Analysis of Fractional-Slot Axial-Flux PM Machines by 3-D FE Simulation

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Abstract — As the concept of hybrid electric vehicles and more electric aircraft are extending nowadays, achieving the desired performance along with decreasing the weight can be of the highest importance for the companies to save the fuel and decrease the costs. Axial-flux PM brushless-dc machines with concentrated windings provide high efficiency, compact construction, and high torque-density and are subsequently excellent choices to be used in direct-driven applications. As pole and slot combination has dominant effect on machine performance, this paper investigates effect of similar pole and slot numbers on machine's performance by three-dimensional finite-element (3-D FE) analysis. Air-gap flux density, back-electromotive force (back-EMF), cogging torque, winding inductance, and unbalanced torque exerted on bearings of two 3.4 kW axial-flux PM brushless-dc machines are obtained using 3-D FE method. It provides useful results to be considered in design of brushless-dc machines.

Keywords — Axial Flux Permanent Magnet, Brushless Dc, Yokeless Segmented Stator, Cogging Torque, Unbalanced Torque, 3-D Finite Element

I. INTRODUCTION

World today is approaching toward applications with high reliability [1], high efficiency, and high power density while achieving low weight and low fuel consumption. For example, as the concept of hybrid electric vehicles and more electric aircraft are extending nowadays, achieving the desired performance along with decreasing the weight can be of the highest importance for the companies to save the fuel and decrease the costs [2]-[4].

Recently, axial-flux PM machine technology is developing [5]-[9]. Axial-flux PM brushless-dc machines with concentrated windings provide high efficiency, high power-density, ease of winding, compact construction; and are excellent choices to be used in direct-driven applications as in more electric aircrafts, electric vehicles and wind turbines [10]-[12], but when used in micro grids, the control selection mode should be taken care of to higher the chance of islanding detection [13].

There are different topologies for Axial-flux PM machines [14]. An Axial-flux PM machine with double-rotor, single-stator, yokeless, and segmented stator designed for electric vehicles [15-17], as shown in Fig. 1, is chosen for this study. Woolmer et al [16] analyzed the topology with sinusoidal back-EMF, and Jafarishiadeh et al [17] investigated this topology for brushless-dc operation, i.e. trapezoidal back-EMF. Also Jafarishiadeh et al [3] showed similar pole and slot combination is better choice with respect to torque-density and fault tolerance compared to conventional pole and slot combination. The machine has a single stator that is sandwiched between two surface-mounted PM rotor discs. Segmented stator with parallel slot-opening is employed so that high filling factor can be achieved.

Fig. 1. Axial-flux PM machine with segmented stator topology [16]

As mentioned before, high efficiency should be of highest importance for the companies to improve the performance and decrease the cost [18-20]. This increasing in the performance can lead to reduce the harmonics induced to the network which helps to reduce the final customer’s cost [21- 22]. In order to achieve high efficiency and decrease the cost by saving the fuel, it is important to decrease the total weight. Axial-flux PM brushless-dc machines with concentrated windings are candidate choices for direct-driven applications. One of the important steps in machine design is choosing number of pole and slot, which determines machine performance. The conventional ratio of number of slots to number of poles in PM brushless-dc machine, which yields to an easy simple winding configuration, is 3:2 [23], such as 15-slot/10-pole machine. This results in a low pitch factor and hence low winding factor and low torque. In the case of using similar slot number and pole number, higher pitch factor can be achieved which results in higher winding factor and hence higher flux linkage and output torque. So as the merit of an axial-flux PM brushless-dc machine is especially its high torque-density for applications with limited space, machines with similar slot number and pole number could be an excellent choice for these applications. This paper investigates axial-flux PM brushless-dc machines with similar number of slots and number of poles; i.e. combinations in which number of pole and number of slot differ by 1 or 2. Equal number of pole and number of slot is not practical. So two 10-pole axial-flux PM brushless-dc machines with similar slot and pole combination are considered: 9-slot/10-pole machine and 12-slot/10-pole.
Table 1. Motor Parameters

<table>
<thead>
<tr>
<th>Machine Type</th>
<th>9-slot/10-ploe</th>
<th>12-slot/10-ploe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of poles</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Number of slots</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Supply voltage, V</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Phase current, A</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>Rated rotational speed, rpm</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Stator outer radius, mm</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>Stator inner radius, mm</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Slot-opening, mm</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Tooth width at average radius, mm</td>
<td>27.41</td>
<td>35.27</td>
</tr>
<tr>
<td>pole-arc to pole-pitch ratio</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Air gap, mm</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Magnet axial length, mm</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Magnet remanence, T</td>
<td>1.22</td>
<td>1.22</td>
</tr>
<tr>
<td>Number of turns per coil</td>
<td>33</td>
<td>25</td>
</tr>
</tbody>
</table>

