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Numerical Analysis of Stator Magnetic Wedge Effects on Equivalent Circuit Parameters of Brushless Doubly Fed Machines

Salman Abdi, Ehsan Abdi and Richard McMahon

[Φ]*Abstract* – **This paper studies the effects of magnetic wedges used for closing stator open slots on the Brushless Doubly Fed Machines' (BDFM) equivalent circuit parameters. The BDFM is an attractive generator solution for offshore wind power and can replace doubly-fed slip-ring induction generators. It is shown in this paper that the use of magnetic wedges, commonly used in large induction machines, reduces the stator windings magnetising currents, reflected in the values of magnetising inductances. But they also increase the leakage flux of the stator windings and hence change the series inductance in the equivalent circuit. The series inductance significantly affects the machine performance as well as the rating of its converter. 2-D Finite element analysis of a 250 kW experimental BDFM is used to investigate the effects of magnetic wedges on the machine's magnetic field distribution and how these can alter the machine's parameters values. Experimental tests have also been carried out to validate the analysis.**

***Index Terms*-- Brushless doubly fed machine (BDFM), Finite Element (FE) method, Coupled-circuit model, Magnetic wedges, Equivalent circuit parameters calculation, iron saturation, Magnetic equivalent circuit (MEC) method.**

I. Introduction

THE Brushless Doubly Fed Machine (BDFM) is a variable speed generator or motor, which has in recent years been investigated as a potential replacement for the Doubly-Fed Induction Generator (DFIG) [1], currently used in the majority of large wind turbines. Similar to the DFIG concept, a BDFM allows variable speed operation using only a fractionally-rated (30-50%) variable voltage, variable frequency converter [1]. The BDFM has no brush gear and slip-rings, and hence is a robust and reliable machine with low maintenance requirements [2].

The BDFM works in a synchronous mode when one of its stator windings, called the power winding (PW) is connected directly to the grid and the second stator winding, called the control winding (CW) is connected to a variable voltage variable frequency converter [1]. The synchronous mode is the desirable mode of operation at which the machine design and performance are optimised [3]. The pole numbers for stator windings are selected in a way to eliminate any direct coupling between the stator windings [4]. Instead, the coupling is enabled through a specially-designed rotor winding [5].

To date, several large BDFMs have been manufactured, for instance a 75 kW machine in Brazil [6], a 200 kW size in China [7], and 250 kW machine in the UK, the largest size reported to date [8]. The latter was built and characterized by the authors and various aspects of its performance were reported in [8] and [9]. The 250 kW BDFM, shown in Fig. 1, was built in a frame size D400.

Fig. 1. 250 kW BDFM (front right) and the load machine on test rig.

The equivalent circuit is a simple method of representing the steady-state performance of the BDFM [10]. Since the meaning of the parameters has a clear physical interpretation and the steady-state measures of the machine can be calculated at low computational time, the equivalent circuit can be very helpful for the understanding, design and optimisation of the BDFM and its associated converter and grid connection.

Open slot design is essentially used in large machines for practicality of manufacturing, causing increases in the machine's magnetising currents. A common solution is to use magnetic wedges to close the slot openings [11]. This can reduce the effective air gap length resulting lower magnetising currents and improving the power factor. However, it will also increase the stator leakage inductances by providing an easier path for leakage fluxes not crossing the air gap and hence will change the series inductance in the BDFM equivalent circuit. Though the effects of magnetic wedges on the performance of induction and permanent

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magnet machines have been studied by others, for example in [11], [12], these methods cannot be readily applied to the BDFM due to its complex design and magnetic field distribution [13].

The magnetic flux pattern in the iron circuit of the BDFM when operating in the synchronous mode is investigated using two non-linear FE models: one taking into account the effects of magnetic wedges and one when the stator slots are left open. The increase of the slot flux leakage due to the use of magnetic wedges will also be studied.

An equivalent circuit parameter estimation method is used to determine the parameter values from steady state performance measures obtained from non-linear FE models as well as experimental tests.

