

Axial Flux PM less Synchronous Machine with Effective Field-Weakening Capability

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Abstract—This paper presents the design and development of an axial flux PM less (AF-PML) machine which has a DC field winding on the stator to provide effective air gap flux weakening. In fact in this construction, instead using the rotor permanent magnet poles, a DC field winding is fixed on the stator to provide the desired rotor iron poles. The machine's key features rest on a simple configuration, which allows the main air gap flux to be adjustable easily and without expend any extra cost. In this manner, the air-gap flux can be controlled over a wide range with a low cost and without demagnetization risk for the permanent magnet materials. In this paper, a full description and operating principles of double-sided AF-PML machine with internal stator is explained. Three-dimensional finite-element method (3-D FEM) results of the proposed machine coincide very well with the experimental results on a 1kW prototype AF-PML machine. The results confirm the excellent field-regulation capability of AF-PML.

Key words— Axial flux PM-less (AF-PML) machine, DC field winding, flux weakening, 3-D FEM.

1. INTRODUCTION

Nowadays, the electrical machines structures are under development and improvement. In fact an electrical machine with the lower cost, higher efficiency and higher power density and also with controllability is required. Although the conventional radial flux PM (RFPM) machines are the most widely used, but lately the axial flux PM (AFPM) machines have been gaining popularity in applications [1]-[5]. The reason for such an interest is the distinct advantages and the suitable disc-shaped structures of AFPM over RFPM machines. Among different configurations of axial flux motors, the double-sided configuration with two rotor disk and one stator between them is the best and the most applicable in the driving electrical vehicles interestingly [6]-[10].

Although PM based electric machines provide obvious power density advantage over the other machines but the availability, price and field control capability of the PM materials are making these machines less favorable. Especially for variable speed applications, the motor has to exhibit a flux-weakening operation region, that is, the constant power speed ranges (CPSR). In the conventional PM synchronous machines due to constant flux of the magnets, the flux-weakening implements hardly. The prevalent methods to control the air-gap flux are the

injecting a negative d-axis of the stator vector current [11,12]. However, due to the high elevated current, a strong demagnetization flux is acted against the magnet and the generated extra losses by the current increase. Therefore, lately, several design approaches have been proposed to increase the CPSR of the PM machines [13].

Recently, to prevent the permanent magnet drawbacks and also to achieve the field-weakening capability in PM machines, a variety of topologies of hybrid excitation synchronous machine (HESM) configurations have been proposed [14]-[22]. These references have been focused on the machine structure, operating principle, magnetic field distribution and control strategy. The major of HESM configurations exploit the PM materials accompanied by a field winding fixed on the stator to provide advantages of PMSM and electric excited machine. Hence, the HESM is a popular choice for field-weakening applications. However despite the advantages of HESM, the defects of permanent magnet materials are the challenges of these constructions. Nevertheless, a design consideration can be present to reach the field weakening operation with low cost and reducing the rotor PM demagnetization risk.

An alternative solution to avoid the undesirable effects of PM machines is the axial flux PM-less machine (AF-PML) which has inherent field control capability [23]. In fact the aim of this machine structure is to explore a new class of electric machine that a DC field winding is fixed on the stator to provide the desired rotor iron poles, instead using the rotor permanent magnet poles. Excitation current adjustment of the field coil allows the AF-PML machine to operate as a synchronous motor with controllable speed, or a synchronous generator with a regulated output voltage. The main advantage of this machine is a simple and low cost construction and especially robust structure of rotor in high speed applications. Furthermore, the absence of brushes and the permanent magnet poles and the ability of effective flux control make this machine the preferred choice for the vast majority of applications such as hybrid electric vehicles and wind turbine generators.

For a 1-kW prototype motor, the 3D modeling is established with finite-element method and is built. The actual test results are discussed, and compared to 3D-FEM simulation results. In next sections, a description and operating principles of double-sided slotted axial flux synchronous machine with internal stator are explained and design equations are derived.

