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Design of Novel Axial Flux Dual Stator Doubly Fed Reluctance Machine

Salman Khaliq[1], Mohammad Modarres[1], Thomas A. Lipo[2], *Life Fellow, IEEE* and
Byung-il Kwon[1], *Senior Member, IEEE*
[1]Department of Electronic Systems Engineering, Hanyang University, Ansan, Korea
[2]Department of Electrical and Computer Engineering, Florida State University, Tallahassee FL, USA

This paper proposes a novel machine termed the axial flux brushless doubly fed reluctance machine (AF-BDFRM) suitable for high torque, low speed direct drive applications. The main potential advantages of AF-BDFRM are its higher torque and power density compared to the radial flux brushless doubly fed reluctance machine (RF-BDFRM). In addition, the proposed machine utilizes a bidirectional power converter of much lower rating as compared to the machine rating depending on the range of speed variation. The proposed machine axial flux topology is composed of two stators and a reluctance iron rotor. The upper stator winding which is connected directly to the power grid, transfers active power to the grid and lower stator winding creates excitation for the machine and connects to the grid through a partially rated converter. The design principles of the proposed AF-BDFRM are studied in this paper. Furthermore, the transient 3D finite element analysis (FEA) result of the improved design is presented.

Index Terms—**Doubly fed, high torque density, reluctance machine, low speed, dual stator, brushless**

I. Introduction

BRUSHLESS DOUBLY FED RELUCTANCE MACHINES (BDRFM'S) are a class of machines that can be controlled using a power converter that has a lower rating compared to the total power rating of the machine. These machines are an attractive solution for applications where speed control over a limited operating range is required. A bidirectional power converter rated 20% of the machine rating can provide a speed control range of 40% with constant average torque output. One of the windings, connected directly to the power grid is called power winding while the other winding is connected through a variable speed drive to control and sustain a constant frequency and voltage at the power winding, is called the control winding. The schematic of the operation of doubly fed machines is shown in Fig. 1. Quantities p and q are the number of pole pairs of the power and control winding, respectively. Typically, the rating of the power converter is significantly smaller than the total power rating of the machine which makes its use more economical as compared to conventional synchronous generators employed in wind energy applications [1], [2]. Doubly fed induction generators (DFIGs) employed in wind generating systems maybe the most well- known application of doubly fed machines. Although, a clear drawback to the use of DFIGs compared to BDFRM is the need for slip rings to supply power to the rotor circuit, which results in increased maintenance cost. In contrast the BDFRM, rotor is winding free and made only of iron, which makes it more robust and easier to manufacture.

Brushless doubly fed machines (BDFMs) are a suitable alternative to the use of slip rings in DFIGs. The fundamental idea behind these machines is almost 100 years old when Hunt presented the cascade induction machine and it was further developed some 40 years ago when Broadway first suggested the use of a reluctance rotor in doubly fed machines [3]- [5].

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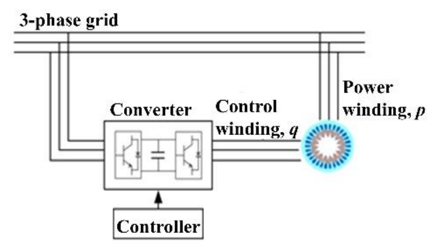

Fig. 1. Schematic of BDFM

Since then BDFRMs has seen increasing interest in various forms especially over the last two decades. Its transient model has been developed and tested [1], [6]. Furthermore, its radial flux model along with its rotor optimized design has been investigated, recently [2], [7]. Thus far, however, a BDFRM axial flux design has not yet been proposed. This paper presents the axial flux dual stator topology of BDFMs. Initial analysis of the proposed machine shows that it exhibits higher torque density compared to its counterpart, the RF-BDFRM.

The proposed AF-BDFRM possesses all the advantages of a RF-BDFRM such as partially rated inverter, power factor control, free of PMs, lower maintenance cost and robustness. However, compared to RF-BDFRM, the proposed AF-BDFRM mechanical structure and assembly is relatively complex. Furthermore, its torque density, which is torque to volume ratio of the machine, is greater than the RF-BDFRM which makes the proposed machine more suitable for applications where constant torque is required over a variable speed range. The RF-BDFRM was investigated thoroughly during the past decade but axial flux model has not yet been investigated.

The proposed AF-BDFRM has two stators and one simple salient reluctance rotor. The configuration and working principle of the proposed machine is discussed in section II. In section III, 3D transient FEA results are discussed. The proposed AF- BDFRM performance is compared with RF-BDFRM in the IV section. Transient 3D FEM analysis is performed using ANSYS MAXWELL software. Finally, in the V section, conclusions of this study are summarized.