II. Prototype Machine Specifications and Instrumentation Details

Table I gives details of the prototype 250 kW machine used in this study. Both stator PW and CW are connected in delta. The rotor is a nested-loop design comprising six nests, each with five loops. All rotor loops are terminated with a common end-ring at one end only [8]. The machine is shown in Fig. 1 on the experimental rig. The magnetisation data for stator and rotor laminations were given by the manufacturer. Speed and position signals are obtained from an incremental encoder with a resolution of 10,000 pulses per revolution. The voltages and currents of each stator phase are measured by LEM AV100-750 and LEM LA 205/305-s transducers, respectively.

TABLE I
D400 BDFM Design Specifications

Frame size	D400
PW pole-pair number	2
PW rated voltage	690V at 50Hz (delta)
PW rated current	178 A (line)
CW pole-pair number	4
CW rated voltage	620V at 18Hz (delta)
CW rated current	74 A (line)
Speed range	500 rpm ± 33%
Rated torque	3700 Nm
Rated power	250 kW
Efficiency	> 96%
Stack length	820 mm

III. BDFM Equivalent Circuit Model

A simplified equivalent circuit for the BDFM is shown in Fig. 2 where all parameters are referred to the PW side and iron losses are neglected [14]. The circuit is valid for all modes of operation, including the induction, cascade and synchronous modes and can be utilized for the analysis of steady-state performance of the BDFM [3]. s_1 and s_2 are the power and control winding slips and are defined as:

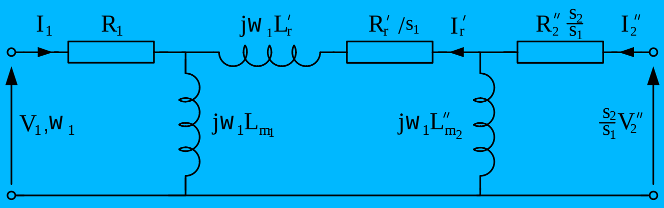


Fig. 2. Simplified equivalent circuit of the BDFM [10]

$$s_1 = \frac{\omega_1 - p_1\omega_r}{\omega_1} \quad (1)$$

$$s_2 = \frac{\omega_2 - p_2\omega_r}{\omega_2} \quad (2)$$

The stator winding resistances, R_1 and R_2 are either calculated from the machine geometry at a certain operating temperature or obtained from the DC measurements. The magnetising inductances L_{m1} and L_{m2} are obtained from the magnetising tests where a single stator winding is supplied in turn while the other winding is left open and the rotor is driven at the synchronous speed to eliminate rotor currents [10].

The referred rotor inductance L'_r in the simplified circuit shown in Fig. 2 represents the series inductances in the full equivalent circuit [10], including the stator PW and CW and rotor leakage inductances. Hence, the effects of stator slot magnetic wedges on the flux leakage will be reflected in the value of the L'_r in the simplified equivalent circuit.

The L'_r can be calculated from the machine geometry, during the design stage, using the method described in [4] to derive the machine's coupled-circuit model followed by performing a series of transformations to obtain the d-q, sequence components and equivalent circuit parameters, respectively.

The L'_r can also be estimated from applying a curve fitting method to the steady-state measures including torque, speed, voltages and currents obtained from BDFM's operation in the cascade mode [10], assuming the stator resistance and magnetising parameters are known. The steady-state data can be from numerical models or experimental tests.

IV. Numerical Analysis of the Prototype BDFM

A. *BDFM finite element development*

The finite element analysis of D400 BDFM is performed using a commercial software application EFFE [15]. The machine is modelled in the synchronous mode of operation. The problem is solved as a voltage fed problem so that simulation results can be compared directly to the measured results. A 2-D analysis is performed, making the assumption that the machine is infinitely long in the direction parallel to the shaft to simplify the field computation. End region effects are incorporated into the analysis using lumped parameters.

