Comparative Study of Three Kinds of Doubly Salient BLDC Generators

Qian Le, Zhuoran Zhang, Yangyang Tao
Jiangsu Key Laboratory of New Energy Generation and Power Conversion, Nanjing University of Aeronautics and Astronautics, Nanjing, China
E-mail: apsc-zzr@nuaa.edu.cn

Abstract—Doubly salient machine with a rectifier circuit constitutes a type of simple BLDC generators, which include doubly salient permanent magnet generator (DSPG), doubly salient electro-magnetic generator (DSEG) and doubly salient hybrid excitation generator (DSHEG). Magnetic field analysis of these generators is carried out based on finite element method (FEM). Hence, a comprehensive comparison of the static characteristics of these three kinds of generators is investigated. The output characteristics of these generators are compared by field-circuit coupled analysis. Results of comparing the three generators such as the voltage regulation, total mass of effective materials, the maximum power, power density and the efficiency are given.

I. INTRODUCTION

Due to advantage of simple construction, fault tolerance, and mechanical robustness, the switched reluctance machine (SRM) has grown significantly in recent years [1]. However, it suffers from the problem of control complexity, excitation power loss, vibration and noise, which has prompted research into the incorporation of permanent-magnets into the basic SRM structure. One of the new topologies proposed in [2] is the permanent-magnet machine (DSPM). The rotor of the DSPM machine is identical to that of the 3-phase SRM. The stator structure is also similar to that of the SRM except that PMs are buried in the core and therefore introduced into the main flux path of the stator windings. And the further research of DSPM is in [3-6]. The doubly salient electromagnetic (DSEM) machine was proposed, with the replacement of PMs in the DSPM by a dc field winding [7-9]. The same structure is also called the brushless doubly fed doubly salient machine (BDFDS) in [10, 11]. Then some new machine topologies have been developed to combine the advantage of DSPM and DSEM, which stator contains PMs and field windings. It called doubly salient hybrid excitation machine (DSHEM). Ref. [12] proposed a DSHEM, which has two separated rotors and two separated stators. In [13], the magnetic bridge was proposed to realize flux control.

II. CONFIGURATION

The cross-sections of these three doubly salient generators are shown in Fig.1, which adopt a three-phase 24/16-pole (24 stator poles and 16 rotor poles) topology. The rotor of all generators are the same. The concentrated armature windings, which lead to low copper consumption and low copper loss due to short end-windings, are employed and a concentrated coil is wound on every stator pole. Fig. 1(a) shows the cross-section of a 3-phase, 24/16-pole DSPG. Eight pieces of PMs are installed in the stator yoke. PMs is magnetized along the tangent direction. Fig. 1(b) shows the cross-section of a 3-phase, 24/16-pole DSEG. Compared to the DSPM, the main difference existing in the configuration is the replacement of PMs by excitation windings. Thus, the voltage regulation and fault protection of DSEG is easy to be realized by regulating the air gap flux. Fig.1(c) shows the cross-section of a 3-phase, 24/16-pole DSHEG [14]. The PMs is also magnetized along the tangent direction. Magnetomotive force (MMF) sources in the stator are produced by both four pieces of PMs and four elements of electrical excitation windings. The dc current in the excitation winding is independently controllable, which serves to weaken or
strengthen the PM flux. So DSHEG can readily control the field flux for output voltage regulation and de-excitation at fault. Each phase winding of these generators is composed of eight coils.

Fig. 1. Cross-sections of 3-phase 24/16-pole doubly salient generators.

III. 2D-FEA OF ELECTROMAGNETIC FIELD

To compare meaningfully, these three kinds of doubly salient generators are designed under the same electric condition, such as rotating speed, stator outer diameter etc. Table I lists the major design specifications and design parameters for these generators.