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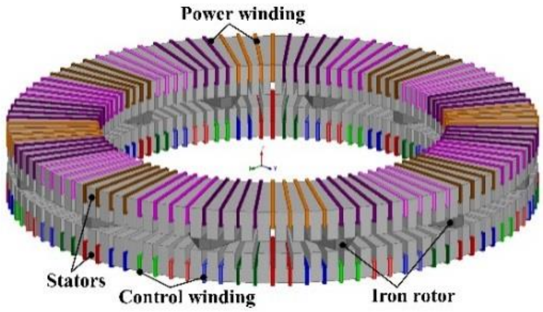
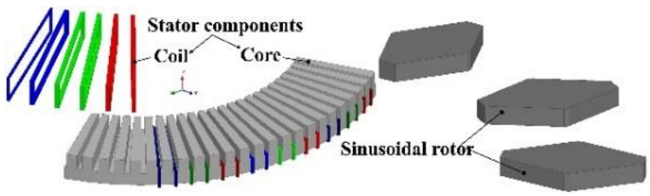


(a)



(b)

Fig. 2. Configuration of the proposed AF- BDFRM. (a) Full machine view (b) Quarter model- detailed view

II. Configuration and working principle of the proposed AF- BDFRM

A. Machine configuration

The proposed AF-BDFRM configuration is described in Fig. 2. It consists of two stators and a salient iron rotor sandwiched between the two stators. Each stator contains 96 slots in which windings are placed in a distributed manner. Both stators are kept unaligned by half a slot pitch to guide the flux properly through the machine and reduce cogging torque by skew effect. A drum winding is used in the proposed machine instead of conventional distributed winding. This resolves the problem of coil fixation while maintaining the same performance with the conventional winding due to coil-ends. Also, the wrapping of drum winding across the stator core does not exhibit any complexity in large power machines [8], [9]. Armature windings on the upper and lower stators are termed as the power and control winding, respectively in Fig. 2(a). A detailed view of a quarter model of the proposed AF-BDFRM is shown in Fig. 2(b). The rotor is a simple salient iron structure. Its pole shape has been modified to improve the induced back EMF shape, reduce the cogging torque and torque ripple [10]. The general and the modified shape of the rotor pole is shown in Fig. 3.

B. Working and design principle

The proposed AF-BDFRM working principle is similar to a DFIG. The difference is that there is no winding on the rotor while the stators have two windings with different number of pole pairs. The power winding pole pair number, p is 4 while the control winding pole pair number, q is 8. Number of saliencies on the rotor is determined by

$$P_r = p \pm q \tag{1}$$

where P_r denotes the number of saliencies in the reluctance rotor which depends upon the direction of the excitation field and rotor rotation. That is


(a) (b)

Fig. 3. Rotor pole (a) General shape (b) Modified shape

- : if direction of excitation field and rotor are in opposite
+ : if direction of excitation field and rotor are same

The rotor electrical angular speed will be [1], [2]:

$$\omega_{rm} = \frac{\omega_1 \pm \omega_2}{2} \tag{2}$$

Where ω_{rm}, ω_1 and ω_2 are the rotor, power and control windings electrical speed, respectively. Generally, there should be no net coupling between the two stator windings having different number of pole pairs. However, the presence of a reluctance rotor makes the magnetic coupling possible. In the proposed AF-BDFRM, when only control winding is excited, its air gap flux is modulated by the rotor poles and enables the flux to link to the power winding on the other side of the rotor having different pole pairs [6]. The proposed machine can operate in sub-synchronous, synchronous or super-synchronous mode depending on whether a negative sequence, zero or a positive sequence frequency is applied to the control winding, respectively. It can also be seen from the above equations that the proposed AF-BDFRM has a natural synchronous speed at which the control winding frequency becomes zero and that speed is half the speed of a conventional synchronous reluctance machine with same number of rotor poles [2]. Furthermore, the torque of a dual air gap machine is written as

$$T = \frac{3}{2}P_r(\lambda_{qs} i_{d2}{'} - \lambda_{ds} i_{q2}{'}) = \frac{3}{2}P_r L_m (i_{d2}{'} i_{q1} - i_{q2}{'} i_{d1}) \tag{3}$$