In the synchronous mode, the PW is connected directly to the grid and the other winding is supplied with variable voltage at variable frequency from a converter. The analysis is performed by the time-stepping method for accurate analysis and includes the non-linear effects because the excitation frequencies of the stator windings are generally different. This is challenging because the excitation required to set a specific load condition cannot be predetermined and the BDFM is not stable in open-loop synchronous operation. Therefore, a closed-loop controller is implemented with details described in [16].

In order to meet the experimental conditions, the CW excitation is adjusted to set the PW reactive power to that of the test condition. The machine's torque in FE can be adjusted by changing the angle between PW and CW phase voltages. The rotor speed and PW and CW voltages and frequencies were set according to the experimental conditions, as shown in Table II.

The power winding and control winding currents and machine torque obtained from the nonlinear FE model and experimental tests are shown in Fig. 3. The *rms* values of currents and the average torque are given in Table III. As shown, the FE results are in close agreement with the experimental data.

TABLE II
BDFM OPERATING CONDITIONS IN SYNCHRONOUS MODE OF OPERATION

Speed (rev/min)	650	f_{4-pole} (Hz)	50
Torque (Nm)	3600	$\lvert V_{8-pole}\rvert$ (V)	610
$\lvert V_{4-pole}\rvert$ (V)	690	f_{8-pole} (Hz)	15

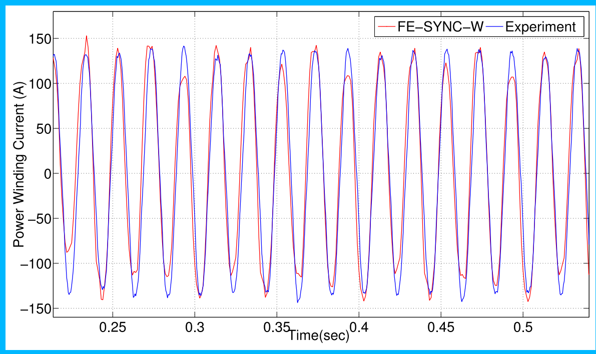
TABLE III
STATOR WINDING CURRENTS AND MACHINES TORQUE OBTAIND FROM FE ANALYSIS AND MEASUREMENT

	$I_{PW}(A)$	$I_{CW}(A)$	$T_{ave}(Nm)$
FE Non-linear	96.6	42.1	3660
Measurement	97.1	43.3	3550
Difference	0.5%	2.8%	3%

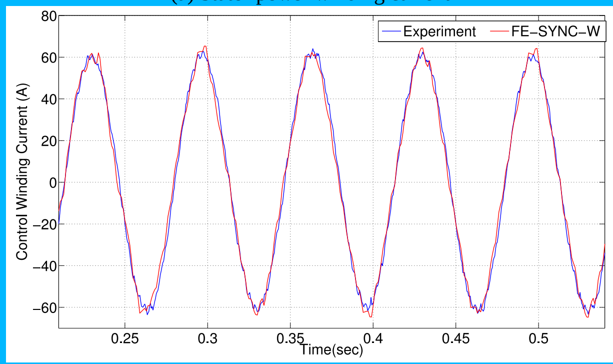
B. *Effect of magnetic wedges on magnetising inductances*

Two FE models are developed for the BDFM, one with magnetic wedges present in the stator slot openings (FE-SYNC-W) which is the experimental case, and one with slots left open (FE-SYNC-NW). The magnetic properties for magnetic wedges in FE-SYNC-W and the B-H curve for stator and rotor iron in both models are non-linear. Fig. 4 shows the magnetic flux distribution in the machine iron circuit obtained from FE-SYNC-W model.

