Peak torque against current density for different pole number

5 Topology comparison

A comparison between the topologies has been performed by manually adjusting each topology to give the greatest torque. For each of the motor topologies (TFM-MFP and TFM-CP) two different pole numbers were selected.

5.1 Torque Density

Both topologies were investigated in 96 pole and 128 pole configurations and the rated current torque values are compared to the BMM machine in Figure 9. The TFM-MFP also offers higher torque density than the TFM-CP topology. Torque gets reduced at higher pole numbers due to the leakage effect as shown before. The proposed topologies can achieve higher torques then the BMM for the same volume.

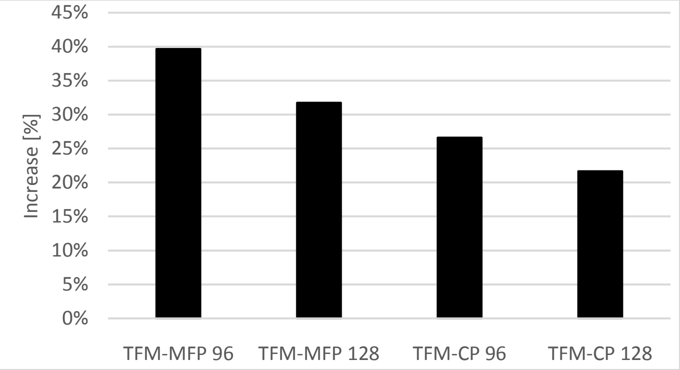

Figure 9: Average torque increase over the BMM for the different topologies during continuous operation

When comparing torque density of the overall machine, Figure 10 shows the Claw Pole topology offers higher torque densities as the weight of the machine is considerably reduced.

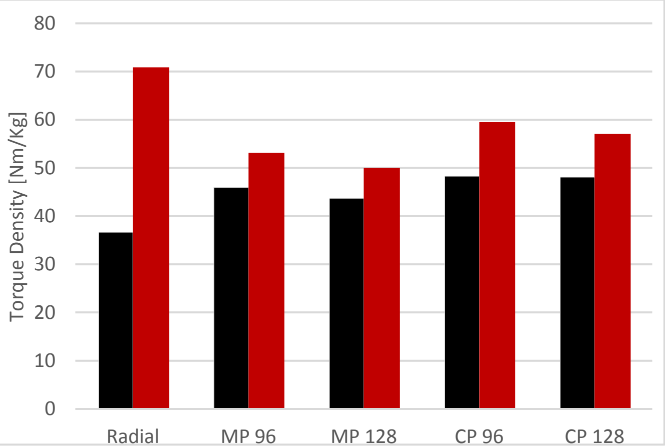

Figure 10: Torque density at continuous (black) and overload (red) operation points

Highest torque density at continuous operation is achieved when using 96 poles and the claw pole topology. In the overload operation, none of the transverse flux topologies achieve the same torque density as the benchmarking machine. Their low overload capability stems from the fact they are close to saturation at rated current. As this application has a good external cooling circuit, the BMM can be run hard and achieve an impressive overload capability. For applications without an external cooling circuit, TFMs remain a good option. []

5.2 Losses and efficiency

Permanent magnet synchronous machines are known by their high efficiency when compared to other topologies. Calculation of losses using FEA gives an insight in the efficiency of the machine although they have not been correlated with tested data. Many factors will affect the losses such as heat treatments, punching and other fabrication processes. Nevertheless loss calculations will give an insight into the relative efficiency of the machines, see. Losses in the proposed topologies are compared to the Benchmarking machine in per unit values in Table 2 and Table 3.

Table 2: Losses in the Benchmarking machine

Losses		BMM
Iron Losses	Eddy current losses [W]	660
	Hysteresis losses [W]	185
	Total Iron Losses [W]	845
Copper Loss [W]		4774
Total losses [W]		5619

Output Power [W]	62365

Table 3: Losses in the proposed topologies

Losses		TFM-MF		TFM-CP	
		96	128	96	128
Iron Losses	Eddy current losses [pu]	4.59	4.81	4.00	8.89
	Hysteresis losses [pu]	4.39	5.69	3.18	4.65
	Total Iron Losses [pu]	4.55	5.00	3.82	7.96
Copper Loss [pu]		1.14	1.02	0.81	0.88
Total losses [pu]		3.76	1.55	1.44	1.32
Output Power [pu]		1.14	1.40	1.32	1.27

Copper losses in TFMs are practically in the same range as in the BMM as all the machines use roughly the same amount of copper and a fixed current density.

Iron losses in TFMs are higher in comparison to the BMM although the material used is the same. This loss increment is due to the increase in pole number and hence electrical frequency coupled with the higher flux density and increased amount of lamination material used in the TFM.

