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Performance of Rotors in a Brushless Doubly-Fed Induction Machine (BDFM)

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Abstract-**The paper presents experimental results to assess the performance of a variety of rotors used in a Brushless Doubly Fed Machine (BDFM). In the experiments the torque-speed characteristics were measured on a BDFM fitted with four rotors with five different windings. The measurements were made of the machine excited with just one stator supply with the second stator supply first open circuit, and then short-circuited. The results give valuable insight into how different rotors, including a novel design of BDFM rotor, will perform in a BDFM configured as a variable speed generator. The results highlight important differences between the rotors related to their winding construction.**

I. INTRODUCTION

The BDFM is attractive as a variable speed generator for wind turbines. In this application, one stator winding is connected to the grid and the other is fed with a variable frequency supply by an inverter. The BDFM operates in synchronous mode with a fixed relationship between the shaft speed, grid frequency and the output frequency of the inverter. In common with the currently used double-fed induction generator (DFIG), the BDFM requires an inverter with a rating which is only a fraction of the total electrical output. However, the BDFM has the important advantage that there is no brushgear. The BDFM is therefore of particular interest for off-shore wind turbine applications where servicing costs are high and it is desirable to avoid brushgear maintenance.

However, to date only relatively small prototype BDFM machines have been demonstrated, the largest being a 160 frame size machine reported by Williamson et al [1]. The authors have recently increased the size of the BDFM by constructing a 180 frame machine as a step towards the construction of a machine with a rating similar to that of existing DFIGs, see Figure 1. The authors' BDFM uses a commercial frame with a stator incorporating four and eight pole windings of equal rating, see Figure 2.

The rotor configuration and performance is the most challenging aspect of the design of a BDFM as the action of the rotor is crucial in determining the overall performance of the machine. For BDFM operation, the rotor must couple to both stator windings and the effectiveness of this coupling depends on rotor configuration. In this paper the authors show how rotor performance can be assessed from measured torque-speed characteristics. The performance of three candidate BDFM rotors has been studied and compared. In addition, to act as benchmark, the performance of the cage rotor normally fitted to that 180 frame size machine has been determined.

The paper answers the following questions:

- What are the relative torques developed by the different rotors and windings in a BDFM?
- How large are these torques, compared to those developed by a normal cage rotor in the same machine?

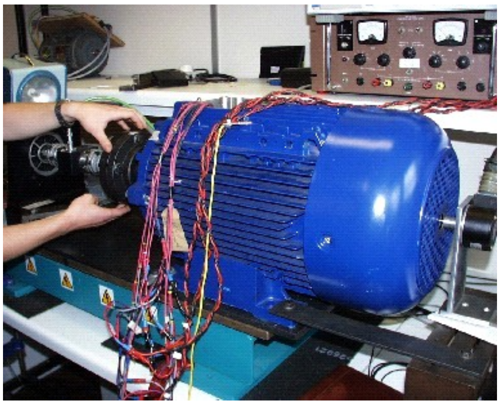

Figure 1, The 180 size BDFM Machine used in these experiments, in an early test configuration.

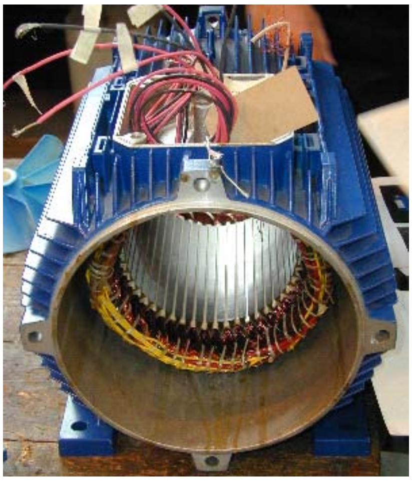

Figure 2, The 180 size BDFM Machine showing the two stator windings in conventional slots.

II. PROTOTYPE BDFM MACHINE

The details of the prototype machine shown in Figs 1 to 5 are given in Table I, the detailed design of the rotors is discussed in Section III.

Table I Prototype Details

Parameter	***Value***
Frame size	D180
Stator core length	190mm
Stator slots	48
Stator winding 1	4 pole, 16 x 10 turn coils, series connected
Stator winding 2	8 pole, 16 x 20 turn coils, series connected
Rated Stator Voltage & Connection	230 Vrms (phase), 50 Hz, star connected
Air gap	0.50-0.58 mm depending on rotor
Rotor slots	36
Rotor 1	6 nested loops spanning 1/6 rotor circumference, as Wallace [6] & Broadway [2], see Fig 3.
Rotor 2	18 independent progressive loops each spanning 7/36 of the rotor circumference.
Rotor 2a	As Rotor 2 but with every third loop omitted making 6 groups of 2 independent loops.
Rotor 3	Novel design consisting of 6 progressively wound groups of coils spanning 1/6 of rotor circumference, see Fig 4.
Rotor 4	Conventional squirrel cage rotor with Boucherot type slots, see Fig 5.

