




A Novel Transverse Flux Machine for Vehicle Traction Applications

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A Novel Transverse Flux Machine for Vehicle Traction Applications

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***Abstract*--A novel transverse flux machine topology for electric vehicle traction applications using ferrite magnets is presented in this paper. The proposed transverse flux topology utilizes novel magnet arrangements in the rotor that are similar to the Halbach array to boost flux linkage; on the stator side, cores are alternately arranged around a pair of ring windings in each phase to make use of the entire rotor flux that eliminates end windings. Analytical design considerations and finite-element methods are used for an optimized design of a scooter in-wheel motor. Simulation results from finite element analysis (FEA) show that the motor achieved comparable torque density to conventional rare-earth permanent magnet (PM) machines. This machine is a viable candidate for direct-drive applications with low cost and high torque density.**

***Index Terms*--ferrites, permanent magnet motors, torque density, transverse flux motors**

I. Introduction

High torque density direct-drive electric machines are highly desirable as electric vehicle traction motors. Direct-drive machines have high torque at low speed, and they provide high reliability and low cost by eliminating the mechanical gearbox, which typically has low efficiencies.

A transverse flux machine (TFM) is inherently suitable for direct-drive applications because of its high torque density [1]-[3]. The distinct feature of a TFM is its "ring" shaped winding, which couples each stator core to the entire armature ampere-turns, and thus avoids the limitation of the "BIL" principle of force production. As a result, high torque is achieved by increasing the pole number without sacrificing electric loading. However, previously designed TFMs often suffer from high leakage flux [3], low winding utilization [4], and complex structure. In addition, such state-of-the-art, high torque/power density machines rely on rare-earth magnets that have limited availability and rising prices.

The design proposed in this paper aims to develop modular, high torque density, direct-drive, non-rare-earth TFMs using flux-focusing techniques. The innovation presented in this design is based on novel rotor magnet arrangements and an innovative stator pole configuration around the ring winding that essentially eliminates the rotor leakage flux while providing modularity and robustness in a manufacturable structure. The flux-focusing technique allows the use of non-rare-earth ferrite magnets, which will overcome the cost and availability issues of rare-earth permanent magnets. A soft magnetic composite (SMC) will be used as the core material to provide a 3D flux path. Design and simulation results are provided for a two-phase scooter in-wheel traction motor.

II. Review of TFM

The theoretical torque density that can be achieved by TFM is several times higher than that of radial flux permanent magnet machines because of its unique way of torque production [5]. According to [6], TFM also boasts low magnet weight and low winding resistance, but it suffers from low power factor, high cogging torque, and excessive axial loading on the bearings that makes it hard to maintain uniform air gaps. The axial flux generator design in [4] is derived from a TFM concept with a double-sided stator to make better use of rotor magnets, but the stator cores make use of only half the winding, exposing the other half as end winding. There are successful TFM designs using SMC [7], which is required to conduct flux in 3D paths. SMC has the benefits of providing for lower core loss and novel structures, but it gives in on magnetic loading capability. Research in [2], [8] suggests that low power factor and core saturation restrict the available torque in TFMs.

III. Machine Structure

An illustration of the proposed concept machine is given in Fig. 1. Fig. 1(a) shows the solid model for one module or phase of the machine. The rotor is in the middle, and the stator cores and windings are located on both sides of the rotor. Fig. 1(b) illustrates the solid model representation of the cross section of the proposed TFM. The sandwiched magnets between the rotor cores allow redirecting the flux direction produced by the permanent magnets. The magnet directions are alternately arranged so that the north poles of the two magnets point either toward or away from each other.

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The clockwise direction of the flux in the stator core (top left in Fig. 1(c) encircling coil winding W1) indicates that the current flows in the top coils in the same direction. The magnetic polarity of the magnets is pointing toward the middle rotor core. The flux leaving the middle rotor core enters the stator core, flows in a clockwise direction, exits at the top of the stator core, and enters the top of the rotor pole. The flux direction in the stator core (top right in Fig. 1(c) encircling coil winding W2) is also clockwise. The flux leaving the middle rotor core enters the stator core, flows in a clockwise direction, exits at the bottom of the stator core, and enters the bottom of the rotor pole.

One pole that is behind this rotor pole is not visible, but it is shown on the right side of Fig. 1(c). The magnetic polarity of this rotor pole is the opposite of the previous rotor pole. The direction points away from the middle rotor core. The flux leaving the top rotor core enters the stator core at the top, flows in a clockwise direction, and exits at the bottom of the stator core into the middle core. The bottom cross-sectional diagram in Fig. 1(c) shows that the counterclockwise direction is consistent with the direction of the current in the winding, as indicated by the top cross-sectional diagram.

