Design Studies of Axial Flux Hybrid Excitation Synchronous Machine with Magnetic Bridge

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Abstract

Air gap flux of Hybrid Excitation Synchronous Machine (HESM) is provided by a combination of permanent magnet and excitation winding MMFs. Thus flux weakening or flux boosting can easily be achieved. HESM can be series or parallel double excited. Many models have been proposed for radial flux HESM structure in literature. However, axial flux machines have some characteristics such as high efficiency, high power/torque density, low noise and vibration. In this study, a novel Axial Flux Hybrid Excitation Synchronous Machine (AFHESM) with magnetic bridge is proposed. The structure and operation principle of the AFHESM are described. No-load and load operation of a 3D generator mode is investigated by Finite Element Method.

1. Introduction

Although permanent magnet machines are the most efficient machines, power control of them is difficult and caution should be exercised because there is demagnetization risk for magnets. Therefore since 1990s, double excited HESMs have been developed with permanent magnet (PM) and DC excitation winding. According to the direction of the main air gap flux, one can classify HESM as axial flux and radial flux machines. The majority of the proposed models in the literature are of radial flux HESM type and axial flux models have been used widely motor mode to weaken air gap flux. But some can also be used to support the air gap flux.

Review of the AFHESM literature; the model of [1] has two slotted stators and one rotor with non-ferromagnetic core. There are permanent magnets and iron poles on the rotor. Double DC toroidal excitation winding that is placed in the outer cover of the machine controls the flux through the iron pole. The air gap flux is changed and induced EMF on the armature winding is controlled. Another AFHESM is called by the name of inventors [2] and the operation principle of this model is based on [3]. To control the EMF induced in the stator between the two rotor cores, DC excitation winding is wound around the ferromagnetic shaft that connects the rotor mechanically and magnetically. There are PMs and iron poles on the rotors. In this model, magnet flux and DC excitation flux paths close over the shaft. Modifying the multiple-rotor-multiple-stator conventional axial flux PM structure by adding one or two DC field windings depending on the machine type to control the air gap flux and providing a path for the DC flux results in different new axial flux machines with field control capability [4]. Each of the two rotors has PMs and iron poles and located on both sides of the stator. Between two stator cores there is a DC field winding.

According to field current, the flux flowing through the rotor core can be controlled, so air gap flux can be controlled too [4-6]. In the flux switching AFHESM model [7-8], all flux sources are placed on the stator and rotor has just salient poles.

2. Hybrid Excitation Synchronous Machine Topologies

Considering how the sources of the magnetic flux are combined, HESM can be classified as series or parallel. The flux generated by the excitation winding flow through over the magnets in series HESM. PMs permeability is very close to vacuum. So excitation flux path reluctance is higher and there is demagnetization risk for magnets [10-14].