Where $\lambda_{ds} = L_m(i_{d1} + i_{d2}{'})$ and $\lambda_{qs} = L_m(i_{q1} + i_{q2}{'})$. $i_{d2}{'}$ and $i_{q2}{'}$ are the quantities referred to the side of power winding. Considering the d and q-axis flux linkages and assuming unity power factor for power winding i.e. $i_{d1} = 0$, equation (3) can be further modified to

$$T = \frac{3}{2}P_r L_m (i_{d2}{'} i_{q1}) = \frac{3}{2}P_r \lambda_{ds} i_{q1} = \frac{3}{2}P_r \phi_{ds} N_1 i_{q1} \tag{4}$$

where $\lambda_{ds} = L_m i_{d2}{'}$. By choosing the radial length of the machine $l = 5Do/6$, $N_2 I_{d2} = N_1 I_{q1}$, and surface current $K_1 = K_2 = K = 6N_1 I_{q1}/\pi D$, where D is the average radial value of the active surface and Do is the outer diameter of the proposed AF-BDFRM. N_1 and N_2 are the total number of turns per phase of the power and control winding, respectively. I_{q1} is the rated current in the power winding. K_1 and K_2 are the surface current densities in the power and control windings, respectively. Finally, torque expression of the proposed machine becomes

$$T = \frac{\pi^2}{128}\left(\frac{P_r}{P_1 + P_2}\right)\left(\frac{\mu_0 K^2}{g_t}\right) D^3 l \tag{5}$$

As can be seen from (5), the torque to volume ratio of the

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TABLE I
DESIGN SPECIFICATIONS OF THE PROPOSED AF-BDFRM

Items	Unit	AF- BDFRM
Power winding pole pair	-	4
Control winding pole pair	-	8
Each air gap length	mm	0.85
Di/Do	-	3/5
No. of slots in upper and lower stator	96	
Axial thickness of rotor	mm	15
Surface current density/ stator (peak)	A/ m	30000
No. of rotor saliencies	-	12
No. of turns/ phase	-	280
Rated current in control winding (rms)	A	11.7
Efficiency %	-	87

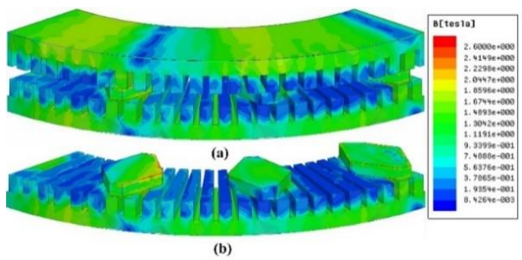

Fig. 4. Flux density plot of the proposed AF-BDFRM (a) Quarter model (b) Lower stator and rotor poles

AF-BDFRM is greater than that of a RF-BDFRM because torque is directly proportional to D^3l in the case of axial flux machines and not to D^2l. Also the surface current density in a RF-BDFRM is limited to $K = K_1+K_2$, where K is the total surface current density. The reason behind that is the RF-BDFRM has one stator while the proposed AF-BDFRM has a dual stator topology which enables the AF-BDFRM to have more surface current density on each stator. The results of a study of the general shape of the rotor tooth showed a higher THD% of the induced back EMF in power winding, higher cogging torque and torque ripple. Therefore the rotor tooth shape was modified as shown in Fig. 2 which resulted in a balanced 3 phase sinusoidal induced back EMF with lower THD % along with lower cogging torque and torque ripple.

III. DESIGN SPECIFICATIONS AND ELECTROMAGNETIC PERFORMANCE OF THE PROPOSED AF-BDFRM

Design specifications of the proposed AF-BDFRM is given in Table I. A conventional machine design approach is followed to design the parameters of the proposed AF-BDFRM. The power and control winding pole pair numbers are different with each other in the proposed machine and selected based on the requirement of low speed operation. Number of rotor saliencies are calculated using (1) which is 12 in this case.

Fig. 4 shows the flux density plot of the proposed AF-BDFRM under full load condition. Fig. 4(a) shows the flux density in quarter model while Fig. 4(b) shows it in the teeth and rotor poles more clearly. It also shows that the bulk of the machine is working under 2.0 T.

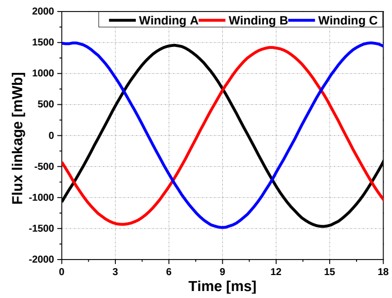

Fig. 5. Power winding flux linkage

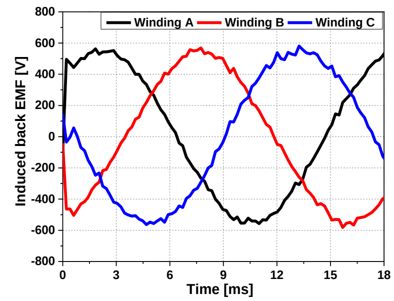

Fig. 6. Induced voltage in power winding

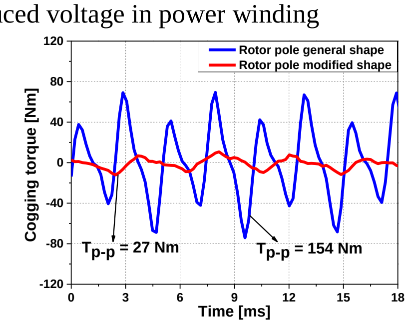

Fig. 7. Cogging torque

Fig. 5 shows the flux linkage to the power winding when only control winding is excited. Value of flux linkage is 3000 mWb peak to peak. The induced voltage in the power winding, can be seen in Fig. 6. The induced voltage rms value in the proposed machine is 400 V with a THD of 5%. The result also shows that the frequency of the induced back EMF is 60 Hz, the same as the grid frequency.