III. BDFM ROTOR DESIGNS

For effective BDFM action, the rotor must cross-couple the stator fields of two different pole numbers. This means that if, for example, the 4 pole winding is excited, you would expect a significant amount of 8 pole field to be produced via the rotor, and vice-versa. Cross-coupling has two requirements:

- That the particular rotor winding links a stator field of one pole number.
- That the resultant current distribution in the rotor winding is constrained in such a way as to link the stator field of the other pole number.

In the present work, four rotor designs were considered. The design of rotors was discussed by Broadway and Burbridge [2], who first proposed the 'nested-loop' design of rotor. In the case of 4 & 8-pole stator windings the rotor winding has 6 such nests. The work of [2] focussed attention on single layer designs suitable for manufacture by casting, as is common for the fabrication of ordinary small cage rotors. Almost all subsequent BDFMs have used this nested loop rotor design proposed by Broadway [2], further investigated by Wallace at al. [3] and Williamson et al. [1]. The authors have constructed a rotor of this design as shown in Fig 3.

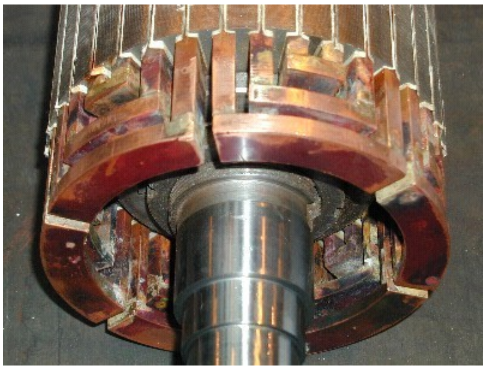

Figure 3, Rotor 1 with nested winding, like [1] & [2].

In [2] the stated aim of the rotor design was to produce a rotor with a single layer construction to minimise manufacturing costs. However in [2] it was noted that a superior design might be obtained using a double layer but the design was ruled out on economic grounds, which are valid for smaller machines. However, this constraint does not apply to larger machines, so the authors have manufactured rotors with double layer windings, Rotors 2 & 3 are of this type.

Rotor 2, with 18 progressive loops pitched over 7 slots was constructed to demonstrate the effects of limited cross-coupling. Loops of pitch 70^{o} were finally chosen for manufacturing reasons and link both 4 and 8 pole fields fulfilling only one of the two requirements for cross-coupling. The current distribution in this winding is relatively unconstrained, as in a squirrel cage rotor, when the rotor is excited with a 4 pole field, so only a 4 pole field is produced. Similarly under excitation from the 8 pole field only an 8 pole current distribution is produced.

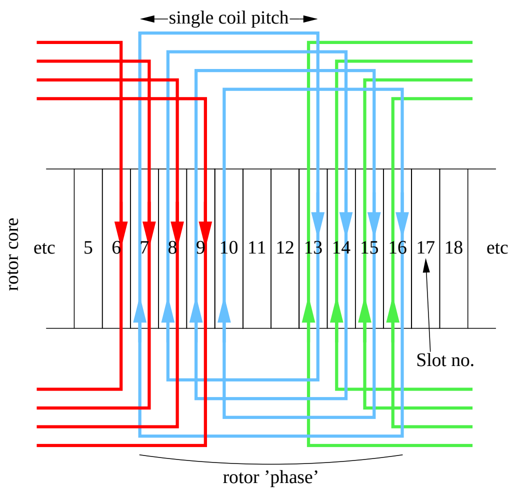

Figure 4, Rotor 3, novel progressive loop design

An additional rotor, identical to Rotor 2 was also available, Rotor 2a. Every third loop of the winding was omitted to enforce 6-fold symmetry on the rotor, ensuring that the right harmonic fields are produced to cross couple between 4 and 8 pole fields. Rotors 2 & 2a serve to illustrate the two requirements for cross-coupling of different pole number fields.