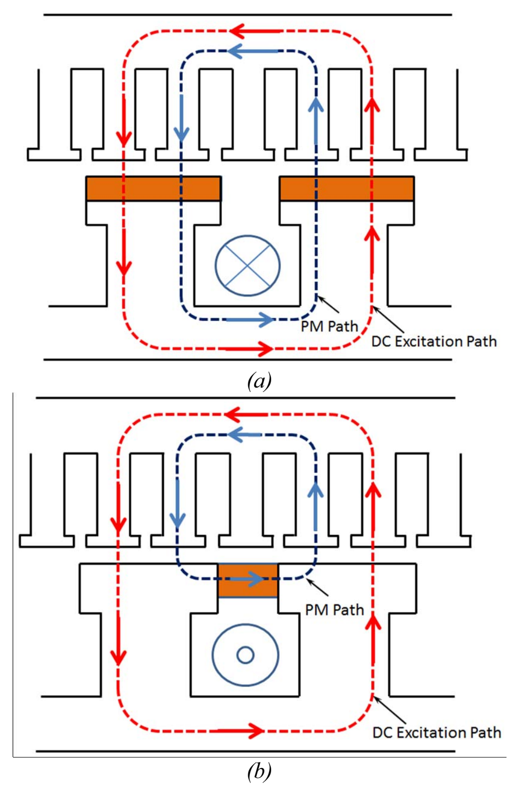


Fig. 1. Flux paths on the HESM a) Series HESM, b) Parallel HESM

Magnet flux path and DC excitation winding flux path circulate in different ways in the parallel HESMs. Flux created by the excitation winding, does not pass through magnets. Series and parallel HESM flux paths are seen in figure 1. The structure of series HESMs is simpler and cheaper. However, total reluctance of the flux path is greater so the ability to control air-gap flux is less than parallel HESMs. Very different configurations can be improved for parallel HESMs.

Parallel HESMs can be grouped depending on where the magnetic flux sources are. For the model which has PMs on rotors and excitation winding on stator [15-20], flux weakening and boosting is possible but excitation winding embedded between stator cores complicate the manufacture of the machine. For the model which has PMs and excitation winding on the stator [21, 22], cooling will be easier because all windings are on the fixed stator. However when no excitation current is present, useful flux is less because magnet flux path is short circuited for the generator mode. So, excitation current is required continuously throughout the operation of the machine. In recent years, the attention of electric machine designers has been concentrated on the model with the magnetic bridge [23-26]. These models are of radial flux type and there has not been extensive work for AFHESM with magnetic bridge.

3. Architecture and Operational Principle

Excitation winding is embedded in the circular magnetic bridge. Magnetic bridge and excitation winding are fixed to the side cover of the machine and thus a brush-ring assembly is not used. N and S rotor pole legs create N and S poles on the rotor core based on excitation current direction. There is an auxiliary air-gap between magnetic bridge and rotor pole legs. Radially oriented magnets are placed between the rotor cores. Thus, when excitation current equals to zero, PMs pass flux through the stator core and induce some amount of EMF but when excitation current is also used, PMs intensify the total flux over the rotor poles. Three phase armature winding are embedded in the slotted TORUS stator. Stator between two rotors like a sandwich and magnetic bridge are fixed to the machine body. For a simpler view of the model, Figure 2 shows a single rotor and stator core.

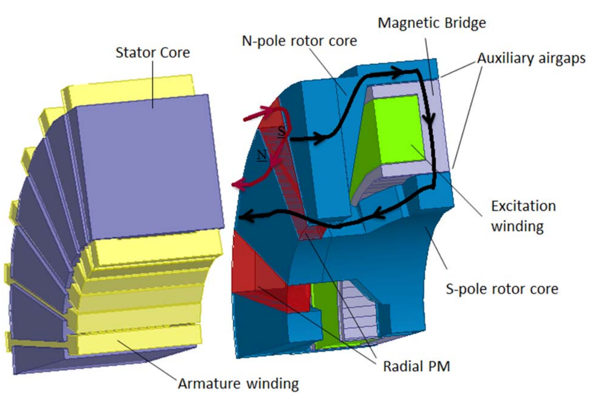
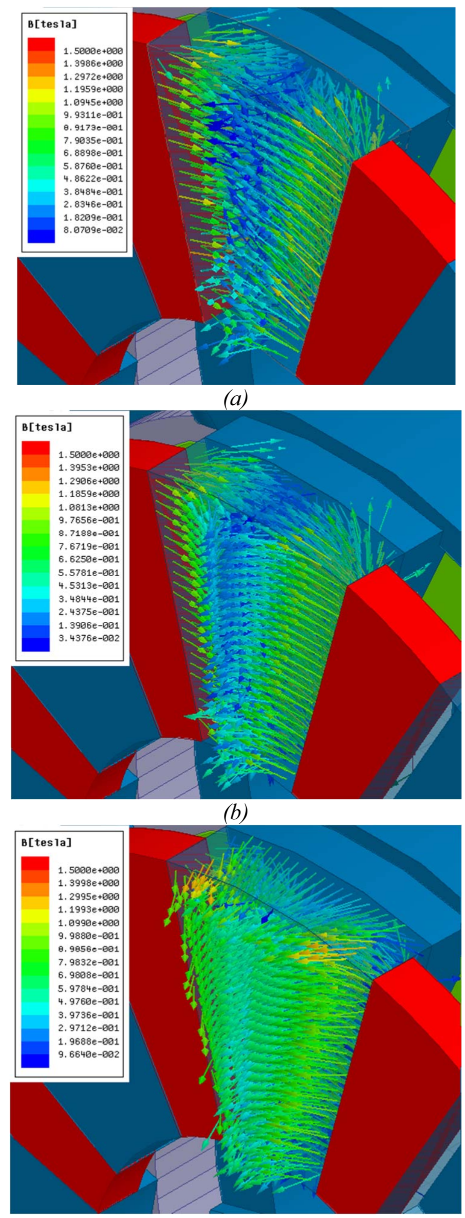


