A Novel Electric Machine Employing Torque Magnification And Flux Concentration Effects

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Abstract – **An evolving family of electric machines using the Torque Magnification (TM) Principle has attracted increasing interest in recent years. In this paper the TM principle is described following the introduction of the Specific Torque Density concept. A TM machine with flux concentration effect is presented, and its working principle explained. The design considerations of the machine, which are common to any TM machine, are studied in detail. Test results taken on a hardware prototype machine prove the concept and make clear that the machine's cost-effectiveness.**

I. Introduction

An electric machine with high torque density (torque per unit volume) has important commercial advantages. For example, such a machine can be made in a smaller size to fit in a limited space, such as for automotive applications. In addition, the machine tends to require less active material and can be made cheaper if manufacturing costs are in line with more conventional machines.

Power electronics has been an enabling technology for a new class of electric machines with improved torque density – Converter Fed Machines (CFM's) [1] [2], such as the Brushless DC Machine, the Switched Reluctance Machine, etc. Among the CFM's, the subgroup of machines using the Torque Magnification (TM) Principle is specifically aimed at achieving high torque density. The Transverse Flux Machine [3] [4], considered by the authors as one member of the TM machine family, has been a popular avenue for exploration of high torque density machines, such as a direct drive for ship propulsion [5]. The Claw Pole Machine [6] and the Axial Flux Circumferential Current Machine [7] can also be regarded as the members of the TM machine family. However, in order to achieve high torque density, most of the TM machines must have three-dimensional working flux distributions (i.e. flux components must exist in all three dimensions), including all the machines mentioned above. Compared with a commercial 2-D flux machine (i.e. one with no useful axial flux component), a 3-D flux machine adds complexity to machine manufacturing and needs special magnetic materials, such as iron powder. These facts make it difficult to justify the cost-effectiveness for commercial applications except for certain special situations.

The working flux of the TM machine presented in this paper is two-dimensional, hence conventional steel laminations can be used. In addition, a spiral arrangement of magnets enables the use of ceramic (ferrite) magnets to replace expensive rare earth magnets. These factors will contribute towards realizing a machine with low cost but retaining high torque density.

In general, the electric machines using the TM Principle are relatively new. These machines also bear other names, such as Transverse Flux Machine [3], Axial Flux Circumferential Current Machine [7], etc. It will be meaningful to regard these machines as being from the same family because of their common essential characteristic of torque magnification.

II. The Torque magnification Principle

It is now appropriate to describe more fully the torque magnification principle. However, it is useful to first set forth the concept of Specific Torque Density, which will be used to describe the torque magnification principle.

A. *Specific Torque Density versus Torque Density*

General torque equations for any electric machine under ideal conditions can be as follows, for each phase

A. $$T_{em} = \frac{p}{\omega} = ei\frac{\partial t}{\partial \theta} = i\frac{\partial \psi}{\partial t}\frac{\partial t}{\partial \theta} = Ni\frac{\partial \phi}{\partial \theta},$$

thus

B. $$T_{em} = Ni\frac{\partial \phi}{\partial \theta}, \quad (1)$$

where T_{em} is the electromagnetic torque contributed by one phase, p the phase power, ω the mechanical angular speed, e the back EMF, ψ (ϕ) the flux linkage (flux) per pole pair, i the operating current, N the equivalent number of turns, and Ni the machine equivalent ampere-turns of a given phase.

The concept of Torque Density τ_v of a machine can be defined as the rated electromagnetic torque divided by the machine volume V.

$$\tau_v = \frac{T_{em}}{V} = \frac{Ni}{V}\frac{\partial \phi}{\partial \theta}. \quad (2)$$

It is clear in (1) and (2) that the torque and the torque density are related to the machine operating current, or ampere-turns. When evaluating a machine's torque producing capability, one hopes to appraise the inherent torque capa-

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bility, excluding the external factors, such as the operating current. Since the amount of operating current or ampere-turns is mainly determined by the machine cooling methods, it will be meaningful to eliminate the influence of current on evaluating inherent torque producing capability. This objective can be achieved by utilizing the relation,

$$Ni = \pi D_i K \qquad (3)$$

where D_i is the machine stator bore diameter and K is the machine's rms surface current density, which is the total rms ampere-turns flowing in stator bore divided by the bore perimeter. Also the per pole flux linkage can be written,

$$\psi = c_1 D_i L B_e \qquad (4)$$

in which c_1 is a constant related to the machine, L the axial stator stack length, and B_e the equivalent air gap flux density also specific to the machine.