Analytical methods such as finite element have been widely used in order to study the performance of engineering structures. Chakherlou and Yaghoobi developed a finite element model to study the effect of cyclic loading on residual stress relaxation of engineering structures [24]. Finite element is also used by Yaghoobi [25] to determine deflection of 3D plates. This work uses finite element to study and predict the performance of engineering structures If saturation effects, stator and rotor slots, or exact geometric sizes are not neglected, these methods will be very complex. To solve this problem and obtain accurate results, the finite-element method is used which uses a precise analysis of magnetic materials considering geometric details and magnetic nonlinearity. Also, axial-flux PM machines are inherently 3-D machines [3]. It was demonstrated by Masoomi et al. [26] that to get accurate response, the results need to be mesh independent. Therefore, a 3-D FE model was developed using software MAXWELL [27] to study the accurate performance of the machines.

**II. DESIGN CONSIDERATIONS**

There are different ways to realize a motor with concentrated windings [24, 30]. It is assumed that the design is performed for three-phase motors with balanced windings which have two coils sides in each slot. The angles of the 4th coil for the concentrated windings are defined as

\[
\theta_c(k) = (k-1) \frac{P}{N_s} 180^\circ E
\]

for \( k = 1, 2, ..., N_s \)

where \( p \) is the number of poles and \( N_s \) is the number of slots. With respect to (1) and for having balanced windings, the 3-phase winding arrangement is A′AA′C′CC′B′B′ for the 9-slot/10-pole machine, while it is A′A′C′BB′A′ACC′B′B′ for the 12-slot/10-pole machine. The winding factors \( K_{wn} \) can be achieved as

\[
K_{wn} = \frac{1}{N_{ph}} \sum_{k=1}^{N_{ph}} e^{-jn\theta_c(k)}
\]

where \( N_{ph} \) represents number of coils per phase, and \( n \) is the order of harmonics.
common divisor between pole number and slot number in 9-slot/10-pole machine and 12-slot/10-pole machine is 1 and 2; respectively. Hence cogging torque waveform components produced by the interaction of PMs and stator teeth are rarely in phase to each other. So peak cogging torque of both machines is very low. Fig. 5 (a) shows flux linkage per phase for the motors which is obtained by 3-D FE transient simulation. Phase back-EMF is one of the most important characteristics of the machine and is computed by the no-load change rate of flux linkage through the corresponding coils. In PM brushless-dc machine, phase-back-EMF waveform is desired to be more trapezoidal in order to have less torque ripples. Phase-back-

EMF waveforms of 9-slot/10-pole motor and 12-slot/10-pole motor are obtained by using 3-D FE transient evaluation and shown in Fig. 5 (b). It is seen that both machines have a co-sinusoidal back-EMF waveforms, but the 12-slot/10-pole motor has a more trapezoidal back-EMF waveform compared to 9-slot/10-pole motor, which makes it better candidate for brushless-dc operation as it may have less torque ripples.

Table II shows self and mutual inductances of the two machines. It is seen that both machines with double-layer concentrated windings have good fault tolerance capability. The 9-slot/10-pole machine has higher self-inductance which can limit short circuit current better than 12-slot/10-pole machine. Also both machines have low mutual-inductance which will isolate phases from each other effectively. So 9-slot/10-pole machine has higher fault tolerance capability compared to 12-slot/10-pole machine.

One of the main characteristics of axial-flux PM machines is high attraction axial force between PMs and stator teeth. For the axial-flux PM machines considered for this research, the total axial force exerted on each rotor discs obtained by 3-D FE analysis is from 2000 N to 2300 N, with respect to rotor position. So the bearing lifetime is of concern. It must be noted that in PM machines which number of slot and number of pole differ by 2, the number of slot is even, which results in symmetric disposition of stator slots and coils. But if asymmetric disposition of stator slots and coils exists, as in 9-
brushless-dc mode (120° elec. rectangular phase current waveforms) which intensifies the amount of undesirable unbalanced torque.

IV. CONCLUSION

Analysis and comparison of axial-flux PM brushless-dc machines having similar slot and pole combination was presented in this paper. The comparison was done for two 10-pole machines with the same dimension and phase current. It is shown that both machines which number of slot and number of pole differ by 1 can better fulfill fault tolerance capability. Axial-flux PM brushless-dc machines which number of slot and number of pole differ by 2 have higher torque average along with less torque ripples which makes them more appropriate for applications requiring high torque-density. Also machines which number of slot and number of pole differ by 1 suffer from high extra unbalanced torque exerted on bearing which reduces its lifetime. So axial-flux PM brushless-dc machines which number of slot and number of pole differ by 2 are better choices.

REFERENCES