The authors have also designed and constructed a novel rotor design, Rotor 3, developed from design notes in [2]. The rotor comprises $N = p_1 + p_2$ 'phases', or sets of progressive loops, rather like a single pole of a distributed winding, with each coil pitched across $2\pi/(p_1 + p_2)$ radians, where p_1 & p_2 are the pole pair numbers of the two stator windings. The prototype machine has 8 and 4 pole stator windings, hence N=6, so the new rotor design comprises 6 sets of progressively wound coils pitched at 60^o. Simulation studies performed suggested that better performance might be obtained by the removal of the outer conductor from each set of loops. Various options were simulated, from removing no loops, to removing 3 loops. Removing two loops from each set was chosen as it gave good performance.

The pitch of the loops within each phase could, in principal, be changed, however under the assumption that the two different pole number fields are of equal magnitude, the maximum total flux linked, summing both pole number fields, as a function of coil pitch, is achieved with a pitch of $2\pi/(p_1 + p_2)$ radians. Figure 4 depicts the final design.

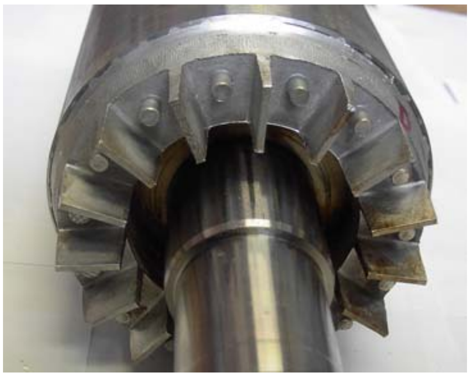

Figure 5, Rotor 4 with conventional cage.

IV. ROTOR PERFORMANCE

The effectiveness of cross-coupling in a rotor can be studied by comparing the operation of the BDFM running in two conditions:

- *Simple induction mode* where one stator winding is energised while the second is left open circuit
- *Cascade induction mode* where one stator winding is energised while the second is short-circuited.

The production of torque by cross-coupling is revealed by the tests in the cascade mode. In contrast, in an ideal rotor there would be no torque produce in the simple induction mode. The ratio of the peak cascade torque to the peak simple induction torque is therefore an indicator of the ideality of the rotor for use in a BDFM. The absolute magnitude of the cascade torque is also an issue; for a BDFM of a given frame size to have a similar rating to a cage rotor machine, or a DFIG, then the cascade torques must be similar to the torque obtained from a conventional cage rotor. Following on from the author's work of [4] it can be shown that by comparing the torque-speed curves of the machine in both modes, it is possible to make these assessments.

These tests were all carried out on the machine shown in Fig 1 with the details shown in Table I at a reduced supply voltage of 90 Vrms (phase), 50 Hz, star connected. This was done to limit currents to acceptable values throughout all the tests and ensure that all the results were obtained at approximately the same flux conditions. The applied voltage gave a nominal airgap flux density throughout the tests of about 0.125 T rms. In the simple induction tests only one fundamental field component was present but in the cascade mode two fundamental field components were present but in all cases the peak flux density was well below a level at which saturation of the iron circuit could occur.

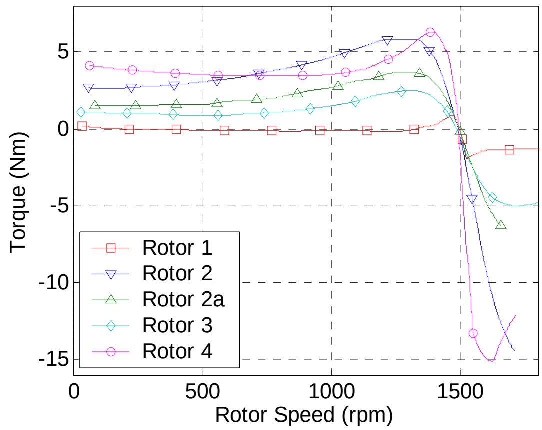

Figure 6, Measured 4 Pole Simple Induction.

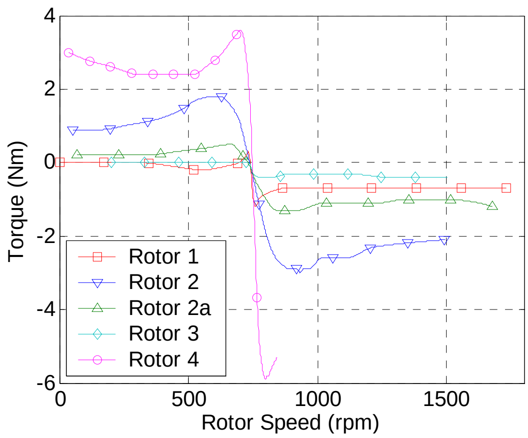

Figure 7, Measured 8 Pole Simple Induction.

