Investigation of a New Topology of Hybrid Excitation Doubly Salient Brushless DC Generator

Zhuoran Zhang, Member, IEEE, Yangyang Tao, and Yangguang Yan

Abstract—This paper proposes and implements a new topology of hybrid excitation doubly salient brushless DC generator. Configuration and flux control principle of the generator are presented. Two-dimensional finite element methods are used to investigate the static field distribution characteristics of this new type of generator. Field-circuit coupled analysis is successfully performed, and the output characteristics of different windings are obtained. A prototype hybrid excitation doubly salient brushless DC generator is designed and developed, and the experimentation is also given to verify the validity of the proposed brushless DC generator with one and dual terminal outputs. The results confirm the excellent field-regulation capability of hybrid excitation doubly salient brushless DC generator, and the rectified output of permanent magnet part can serve as the independent power of the excitation winding when the hybrid excitation doubly salient brushless DC generator has two sets of output windings.

Index Terms—Brushless machine, permanent magnet, doubly salient, finite element methods, hybrid excitation, magnetic flux, wind power generation.

I. INTRODUCTION

DOUBLY salient permanent magnet machine (DSPM) proposed in the early 1990s [1], which resembles the simple structure of a switched reluctance machine (SRM) [2-4], has received wide attention [5-9]. As a kind of stator-PM (magnets located in the stator) brushless machine, DSPM can offer higher efficiency and higher power density [10-14]. However, DSPM suffers from the problem of uncontrollable PM flux and high PM material cost, just as the other PM machines. With the replacement of the permanent magnets in DSPM by dc electrical excitation windings, the doubly salient electromagnetic machine (DSEM) is constructed. Thus, the voltage regulation and fault protection of DSEM is easy to be realized by regulating the air gap flux. Meanwhile, excitation power loss in DSEM may exert a negative impact on the efficiency and power density of the machine [15-20].

Recently, the concept of hybrid excitation doubly salient machine (HEDSM), which strives to combine the merits of DSPM and DSEM, is proposed. The HEDSM not only maintains the advantages of DSPM but also has the ability of controlling magnetic field flux by field windings. Dr. Chen presented a coordinate structure HEDSM composed of a DSPM and a DSEM [21]. The magnetic paths of the DSPM and DSEM are independent from each other, which means that the HEDSM machine can be equal to the addition of a DSPM machine and a DSEM machine. Dr. Zhu proposed a stator hybrid excited doubly salient machine with the PMs located in the stator back-iron [22]. The novelty of this machine is the addition of an extra flux path in shunt with each PM pole, hence amplifying the effect of flux weakening for constant power operation [23-24].

Moreover, by reducing the magnets in flux-switching PM (FSPM) machine to accommodate the excitation windings, novel hybrid excited flux-switching machines (HEFSM) are proposed. In [25], a new structure of (HEFSM) which may be used as a low speed gearless wind generator is proposed. The advantage of the structure is the possibility to modulate the excitation flux and its consequence on iron losses. In [26] and [27], another structure of HEFSM machine with iron flux bridges is introduced. By adding an iron bridge at outer radius of the machine, the field coil excitation can be effectively increased at the cost of slightly reduced torque density. A novel

NOMENCLATURE

<table>
<thead>
<tr>
<th>2D-FEA</th>
<th>Two-dimensional finite element analyses.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>Permanent magnet.</td>
</tr>
<tr>
<td>DSPM</td>
<td>Doubly salient permanent magnet.</td>
</tr>
<tr>
<td>SRM</td>
<td>Switched reluctance machine.</td>
</tr>
<tr>
<td>DSEM</td>
<td>Doubly salient electromagnet machine.</td>
</tr>
<tr>
<td>HEDSM</td>
<td>Hybrid excitation doubly salient machine.</td>
</tr>
<tr>
<td>FSPM</td>
<td>Flux-switching permanent magnet.</td>
</tr>
<tr>
<td>HEFSM</td>
<td>Hybrid excited flux-switching machine.</td>
</tr>
<tr>
<td>HEDS-BLDCG</td>
<td>Hybrid excitation doubly salient brushless DC generator.</td>
</tr>
<tr>
<td>MMF</td>
<td>Magnetomotive force.</td>
</tr>
<tr>
<td>If</td>
<td>Excitation current.</td>
</tr>
</tbody>
</table>

This work was supported by the national Natural Science Foundation of China under Award 50877023, National Basic Research Program of China (973 Program) under Project 2007CB210302, and by the aeronautical science foundation of China under project 2010ZC52034.

