Investigation of Field Regulation Performance of a New Hybrid Excitation Synchronous Machine with Dual-Direction Magnetic Shunt Rotor

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Abstract — This paper presents a new topology of hybrid excitation synchronous machines (HESM) with dual-direction magnetic shunt rotor. Firstly, the configuration characteristic, basic operation principle, and equivalent magnetic circuit are introduced. Then, 3D-FEA model of the proposed HESM are established. 3D-FEA results demonstrate that the proposed HESM has wide field regulation range and fault-tolerant ability. It is an efficient topology that significantly broadens the application of HESM with magnetic shunt rotor.

I. INTRODUCTION

Hybrid excitation synchronous machines combine permanent-magnet (PM) excitation with wound field excitation. The goal behind using two excitation field sources is to combine advantages of PM excited machines and wound field synchronous machines. On one hand, HESM remains the advantages of high power density and high efficiency as conventional PM machines because of the existence of PMs. On the other hand, the engagement of wound field excitation makes it easy to adjust the main flux, which is fixed in PM machines. Due to these features, HESM is a new class of electric machine that has a bright further in vehicle drive application of HESM with magnetic shunt rotor.

Hybrid excitation synchronous machine with single-direction magnetic shunt rotor is developed on basis of conventional interior PM synchronous machines [15]. The field coil is located in magnetic bridge fixed in the end of the stator. An example of design, shown in [15], has proved that this structure is effective to obtain wide field regulation range. In order to obtain wide field regulation range, the reluctance of axial flux path is looked forward to be as small as possible. Hence, hybrid excitation synchronous machine with single-direction magnetic shunt rotor is essentially designed as short and thick in structure. For this reason, the application of the HESM with single-direction magnetic shunt rotor is restricted. This paper presents a new topology of HESM with dual-direction magnetic shunt rotor, which significantly broadens the application of HESM with magnetic shunt rotor.

II. CONSTRUCTION AND EQUIVALENT MAGNETIC CIRCUIT

A. Construction

Fig. 1 shows a general view of the proposed HESM with 8 poles/48 slots as an example. To illustrate, nonmagnetic shaft and armature windings are omitted in Fig. 1. The stator core is exactly the same with that of the conventional permanent magnet synchronous machines. The rotor of the proposed HESM can be consider as composing of two rotors of the HESM with single-direction magnetic shunt rotor. Two N- and S-pole cores are magnetic in the axial and radial direction at the same time. The stationary magnetic bridge with toroidal field coil is jointed at each end of machine. Therefore, a brushless excitation structure is implemented. Two field windings can be connected in series or parallel according to different application.
B. Radial/Axial Magnetic Circuit Characteristics

Radial magnetic flux path and axial magnetic flux path exist at the same time in the proposed HESM, which is similar to the HESM with single-direction magnetic shunt rotor. Radial magnetic flux passes by the main air gap (effective air gap compared with auxiliary air gap is defined as main air gap). However, there are two axial flux paths corresponding to each radial flux path. Axial flux starts from the N-pole of the permanent magnet and passes by the N-pole core, auxiliary air gap 1a, magnetic bridge, auxiliary air gap 1b, S-pole core, and finally returns to the S pole of the permanent magnet, namely axial flux path1 and path2 shown in Fig. 2.

C. Equivalent Magnetic Circuit

Performance of the proposed HESM are determined by the relationship between main air gap magnetic field and electrical MMFs. Equivalent magnetic circuit method is helpful to the preliminary design of HESM. According to the principle of the proposed HESM, the equivalent magnetic circuit model is developed to make a rapid analysis of field regulation characteristics, which is shown in Fig. 3 and Fig. 4.
When the electrical MMF \( (F_{i1}, F_{i2}) \) is zero, permanent magnetic potential produces main air gap flux and axial magnetic flux by radial magnetic path and axial magnetic path, respectively. Under the positive electrical MMFs \( (F_{i1}, F_{i2}>0) \), axial magnetic flux \( (\Phi_{\delta 1}, \Phi_{\delta 2}) \) decreases, and magnetic flux in main air gap \( (\Phi_e) \) increases. The equivalent magnetic circuit is given in Fig. 3(a). With the increase of electrical MMFs, axial magnetic flux will be reversed, and electrical MMFs further enhance the magnetic field in the main air gap. Fig. 3(b) shows the equivalent magnetic circuit in this case. When the electrical MMFs \( (F_{i1}, F_{i2}) \) is negative, axial magnetic flux increases, and main air gap flux is reduced, as shown in Fig. 4(a). Negative electrical MMFs can be so tremendous that main air gap flux may be reversed. This state is described in Fig. 4(b). However, in reality, due to the relatively low electrical MMFs compared to permanent MMFs, and the seriously saturated axial magnetic path, the state of magnetic path shown in Fig. 4(b) does not actually happen.