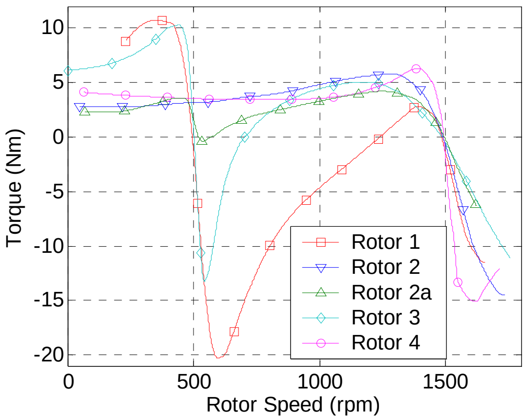

Figure 8, Measured 4 Pole Cascade.

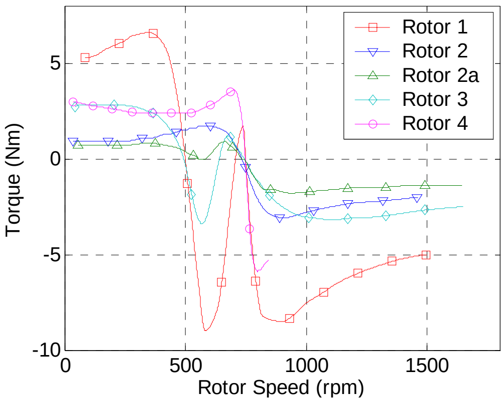

Figure 9, Measured 8 Pole Cascade.

Figure 6 shows Rotors 1-3 running in *simple induction* mode when supplied from the 4 pole winding, compared to the standard cage, Rotor 4, at the same supplied voltage.

Figure 7 shows Rotors 1-3 running in *simple induction* mode when supplied from the 8 pole winding, again compared to Rotor 4.

Figure 8 & 9 show the rotors running in *cascade*, supplied successively from the 4 and 8 pole windings, again compared to the standard cage rotor.

V. DISCUSSION

The results shown in Figures 5-8 exhibit a number of important features as follows:

- Simple induction action:
  - All five rotors show some simple induction action. Rotor 4 was the strongest, because it was designed for that purpose, Rotor 2 also showed strong induction action.
  - The peaks of the 4 pole and 8 pole Torque-Speed curves of Rotor 4 differ due to differing pole numbers and equivalent circuit impedances.
  - The peak torques of the 4 pole and 8 pole Torque-Speed curves of Rotor 2 are slightly different to those of rotor 4. The relatively lower torque of the 4 pole characteristic is due to the increased chosen pitch of 70^o.
- Cascade action:
  - Rotors 1 & 3 exhibit strong cascade action as predicted by Williamson [1] & Broadway [2], again because they were designed for that purpose. However, they both exhibit weak simple induction action.
  - Rotor 2a exhibits weak cascade action with the same structure as Rotors 1 & 3 but reduced amplitude, particularly with the 8 pole stator excited. This is due to the weak cross-coupling present in the rotor.
  - Rotors 1, 3 & 2a show the Torque-Speed curve passing through zero at three points:
    - The cascade synchronous (natural) Speed 500 rev/min
    - The Synchronous Speed, 1500 rev/min when energised on the 4 pole winding, 750 rev/min when energised on the 8 pole winding.
    - An intermediate speed between the Natural and Synchronous Speeds.
  - Rotors 2 & 4 exhibit no measurable cascade action.
  - Rotors 1 & 3 in cascade action exhibit torques in motoring and generation equal to or greater than developed by the conventional squirrel cage Rotor 4. There is no diminution in the torque capability in the cascade mode.

VI. ROTOR PERFORMANCE

In the case of Rotor 4, the standard cage rotor, the peak torque and the speed at which it was generated can be estimated from calculations using equivalent circuit parameters. As the BDFM windings are such that a given excitation produces very nearly the same flux as in the normal induction motor, within 1% for the 4-pole winding and 3% for the 8-pole winding, it is reasonable to use the manufacturer's given parameters for rotor quantities. However, as the cage rotor has closed Boucherot type slots, the parameters will vary with slip. Nevertheless, an estimate of expected torque can be obtained using normal running parameters.