2. THE AF-PML MACHINE CONFIGURATION AND OPERATION

Figure 1 shows a schematic diagram of the structure and the actual prototype of AF-PML machine. The rotor consists of two discs mounted on a common shaft and is entirely ferromagnetic. Each disc carries a set of alternate north and south iron poles directed axially toward the stator and are ferromagnetic steel. The second disc is the same first disc and the north poles are located opposite the south poles of the second disc. South and north poles of two rotors are provided by DC field winding surrounding the shaft and fixed on the stator.

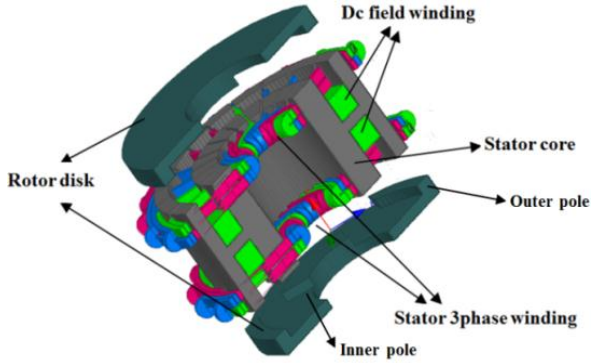


Figure1: Structure of the AF-PML machine.

The stator is placed between the two rotor discs, so carries flux tangentially between the rotor north and south poles. The both stator and rotor cores are punched of the strip wound cores; in fact, the both stator and rotor cores are constructed with entirely ferromagnetic laminated steel. A conventional ac three phase winding is allocated in slots around the periphery of the inner and outer diameter. A circumferential field winding is placed in the middle of the stator, which is excited by a DC current (as shown in fig. 1). The use of DC field winding in stator core rather than conventional PM machine causes several advantages as: simple and cheap constructor, main flux controllability and absence of demagnetization and aging risk of permanent magnet materials. In fact the AF-PML machine, described here, is an attempt to exploit a field winding fixed to the stator to provide the desired features in a machine.

In this case, injecting DC current into the field winding generates a magnetic flux which flows from one iron pole in first rotor to the next iron pole in second rotor. This flux flows through the first rotor disc, air gap, stator, air gap and second rotor disc respectively, with a path entirely composed by iron, except for the main air gap. Due to the comparatively low reluctance of this path, the DC current flowing in the field winding is reduced and this flux component can be easily controlled. In fact when the field

excitation is zero, no magnetic flux travels axially from one rotor to the other through the stator [Figure 2(a)]. When a positive or negative current is applied to the field winding, the air gap flux travels axially from one rotor to the other through the stator. In this status the outer and inner iron poles of rotor discs are magnetized as N-poles and S-poles respectively as shown in Figure 2(b) and Figure 2(c).

On the other hands, when the excitation intensity of the DC field winding increases, the flux intensity on inner and outer of the rotor poles is increased. Thus this makes strengthening the magnetic field and increasing the flux linking the stator armature windings. Also, decreasing excitation of the field winding will decrease the flux in both inner and outer portions of the rotor disks, thereby achieving field weakening. It should be noted that the flux boosting is limited both by the iron saturation and the current density of the DC field winding.

3. SIZING EQUATIONS OF AXIAL FLUX PM-LESS MACHINE

The main dimensions of an axial-flux machine can be calculated by means of its output power equation [23]. The general purpose sizing equation for axial flux machines has the following form:

$$P_{out} = \eta \frac{m}{T} \int_0^T e(t) \cdot i(t) dt = \eta m K_p E_{PK} I_{PK} \quad (1)$$

where, $e(t)$, E_{PK} , $i(t)$ and I_{PK} are instantaneous phase back EMF, its peak value, instantaneous phase current and peak phase current respectively. P_{out} , η and m are the rated output power, machine efficiency and the number of total phases respectively. The factor K_p is defined the electrical power waveform factor.

As a result of the AF-PMLess machine that has been provided by the [17], the rated output power has the following form:

$$P_{out} = \frac{m}{m_1} \pi K_w K_i K_p \eta f B_g \frac{\alpha_p \pi}{4p} \left(\frac{D_{if}^2}{D_o^2} - \lambda^2 \right) \times \left(A \pi \frac{(1+\lambda)}{2} D_o^3 - N_f I_f D_o^2 \right) \quad (2)$$

where, f , K_w , K_i and B_g are the power source frequency, the winding coefficient, the current waveform factor and the peak of pole flux density. In this equation, N_f and I_f are the number of turn and current of DC field coil.

