Design and Analysis of Brushless Doubly Fed Induction Machine with 2/6 pole configuration

Resmi R, V Vanitha

Abstract*: *In the recent years, generation of electricity with the help of renewable energy sources has gained more importance because of the minimal environmental impacts. Brushless Doubly Fed Induction Machine (BDFIM) is one of the upcoming machines that can be used in wind power generation, especially in offshore wind farms due to the lack of brushes and slip rings which make the system maintenance free. High torque ripple due to the complex structure of BDFIM is the major problem which prevents commercialization of the machine. In this paper, 3.5 kW Brushless Doubly Fed Induction Machine (BDFIM) is designed for 2/6 pole configuration. The analysis is carried out for all modes of operation of BDFIM using ANSYS MAXWELL software, which is an effective tool to design and analyze electrical machines. The different modes of operation are simple induction mode, cascade induction mode and synchronous mode. With the advancement in technologies, the superiority of BDFM over the conventional machines will be proved soon and in few years, these machines will be used in most of the applications.

***Index Terms*: Brushless Doubly Fed Induction Machine (BDFIM), simple induction mode, cascade induction mode, synchronous mode.**

I. INTRODUCTION

The idea of brushless doubly fed induction machine (BDFIM) can be traced long back from the self-cascaded machine i.e. with two windings in the same stator [1]. As the name implies, it has two balanced accessible three phase AC windings through which electrical power can be fed/extracted with different pole-pairs, so that the mutual inductance in the stator windings are zero. This is achieved through a special rotor structure called nested loop rotor. In this structure, the rotor consists of nests equal to the sum of stator winding pole pairs to give indirect cross coupling to the stator winding fields and each loop in the nest are shorted through an end ring. One of the stator windings, here named as the Synchronous Power Winding (SPW) is directly connected with the grid. The other one, named as the Asynchronous Power Winding (APW) is connected to the grid through a converter giving a variable frequency and voltage. BDFIM is particularly attractive as an alternative for Doubly Fed Induction Machine (DFIM) in wind power plants with the elimination of multi-level gear box, brushes and slip rings [2]. Thus it reduces maintenance and increases reliability. Accounting its benefits, it has great potential as a generator especially in off-shore variable speed wind turbines with increasing interest in sustainable forms of energy for electricity production and as a motor in variable speed drive applications, making it an ideal choice in pumping. It is important to do a better modeling and design for the BDFIM to make it commercially usable with feasible manufacturing cost and better efficiency. The air-gap contains two main magnetic fields with two different pole-pairs and two different frequencies resulting in a complicated distribution of the magnetic field in this machine. Considering accuracy and complex magnetic field distribution, Finite Element (FE) modeling has the advantages of considering the intricate geometry and nonlinear effect with the help of ANSYS Maxwell Software.

This paper presents the FEM analysis of the BDFIM in its three modes of operation namely, simple induction, cascade induction and synchronous mode of operation for a designed 3.5 kW BDFIM in 2/6 pole configuration.Fig.1 is the schematic diagram of BDFIM during synchronous mode of operation.

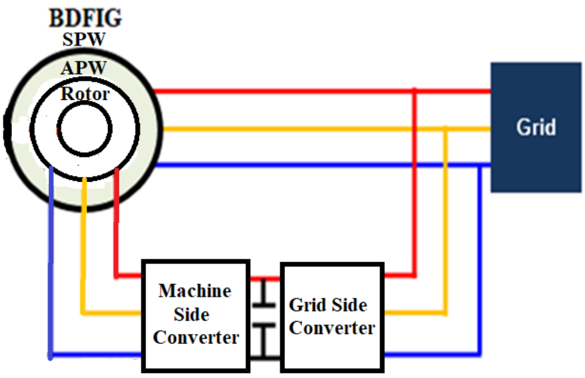

Fig. 1 Schematic diagram of BDFIM in synchronous mode

II. CONSTRUCTION AND OPERATION OF BDFIM

A. Construction

The design of BDFIM is slightly different from a normal induction machine since it has two stator windings in a magnetic frame and a nested loop rotor. The selection of motor ratings solely depends on the application. BDFIM is designed for 3.5kW as the aim is to develop a laboratory prototype model of the machine to study its behavior n static and dynamic conditions.