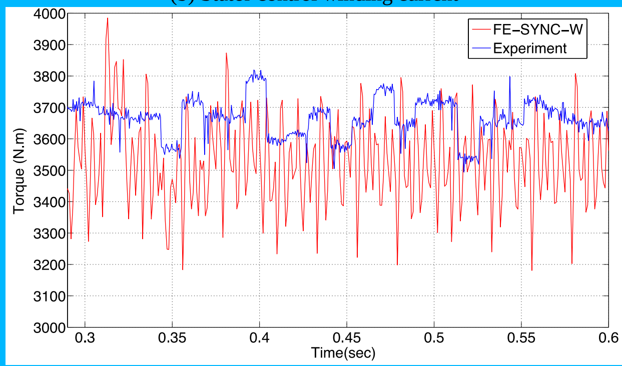
Fig. 5 compares the magnetic fields linking stator and rotor magnetic circuits for the two FE-SYNC-W and FE-SYNC-NW models. It can be seen that the field lines linking stator and rotor find an easier path through magnetic wedges than when the slots are left open. In the absence of magnetic wedges, the linking magnetic fields travel longer distance in air, causing higher magnetising currents and hence magnetising inductances.



(a) Stator power winding current



(b) Stator control winding current



(c) Machine torque

Fig. 3. Comparison of stator currents and machine torque obtained from experimental tests and non-linear FE analysis.

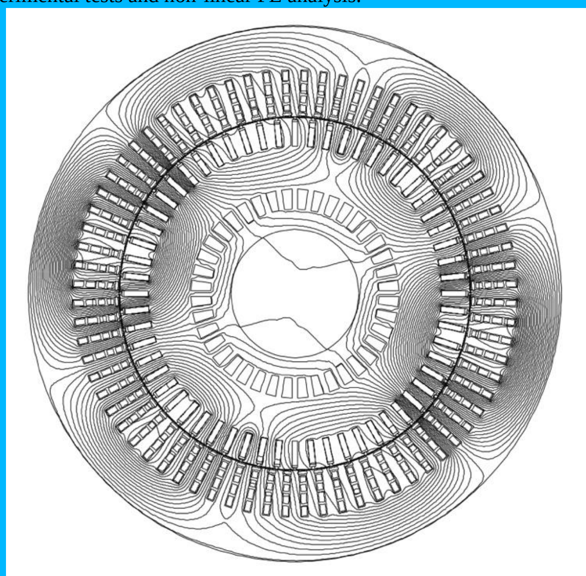
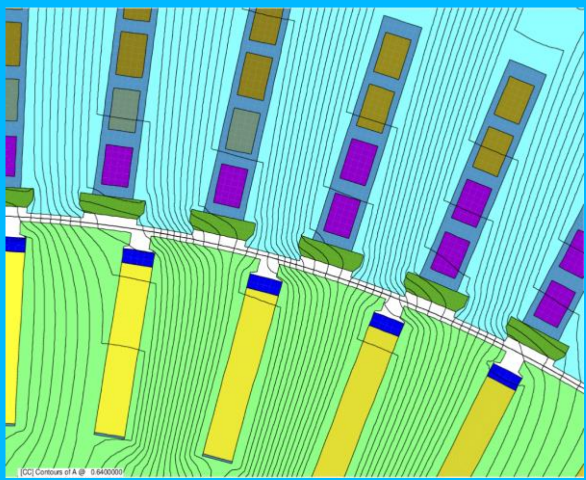


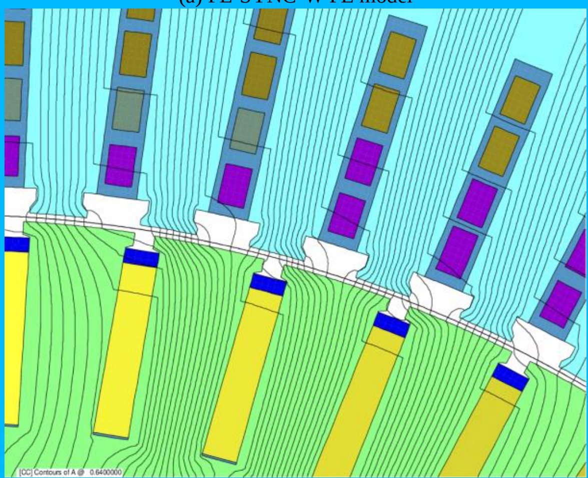
Fig. 4. BDFM magnetic flux distribution in synchronous mode of operation obtained from 2-D Finite Element (FE) simulation.