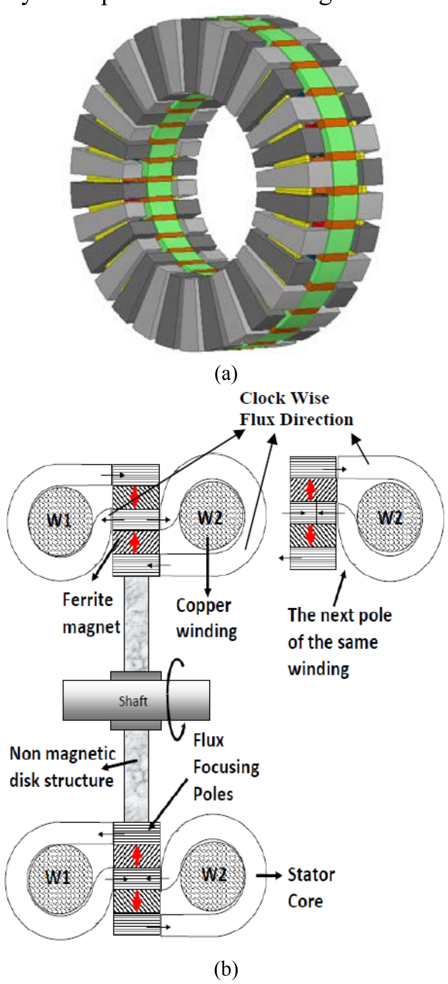


Fig. 1. (a) 30-pole TFM, (b) PM magnetization and flux path

IV. Design Considerations

A. Rotor Flux Leakage Prevention

TFMs suffer from poor rotor magnet flux utilization primarily for two reasons. One, according to [2], [9], is that when one magnet is in the aligned position to establish flux linkage, the neighboring magnets with opposite polarity produce fringing flux that subtracts from the total back-EMF-inducing flux. Another reason is because of the direct leakage flux in the circumferential direction between neighboring heteropolar magnets [10].

Magnetic shunts were introduced in [9] to counter the negative effect of fringing flux; however, the shunts only passively direct the fringing flux away from the main flux path. In the proposed machine structure, the alternating stator core design makes active use of all the rotor magnets to build flux linkage in the coil such that what would have been fringing flux are equally utilized to induce back-EMF. FEA simulation results in Fig. 2 show that when two sets of alternating stator cores are used, the coil flux linkage more than doubles compared to when only one set of cores is used.

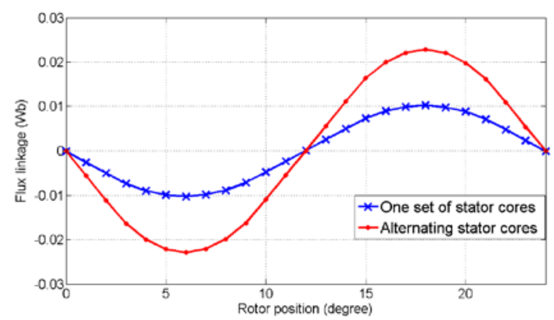


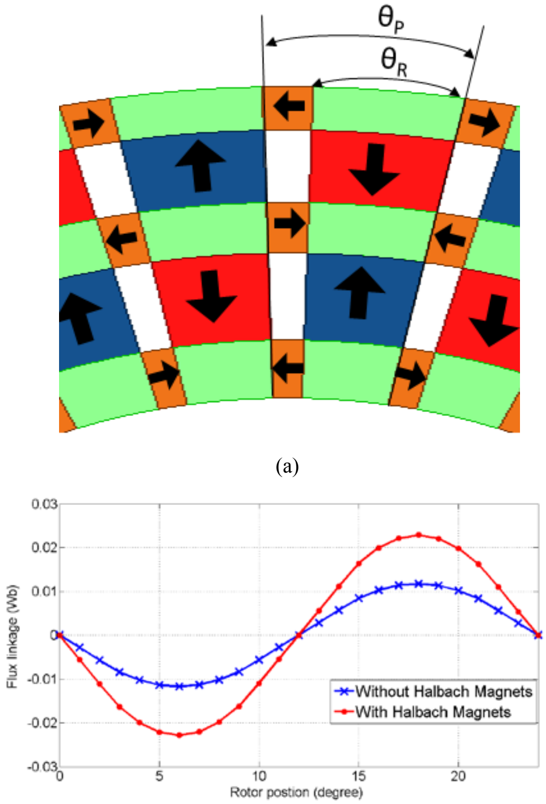
Fig. 2. Flux linkage with and without alternating stators