In the above equation, p , m_1 and α_p are poles number, the number of phases on each stator side and the ratio of pole arc to pole pitch (pole span) respectively. Also, D_o , D_i , D_{of} and D_{if} are the outer and inner diameters of machine and dc field winding as shown in fig. 3.

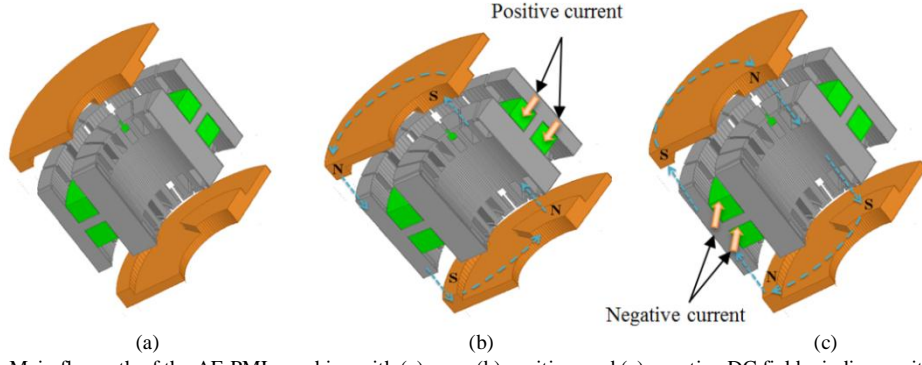


Fig.2: Main flux path of the AF-PML machine with (a) zero, (b) positive, and (c) negative DC field winding excitation.

The area per pole for this machine, A_p , and the diameter ratio (λ) is calculated as:

$$A_p = \alpha_p \frac{(r_o^2 - r_{of}^2)\pi}{p} = \alpha_p \frac{(r_{if}^2 - r_i^2)\pi}{p} \quad (3)$$

$$\lambda = \frac{D_i}{D_o} \quad (4)$$

where r_o and r_i are outer and inner radiuses of the machine, r_{of} and r_{if} are outer and inner radiuses of the DC field winding that are shown in figure 3.

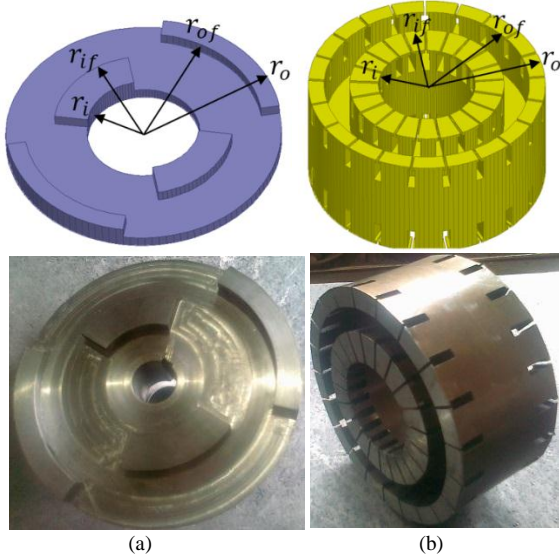


Figure3: 3D views of (a) rotor and (b) stator of AF-PML machine

By means of the equation (2) and for a desired efficiency and power density, the main machine dimensions and parameters are carried out. For full load efficiency 75% and maximum power density, the constants and design data are summarized in Table I and II. It should be noted that two parallel coils per phase on each side are connected in series with each other.

TABLE I: CONSTANTS DATA OF THE PROPOSED MACHINE

Rated output power(kw)	1
efficiency	75%
Line voltage of stator (VLL)	100
Number of poles	4
Rated speed	1500
Number of phases	3

TABLE II: DESIGN DATA OF THE PROPOSED MACHINE

Number of slots of stator	21
Stator outer diameter (mm)	186

Stator inner diameter (mm)	76
Stator axial length(mm)	92
Rotor axial length (mm)	15
Air gap length (mm)	1
Number of turns of DC winding	300
Number of turns per phase	112
pole span(electrical degrees)	144
3phase rated current (A, rms)	7.7
DC field rated current (A)	15

4. 3D-FEM SIMULATION RESULTS OF AF-PML MACHINE

In this section, the simulation results of designing double-sided slotted axial flux PM less motor is presented by 3-D FEM. The detailed results of flux lines of AF-PML machine are shown in figure 4. By means of 3-D FEM, the magnetic flux can be achieved for any time and position. Namely the magnetic flux density for teeth area for a given time and rotor positions are shown in figure 5. Machine torque and 3-phase back EMF waveforms for full load condition are shown in figures 6 and 7 respectively. As can be seen, the finite-element results agree well with parameters and related restriction of the designed motor.

