The Journal of Engineering

The 9th International Conference on Power Electronics, Machines and Drives (PEMD 2018)

eISSN 2051-3305
Received on 25th June 2018
Accepted on 30th July 2018
E-First on 31st May 2019
doi: 10.1049/joe.2018.8184
www.ietdl.org

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). First, the proposed TFM topologies are studied using FEA to understand the torque capability of both topologies. Second, 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 (PF). Finally, it is presented as a comparison on the torque capabilities when constraining the magnet mass. It is shown that the TFMs selected can deliver higher torques than the base motor during continuous operation, but have failed to deliver the required overload torque. Furthermore, low PF and low efficiency make 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 Fig. 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, while 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.

Fig. 1 *Protean integrated drive*

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/mm2	19.4
discontinuous current density (RMS), A/mm2	51

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], demagnetisation 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]. Here, results were obtained from 3D FEA.

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.

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 than at continuous operation.

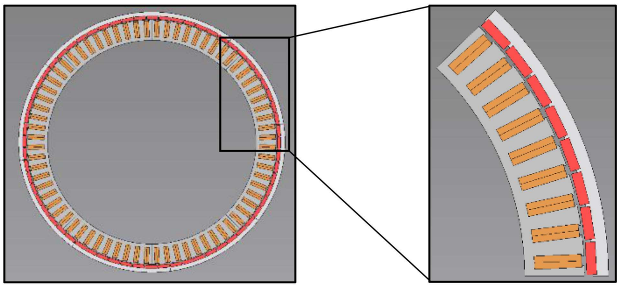

Fig. 2 *2D model of the benchmarking machine*

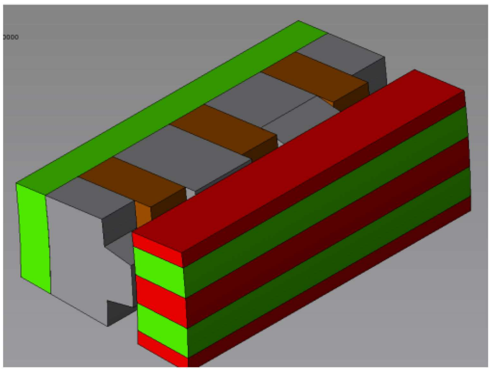

Fig. 3 *3D model of the TFM-MP*

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, see Fig. 2.

3 Transverse flux machine

TFMs 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 Fig. 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.

For a fixed volumetric envelope, TFMs 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 Fig. 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.

Fig. 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

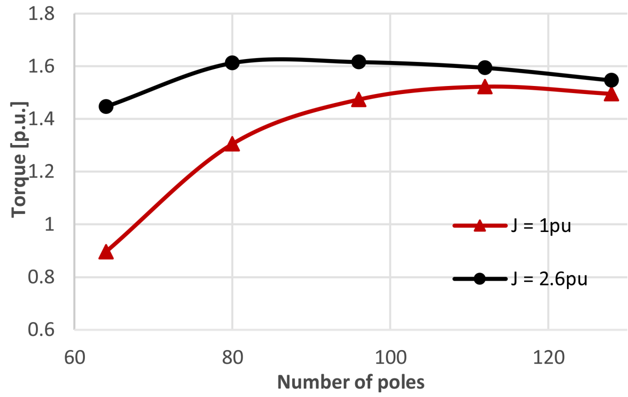

Fig. 4 *Peak torque for different pole number at different current densities*

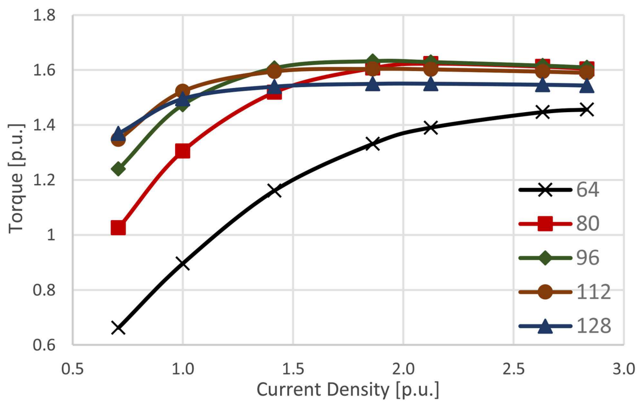

Fig. 5 *Peak torque against current density for different pole number*

a bigger amount of flux to leak to the next pole instead of following its design path. As shown in Fig. 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).