Combining the above four equations and using a second constant c_2, which is also specific to the machine the torque density can be expressed,

$$\tau_v = c_2 K \frac{dB_e}{d\theta}. \qquad (5)$$

The quantity K is a more appropriate variable than i since it represents the "electrical loading" of a machine. At this point, the concept of Specific Torque Density τ_{sp} can be introduced as

$$\tau_{sp} = \frac{T_{em}}{VK}. \qquad (6)$$

or

$$\tau_{sp} = c_2 \frac{dB_e}{d\theta}. \qquad (7)$$

Eq. (6) can be used to easily calculate the specific torque density of an electric machine. Eq. (7) demonstrates that the torque density is proportional to the number of flux density reversals per second, i.e. frequency of the induced voltage.

C. *Torque Magnification Principle*

For most electrical machines, such as conventional induction, DC commutator, or Brushless DC machines, output torque is basically determined only by the airgap volume of the machine. In other words, once the machine air gap volume and surface current density are chosen, the machine's torque capability is set to a prescribed value. However, this generally true phenomenon can not be applied for a machine using the torque magnification principle, that is, a TM machine.

A TM machine has the following characteristics:

- The machine has a multiple flux-loop structure. Each flux loop is an integral element and provides a closed path for magnetic flux.
- Each coil is magnetically coupled with multiple flux loops. The coil flux linkage changes at the frequency of the "rate of polarity reversals" of the flux loops due to the relative movement between the stator and rotor.
- Ideally, the specific torque density reverses in proportional to the angular pitch of each flux loop. In many cases but not all cases the specific torque density is proportional to the number of flux loops coupled by the armature coil.

The Transverse Flux Machine shown in Fig. 1 is taken as an example to explain the above concept. In this machine two concentric armature windings are placed above and below an indigitated cylinder comprised of magnets and iron pieces. The blocks with arrows are magnets with the flux directions as shown. The iron blocks have letters of "N" and "S" because of the magnetization by the magnets. It is clear that both the stator and the rotor cores constitute multiple repetitive flux loops. Both the outside and inside stator toroidal winding link the flux from all the flux loops. Note for this machine, the number of flux loops is inversely proportional to the angular pitch of each flux loop. Under ideal conditions, if the number of flux loops increases, flux change rate increases proportionally. Applying (1), the torque will increase accordingly under a same value of ampere-turns. And by (7), the specific torque density increases proportionally with the number of flux loops.

Note that for this toroidal wound armature the concept of surface current density remains valid and can be defined as the total ampere-turns being divided by axial length of the machine.

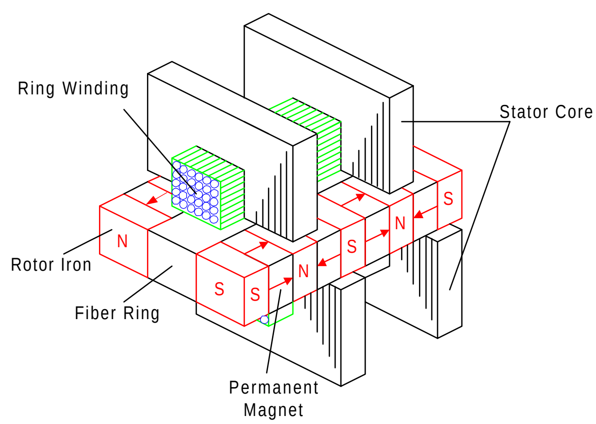

Fig. 1 Transverse Flux Machine proposed by H. Weh

The concept of flux loops cam also be applied to any electric machine for the purpose of establishing torque capability. Using a 4-pole field wound synchronous machine for example, the total torque is a summation of the torque provided by each pole pair and phase. Based on the nature of the synchronous machine, each pole pair has only one flux loop. Therefore the specific torque density is relatively fixed. The flux spatial change frequency can increase with the increase of the number of pole pairs, however, the amount of flux of each pole pair will decrease accordingly. Thus the flux change rate will be the same and a same torque will result under a same surface current density regardless of the number of poles.