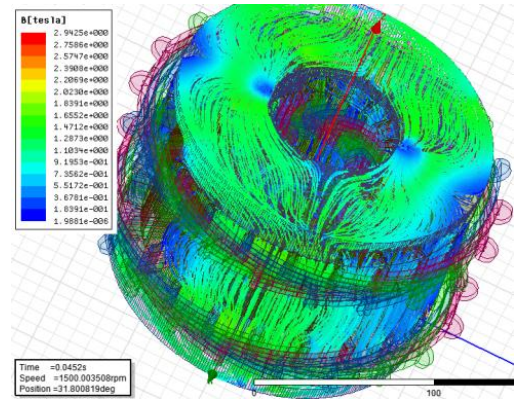


Figure 4: Flux lines of the AF-PML machine

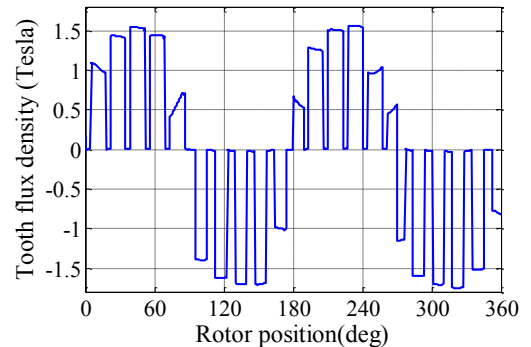


Figure 5: the stator teeth flux density as rotor positions

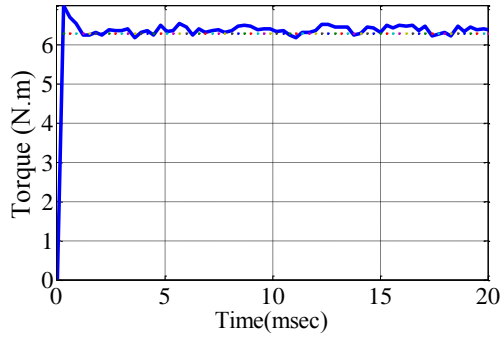


Figure 6: Full load torque of the AF-PML machine

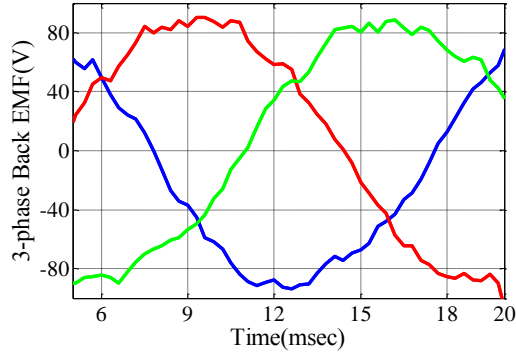


Figure 7: 3-phase back EMF of the AF-PML machine.

The air gap flux density at no load and full load conditions for a given time and rotor positions are shown in fig 8. This figure illustrates the effect of armature reaction in the space distribution of air gap flux density. At no load condition as the armature reaction is zero hence the air gap flux density below the poles is smooth. But at full load condition, the armature reaction cause to increasing the air gap flux density at one side of each pole and decreasing at other side of each pole. This concept shows that the perfect results are achieved in the 3-D FEM simulation.