Fig. 2. Architecture of proposed AFHESM

3.1. Operational Principle

As can be seen in Figure 1, the air-gap flux is the total flux of the magnet flux and electrical excitation flux. When there is no excitation current, just the magnet flux passes the basic air-gap and induce EMF in the armature coil. When excitation current is applied, the magnetic flux through the rotor core legs change according to the direction and intensity of excitation winding current. Magnetic flux of the rotor pole cores are seen in Figure 3 at different electrical excitation MMFs. So the flux created by the electrical MMFs flows; “magnetic bridge – auxiliary air-gap1 – rotor core leg1 – basic air-gap – stator core – basic air-gap – rotor core leg2 – auxiliary air-gap2 – magnetic bridge” and complete the path. If negative current is applied to the excitation winding, some magnetic flux pass through the basic air-gap and others circulate in the rotor. Thereby flux weakening can be achieved.



(a) *(b)* *(c)*

Fig. 3. Magnetic flux on rotor pole surfaces at different excitation current, a) -520 AT, b) 0 AT, c) 520AT

One of rotor core legs separated by auxiliary air-gap from magnetic bridge is N form and the other one is S form according to direction of excitation current. Figure 4 shows the flux distribution in the rotor cores for 1040 AT MMFs. Pole polarization may be reversed when applying high negative MMFs but excitation flux does not pass through the magnet there is no demagnetization risk.

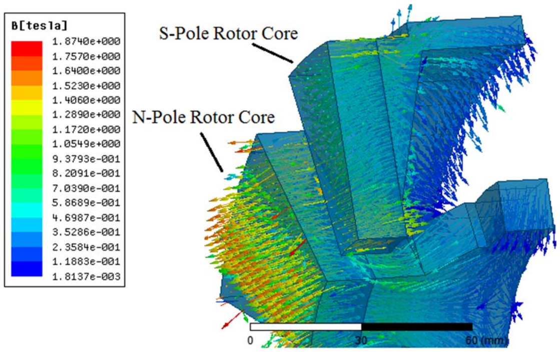


Fig. 4. Magnetic flux in the rotor cores at 1040 AT

4. FEA Simulation Results

¼ symmetrical part of the model is used for all analyses. Stator core have been selected to be of laminated steel but rotor cores and magnetic bridge have been selected as solid core because of 3D flux distributions. Rotor poles are of laminated type to intensify the total flux in the axial direction. NdFeB30 magnets between rotor poles have been polarized on the cylindrical axis as in figure1. The model has two rotors and one stator but other configurations of the model can be evaluated as well. Table 1 shows the design parameters of the proposed model.