III. 3D-FEA RESULTS

Table I gives key parameters of a design example.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>Number of slots</td>
<td>48</td>
</tr>
<tr>
<td>Number of pole-pairs</td>
<td>4</td>
</tr>
<tr>
<td>Out diameter of stator(mm)</td>
<td>270</td>
</tr>
<tr>
<td>Inner diameter of stator(mm)</td>
<td>210</td>
</tr>
<tr>
<td>Out diameter of rotor(mm)</td>
<td>206</td>
</tr>
<tr>
<td>Inner diameter of rotor(mm)</td>
<td>146</td>
</tr>
<tr>
<td>Main air gap length(mm)</td>
<td>2</td>
</tr>
<tr>
<td>Auxiliary air gap1(mm)</td>
<td>0.3</td>
</tr>
<tr>
<td>Auxiliary air gap2(mm)</td>
<td>0.3</td>
</tr>
<tr>
<td>Stator core length (mm)</td>
<td>80</td>
</tr>
<tr>
<td>Rotor core length (mm)</td>
<td>240</td>
</tr>
</tbody>
</table>

This paper analyses the field distribution characteristics of proposed HESM with different electrical MMFs by Maxwell 3D. Reasonable mesh is especially important for 3D-FEA. The satisfied 3D mesh of FEA model shown in Fig. 5 ensures the accuracy of 3D-FEA results. In order to observe the distribution of the flux density along the axial direction in the main air gap, three mark curves, curve1, curve2 and curve3 shown in Fig. 6, are defined.

**A. Symmetrical field excitation \( (F_{i1}=F_{i2}) \)**

Two field windings are allowed to be connected in series or parallel. Different external excitation circuits make it easy to control the excitation current. According to the relationship of the current via the two field windings, the operating mode can be divided into two modes: symmetrical field excitation \( (F_{i1}=F_{i2}) \) and asymmetrical field excitation \( (F_{i1} \neq F_{i2}) \).
Fig. 7. Flux density vector in rotor and magnetic bridge with different field excitation. (a) $F_{i1}=F_{i2}=-2000AT$. (b) $F_{i1}=F_{i2}=0AT$. (c) $F_{i1}=F_{i2}=4000AT$.

Fig. 7 presents flux density vector of rotor core and magnetic bridge under the three typical conditions with different field excitation. When the field excitation is equal to 4000AT, the direction of axial flux is opposite to that with field excitation 0AT, as shown in Fig. 6. Whereas the direction of axial flux with field excitation -2000 AT is same as that with field excitation 0AT. As the field excitation decreasing to -2000AT, serious magnetic saturation in the transition parts of the rotor core resulting in limited decrease space for the main air gap flux density compared with that under field excitation 0AT.

Fig. 8 Flux density of main air gap with different excitation. (a) $F_{i1}=F_{i2}=-2000AT$, (b) $F_{i1}=F_{i2}=0AT$, (c) $F_{i1}=F_{i2}=4000AT$.

Fig. 9 Flux density of main air gap ($F_{i1}=F_{i2}=4000AT$)
Fig. 8 shows the 3D results of flux density waveform in the main air gap with different field excitation corresponding to curve1. In Fig. 9, the waveforms of flux density in the main air gap corresponding to different position in axial direction are nearly the same, which indicates that the flux density in the main air gap is well-distributed in axial direction.

![Fig. 10. Relationship between main air gap flux density and electrical MMFs.](image)

Fig. 10. Relationship between main air gap flux density and electrical MMFs.

![Fig. 11 Cloud picture of flux density of S-pole core when \(F_{11} = F_{12} = 4000\text{AT}\).](image)

Fig. 11 Cloud picture of flux density of S-pole core when \(F_{11} = F_{12} = 4000\text{AT}\).

The relationship between the average flux density in the main air-gap and electrical MMFs with different field excitation is shown in Fig. 10. Fig. 11 shows cloud picture of flux density of S-pole core when \(F_{11} = 4000\text{AT}\) and \(F_{12}\) is equal to the max field excitation 4000AT, which indicates the S-pole core is magnetic saturated. Field excitation higher than 4000AT can’t enhance the flux density in the main air gap any more. When the field excitation \(F_{11}\) and \(F_{12}\) varies from -2000AT to 4000AT, the average flux density in the main air-gap increases from 0.24T to 0.69T correspondingly, which imply the flux-strengthening capability is higher than the flux weakening capability. The flux density of main air-gap increases to 3 times nearly. According to the 3D-FEA results, the proposed HESM possesses the feature of a wide regulation range of the air-gap magnetic field.

B. Asymmetrical field excitation \(F_{11} \neq F_{12}\)

![Fig. 12 Flux density of main air gap \(F_{11}=0, F_{12}=4000\text{AT}\).](image)

It is assumed that the two field windings are independent. When the field excitation \(F_{11}\) is zero and \(F_{12}\) is equal to 4000AT, the flux density in the main air gap shown in Fig. 12 indicates that the proposed HESM can still works in the case of one field winding is open circuit. Consequently, from the standpoint of reliability, the proposed HESM has fault-tolerant ability.

IV. CONCLUSION

A new topology of HESM has been presented in this paper. The construction, basic operation principle, and equivalent magnetic circuit are introduced in detail. The 3D-FEA results indicate the proposed HESM possess the characteristics as follows.

1) The flux density in the main air gap can be regulated by changing the current via the two field windings. The flux-strengthening capability is higher than the flux weakening capability.

2) The field regulation range of the proposed HESM is up to 2:1.

3) Setting two field windings in the proposed machine makes it more reliable. Even open-circuit fault occurs in either of field windings, the proposed machine can still work normally.

4) The proposed HESM is capable of meeting the requirement of large length-diameter ratio in some application.

REFERENCES


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