It is interesting that the many modern stepping motors already use the torque magnification principle [8]. However, the authors believe the primary intention is for an accurate position control – a possibly more important performance measure.

It should be pointed out that in reality there is a limit for specific toque density increase for a TM machine. When the number of flux loops exceeds a certain value, the fringing or leakage flux problem will be dominant so that there is no increase (but a decrease) of specific torque density. In addition, a large number of flux loops make the operating electric frequency high for a given target rotor speed, which will cause difficulties such as excessive iron loss.

Typically a TM machine such as the Transverse Flux Machine has a sophisticated topology. To have an efficient coupling between the coil(s) and the multiple flux loops, three dimensions are generally employed. The 3-D structure gives rise to a 3-D working flux distribution, which makes it difficult to use 2-D steel laminations to construct the machines. Thus a high cost is inevitable, although it may be justified by the increased torque output for certain applications. This paper explores a TM machine having a 2-D topology which reduces cost but still maintains its good torque density performance.

III. Principle of Operation

In this paper a novel spiral magnet TM (SMTM) machine employing the torque magnification principle is introduced as shown in Fig. 2, Based on the Doubly Salient Permanent Magnet (DSPM) Machine principle [9],[10],[11] previously developed at the University of Wisconsin-Madison. The machine has a spiral magnet arrangement, a concentric winding in the stator, and a simple robust rotor. There is also a field winding designated with the letter “F” for field weakening or strengthening. If rare earth magnets are used, the machine topology can be simplified as shown in Fig. 3.

Since the energy product of a ceramic magnet is normally about 10% of that of a rare earth magnet, it is difficult to design a high toque density machine using ceramic magnets. Nevertheless, it was found that in some situations the magnet performance can be “boosted” by employing the flux concentration effect. Flux concentration concerns the process of increasing the flux density in working air gap areas, by arranging the total working areas to be less than the magnet cross-sectional area. By incorporating a spiral arrangement for ceramic magnets to increase magnet area, air gap flux density reaches the same value as that obtained from the rare earth magnets in Fig. 3.

It is clear that the machines in Figs. 2 and 3 share the same working principle. When rotor moves between positions of different full teeth alignment, the flux linkage in the coil changes from the peak value with one polarity to the peak value to the opposite polarity. The change of coil flux linkage induces a back EMF, which initiates electromechanical energy conversion.

The two TM machine versions originate from a DSPM machine proposed by Dr. X. Luo [9]. The DSPM machine has the same operating principle as the machines in Fig. 2 and Fig. 3, except does not have the torque magnification capability. By reducing the angular pitch of both the stator and rotor poles by a factor of three the TM machines in Fig. 2 and Fig. 3 evolve. Ideally the torque capability can be increased by three times – proportional to the increase in the number of flux loops.