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SPW and APW are designed with a power of 2.625 kW and 0.825 kW respectively considering fraction of corresponding poles to total number of poles. Starting off with the design steps, the following parameters are first are fixed at a particular value [3] and [5]. The machine diameter (D) is fixed as 140 mm by considering the standard design in industries. Stator slot design has been done taking into consideration that Synchronous and Asynchronous Power windings have to be fitted in the same slot. Table 1 to Table 4 shows the analytical design details of 3.5 kW, 2/6 pole BDFIM. The rotor is traditionally designed as nested loop [6], which couples the stator magnetic fields indirectly. Since nested rotor loop structure is used, copper bars are inserted into the rotor slots as conductors. The size of the bars and the end rings have been designed accordingly to carry the required bar current.

The number of loops required for designing the nested loop rotor is attained by dividing the total number of rotor slots by the sum of SPW and APW pole pairs, which is equal to the number of nests. Considering the 2/6 pole configuration with 24 rotor slots, the number of nests = 24 / (1+3) = 6 nests; each nest has 4 loops.

Table 1. Machine Data

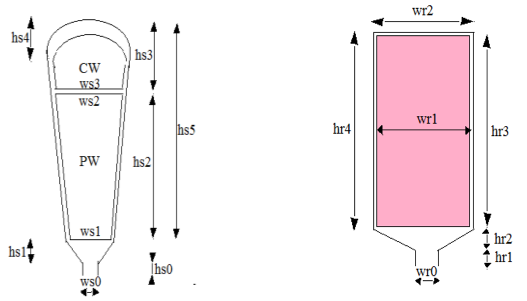
Design Parameters	Value
Machine Type	BDFIM
No. of phases	3
Frequency in PW(Hz)	50
Frequency in CW(Hz)	10
Rated Output (kW)	3.5
Power factor	0.81
Efficiency (%)	87

Table 2. Stator Data

Design Parameters	Value
Outer diameter (mm)	250
Inner diameter D (mm)	140
Core depth (mm)	12
Number of slots	36
Stacking factor	0.9

Table 3. Rotor Data

Design Parameters	Value
Outer diameter (mm)	139.5
Number of slots	24
Core depth (mm)	16.45
Shaft diameter (mm)	45
Conductor type	Bar (Nested loop)
Bar depth (mm)	30
Bar width (mm)	7



(a) (b)

Fig. 2 (a) stator winding (b) Rotor bar

B. Operating Modes of BDFIM

There are three different modes of operation namely the simple induction mode, cascade induction mode and synchronous mode [7]. The simple induction and cascade induction mode comes under asynchronous modes of operation. The basic mode of operation of BDFIM is through single excitation i.e. induction mode. Consider that the machine has P_{SP} and P_{AP} poles in the SPW and APW respectively. In the simple induction mode of operation, one of the stator windings is open-circuited and the other winding is supplied through a three phase source. Generally, the Synchronous Power Winding is open-circuited. This situation takes place in case of converter failures. In this mode, the machine acts approximately similar to an induction machine. But the performance will be poor. BDFIM with the converter control to use as a part of WECS is given in [9] and mathematical modeling of BDFIM is given in [10].

In the cascade induction mode of operation, one of the stator windings is short-circuited and the other winding is supplied through a three phase source. In the cascade induction mode, the machine acts like an induction machine with $P_{SP} + P_{AP}$ pole pairs.

In the synchronous mode, the machine has double feeds through the stator windings. This is the desired mode of operation of BDFIM. The synchronous speed, N_s is determined by f_{SP} and f_{AP} which is the excitation frequency of the SPW and the APW respectively, given in equation 1. SPW frequency of 50 Hz and APW frequency can be varied with a power electronic converter to get varying speed of operation during synchronous mode of operation of BDFIM.

$$N_S = 120\,\frac{f_{SP} \pm f_{AP}}{P_{SP} + P_{AP}} \qquad (1)$$

III. FINITE ELEMENT BASED ANALYSIS

The BDFIM is analyzed in all the three modes of operation under motoring operation namely simple induction mode, cascade induction mode and synchronous mode. The following results were obtained through simulation in ANSYS software. This is a finite element method based software [4].For analysis; the simulation has been done for 2 seconds with a step size of 0.002 seconds.