Copyright (c) 2009 IEEE. Personal use of this material is permitted. However, permission to use this material for any other purposes must be obtained from the IEEE by sending a request to pubs-permissions@ieee.org.

The authors are with the Jiangsu Key Laboratory of New Energy Generation and Power Conversion, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China (email: apsc-zrz@nuaa.edu.cn).
HEFSM proposed in [28] exhibits good flux-regulation capability, in which the PM flux can be strengthened double of that of pure-PM topology and weakened to almost zero [29].

In this paper, a new type of HEDSM with rectified output, which may be used as hybrid excitation doubly salient brushless DC generator (HEDS-BLDCG), is proposed and investigated. Relative to the hybrid excitation machines mentioned above, this HEDSM may have great superiority in the situation of independent generation systems because of its special structure. The configuration and flux control principle are introduced in Section II. In order to predict the electromagnetic performances and output characteristics of the proposed generator, two-dimensional finite element analyses (2D-FEA) and field-circuit coupled analysis are successfully performed. Moreover, a prototype 24/16-pole HEDSM has been designed and developed. Experimental results are given to verify the new topology of HEDSM.

II. CONFIGURATION AND FLUX CONTROL PRINCIPLE

A. Configuration

The proposed HEDSM has 6N stator poles and 4N rotor poles (N is an integer which should be greater than or equal to 3). There are two magnetomotive force(MMF) sources in the stator: MMF produced by permanent magnets and MMF produced by electrical excitation windings. MMF produced by electrical excitation windings serves to weaken or strengthen the PM flux. Since the dc current in the excitation winding is independently controllable, HEDSM can readily control the field flux for output voltage regulation and de-excitation at fault. Thus, the HEDSM consists of two types of stator windings: one is excitation winding, and another one is armature winding.

Fig. 1 shows the structure of a 24/16-pole HEDSM, while the N is equal to 4. There are three sets of three-phase armature windings in HEDSM. A1, B1 and C1 phase windings consist of the concentrated armature windings wound around the six stator poles between the two groups of PMs. A2, B2 and C2 phase windings are composed of the concentrated armature windings wound around the six stator poles between the two groups of excitation windings, and A3, B3, C3 phase windings are constructed by the other armature windings, as shown in Fig. 1. The connection mode of each armature winding is the same to that of conventional doubly salient machine. Likewise, the rotor has neither PMs nor electrical windings, hence, offering high reliability.

B. Flux Control Principle

Fig.2 shows the flux control principle of the proposed HEDSM with different excitation currents. While the excitation current is not applied, the magnetic flux in stator is completely produced by PMs, as shown in Fig.2(a). When field current in excitation winding is negative, flux strengthening occurs in the stator poles on one side of the excitation winding, and flux weakening on the other side, as shown in Fig.2(b). The magnetic flux in the stator poles between excitation winding and PM may be reversed while the DC field ampere-turns are sufficiently large, as shown in Fig.2(c). The similar flux variation also appears in the stator poles on the other side of the excitation winding when positive DC excitation current is applied, as shown in Fig.2(d) and Fig.2(e). Due to the high magnetic resistance characteristics of the PMs, the magnetic field in the stator poles between the two PMs presents less variation while the DC excitation current is changed. It can be seen that the flux of three stator poles between the two PMs is strengthened by negative DC excitation current, and flux weakened by positive excitation current.

Fig. 1. Configuration of the proposed 24/16-pole HEDSM.
III. 2-DIMENSIONAL FINITE ELEMENT ANALYSES OF ELECTROMAGNETIC FIELD

The flux distributions of the HEDSM at different excitation current are shown in Fig. 3, and the corresponding radial air-gap flux density distributions are shown in Fig. 4.