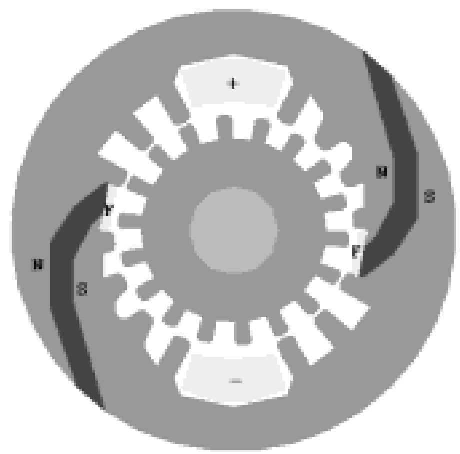

Fig. 2: The SMTM machine using ceramic magnets

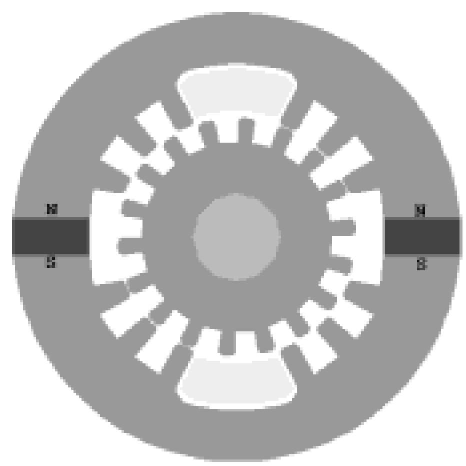

Fig. 3: A 2-D TM machine using rare earth magnets

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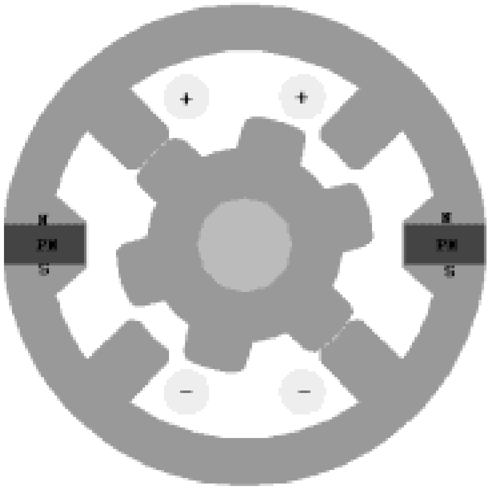

Fig. 4: The machine proposed by X. Luo

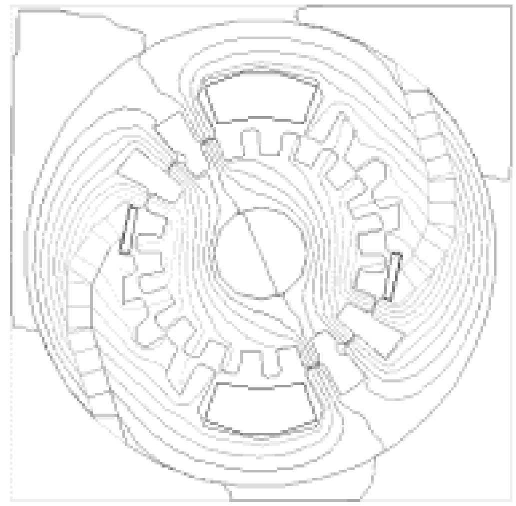

Fig. 5: Flux distribution with zero armature current

IV. DESIGN CONSIDERATIONS

The principle of operation of the SMTM machine suggests the machine's high specific torque density potential. In this section, other important properties of the machine will be studied for design purposes. Due to the unusual shape and complicated fringing flux patterns, conventional magnetic circuit modeling method is difficult and inefficient to apply. Finite Element Analysis (FEA) by using Ansoft Maxwell 2D Field Simulator was selected as the analytical tool.

A. Flux Concentration Effect

Fig. 5 shows the flux distribution for zero armature and field current. In the figure, there are a total of 20 flux lines, 10 lines from each side magnet set. Since the density of the flux lines indicates the flux density, it can be observed that the air gap flux density for the aligned teeth is about 4 times that of each magnet. This observation is verified by flux density measurement in Ansoft, which gives the value of air gap flux density roughly 1.5 Tesla. This value is almost the same as the air gap flux density of the model of Fig. 3 and is close to the saturation point of the magnetic steel. Therefore it can be concluded that the flux concentration has been achieved satisfactorily.

B. Fringing Flux and the Number of Flux Loops

Fringing flux or leakage flux, which can be classified as the flux that enters the stator and rotor teeth which are fully non-aligned, is one of the most important concerns for a TM machine. The operating principle of any TM machines is built on premise of a large net peak flux change with regard to different rotor positions. The specific torque density of the machine is proportional to the net flux change, which is clearly affected by the fringing flux. The larger the fringing flux, the less the net flux change. It is the fringing flux that limits the torque increase of a TM machine. With a decrease of the angular pitch of a flux loop (increase in tooth number), the ratio of fringing flux over total flux increases and finally prevents further increase of the specific torque density.

Ideally, all flux should pass through the fully aligned teeth – a zero fringing flux situation. However, due to the existence of a non-zero length air gap and limited permeability of the magnetic steel, fringing flux is unavoidable.

It was found that the tooth shape and width have a considerable influence on the fringing flux. For example a machine with wide and sharp-corner teeth has more fringing flux than a machine with narrow and round-shape teeth. For the SMTM machine, this study showed that a machine with proper a tooth design may double the specific torque density over a machine without careful tooth shape consideration.

The influence of the flux loop angular pitch, or the number of rotor teeth, was also studied. The result is shown in Fig. 6 for a SMTM machine with its surface current density being at 150 A/cm. It can be observed that specific torque density increases sharply at the initially for small numbers of teeth. However, an increase of the number of rotor teeth eventually decreases the torque output due to the impact of the fringing flux.