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 TFMs as seen in [14–16].

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 Fig. 6.

The same study performed in the TFM-MP was repeated for the TFM-CP. A similar behaviour can be observed in Fig. 7, however higher peak torque was achieved.

Figure 8 shows that 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.

5 Topology comparison

A comparison between the topologies has been performed by manually adjusting each topology to give the greatest torque. For

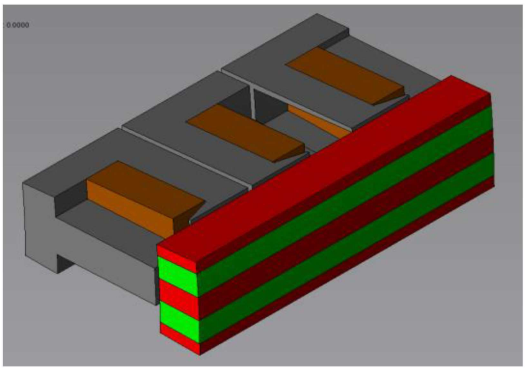

Fig. 6 *Claw pole transverse flux machine 3D model*

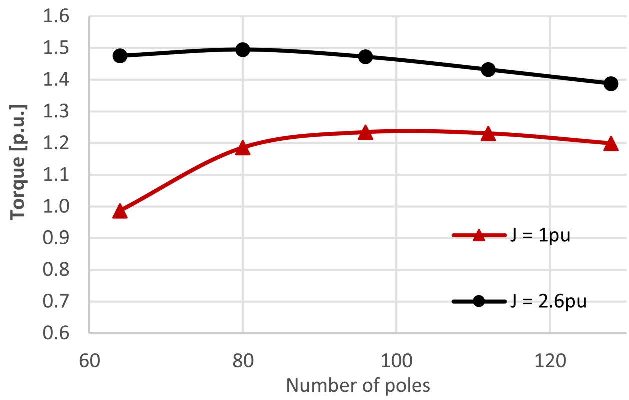

Fig. 7 *Peak torque for different pole number at different current densities in TFM-CP*

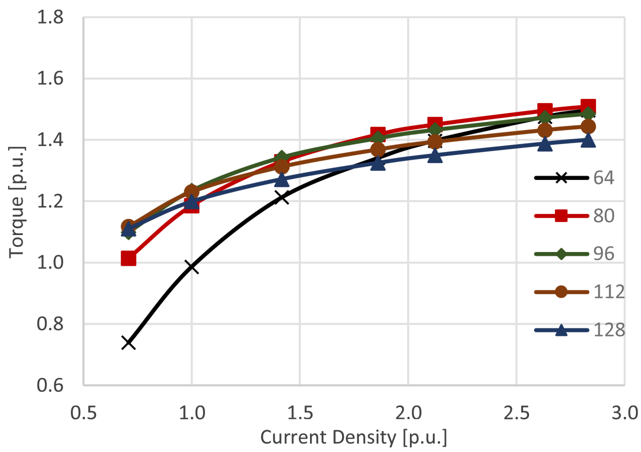

Fig. 8 *Peak torque against current density for different pole number*

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 Fig. 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 than the BMM for the same volume.

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

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

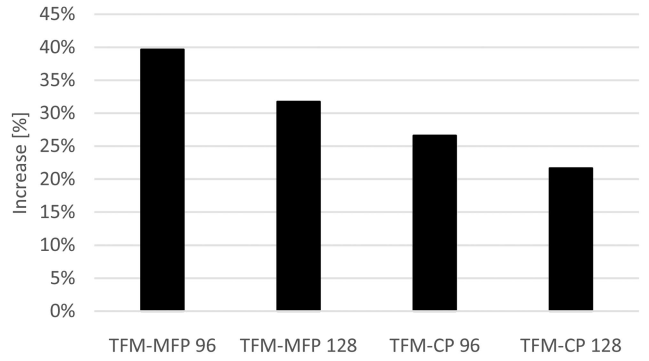

Fig. 9 *Average torque increase over the BMM for the different topologies during continuous operation*