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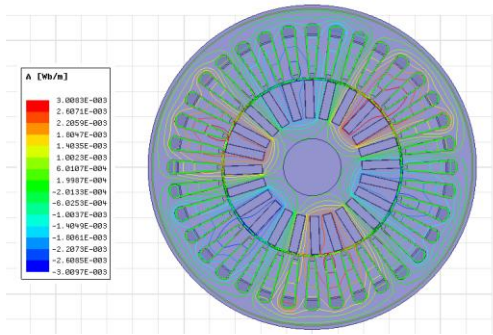
A. Simple Induction Mode

Figure 3(a),(b),(c) and (d) respectively show the Magnetic Vector Potential (A) plot in Wb/m, Magnetic Flux Density Contour Plot in Tesla, torque and speed profile of 2/6 pole BDFIM when only the SPW is excited. A clear flux linkage pattern can be observed around 6 poles of the machine and the magnetic flex density is coming within the limits with reference to Table 4 [5]. The torque curve under no load condition consists of ripples in the waveform oscillating around the base zero reference since it is on no load and which is then shifted to full load condition with 25 Nm at 0.56 seconds. For 6 pole mode, the synchronous speed is 1000 rpm as given in equation 2. From the results, it is proved that the machine runs in induction mode of operation with a value of speed below the synchronous speed and when got loaded to 25 Nm, the speed of machine decreased to 780 rpm.

$$N_{SP} = 120\,\frac{f_{SP}}{p_{SP}} \qquad (2)$$

Table 4: Flux density distribution in BDFIM [5]

	Designed B range	Simulated B range
Winding connection		Delta/Delta
B_{max} in stator teeth (T)	1.4-2.1	1.7
B_{max} in rotor teeth (T)	1.5-2.2	1.75
B_{max} in stator yoke (T)	1.1-1.7	1.35
B_{max} in rotor yoke (T)	1.2-1.7	1.35
B_{max} in air gap (T)	0.65-0.82	0.68



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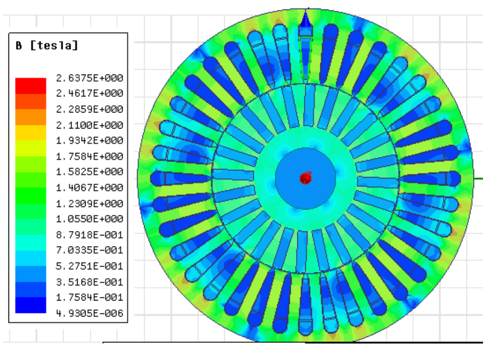

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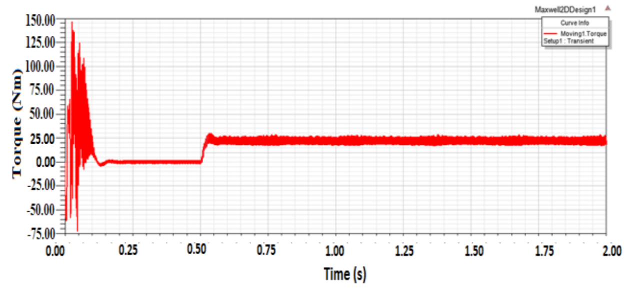

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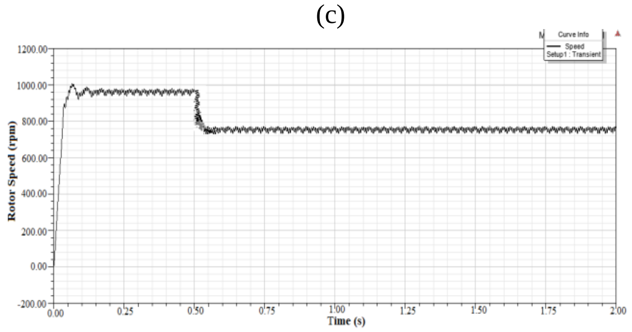
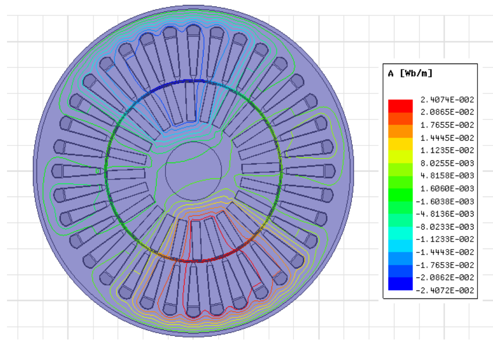


(d)

Fig.3 Simulation results for 2/6 pole in Simple induction mode with SPW excited.
(a) Magnetic Vector Potential (A) plot (Wb/m) (b) Magnetic Flux Density Contour Plot (Tesla) (c) Torque (d) Speed