One common way to reduce inter-polar flux leakage is to increase the physical separation and thus also increase the magnetic reluctance between rotor magnets, but this also sacrifices effective pole face area. In the proposed design innovation, extra magnets are put into the separation between the rotor poles, and they are magnetized in the direction opposing inter-polar leakage, as shown in Fig. 3(a). Such a magnet arrangement when combined with rotor cores creates a flux pattern similar to that of a Halbach array [11]. Thus, instead of passively relying on the air reluctance to suppress flux leakage, the spaces are actively utilized to contribute to flux linkage. As shown in Fig. 3(b), by using extra “Halbach magnets,” flux linkage is increased by 90% compared to the case without them.

To determine the optimal thickness of the Halbach magnets, a rotor separation factor K_r is defined as

$$K_r = \frac{\theta_R}{\theta_P} \quad (1)$$

in which, as shown in Fig. 3(a), θ_R is the rotor arc span, and θ_P is the pole pitch, and hence the thickness of the Halbach magnets will be proportional to $1\text{-}K_r$. Based on 3D FEA simulation, to maximize winding flux linkage the optimum value for K_r is 0.65, which provides a large enough pole face area while at the same time maintains a reasonable thickness for the Halbach magnets.



(a)

(b)

Fig. 3. (a) Rotor magnetization and (b) flux linkage with and without Halbach magnets

B. Rotor Flux Concentrator Design

Magnetic flux in the rotor is guided by the metal parts, which are referred to as flux concentrators. Such naming is reasonable because these segments are designed in a manner that increases the flux density in the air gap compared to that along the magnet cross sections. Because ferrite magnets exhibit lower remnant flux density, careful design of these rotor flux concentrators results in a higher air-gap flux density, comparable to that achieved by stronger rare-earth material magnets. The concept can be better visualized from the cross-sectional view shown in Fig. 1(c). The magnetic flux path in the radial plane is proportional to the axial length of the magnet labeled L_A. The rotor pole area exposed to the air gap is proportional to the radial length of the corresponding flux concentrator, labeled L_R, for the outermost rotor segment shown in Fig. 1(c). Thus, the concentration factor can then be defined as

$$Concentration\ Factor\ K_f = \frac{L_A}{L_R} \tag{2}$$

The operating flux density inside the magnets can be roughly estimated considering the infinitely permeable stator and rotor metal area and is given by

$$B_m = \frac{M_L}{2 \times Airgap \times K_f + M_L} \tag{3}$$

Here, $M_L = Magnet\ radial\ length$

The air-gap flux density is simply magnified by the concentration factor K_f and can be given as

$$B_{AG} = B_m \times K_f \tag{4}$$

Because the operating point of the magnet reduces with a higher concentration factor, there exists an optimum point that maximizes flux linkage. Considering a nonlinear BH curve for the core material, the optimum concentration factor depends on the magnetic saturation of metal, remnant flux density of the magnets, air gap, and number of pole pairs in the design.

In another aspect, the use of SMC is essential for this rotor design for two reasons: one is that the 3D nature of the flux requires isotropic material and thus excludes laminated steel; another is that the flux direction changes twice from cycle to cycle, so solid iron is not applicable because of excessive eddy current loss.

C. Stator Core Shape and Winding Window Area

The stator cores are alternating "C" shaped. The coil window area is designed as a rectangular shape so that it can be linearly scaled in the axial direction to accommodate required ampere-turns at a certain current density. Also, such a shape reduces axial length compared to a circular-shape window area, which is beneficial in a wheel-hub environment that has limited width.

Because all the stator and rotor iron cores are arc-shaped, similar to a slice of pizza, to make a circular machine, the arc lengths are different at different radii, which results in varying cross-sectional areas in the stator core. Ignoring fringing and leakage, if the same amount of flux flows through the entire stator core, then higher flux density will be observed in inner radius areas and lower flux density in outer radius areas. Arguably, uniform flux density is desired in the magnetic cores to avoid early saturation and underutilization. Therefore, the stator core shape is adjusted to have decreasing thickness with increasing radius, as illustrated in Fig. 4, thereby achieving same cross-sectional area for the flux path.