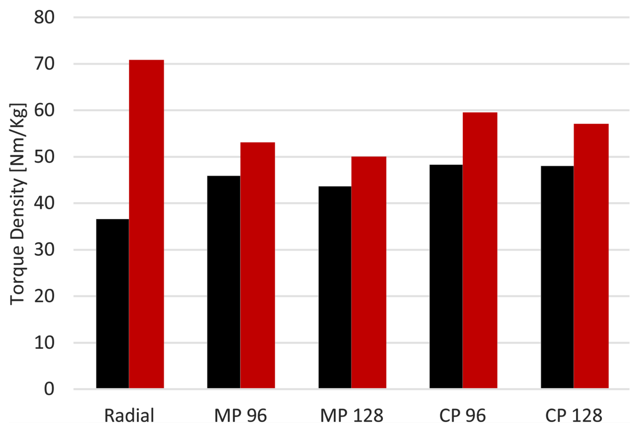

Fig. 10 *Torque density at continuous (black) and overload (red) operation points*

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		62,365

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. [17, 18]

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. Losses in the proposed topologies are compared to the benchmarking machine in per-unit values in Tables 2 and 3, being the per-unit base the losses of Table 2.

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 with 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 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	0.89
	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

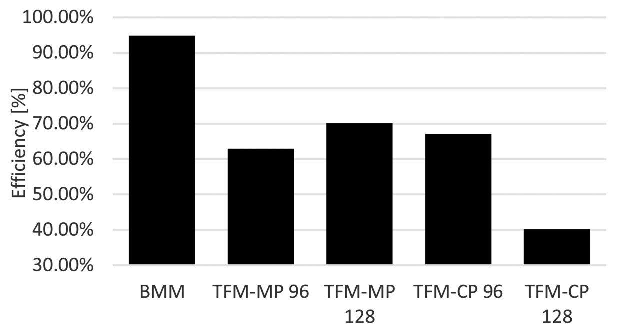

Fig. 11 *Efficiency comparison*

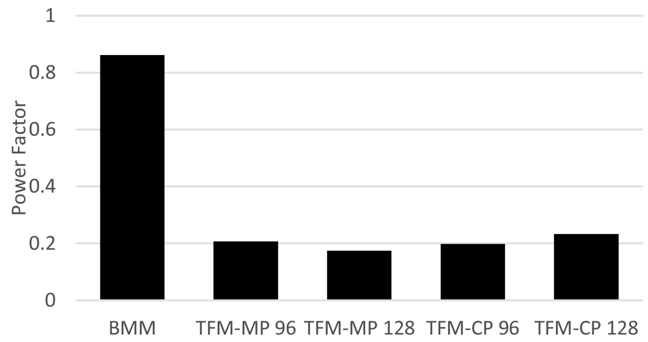

Fig. 12 *Power factor comparison*

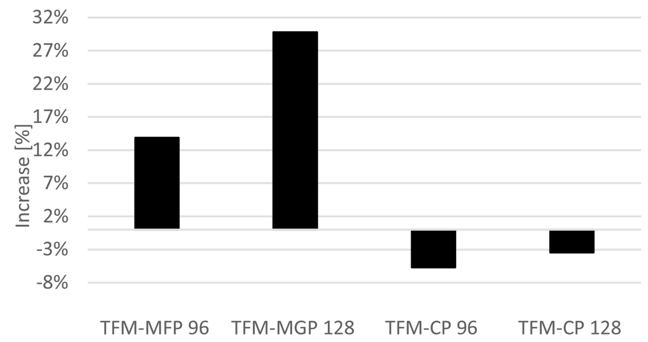

Fig. 13 *Torque increase when constraining magnet mass during continuous operation*

Table 3 clearly shows that the high iron losses in the TFMs result in the radial flux machine (RFM) having a better efficiency. Despite the TFM-CP topologies having lower losses, they also deliver a lower output torque and power, thus have a lower overall efficiency. This can be seen in Fig. 11, in which efficiency really drops for the TFM-CP machine with 128 poles.

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 [19]. Previous work has shown PF could be improved at the cost of reducing torque density [20, 21].

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

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. Fig. 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 remain similar to the previously shown results in Figs. 11 and 12.

6 Conclusion

Two different TFMs 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 TFM, 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 ∼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.

PF 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 cannot achieve the torque level of the compared radial flux machine.

The low overload capability, poor PF and low efficiency makes the TFM topology unsuitable for this in-wheel, liquid-cooled application [18].

7 Acknowledgments

The work done here has been done thanks to the funding provided by Protean Electric Limited.

We would like to acknowledge the technical support received from Powersys in the use of JMAG Designer and the use of its licenses from JSOL Corporation.

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