C. Effect of magnetic wedges on stator winding leakage inductance

However, the easier path for the magnetic fields through magnetic wedges also increases the chance of the filed lines linking back from one tooth to the adjacent tooth, hence increasing the leakage flux. In Figs. 6, the middle magnetic wedge provides a bridge for two field lines crossing the adjacent teeth. Therefore, the leakage inductance of stator PW and CW increases as a result of using magnetic wedge. This is reflected in a larger series inductance L'_r.



(a) FE-SYNC-W FE model

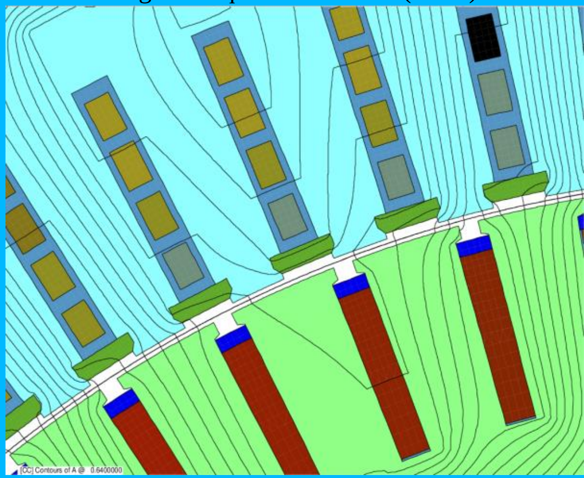


(b) FE-SYNC-NW FE model

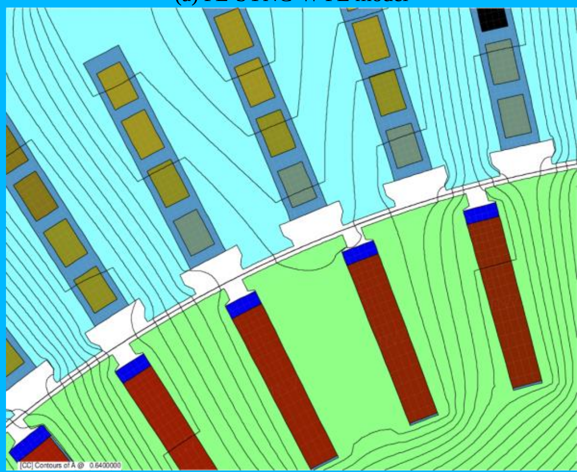
Fig. 5. Magnetic flux lines linking stator and rotor magnetic circuits obtained from non-linear FE analysis in the synchronous mode of operation: (a) FE-SYNC-W model with stator wedges present, and (b) FE-SYNC-NW model with open slots.

V. Equivalent Circuit Parameter Estimation

The magnetising inductances of electrical machines correspond to the magnetic flux that links the stator and rotor, passing the air gap twice. The effects of stator and rotor slotting in the magnetising inductance are often modelled by Carter factors, which effectively scale the air gap length [17]. The effect of magnetic wedges in reducing magnetising currents, hence increasing magnetising inductances, can also be modelled by scaling the air gap length, similar to the concept of Carter factors. A modified Carter factor has been proposed by the authors in [18] to take into account the effect of both slotting and magnetic wedges based on the magnetic equivalent circuit (MEC) method.



(a) FE-SYNC-W FE model



(b) FE-SYNC-NW FE model

Fig. 6. Comparison of slot leakage flux with (a) and without (b) stator magnetic wedges. The middle magnetic wedge in (a) bridges the magnetic field between the two adjacent teeth, resulting in higher leakage flux.