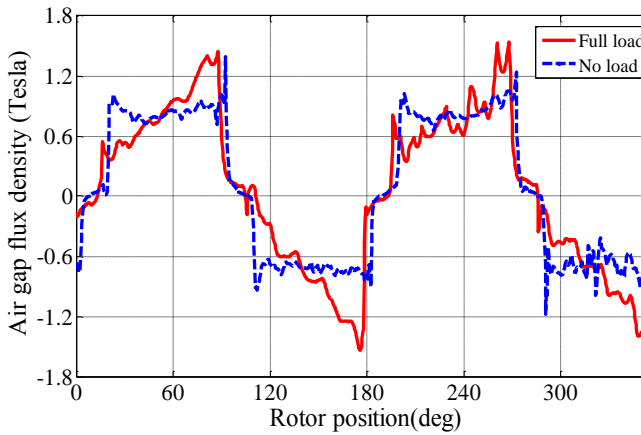


Fig.8: No load and full load air gap flux density below the inner and outer poles.

In the next section for further investigation and verification of the proposed machine concept, a prototype of the proposed AF-PML machine is fabricated and tested.

5. EXPERIMENTAL RESULTS OF AF-PML MACHINE

The experimental setup of this machine is shown in figure 9. It is tested for various loads at different speeds to evaluate its performance.



Figure 9: experimental setup of AF-PML machine

As it is not feasible to measure the value of the per pole air-gap flux directly, thus a search coil is placed in the stator teeth, under one pole as shown in figure 10. The experimental and the FEM results of induced voltage in the search coil are shown as figure 11.

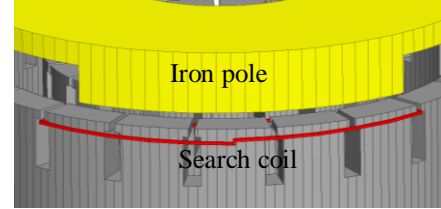


Figure 10: search coil placed in the stator teeth under outer rotor pole

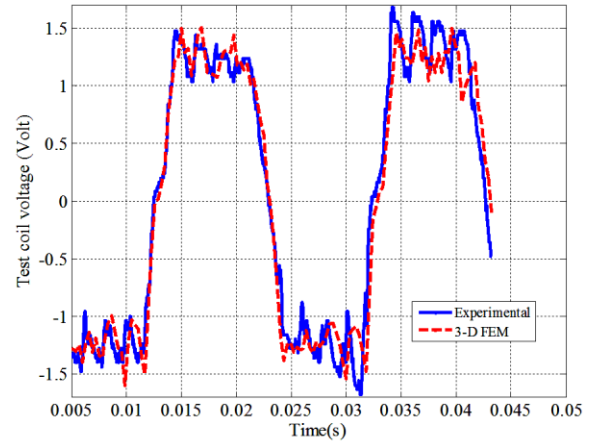


Figure 11: The induced voltage in the search coil is measured

As can be seen, good agreement is achieved in both the experimental and the FEM results of the designed motor. Herein by measuring the induced voltages in the search coil, the air-gap flux per pole is calculated as below:

$$e_c = N_c \frac{d\phi_p}{dt} \Rightarrow \phi_p = \frac{1}{N_c} \int e_c dt \quad (9)$$

where e_c , ϕ_p and N_c are the induced voltages in the search coil, the air-gap flux per pole and the number of turn of search coil respectively. Therefore the air-gap flux is derived from the voltage waveform.

Figure 12 shows the measured open-circuit line-to-neutral back EMF waveforms for the prototype AF-PML machine. Figure 13 shows the output torque and efficiency variations as a function of armature phase current and figure 14 shows

the output power and torque variations as a function of rotor speed. The measured waveforms are achieved for a set of three dc current values of field winding. As can be seen, the output power and torque are controlled easily by field current adjustment and also the efficiency increases with decreasing field current.