C. *Armature Reaction Concern*

Armature reaction of an electric machine concerns the impact of armature current on the air gap magnetic field and associated performance. The armature reaction of the SMTM machine with a negative current, which produces a field opposing the magnet flux, is plotted in Fig. 7, with an operating current equivalent to a surface current density of 160 A/cm. Fig. 7 shows a severe armature reaction. With a strong current, majority of the flux lines switches from fully aligned teeth to the non-aligned teeth. Because of the non-linearity of steel B-H curve, armature reaction reduces the net flux change, thus decreases the machine's specific torque density at a high current level, as shown in Fig. 8.

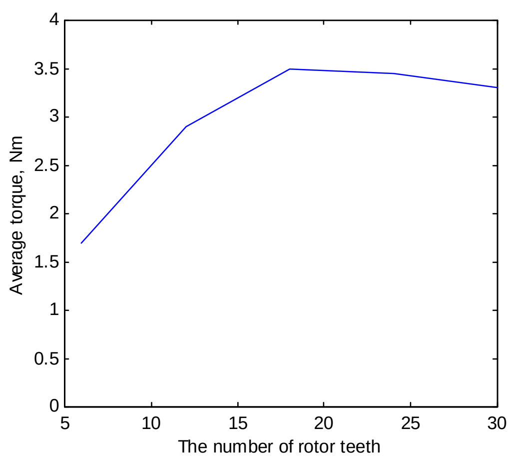

Fig. 6: The effect of number of flux loops over torque capability

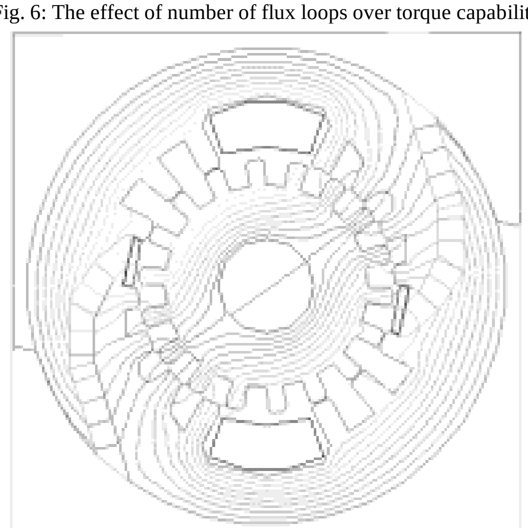

Fig. 7: Flux distribution with a negative armature current

Unlike an induction machine, for which the torque rises proportionally with the torque component of stator current I_{st}, the torque of the SMTM machine bends down at a high current level. Also, the specific current density decreases in the high current region. Since torque density is a product of the specific torque density and surface current density, a severe armature reaction will reduce the torque density. Hence, a TM machine has a relatively complicated winding flux path and could have a severe armature reaction problem. However, if carefully addressed, the negative effect by the problem can be reduced.

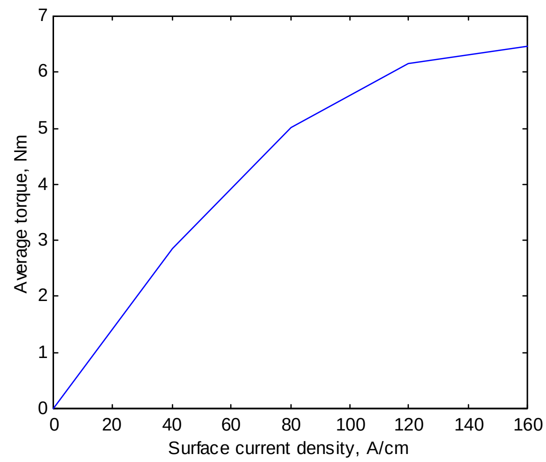

Fig. 8: Torque-current relation due to armature reaction

D. *Pulsating Torque and Starting Capability*

In order to have sufficient number of flux loops to realize the torque magnification effect, most TM machines are single winding single-phase machines, as is case for the SMTM machine. Due to the alternating flux linkage, rotor positions exist where the flux change rate is zero, which leads to zero instantaneous torque according to (1) at these rotor positions. While negative instantaneous torque can be avoided by making current always in phase with back EMF, zero instantaneous torque is inevitable. The nature of a single winding single-phase machine torque is a pulsating quantity as shown in Fig. 9 obtained from a design model of a SMTM machine.