Fig. 7 compares the cogging torque between the rotor poles with general and the modified shape, which is obtained when only control winding is excited. It shows that the cogging torque which was 154 Nm with the general rotor pole shape, has been reduced to 27 Nm with the modified shape. Its value is improved from 48% to 8% of average torque output. Comparison of the average torque output of both rotor shapes mentioned in Fig. 8. Both rotor pole shapes produce almost the same average torque. The torque ripple with the general shape are significantly higher than the modified shape of rotor pole. Ratio of the peak difference to the average torque is, 70% and 26% for the general and the modified shape, respectively. It is clear from the above comparison that the rotor pole shape plays a vital role for the smooth operation of the proposed AF-BDFRM. However, the reduction in the average torque output analyzed by FEM compared to analytical value is mainly caused by the more leakage flux due to the dual air gap topology.

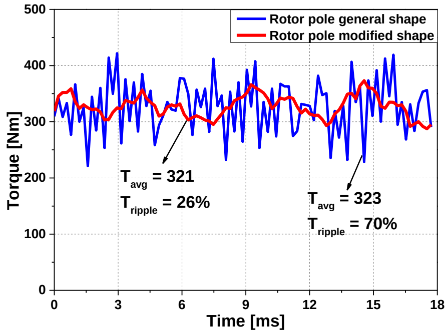

Fig. 8. Output torque

TABLE II
PERFORMANCE COMPARISON OF THE PROPOSED AF- BDFRM WITH THE RF-BDFRM

Items	Unit	RF- BDFRM	AF- BDFRM
Calculated design variables			
Grid side winding power	kW	16	
Outer diameter of the stator	mm	420	710
Axial length	mm	251	101
Synchronous speed	rpm	500	300
Induced EMF frequency	Hz	50	60
Induced EMF (rms)	V	400	
Average output torque	Nm	302	408
Volume	m^3	0.0348	0.022
Torque density	Nm/ m^3	8.6×10^3	18.6×10^3
Total machine active weight	kg	272	211
Transient FEA results			
Average output torque	Nm	267	323
Torque density	Nm/ m^3	7.7×10^3	14.7×10^3
Torque ripple %	-	14.5	26

IV. PERFORMANCE COMPARISON OF THE PROPOSED AF-BDFRM WITH THE RF-BDFRM

Table II compares the electromagnetic performance of the proposed AF- BDFRM with the RF-BDFRM. It shows that the Grid side winding power of both machines is same. However, the proposed AF-BDFRM exhibits higher average torque than the RF-BDFRM while the volume of the former is smaller at the same time as described in Table II. Therefore, the torque density of the proposed machine, is 117% higher than the RF-BDFRM. Furthermore, the total weight of the proposed AF-BDFRM is 211 kg, 22.5% lighter than the RF-BDFRM. Then, the transient FEA results are compared. The proposed machine torque density is still higher than the RF-BDFRM but now it is only 91% higher, a little less than the calculated prediction. The reason behind that is the presence of dual air gap in the proposed machine, which contributes to the leakage flux more while there is only one air gap in the RF-BDFRM. Torque ripple was reduced significantly after rotor pole shape modification but it is still a bit higher in the proposed machine as compared to RF-BDFRM. However, the proposed machine exhibits higher torque density which makes it a more viable option for variable speed applications e.g. wind turbines. It is also clear that the rotor pole shape is very important for reducing the torque ripple.

V. CONCLUSION

In this paper, a novel AF- BDFRM is presented which possesses the advantages of robustness, free of PM, power factor control and higher torque density. The proposed machine brushless structure and absence of slip rings makes it more reliable and robust than a DFIM. But like the DFIM it only utilizes a partially rated converter as compared to the machine total power rating, reducing the cost of the overall system. The proposed machine is most suitable for applications that require speed control over a limited range like in wind turbines. A transient 3D FEM analysis was done to analyze the performance of the proposed AF-BDFRM. Transient FEA results show that the proposed machine exhibits 91% higher torque density when compared with the already developed RF-BDFRM whereas the weight of the proposed machine is 22.5% lighter. Furthermore, the proposed machine optimization studies will be continued in future for even better performance.

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