Figure 4(a),(b),(c) and (d) respectively show the Magnetic Vector Potential (A) plot in Wb/m, Magnetic Flux Density Contour Plot in Tesla, torque and speed profile of 2/6 pole BDFIM when only the APW is excited. A clear magnetic vector potential can be observed around 2 poles of the machine and the magnetic flex density is coming within the limits. The torque curve under no load condition consists of ripples in the waveform oscillating around the base zero reference since it is on no load and which is then shifted to3 Nm reference since it is loaded to full load condition of APW, 3 Nm at 0.56 seconds. For 2 pole mode, the synchronous speed is 3000 rpm, given by equation 4. From the results, it is proved that the machine runs in induction mode of operation with a value of speed below the synchronous speed of 2800 rpm and when got loaded to 3 Nm, the speed of machine decreased to2400 rpm.

$$N_{SA} = 120\,\frac{f_{AP}}{p_{AP}} \qquad (3)$$



(a)

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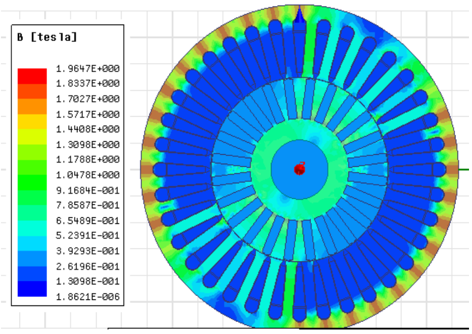

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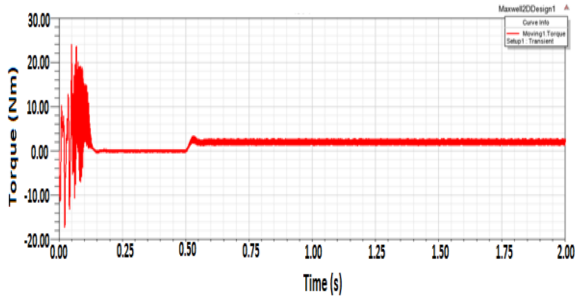

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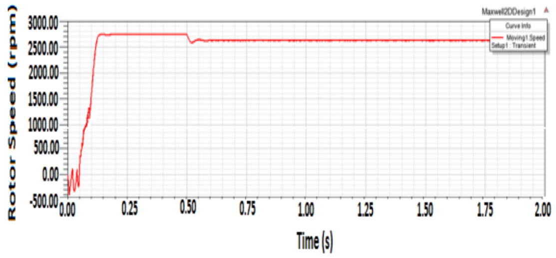


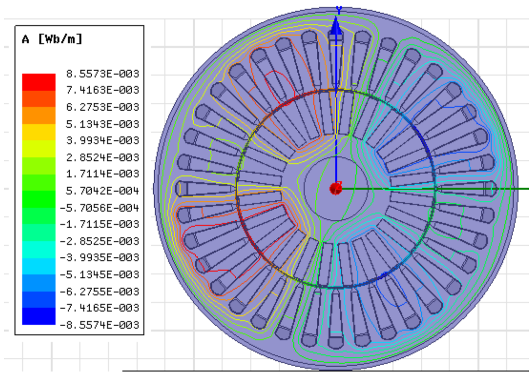
(d)

Fig.4 Simulation results for 2/6 pole in Simple induction mode with APW excited.
(a) Magnetic Vector Potential (A) plot (Wb/m) (b) Magnetic Flux Density Contour Plot (Tesla) (c) Torque (d) Speed

B. Cascade Induction Mode

Fig.5(a),(b),(c) and (d) respectively shows the Magnetic Vector Potential (A) plot in Wb/m, Magnetic Flux Density Contour Plot in Tesla, torque and speed profile of 2/6 pole BDFIM under cascade mode of operation. In this condition, the speed characteristic will be similar to an induction machine with P_{SP}+P_{AP} pole pairs. The supply frequency is 50 Hz with 8 poles in total. Hence the speed will settle at a value which is below the synchronous speed of 750 rpm based on equation 4 as shown in Fig.5 (d), when the machine at no load condition and a decrease in speed is observed when the machine is loaded at 30 Nm, at its full load condition. The torque curve of 2/6 pole BDFIG under no load condition in cascade induction mode along with loaded condition with 30 Nm is shown in Fig.5 (c). It consists of ripples in the waveform oscillating around the base zero reference under no load condition and then the loaded condition is applied at 30 Nm so that the speed is decreased.