The equivalent circuit parameters can be extracted from steady-state tests conducted by experiments or using FE modelling. The magnetising inductance can be obtained from magnetising tests conducted in the induction mode [19]. The series inductance L'_r and rotor resistance R'_r can then be estimated using curve fitting methods applied to the results from cascade tests [19]. Table IV shows the values of stator windings magnetising inductances, L_{m1} and L_{m2} , and the series inductance L'_r obtained from FE-SYNC-NW and FE-SYNC-W models and experimental tests. As can be seen, there is close agreement between the parameter values obtained from FE-SYNC-W models (which takes into account the magnetic wedges) and experiments, confirming that the FE method is a suitable tool to determine the equivalent circuit parameters. In addition, it can be seen from the parameters in Table IV that the inductance values obtained for a machine with open slots i.e. FE-SYNC-NW are considerably lower than those of the machine with magnetic wedges i.e. FE-SYNC-W and experiments. This validates the findings in Section IV that the magnetic wedges provide an easy path for magnetic fields, making the linkage between stator and rotor achieved with smaller magnetising currents (i.e. larger magnetising inductances), but at the same time, bridging between adjacent teeth and thus increasing the leakage flux (i.e. larger series inductance).

TABLE IV
D400 BDFM DESIGN SPECIFICATIONS

		L_{m1} (mH)	L_{m2} (mH)	L'_r (mH)
No magnetic wedge	FE-SYNC-NW	83.5	284	9.67
With magnetic wedge	FE-SYNC-W	97.1	341	13.3
	Experiment	104	368	12.45

VI. CONCLUSIONS

The use of magnetic wedges in large electrical machines is common and expected to be utilised in large BDFMs. In this paper, the magnetic circuit of a large scale BDFM i.e. 250 kW has been analysed using a 2-D finite element (FE) tool in the presence of magnetic wedges in stator slot openings. It has been shown that the magnetic wedges provide easier paths for air gap magnetic fields linking the stator and rotor and hence reduce the need for excessive stator currents to magnetise the machine. It has also been shown that the ultimate effect of magnetic wedges on magnetising currents can be reflected in the values of the stator magnetising inductances of equivalent circuit parameters.

The effect of magnetic wedges on increasing the stator slot flux leakage has also been studied. This essentially increases the series inductance in the equivalent circuit which plays an important role in reactive power control, the rating of the converter and the management of low-voltage grid ride-through faults.

The steady-state data obtained from experimental tests and FE models have been used to estimate the equivalent circuit parameters both with and without the presence magnetic wedges. The results confirmed the accuracy of the FE models in estimating the equivalent circuit parameters. The FE model has been shown to be in close agreement with experiments confirming its validity for the analysis of the BDFM operation.

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VIII. BIOGRAPHIES

Salman Abdi received the B.Sc. degree from Ferdowsi University, Mashhad, Iran, in 2009 and the M.Sc. degree from Sharif University of Technology, Tehran, Iran, in 2011, both in electrical engineering. He then received his Ph.D. degree in electrical machines design and modeling and instrumentation in July 2015 from Cambridge University, UK. He was appointed as a Research Associate in Cambridge University, Engineering Department in 2015, and then as a Research Fellow in Warwick Manufacturing Group (WMG), University of Warwick in 2016. He is currently a Lecturer in Electrical Engineering in the Faculty of Engineering, Environment and Computing, Coventry University, UK. His main research interests include electrical machines and drives for renewable power generation, Power Electronics and Control Systems.

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Richard McMahon received the B.A. degree in electrical sciences and the Ph.D. degree in electrical engineering from Cambridge University, Cambridge, U.K., in 1976 and 1980, respectively. Following postdoctoral work on semiconductor device processing, he was appointed as the University Lecturer in the Department of Electrical Engineering, Cambridge University, in 1989, and became a Senior Lecturer in 2000. In 2016 he was appointed as the Head of Power Electronics group in Warwick Manufacturing Group (WMG), University of Warwick, and became a Professor. His research interests include electrical drives, power electronics, and semiconductor materials