Pulsating torque will cause concerns such as mechanical vibration, acoustic noise and starting capability. While the vibration and noise problems are regarded as inherent, they can be reduced with a careful design and the starting capability can be resolved completely. By mounting multiple same rotors on a common shaft with a proper angle shift between the rotors, the combined torque waveform could be very smooth, which is suitable for a load with a large starting torque.

An alternative solution is to modify the machine design to a two-phase machine as shown in Fig. 10. The two-phase version looses some specific torque density but can readily start under full load, has a relatively smooth torque and the acoustic noise can be reduced significantly.

D. *High Frequency Iron Loss*

A TM machine must operate under a relatively high electrical frequency to achieve a certain mechanical speed. This fact will increase the alternating flux frequency in magnetic steel and increase iron loss by more than the first order of frequency.

Fortunately the iron loss of a machine is normally much lower than its I^2R loss. This fact helps to a certain degree the heating and efficiency concerns of a TM machine. If necessary, thin silicon steel laminations can be applied, although there is, of course, an increase in cost. Examining the SMTM machine, it is interesting to find that some potions in the laminations only have DC flux, which clearly helps reduce the iron loss. Study shows that the SMTM machine can operate up to 1,500 RPM without considerable problems.

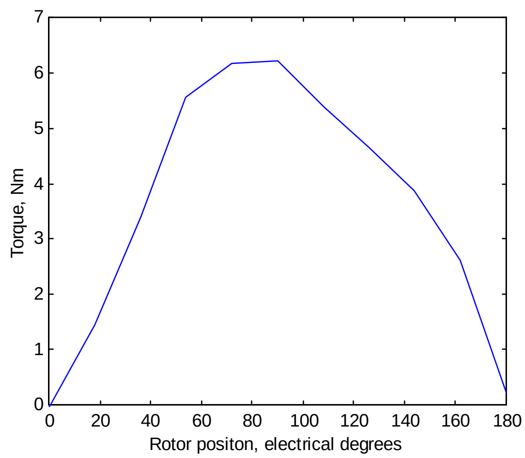

Fig. 9. Torque waveform with rotor position

E. Power Factor

The large number of flux loops of the SMTM machine provide a large area for winding flux paths and hence increase the per unit reactance of the machine, which results a low power factor. Low power factor is believed to be a drawback for all TM machines.

F. Cogging Torque

Cogging torque, which concerns the electromagnetic torque at zero armature current, which is significant for a TM machine. With a careful tooth shape design for a SMTM machine, the peak cogging torque can be limited to within 5% of the rated peak torque.

G. Field Weakening Capability

Unlike the above properties, which are common to all the TM machines, field weakening capability and the following manufacturing consideration is specific to the SMTM machine.

One important performance limitation of a PM machine is its field weakening capability, which enables a PM machine to operates in a wide speed range under a constant inverter DC bus voltage. The SMTM machine has a large magnet area, which provides lower magnetic reluctance for the field winding. Hence, it is possible to change the magnetic field considerably with a reasonable amount of field current. FEM analysis shows that by making the magnets thinner, the air gap field of the SMTM can be reduced by 50% without considerable toque reduction.

Note that armature current flux is orthogonal to both the magnet and field current flux. This fact leads to two advantages. Not only the interference between the two winding currents is reduced to minimum, but also the risk of magnet demagnetization is low.

H. Manufacturing Considerations

The topology of the SMTM machine is very simple compared with many other TM machines. The stator and rotor stacks can easily be made of laminations. The magnet within the machine does not rotate. Although the magnets need grinding to have an accurate thickness, it should not be a large cost hurdle for high volume production.

V. The Prototype Machine

The prototype design relies on the design considerations discussed in the preceding section. The design process basically concerned iterating on different design variables to realize a satisfactory performance for each design consideration. However, there is still large room for optimization because of the novelty of the SMTM machine. The top-level machine parameters are summarized in Table I.

To aid in the construction of the prototype machine, there are 0.75-mm wide bridges connecting the two sections of the stator laminations shown in Fig. 11.