Table 1. Parameter of AFHEM Model

	Size		Size
Outer Diameter of stator (mm)	202	Magnet	B_r = 1.1T H_c = 838kA/m
Inner Diameter of stator(mm)	90		V= 176 mm^3 L_m = 10 mm
Total length (mm)	180	Phase Resistance (Ω)	0.582
Main air gap (mm)	0.8	Frequency	50Hz
Auxiliary air gap(mm)	0.5	Number of Phase	3
Number of Poles	8	Number of Excitation winding turns	520
Number of slots	24	Number of armature coil turns	40

4.1. Simulation Results at No-load

Induced voltage of generator one phase winding:

$$e(t) = \frac{d\Psi(t)}{dt} \tag{1}$$

Here Ψ is total flux linkage and is obtained by summing the magnetic flux linkage and electrical excitation flux linkage.

$$\Psi = \Psi_{pm} \pm \Psi_{em} \tag{2}$$

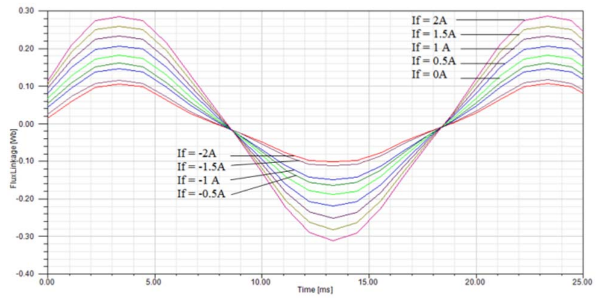


Fig. 4. Flux Linkage of AFHESM at different excitation current

Magnet flux linkage is constant if armature reaction is neglected for no-load and load operation. Therefore, the electrical excitation flux linkage can increase or decrease the induced voltage. Even if Ψ_{em} = - Ψ_{pm} induced voltage is equal to zero. Figure 4 shows the total flux linkage over time at different excitation currents. At different excitation current one phase induced voltage can be seen Figure 5, when no-load.

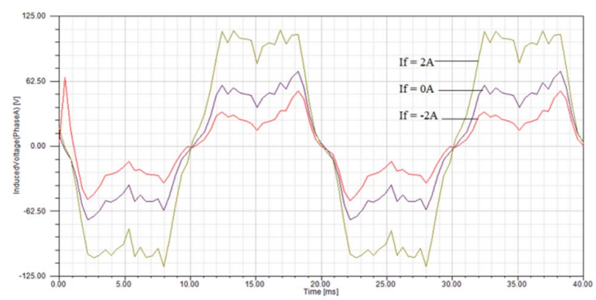


Fig. 5. Induced voltage of phase A at different excitation current

4.2. Simulation Results at 30 Ω

Star connected generator phase windings are loaded with 30 Ω resistive loads and induced phase voltage change with time can be seen in Figure 6 at different excitation currents. Output power:

$$P_{out} = 3xV_{phase}xI_{phase} \tag{3}$$

According to (3), output power is calculated to 178.4 W when I_f = 0A, so 0 AT. At I_f = 2A, so 1040 AT MMF, output power is calculated to 637.85W.

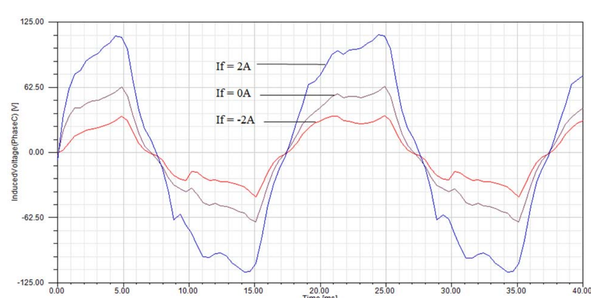


Fig. 6. Induced voltage of phaseA at omic load

5. Conclusions

The AFHESM model for generator mode is investigated using magnetostatic and transient Finite Element analysis for no-load and resistive load operation. Induced phase voltage is increased by 85% for 1040 AT excitation MMF and reduced by 40% by -1040 AT at no-load. For ohmic load analysis, star-connected phase windings are connected to 30 Ω load. More output power is calculated at 1040 AT than no excitation current, approximately 460 W.

Disadvantages of the AFHESM are as follows: firstly considering the size of the model power density is not good. Secondly sinusoidal waveform of induced voltage deteriorates when loaded. Future studies, the optimization of the AFHESM model should be made to resolve these disadvantages.

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