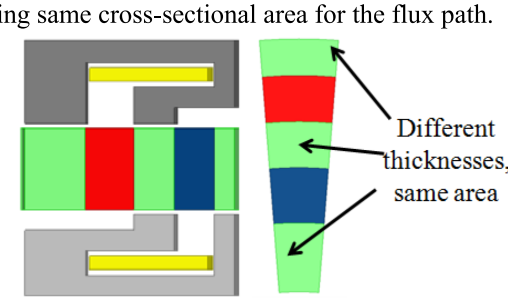


Fig. 4. Stator shape and core area corrections

V. Design and Performance of a Two-Phase Machine

A. Two-Phase 800-W Motor for Scooter In-Wheel Application

The TFM design targeting electric scooter in-wheel traction applications has been finalized and simulated in FEA using Flux 3D. Several practical constraints are put on the design, such as limited outer dimensions, 48-V DC bus voltage, 1-mm rotor-stator air gap, and 6-A/mm^2 current density, which is compatible with natural air cooling.

The space restriction in a wheel-hub environment, especially the limited axial length, dictates that only a single module with one rotor plate and two stator plates could be used; however, one module or one phase of the proposed machine has an output torque that pulsates from zero to the maximum value, which is unacceptable for traction application. To achieve ideally constant output torque, the two stator plates are physically shifted against each other at a mechanical angle that corresponds to 90 electrical degrees, and the currents in these two coils are also phase shifted accordingly, thus creating a two-phase motor, shown in Fig. 5.

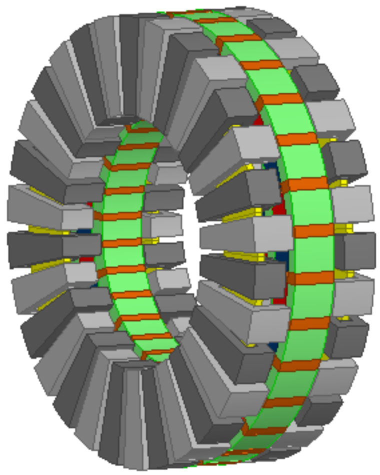


Fig. 5. Two-phase design

The base speed for the designed machine is 300 rpm, which translates to 25 km/h vehicle speed. Operation at higher speeds is possible with flux weakening operation. The torque needed for an electric scooter direct-drive motor is calculated as 24 Nm to achieve 0.1g acceleration and 10% road grade.

The material for the motor iron cores is Somaloy 3P 1000 by Höganäs, with initial relative permeability of 850 and flux density of 1.63T at 10,000 A/m. The permanent magnet used in the simulation is C8 ferrite wit ah remnant flux density of 0.39T and relative permeability of 1.05. Detailed design parameters and FEA simulated motor performances are listed in Table I.

TABLE I

SCOOTER MOTOR DESIGN PARAMETERS AND PERFORMANCES

Design Parameter	Pole number	30
	Outer diameter (mm)	200
	Inner diameter (mm)	115
	Axial length (mm)	90
	Weight (kg)	7.4
	Coil number	15
	Current RMS (A)	70
	Current density (A/mm^2)	6
	Coil resistance (ohm)	0.01
	Electrical frequency (Hz)	75
	Base speed (rpm)	300
Performance	Average torque (Nm)	26
	Output power (W)	816
	Estimated core loss (W)	68
	Copper loss (W)	74
	Efficiency (%)	85
	Torque density (Nm/kg)	3.5
	Torque density (Nm/m^3)	9300

B. No-Load Back-EMF

The no-load back-EMF plot in Fig. 6 shows that the designed machine has a waveform closer to trapezoidal than to sinusoidal. This waveform provides a higher RMS value but requires a non-sinusoidal current to achieve a smooth torque output.

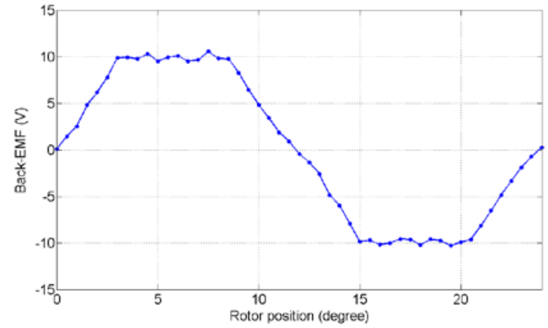


Fig. 6. Open-circuit back-EMF

C. Electromagnetic Torque and Cogging Torque

When driven by two-phase sinusoidal currents, the averaged output torque is 26 Nm with torque varying between 21 Nm and 30 Nm. There are two components in the torque ripple: one is electromagnetic in nature, which comes from the non-sinusoidal back-EMF waveform; another is cogging torque. In Fig. 7, cogging torque is shown to have an amplitude of 4 Nm, which is a major contribution to the total torque ripple. Further research could be done to produce smooth torque by reducing cogging torque and appropriately shaping the input current.