<table>
<thead>
<tr>
<th>Items</th>
<th>DSPG</th>
<th>DSEG</th>
<th>DSHEG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of phases</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Number of stator poles</td>
<td>24</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Number of rotor poles</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Stator outer diameter (mm)</td>
<td>330</td>
<td>330</td>
<td>330</td>
</tr>
<tr>
<td>Stator inner diameter (mm)</td>
<td>220</td>
<td>220</td>
<td>220</td>
</tr>
<tr>
<td>Rotor outer diameter (mm)</td>
<td>219.4</td>
<td>219.4</td>
<td>219.4</td>
</tr>
<tr>
<td>Rotor inner diameter (mm)</td>
<td>144.2</td>
<td>144.2</td>
<td>144.2</td>
</tr>
<tr>
<td>Stack length (mm)</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Air-gap length (mm)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Turns-in-series per pole</td>
<td>145</td>
<td>145</td>
<td>145</td>
</tr>
<tr>
<td>Magnet dimensions (mm<em>mm</em>mm)</td>
<td>120<em>30</em>6</td>
<td>/</td>
<td>120<em>22</em>9</td>
</tr>
<tr>
<td>Total magnet volume (mm³)</td>
<td>172800</td>
<td>/</td>
<td>95040</td>
</tr>
<tr>
<td>Number of turns/excitation winding</td>
<td>/</td>
<td>120</td>
<td>120</td>
</tr>
</tbody>
</table>

Finite element analysis models of the 24/16-pole generators are built to acquire the detail characteristic.

Fig. 2 shows the flux distribution of DSPG. It can be seen that magnetomotive force (MMF) sources in the stator are produced by PMs. Fig. 3 shows the flux distribution of DSEG. MMF sources in the stator are produced by excitation windings. Fig. 4 shows the flux distribution of DSHEG. While the excitation current is not applied, MMF sources in stator are completely produced by PMs, as shown in Fig. 4 (a). Obviously, the flux density of iron core around the field excitation windings is increased with the increase of positive excitation current, which can be observed in the comparison of Fig. 4 (a) and (b). When the negative excitation current is applied, the flux density of iron core between field excitation winding and PM is weakening, as shown in Fig. 4 (c). Though the DC excitation current is changed, the flux distribution in the stator core between the two PMs has changed a little. This is because the PMs have the high magnetic resistance characteristics. The flux path of these three doubly salient generators is the same, when the excitation current of DSHEG is the certain direction.
When the excitation current of DSEG and DSHEG is 10A, Fig.5 shows the air-gap flux density distributions of these three kinds of doubly salient BLDC generators, which are similar. Due to the doubly salient structure, the air-gap flux density distributions are far away from sinusoidal. The maximum air-gap flux density reaches 1.6T at the right corresponding position of stator pole and rotor pole. The similar air-gap flux density settles a basis to analysis and compare meaningfully.

IV. FIELD-CIRCUIT COUPLE ANALYSIS

Due to the non-sinusoidal induced potential, doubly salient machine is generally not used as AC generator. Doubly salient BLDC generators are built in MAXWELL2D, and field-circuit coupled analysis is successfully performed.

Fig.6 compares flux linkage of these three generators under no-load, while excitation current of DSEG and DSHEG is 10A. The rotation speed is 500r/m. The flux linkages are also similar. The range of the flux linkage is 0.28Wb to 3Wb. The back-EMF waveforms of these three generators are compared in Fig.7. These three generators can obtain the same phase voltage waveform.
Fig. 6. Flux waveforms at no-load.

Fig. 7. Phase back-emf at no-load.

Fig. 8 shows phase self-inductance of these three generators respectively. These three generators adopt parallel pole and the position of PMs or excitation windings unbalanced, so the flux path and phase self-inductance of phase A are different from phase B and C. Due to the flux path of phase B and phase C are balance, the phase self-inductance of these two phases are almost the same, which just have a difference of phase angle. Obviously, the maximum phase self-inductance of DSPG is the lowest. Highest of all is the maximum phase self-inductance of DSEG. The maximum phase self-inductance of DSHEG is between the two generators above. When the rotor located at the overlap of rotor and stator, the permeance increases. The phase self-inductance reaches the maximum value. Due to the yoke saturation around PMs, the self-inductance waveform of DSPG presents “saddle shape”. Meanwhile, self-inductance waveforms of DSEG and DSHEG seem like a triangle. If the excitation current increases, deep saturation of the two generators will also lead to a “saddle shape” of self-inductance waveforms.