It can be seen that the magnetic flux in iron core and air-gap can be regulated in a wide range. In comparison, the magnetic flux in the iron core and air-gap between the two PMs (named PM part, corresponding to phase A1, B1, C1) presents less variation. While the excitation current is -5A, the magnetic flux in iron core and air-gap between the excitation winding and PM is almost reduced to zero, as shown in Fig. 3(b), which is due to the combined action of PM MMFs and excitation MMFs. At the

Fig. 2. Flux control principle of HEDSM with different excitation currents. (a) If=0, (b) If<0, less DC field ampere-turns, (c) If<0, larger DC field ampere-turns, (d) If>0, less DC field ampere-turns, (e) If>0, larger DC field ampere-turns.
Fig. 3. Flux distributions with different excitation current:
(a) If = -14.7A. (b) If = 5A. (c) If = 0. (d) If = 14.7A.

same time, the magnetic flux flow through the iron core between the two PMs and the magnetic flux between the excitation windings are equal in magnitude but opposite in direction. While the negative excitation current is increased to 14.7A, the magnetic flux in iron core and air-gap between the excitation winding and PM is reversed, as shown in Fig. 2(c) and Fig. 3(a). When the excitation current is positive and increased to 14.7A, the air-gap flux is effectively strengthened and the maximum flux density reaches 1.3T. The analysis results give a good verification to the flux control principle presented above.

Fig. 4. Air-gap flux density distributions with different dc excitation currents.

Table I

<table>
<thead>
<tr>
<th>Prototype Machine Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
</tr>
<tr>
<td>Rated voltage</td>
</tr>
<tr>
<td>Number of stator poles</td>
</tr>
<tr>
<td>Number of rotor poles</td>
</tr>
<tr>
<td>Stator outer diameter</td>
</tr>
<tr>
<td>Stator inner diameter</td>
</tr>
<tr>
<td>Rotor outer diameter</td>
</tr>
<tr>
<td>Rotor inner diameter</td>
</tr>
<tr>
<td>Stator pole height</td>
</tr>
<tr>
<td>Rotor pole height</td>
</tr>
<tr>
<td>Stack length</td>
</tr>
</tbody>
</table>

IV. SIMULATION AND VERIFICATION

Generally, doubly salient machine cannot be used as AC generator because of its non-sinusoidal induced potential. Thus, the proposed HEDS-BLDCG is constructed by the HEDSM and

Fig. 5. Test rig for experimental examination of HEDS-BLDCG.

Fig. 6. Field-circuit coupled model of HEDS-BLDCG.

(a)
Fig. 7. Phase voltage waveforms of winding I. (a) simulated. (b) measured (100 V/div, 2.5 ms/div).

Fig. 8. Phase voltage waveforms of winding II. (a) simulated. (b) measured (400 V/div, 2.5 ms/div).

Fig. 9. Output voltage versus excitation current. (a) Winding I. (b) Winding II.

output rectified circuits. The different connection of the armature windings of HEDSM may form one or more sets of three-phase windings, so the HEDS-BLDCG can also provide one or more terminal DC power outputs.

A prototype machine of HEDS-BLDCG has been developed. Table I gives key parameters of the generator. Fig. 5 shows the test rig for experimental examination of HEDS-BLDCG.

A. Dual terminal outputs

Considering the less variation of PM flux, phase A1, B1, C1 provide three-phase output independently, formed Winding I. Meanwhile, phase A2, B2, C2 winding and phase A3, B3, C3 winding are connected in series to constitute winding II. The outputs of Winding I and Winding II connected with rectified circuits can produce dual DC terminal outputs of HEDS-BLDCG, which field-circuit coupled model is established and shown in Fig. 6.

Fig. 7 and Fig. 8 respectively show phase voltage waveforms of two different windings of the HEDSM at no-load, while excitation current is 14.7A. The phase voltage waveform is similar to that of conventional doubly salient machine, and the simulated waveforms agree well with the measured ones.

Fig. 9 shows the simulated and measured results of relationship between output dc voltage and excitation current. It can be seen that the output voltage of winding I is decreased with the increase of excitation current, which is consistent with the flux control principle discussed above. The output voltage of winding II can be widely regulated by changing the positive
excitation current, and output voltage increases with increasing the excitation current. While low negative excitation current is applied, the output voltage value may be decreased almost to zero. On the other hand, the output voltage is also increased by enhancing the negative excitation current.