$$N_{SC} = 120 \frac{f_{SP}}{P_{SP}+P_{AP}} \qquad (4)$$



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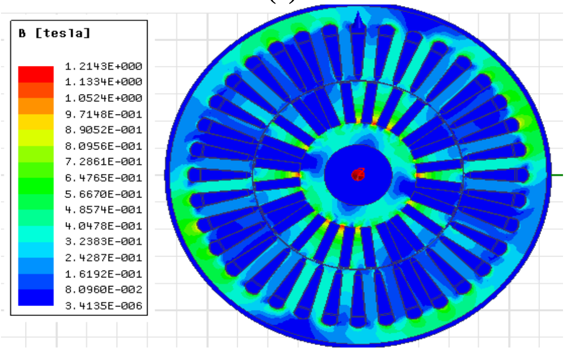

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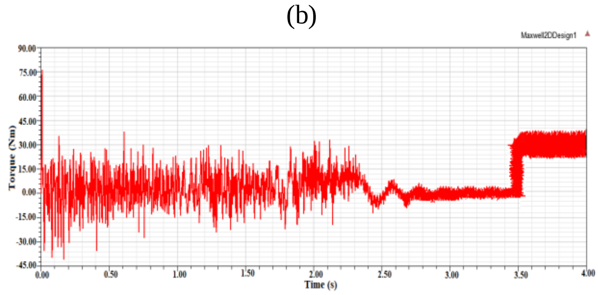

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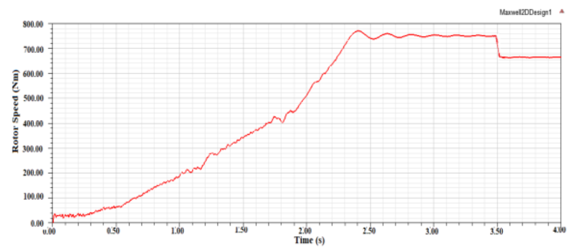

(d)

Fig.5 Simulation results for 2/6 pole in Cascade induction mode with SPW excited.
(a) Magnetic Vector Potential (A) plot (Wb/m) (b) Magnetic Flux Density Contour Plot (Tesla) (c) Torque (d) Speed

C. Synchronous Mode

Fig.6 (a),(b),(c) and (d) respectively shows the Magnetic Vector Potential (A) plot in Wb/m, Magnetic Flux Density Contour Plot in Tesla, torque and speed profile of 2/6 pole BDFIM under synchronous mode of operation. A clear flux linkage pattern can be observed around each pole of the machine. This validates the combined 2 and 6 poles in synchronous mode. Both windings are connected to 3 phase delta supply and the machine is provided with a load profile variations from no load to full load ie 0 to 35 Nm.

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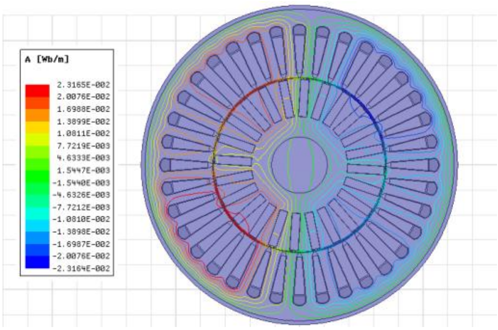
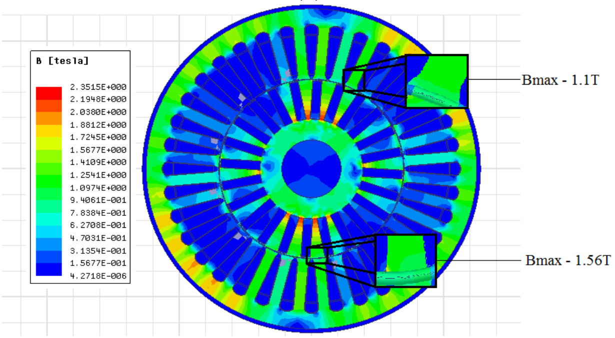
It consists of ripples in the waveform oscillating around the base zero reference in starting since it is no load condition and at 0.56 seconds it is loaded with 20 Nm. So in speed curve of 2/6 pole BDFIM under no load condition in synchronous mode it runs at 900 rpm. In this condition, the frequency is equal to the summation of excitation frequency of SPW and APW with $P_{SP}+P_{AP}$ pole pairs. The excitation frequency of SPW and APW is 50 Hz and 10 Hz respectively and consists of 8 poles in total. Hence the speed will settle at 900 rpm considering equation 1. The speed got reduced to 780 rpm under loaded condition. Fig.6 (b) shows the flux distribution pattern of 2/6 pole BDFIM when both the windings are excited with 3 phase delta connection. The assumed values of maximum flux density in stator and rotor teeth are 1.74 T and 2.26 T. It is observed that the flux densities are within the prescribed limits as that of design values which is shown in Table.4.