Fig. 9 shows the simulation curves of output characteristics of these three BLDC generators, while excitation current is 10A, and rotating speed is 500r/m. The output voltage versus load current curve of DSPG drops slighter than other generators. Furthermore, the calculation results of power characteristic are shown in Fig.10. It can be found that DSPG reaches the maximum power, which is up to 4.34kW. The maximum power of DSHEG is 3.51kW. Lowest of all is DSEG, which reaches 3.38kW.
The calculation of voltage regulation is division the difference in no-load voltage and rated voltage by no-load voltage. The voltage regulation is lower, the output voltage drops less. From Table II, the voltage regulation of DSPG is the lowest of these three generators. As DSPG has a lowest inductance value, the voltage drop caused by inductance is much lower than the other two. Power density is the amount of power per unit weight. The power density of DSPG is 35% higher than DSEG and 28% higher than DSHEG in this case. Furthermore, the power density of DSHEG is 6% higher than DSEG.

### TABLE II

<table>
<thead>
<tr>
<th>Generator</th>
<th>$\Delta V_{\text{IN}}$ (I=3.5A)</th>
<th>Total mass (kg)</th>
<th>Maximum power (W)</th>
<th>Power density (W/kg)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSPG</td>
<td>39.9%</td>
<td>50.5</td>
<td>4337.3</td>
<td>85.9</td>
<td>95%</td>
</tr>
<tr>
<td>DSEG</td>
<td>54.1%</td>
<td>53.3</td>
<td>3380.8</td>
<td>63.4</td>
<td>91%</td>
</tr>
<tr>
<td>DSHEG</td>
<td>51.1%</td>
<td>52.2</td>
<td>3512.3</td>
<td>67.3</td>
<td>93%</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS

When the three kinds of doubly salient BLDC generators have the same configuration and the similar air-gap flux density, flux linkage and back-EMF at 500 rpm, comparative study of these three generators are investigated. Several important conclusions are drawn as follows:

1) The voltage regulation of DSPG is lowest. DSPG has high power density. Moreover, DSPG has high efficiency. However, flux density in the main air-gap of DSPG is hard to control.

2) With the use of DC excitation current control, DSEG has the easy controllability and high reliability. However, excitation windings bring copper loss. So the efficiency is relatively low.

3) DSHEG has wide operating range by adjusting the excitation magnetic force. Moreover, the voltage regulation of DSHEG is lower than DSEG. The power density and efficiency of DSHEG is higher than DSEG. So DSHEG only has high power density and low exciting power, but also its air-gap flux can be regulated easily.

REFERENCES


Qian Le received the B.S. degree in electrical engineering from Tongji University, Shanghai, China, in 2010. She is currently working toward the Master. degree in electrical engineering at Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China. Her main research interests include doubly salient electrical machine, permanent magnet machine.

Zhuoran Zhang (M’09) received the B.S. degree in measurement engineering from Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2000, the M.S. and Ph.D. degrees in electrical engineering from NUAA, in 2003 and 2009, respectively. He is currently a professor and the vice director in the Department of Electrical Engineering, College of Automation Engineering, NUAA. His
research interests include doubly salient electrical machine, permanent magnet machine, hybrid excitation electrical machine, renewable power system and aeronautical power supply systems. He has authored or coauthored of over 40 technical papers and is the holder of eleven patents in these areas.

Yangyang Tao received the B.S. degree in electrical engineering from Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2009. He is currently working toward the Master. degree in electrical engineering at the same university. His main research interests include doubly salient electrical machine, permanent magnet machine.