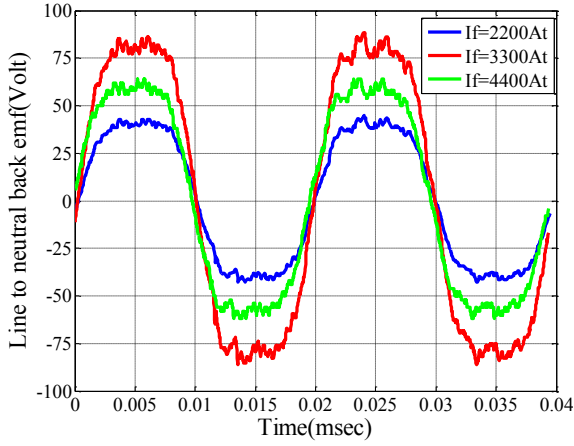
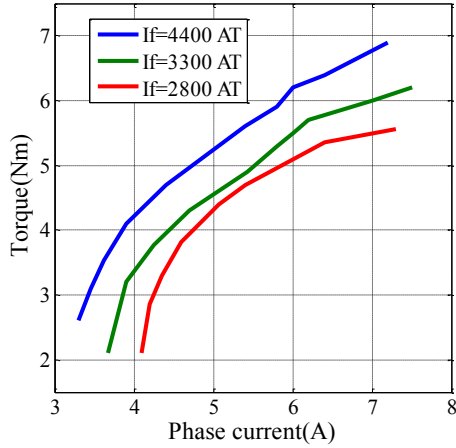
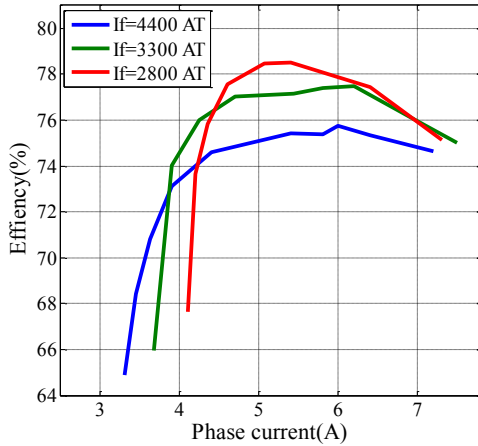


Fig.12: measured open-circuit line-to-neutral back EMF

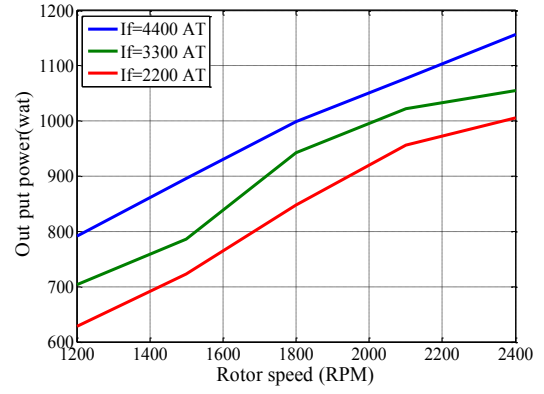


(a)

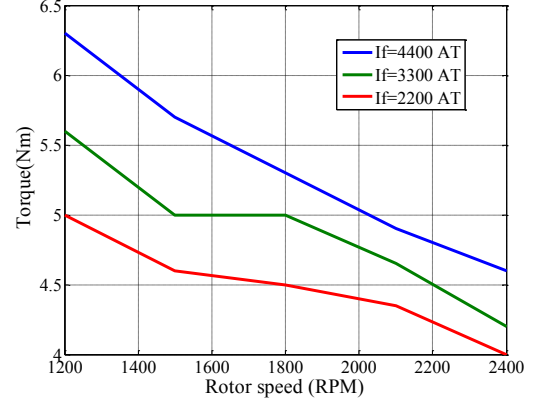


(b)

Figure 13: measured machine (a) torque and (b) efficiency for various values of the stator and field currents



(a)



(b)

Figure 14: measured (a) output power and (b) torque for various values speed and field currents

6. CONCLUSION

This paper presented the design and configuration of a new axial flux PM-less (AF-PML) motor with double-rotor and single-stator structure (torus type). A key feature of the motor rests on the new configuration for the rotor cores without PM of an axial flux machine, resulting in low cost manufacture and simple air gap flux controllability. This controllability in air gap flux will be important for variable speed and variable output voltage applications. The optimal design was carried out using the analytical sizing equations and genetic algorithm, which was then confirmed by close agreements of the results obtained by 3-D FEM modeling. The optimal design was accomplished with maximum torque density and efficiency. In this paper, the flux weakening was easily implemented by field current adjustment and therefore the output power and the back EMF could be controlled easily. The correctness of both design equations and finite element model, on which the optimization procedure is based, are proved by measurements on a prototype.

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