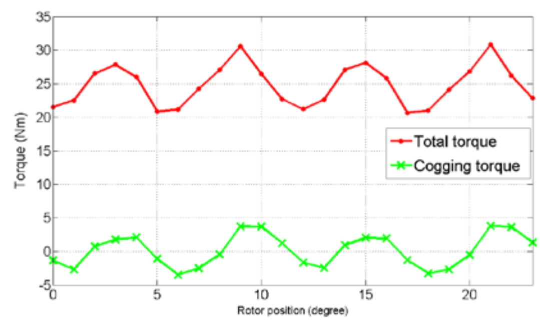


Fig. 7. Output torque

D. Torque Density

The machine active weight, which includes only permanent magnets, copper windings, and iron cores, is 7.4 kg. The cylinder volume of the TFM is 0.0028 m^3. Therefore, the achieved torque density per weight and per volume is 3.5 Nm/kg and 9,300 Nm/m^3, respectively.

The achieved torque density is quite acceptable considering the use of natural air cooling for the designed current density and low-power ferrite magnets. If an advanced cooling mechanism and rare-earth magnets were to be used on the proposed machine design with further optimization, the same torque could be produced by a much smaller motor, which would result in a much higher torque density.

VI. CONCLUSION

The novel machine structure described in this paper inherited torque production characteristics of a traditional TFM, with rotor magnetization and stator core design innovations that address flux leakage issues faced by a TFM. The design of a scooter wheel-hub motor shows promising performance in terms of torque density. There is room for further research on reducing torque ripple and on design optimization.

REFERENCES

[1] H. Weh and H. May, "Achievable force densities for permanent magnet excited machines in new configurations," in *Proc. 1986 Int. Conf. Electrical Machines*, pp. 1107–1111.

[2] M. R. Harris, G. H. Pajooman, and S. M. A. Sharkh, "Performance and design optimization of electric motors with heteropolar surface magnets and homopolar windings," in *Proc. 1996 Inst. Elect. Eng.*, *Elect. Power Appl.*, vol. 143, pp. 429–436.

[3] W. M. Arshad, T. Bäckström, and C. Sadarangani, "Analytical design and analysis procedure for a transverse flux machine," in *Proc. 2001 IEEE Conf. Elec. Mach. and Drives*, pp. 115–121.

[4] E. Muljadi, C. P. Butterfield, and Y. H. Wan, "Axial-flux modular permanent-magnet generator with a toroidal winding for wind-turbine applications," *IEEE Trans. Ind. Appl.*, vol. 35, no. 4, pp. 831–836, Jul./Aug. 1999.

[5] S. Huang, J. Luo, and T. A. Lipo, "Analysis and evaluation of the transverse flux circumferential current machine," in *Conf. 1997, Rec. IEEE-IAS Annu. Meeting*, vol. 1, pp. 378–384.

[6] Z. Rahman, "Evaluating radial, axial and transverse flux topologies for 'in-wheel' motor," in *Proc. 2004 Power Electronics in Transportation Conf.*, pp.75–81.

[7] Y. G. Guo, J. G. Zhu, P. A. Watterson, and W. Wu, "Development of a permanent magnet transverse flux motor with soft magnetic composite core," *IEEE Trans. Energy Convers.*, vol. 21, no. 2, pp. 429–437, June 2006.

[8] M. R. Harris, G. H. Pajooman, and S. M. Abu Sharkh, "The problem of power factor in VRPM (transverse-flux) machines," in *Proc. 1997 IEEE Colloq. Electr. Machines Drives*, pp. 386–390.

[9] D. Oleksandr, "Study on permanent magnet transverse flux machine," Ph.D dissertation, Dept. of Elec. and Computer Eng., Louisiana State Univ., Baton Rouge, 2012.

[10] K. Lu, P. O. Rasmussen, and E. Ritchie, "Design considerations of permanent magnet transverse flux machines," *IEEE Trans. Magn.*, vol. 47, no. 10, pp. 2804–2807, Oct. 2011.

[11] K. Halbach, "Design of permanent magnet multipole magnets with oriented rare earth cobalt material," *Nucl. Instrum. Methods*, vol. 169, pp. 1–10, 1980.