(a)



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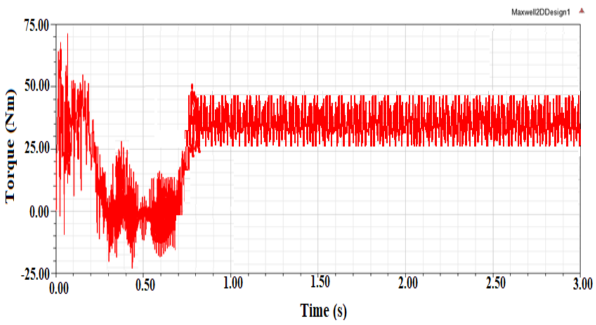

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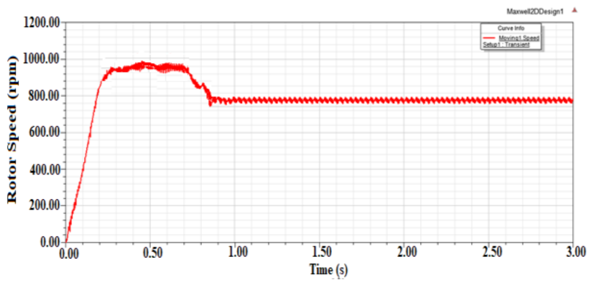

(d)

Fig.6 Simulation results for 2/6 pole in Synchronous mode with SPW excited with 50 Hz and APW with 10 Hz.
(a) Magnetic Vector Potential (A) plot (Wb/m) (b) Magnetic Flux Density Contour Plot (Tesla) (c) Torque (d) Speed

Fig.6 (c) shows the torque ripple variation during synchronous mode of operation with delta connection for both SPW and APW. The impact of torque ripple in BDFIM with mathematical analysis is expressed in [8].The torque ripple percentage for the designed BDFIM with delta connection on both windings is 47.4%.It is given in Table 5.

$$\% T_{ripple} = \frac{T_{max} - T_{min}}{T_{mean}} * 100\% \qquad (5)$$

Table 5. Torque ripple

Connection	Delta/Delta
%Tripple	47.4

Fig.7 shows the air gap flux density distribution during synchronous mode of operation. In Table 6, air gap flux density Total Harmonic Distortion (THD) of designed BDFIM with delta/delta connection for 2/6 pole configuration is shown as 28.74. In [11], it is found that the THD in the space harmonics is coming as 39.87 for 2/4 pole configuration BDFIM with standard delta/delta winding connection. So choice of proper dimensions and pole configurations of the BDFIM also results in decrement of THD.

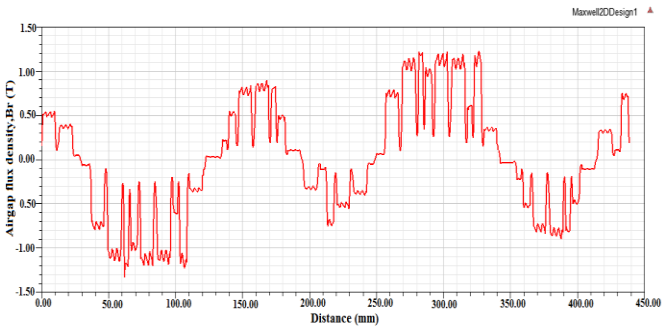

Fig.7 Air gap flux for 2/6 pole BDFIM

Table 6. Air gap flux density THD in BDFIM

Winding connection	Delta/Delta
Air gap flux density THD (%)	28.74

IV. CONCLUSION

In this paper, design and analysis of 3 phase, 400 V, 2/6 pole configuration BDFIM is carried out under motoring mode of operation with conventional delta winding connection for both Synchronous and Asynchronous power windings. From the Finite Element based analysis it is observed that the induced flux density is as per the designed value and it is within limits in all parts of the BDFIM. BDFIM is working properly in all modes of operation as expected in no-load as well as in full loaded condition.

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From literatures the major problem found in BDFIM is torque ripple in it due to its complex structure because of two stator windings and a nested loop rotor. By using delta connection for both SPW and APW the torque ripple is 47.4%. Refinements in rotors are found in literatures to reduce torque ripple, and nested loop rotor is one among them. So modification in stator windings and optimization in dimensions of stator and rotor can be introduced further for the torque ripple reduction in BDFIM.

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