The BDFM has two stator windings and so the resistances of the individual windings will be higher than the resistance of the stator winding in the induction motor. Measured values have been used for the two windings. It is not possible to determine the stator leakage reactance in a simple way and so the usual approximation of making it equal to the rotor leakage reactance has been used in the first instance. As the air gap in the present BDFM is slightly different to that in the standard induction motor, a value for the magnetizing reactance was determined from a No Load Test. The Test results are shown below in Table 2.

Table 2 Rotor 4, Initial Parameter Values

4-pole operation	
R_2' = 0.459 Ohm	X_2' = 1.88 Ohm
R_1 = 3.47 Ohm	X_1 = 1.88 Ohm
X_m = 76.65 Ohm	
8-pole operation	
R_2' = 2.18 Ohm	X_2' = 6.03 Ohm
R_1 = 5.08 Ohm	X_1 = 6.03 Ohm
X_m = 85.6 Ohm	

From these values, the results in Table 3 were obtained.

Table 3 Rotor 4, Torques Measured & Predicted Using Initial Parameters

4-pole motoring	
Theory: 8.5 Nm @ 1365 rev/min	Measured: 6.3 Nm @ 1400 rev/min
4-pole generating	
Not calculated	
8-pole motoring	
Theory: 8.5 Nm @ 625 rev/min	Measured: 3.5 Nm @ 700 rev/min
8- pole generating	
Not calculated	

From the results in Table 3 it can be seen that the predicted torques are rather greater than measured. The predicted torques for Rotor 4 in the BDFM frame are lower than those obtained in the normal configuration, principally because the stator resistance in the BDFM is higher. It is possible that the stator leakage reactance is also greater than the simple estimate and such an increase would also reduce the predicted torques. The observed magnetizing inductance, determined from open circuit tests, is 250 mH as opposed to 150 mH quoted by the Manufacturer, so we can argue that we have a smaller effective air gap. We can further argue that leakage reactances should be increased in the same proportion. The parameters then become as shown below.

Table 4 Rotor 4, Modified Parameter Values

4-pole operation	
R_2' = 0.459 Ohm	X_2' = 3.13 Ohm
R_1 = 3.47 Ohm	X_1 = 3.13 Ohm
X_m = 76.65 Ohm	
8-pole operation	
R_2' = 2.18 Ohm	X_2' = 10.05 Ohm
R_1 = 5.08 Ohm	X_1 =10.05 Ohm
X_m = 85.6 Ohm	

Using these values, the results in Table 5 were obtained.

Table 5 Rotor 4, Torques Measured & Predicted Using Modified Parameters

4-pole motoring	
Theory: 7.3 Nm @ 1404 rev/min	Measured: 6.3 Nm @ 1400 rev/min
4-pole generating	
Theory: 21.5 Nm @ 1596 rev/min	Measured: 16.5 Nm @ 1594 rev/min
8-pole motoring	
Theory: 3.0 Nm @ 671 rev/min	Measured: 3.6 Nm @ 703 rev/min
8-pole generating	
Theory: 4.9 Nm @ 829 rev/min	Measured: 5.4 Nm @ 826 rev/min

From the results in Table 5 it can be seen that the predicted torques are generally close to the measured torques. Overall, we can conclude that Rotor 4 is delivering close to expected torques in the BDFM frame when the airgap dimension and stator resistances are correctly considered.

VII. CHARACTERISATION

The previous section has shown how a conventional induction motor can be analysed and designed using an equivalent circuit model, the parameters for which can be elicited from classical No-Load (Open Circuit) and Locked Rotor (Short Circuit) Tests.

The BDFM is clearly a more complex machine, as can be seen from the Torque-Speed characteristics presented. However the measurements have shown that the Torque-Speed characteristics of the motor in cascade are related to the simple induction characteristic and should submit to an equivalent circuit model, related to that produced for the conventional induction machine. The parameters for such an equivalent circuit can then be obtained from the Torque-Speed curve measured in cascade operation. An additional aid to the process of parameter extraction is that the authors have perfected the means to measure the current flowing in the rotor winding, see [5]. It is proposed that the next step in this work will be to find that equivalent circuit and predict the performance from the parameters obtained.

VIII. CONCLUSIONS

It is clear from the measured results that Rotors 1 and 3 are viable BDFM rotors, as they both exhibit strong cross-coupling torques. The measurements have also shown that these torques are similar to those developed by a conventional cage, Rotor 4, at similar levels of excitation. The measurements give confidence that the performance of a BDFM can be represented by an equivalent circuit model, similar to a conventional induction motor and that the equivalent circuit could be derived from the Torque-Speed characteristic measured in cascade action.

ACKNOWLEDGEMENT

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