Reduction of the unbalanced magnetic force of a transverse flux machine by using symmetric multipair cores

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This paper investigates the characteristics of the magnetic force and the torque in the conventional rotatory two-phase transverse flux machine (TFM) by using the three-dimensional finite element method. This research shows that the unbalanced magnetic force is one of the dominant excitation forces in this machine, and it proposes a TFM with symmetric multipair cores in which each stator core of phases A and B is divided into two and the divided cores are disposed symmetrically to cancel the unbalanced magnetic force of each phase of a TFM. However, symmetric multipair cores of a TFM may reduce the winding space of coil which results in the reduction of torque and power. This research performs the optimization of teeth-slot configuration of the stator to overcome this shortcoming. It shows that the unbalance magnetic force of a TFM can be effectively eliminated without sacrificing torque or power by introducing symmetric multipair cores. © 2008 American Institute of Physics. [DOI: 10.1063/1.2830636]

I. INTRODUCTION

A transverse flux machine (TFM) was first proposed by Weh and May in 1980.1 This motor has short iron core path with short pole pitch. Due to this unique structure, this machine has high power density, high torque, and high efficiency in comparison to conventional electrical motors. However, TFMs have not been widely applied in industry because they have manufacturing difficulty due to complex construction and high possibility of the magnetically induced vibration.

Many researchers have proposed several designs of TFMs and they also investigated their performance. Maddison et al. proposed a claw-pole design of a TFM for easy manufacturing and high torque.2 Kang and Jeong proposed a TFM with superconducting material between teeth to produce high power.3 Guo et al. applied the soft magnetic composite (SMC) to the stator and rotor of a TFM to reduce iron loss.4 Masmoudi et al. proposed the magnet skewing of a TFM rotor to reduce cogging torque.5 Most of the researchers have investigated the TFMs in terms of power, torque, and efficiency, but they did not study magnetically induced vibration due to the unbalanced magnetic force of TFM.

This paper investigates the characteristics of the magnetic force and the torque in a rotatory two-phase TFM by using the three-dimensional finite element method. This research shows that the unbalanced magnetic force is one of the dominant excitation forces in this machine, and it proposes a new topology, i.e., symmetric multipair cores of a rotatory two-phase TFM to eliminate the unbalanced magnetic force.

II. FINITE ELEMENT ANALYSIS AND VERIFICATION

Figures 1(a) and 1(b) show the stator and the rotor of a conventional rotatory two-phase TFM with the rated speed of 300 rpm. The stator is composed of SMC to reduce iron loss, and it is separated to top and bottom cores for each phase. Each top and bottom cores has 14.5 teeth, shifted by 1/2 tooth pitch. The rotor has 32 pairs of north pole, SMC, and south pole, and they are alternatively arranged along the circumferential direction. The active number of pole pairs to generate torque is 29 due to the gap between two stator cores. The rectangular shape of current with the mmf of 1250 A turns is assumed to be applied to each phase. Table I shows the energizing sequence, and $2\pi$ is the angle corresponding to one tooth pitch or one pole pair (360 electrical degree, 11.25 mechanical degree). Once the current is energized, magnetic flux flows from the teeth to the rotor. Magnetic flux is concentrated on the SMC by the permanent magnet with opposite polarities, and it returns to the stator.

![Fig. 1. (Color online) Stator and rotor of a rotatory two-phase TFM. (a) Conventional two-core stator. (b) Rotor. (c) Proposed four-core stator.](image)
Full finite element model of a rotatory two-phase TFM is developed to analyze the whole motor. It was modeled by using eight-node hexahedral element, and the numbers of node and element of full model are 614 448 and 559 376, respectively. This model is divided every 0.281 25° in the circumferential direction. ANSYS, a commercial finite element program, is used to solve the magnetic field. Once the magnetic field of a given position is solved, B-H properties of the elements in the rotor side are redefined to consider the rotation of a rotor without remeshing the whole element. Torque and magnetic force are calculated by using virtual work method every 0.281 25° while the rotor passes a period of pole pair.

This research measures the torque of a rotatory two-phase TFM by using a dynamometer in order to verify the simulation result. Figure 2 shows the simulated and measured torque profiles while only phase A is energized. It shows that the simulated torque matches with the measured one.

### III. RESULTS AND DISCUSSION

Magnetic field of the electric motors generates not only the torque to drive source motors but also the magnetic force which is the major source of noise and vibration. The magnetic force is generated along the air gap by the interaction between permanent magnet and applied current. It can be canceled in the rotational symmetric structure without sacrificing torque or efficiency. However, a rotatory two-core two-phase TFM is a rotational asymmetric structure and it always generates the unbalanced magnetic force not only because two phases are energized by the current with the phase angle of 90 electrical degrees but also because the

<table>
<thead>
<tr>
<th>Position</th>
<th>Phase A</th>
<th>Phase B</th>
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<tbody>
<tr>
<td>0°–0.5r</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>0.5r–1.0r</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>1.0r–1.5r</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>1.5r–2.0r</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

The geometry of the stator and rotor in Figs. 1(a) and 1(b) is almost symmetric with respect to the y axis, so that the magnetic force in the x direction is almost balanced for each core. However, the magnetic force in the y direction of core A is not balanced by that of core B because the phase currents A and B are energized differently depending on the commutation period. It may result in the bigger magnetic force in the y direction than that in the x direction.

This research proposes the symmetric multipair cores to cancel the unbalanced magnetic force of a rotatory two-phase TFM. Figure 1(c) shows a proposed stator with four cores for a rotatory two-phase TFM, in which each phases A and B is divided into two, and they are symmetrically arranged. Each of four cores has 6.5 teeth, shifted by 1/2 tooth pitch. This design does not generate the unbalanced magnetic force because the magnetic force generated by cores A1 and B1 is canceled by that of cores A2 and B2, respectively.

The active number of pole pairs for the proposed design is reduced to 26 due to the increased number of gap between cores, so that the average torque of the proposed design is smaller than the conventional one by 10%. This research investigates the mechanism of the torque production due to the teeth topology in order to maximize the torque production without generating the unbalanced magnetic force. Figure 4 shows the conventional and the optimized shapes of the teeth of the upper and lower cores. It shows that the increased axial length of teeth between the upper and lower core reduces the magnetic leakage and magnetic saturation to increase the torque. Figure 5 shows the torque profiles for the conventional design, four-core design with and without optimizing teeth topology. It shows that the torque reduction of multipair core design can be overcome by optimizing the teeth topology.
IV. CONCLUSION

This research shows that the unbalanced magnetic force always exists for the conventional two-phase and two-core design of a TFM. This research proposes a TFM with symmetric multipair cores in which each stator core of phases A and B is divided into two and the divided cores are disposed symmetrically to cancel the unbalanced magnetic force of each phase of a TFM. However, symmetric multipair cores of a TFM may reduce the winding space of coil which results in the reduction of torque and power. This research performs the optimization of teeth-slot configuration of the stator to overcome this shortcoming. It shows that the unbalance magnetic force of a TFM can be effectively eliminated without sacrificing torque or power by introducing symmetric multipair cores. This research may contribute to reduce the magnetically induced vibration of a TFM.