Table 3 clearly shows that the high iron losses in the TFMs result in the radial flux machine having a better efficiency. In addition, althought TFM-CP topologies have lower iron losses, they can’t deliver as much torque hence their lower power and hence efficiency. This can be seen in Figure 11, in which efficiency really drops for the TFM-CP machine with 128 poles.

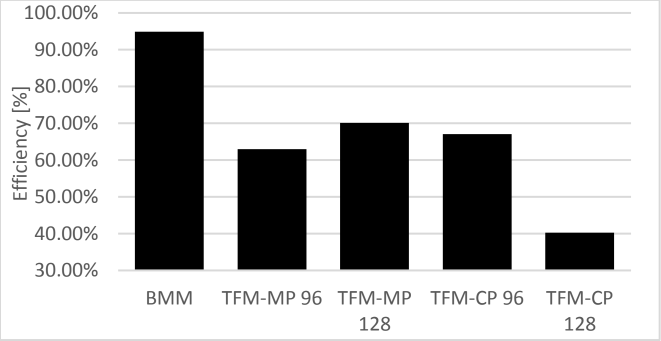

Figure 11: Efficiency comparison

5.3 Power Factor

TFMs are known by their low Power Factor (PF) due to their high reactance. Improving this parameter, for example by reducing electric loading, leads to a corresponding loss of torque [17]. Previous work has shown power factor could be improved at the cost of reducing torque density[18], [19].

Power factor of the proposed machines is much lower than that of the benchmarking machine, as shown in Figure 12. No optimisation regarding this parameter has been done in this work.

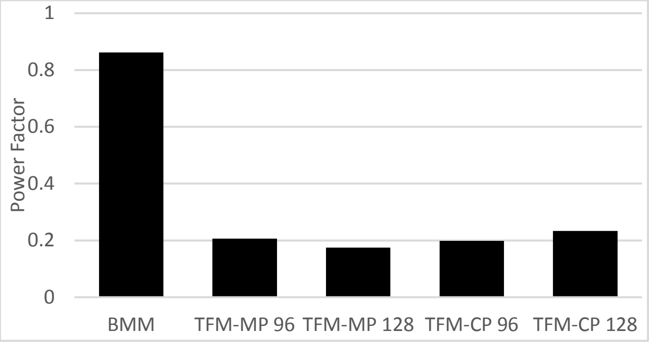

Figure 12: Power Factor comparison

5.4 Fixed magnet mass

The aim of this work was to consider maximum torque capability, not the machine cost. The results above are a comparison with fixed outer volumetric constraints for the rotor and stator, not for a fixed magnet mass. Hence the topologies showed above use a higher amount of magnet material than the BMM.

In this section, the magnet material is constrained to the same amount as the BMM. Figure 13 shows the results for rated current, including a big drop in torque for the Claw Pole configurations, now lower than that of the BMM machine.

Efficiency and power factor results for constrained magnet mass topologies remains similar to the previous shown results in Figure 11 and Figure 12.

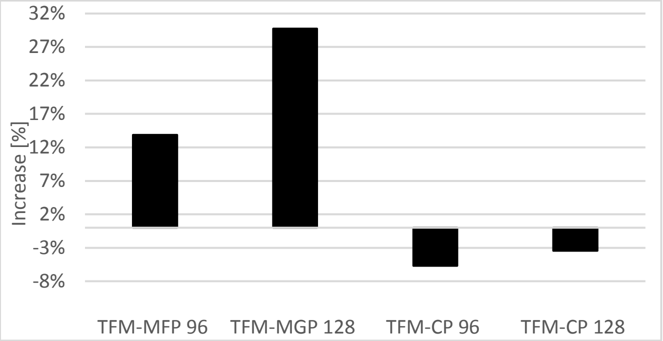

Figure 13: Torque increase when constraining magnet mass

6 Conclusion

Two different transverse flux machines were simulated and compared against an existing radial flux machine. It has been proved, that by increasing the pole number in a TFM, torque is also increased.

While altering the pole number and the current density in the transverse flux machine, two effects were found:

- Increase of current density leads into a high saturation of the TFM
- The increase of number of poles leads into a maximum torque limit, in which increasing current density could even be counter productive

The aim of the work was to find high torque designs and the TFM has been shown to increase rated torque by approximately 40% during continuous operation, if outer dimensions are constrained to that required by an in wheel motor and magnet mass is not constrained. However, active cooling in this application allows for a high overload current and the surface mounted machine is shown to deliver a higher overload torque.

Power factor is a known problem for TFMs, which in the simulated machines is of the order of just 0.2, which is not acceptable for the application due to the inverter ratings required.

When fixing the magnet mass, torque is drastically reduced for the low pole topologies and moreover the TFM-CP can't achieve the torque level of the compared radial flux machine.

The low overload capability, poor power factor and low efficiency makes the transverse flux machine topology unsuitable for this in-wheel, liquid cooled application cooled application.

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