TABLE I
Prototype Machine Top-Level Parameters

Number of flux loops	3
Stator outer diameter	137.3 mm
Stator bore	74.4 mm
Stack length	25.4 mm
Air gap	0.3 mm
Magnet	Ceramic 8
Number of turns	140
Surface current density	10 A/mm
Solid current density	6.0 A/mm^2
Rated current	8.5 A rms
Rated speed	1,000 RPM
Rated torque	3.2 Nm

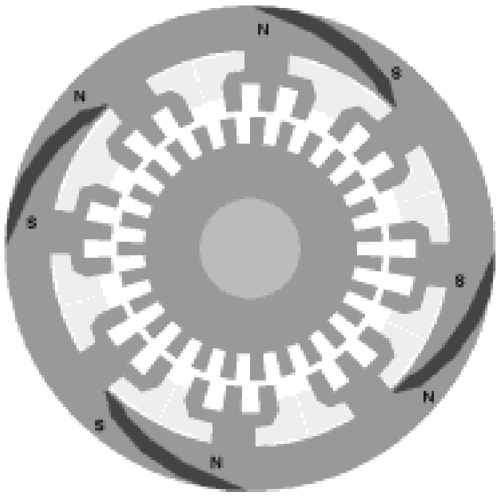

Fig. 10 Two phase spiral magnet machine

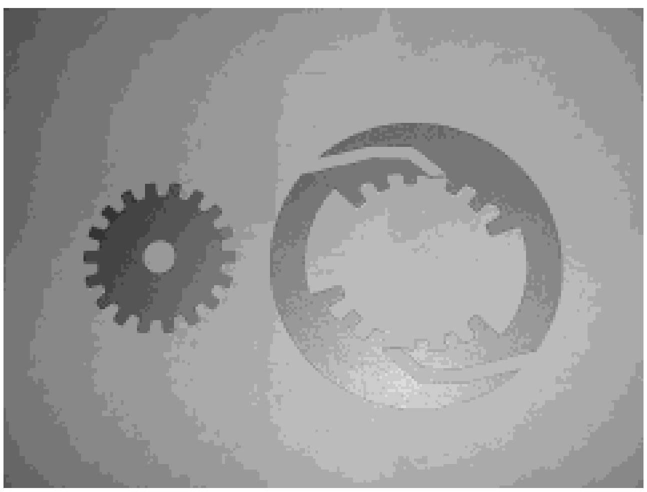

Fig. 11. Stator and rotor laminations of the prototype machine

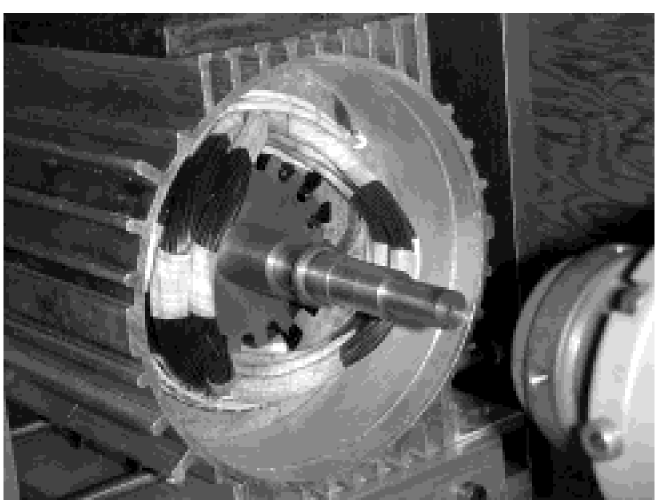

Fig. 12. Prototype machine assembly

VI. Test and Evaluation

Tests were conducted extensively to evaluate the prototype machine performance criterion considered in the design, with a focus on the machine's torque capability.

E. Back EMF

The SMTM machine was first tested as a generator for back EMF measurement, shown in Fig. 13, with the recognition that back EMF is an indicator for good torque characteristics. The measurement value is about 88% of that predicted by 2D Ansoft. The difference could be the underestimation of the magnet flux leakage at both ends of the stack, etc.

F. Torque

Utilizing rotor position feedback and a current control, the prototype machine was tested as a motor under different operating currents and speeds. Figs. 14 and 15 show the current waveform under low and high speed, respectively. Mechanical torque output from the SMTM machine was calculated from measure output power. Torque density and specific torque density were calculated, and compared with a modern 2-horsepower induction machine with a similar frame size. The 4-pole induction machine made in USA has an open ventilation and Class B insulation. By using (2), the SMTM machine has a torque density of 7.5 kNm/m^3 – 2.1 times of that of the induction machine.