Fig.10 and Fig.11 respectively show the measured and simulated phase voltage waveforms of Winding I with 1.2A dc load current and Winding II with 0.81A dc load. The experimental waveforms agree well with the simulation waveforms. The results indicate that the phase potential of the HEDS-BLDCG with load is distorted, due to the armature reaction and commutation overlap.

Fig.12 shows the measured and simulation curves of load characteristics of HEDS-BLDCG while excitation current is 14.7A, and rotating speed is 500r/m. The results present the relationship between the rectified output voltage and dc load current. It can be seen that the voltage regulation factor of rectified output of winding I is relatively low. In general, the DC output voltage generated by winding I presents less variation while the excitation and load current are changed. Therefore, the rectified output of Winding I, which is used as excitation source, may provide the DC current for excitation windings. Due to the high winding inductance and commutation voltage loss, the rectified output voltage of winding II is significantly decreased while the load current is increased. When the rotating speed and load current are changed, the rectified output voltage of Winding II can be maintained at an invariable level by regulating the excitation current.

B. One terminal output

Furthermore, the condition of all the armature windings connected together is also considered. In this case, the HEDS-BLDCG has only one set of three phase winding and one rectification, as shown in Fig.13.

Fig.14 shows phase voltage waveforms of the HEDS-BLDCG with one terminal output under no-load, while excitation current is 14.7A. Fig.15 shows the measured and simulated phase voltage waveforms of HEDS-BLDCG with 2.1A dc load current. The simulated waveforms also agree well with the measured ones. The phase potential of the HEDS-BLDCG under load is also distorted because of the
armature reaction and commutation overlap. However, it has no

Fig. 13. Field-circuit coupled model of HEDS-BLDCG.

Fig. 14. No-load phase voltage waveforms (400 V/div, 2.5 ms/div).

Fig. 15. Phase voltage waveforms of HEDS-BLDCG with 2.1A dc load current (400 V/div, 2.5 ms/div).

Fig. 16. Output voltage versus excitation current of HEDS-BLDCG with one terminal output.

Fig. 17. Output voltage versus load current of HEDS-BLDCG with one terminal output.

negative influence on the rectified output voltage.

Fig.16 shows the simulated and measured results of relationship between output dc voltage and excitation current. It can be seen that the output voltage can be widely regulated by changing the positive excitation current, and output voltage increases with increasing the excitation current. While low negative excitation current (about -5A) is applied, the output voltage may be decreased almost to zero, which is in well agreement with the above analysis of section III. Moreover, the output voltage can also be increased by enhancing the negative excitation current, and the trend is similar to that of the winding II of HEDS-BLDCG with dual terminal outputs.

Fig.17 shows the measured and simulation curves of load characteristics of HEDS-BLDCG while excitation current is 14.7A, and rotating speed is 500r/m.

V. CONCLUSIONS

In this paper, a new topology of HEDSM is proposed and implemented. The developed machine has one or more sets of three-phase windings, which can offer one or multi- power supply via rectifications. When the HEDS-BLDCG composed
of the HEDSM and rectifications has dual terminal outputs, the rectified output voltage of winding I presents less variation, and it can be used as an independent excitation source which provides the field current for excitation winding of the HEDS-BLDCG. The rectified output of winding II is determined by both PM MMFs and electrical excitation MMFs, hence may be effectively regulated over a wide voltage range. When the different armature windings are connected together in series, the HEDS-BLDCG has one terminal output, which voltage can also be regulated from zero to the rated value. Both in parallel and in series, the HEDS-BLDCG has one terminal output, which can be used as an independent excitation source which provides the field current for excitation winding of the doubly salient permanent magnet machine, which should provide a new solution scheme for independent generation systems such as wind power generation, aero-power system, and so on.

REFERENCES

Zhuoran Zhang (M’09) was born in Anhui Province, China, in 1978. He 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 was born in Jiangsu Province, China, in 1987. He 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.

Yangguang Yan was born in Zhejiang Province, China, in 1935. He received the B.S. degree in electrical engineering from Nanjing Aeronautical Institute, Nanjing, China, in 1958.

He is a Professor at College of Automation Engineering, and he is the Founder of the Aero-Power Sci-tech Center (APSC), a national engineering research center in China. His main research interests include aeronautical power supply systems, and secondary power supplies for aircraft.