Since it is difficult to measure the surface current density of the induction machine, an estimated value of K of 23 A/mm based on common knowledge, is used for specific toque density calculation by (6). Results show that the SMTM machine has 4.5 times the specific torque density over an induction machine.

It should be pointed that while the SMTM machine has very favorable specific torque density, its torque density is limited by armature reaction.

G. Other Performance Criterion

Starting capability tests show that the prototype machine can always self-start in the desired direction under a light load. The acoustic noise level is somewhat higher than an induction machine but is not considered to be a problem.

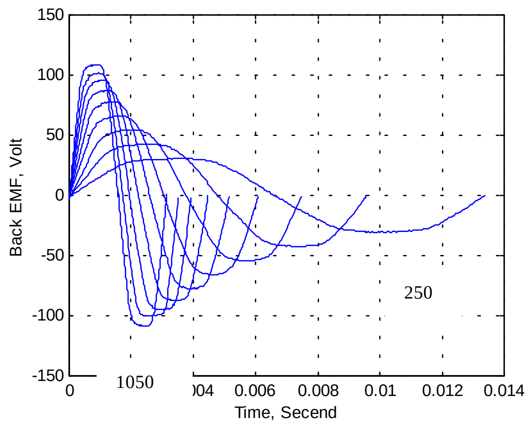

Fig. 13. Back EMF for speeds 250~1,050 RPM, 100 RPM increments

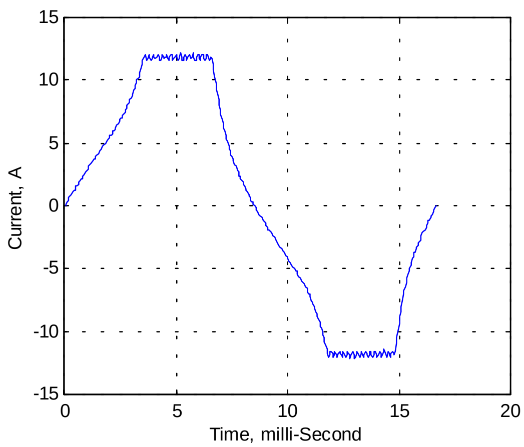

Fig. 14. One cycle machine current waveform at 200 RPM

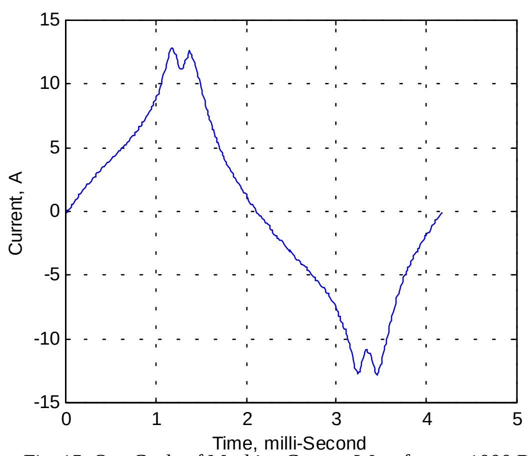

Fig. 15 One Cycle of Machine Current Waveform at 1000 RPM

Efficiency calculations indicate an advantage over the induction machine, realized mainly by eliminating the rotor I^2R loss.

VII. Conclusions

It has been demonstrated how the family of electric machines using the torque magnification principle are capable of both high specific torque density and torque density. However, a careful design is necessary to ameliorate some inherent problems, such as fringing flux, armature reaction, pulsating torque, iron loss, etc. The spiral magnet TM machine presented in this paper has achieved an effective flux concentration effect and a very high specific torque density, while still maintaining a simple 2-D topology. Some of the natural drawbacks of a TM machine have been reduced. The overall performance-cost ratio may enable the machine to be applied for certain high performance applications.

VIII. Acknowledgement

The authors would like to thank the funding from the member companies of WEMPEC. It is also grateful to Jerry Lloyd and William Fei at Emerson Electric Corporation, and David Stahl of Capstone Turbine Corporation for help in constructing the prototype machine.

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