Rotor Design & Performance for a BDFM


Abstract—Analysis of the behaviour of the Brushless Doubly Fed Machine (BDFM) has received considerable attention in the literature. The BDFM is typified by its complex airgap flux distribution. This paper will build upon performance-prediction work, concentrating on the design and electromagnetic behaviour of the BDFM rotor, considering 2 different sizes of 4/8-pole stator machines and comparing test results from 2 different 6-pole rotor windings fitted to each of these machines, with predictions from their equivalent circuits and from FEA. The authors will use these results to conclude the important features of the rotor core and winding design for effective BDFM performance.

Index Terms—BDFM, Equivalent Circuit, Time-stepping Finite Element Analysis.

I. INTRODUCTION

Analysis of the behaviour of the Brushless Doubly Fed Machine (BDFM) has received considerable attention in the literature, exemplified by Broadway et al [1] and Williamson et al [2]. The BDFM is typified by its complex airgap flux distribution. The authors have added to this literature with recent work [3-10] which:

- Developed an equivalent circuit model for the BDFM.
- Developed a method for extracting the parameters,
- Tested different machines, measuring both stator & rotor quantities,
- Predicted the electric and magnetic loading and potential ultimate rating of the BDFM.
- Compared test results, including rotor current measurement, with performance predicted by both the equivalent circuit and the time-stepping finite element analysis (FEA).

Another strand of that work, included in [6], has been the control of the BDFM, but that is not the subject of this paper.

II. PRACTICAL MACHINES & ROTORS

Two 4/8-pole BDFM machines, with D180 and D160 frames, as shown in Figure 1, were tested at the authors’ two universities. These machines were both based upon 4-pole squirrel cage induction motor designs from the same factory, as can be seen from the photographs, using similar materials and manufacturing techniques. A variety of 6-pole rotor designs were tested in these machines as described in detail in the references [3-10].

One rotor was based on a design recommended by earlier authors but 3 rotors incorporate new, two-layer designs. Figure 2 shows the rotor designs adopted for testing within the machines shown in Figure 1 and they are described as follows:

- Rotor 1, applied to the D180 machine. Figure 2a shows a 3 loop, nested, bar-conductor winding, proposed by Broadway & Burbridge [1]. This had been advocated for manufacturing reasons, because of the simple bar and end-ring construction at one end of the winding. However, the segmented, brazed, end-ring construction at the other end of the winding, visible in Figure 2a, is complex and difficult to manufacture.
- Rotor 3, applied to the D180 machine. Figure 2b shows a 4 turn, two-layer, bar-conductor winding, suggested by a manufacturing arrangement used by one of the associated companies [11]. This arrangement allows a greater flexibility of winding distribution and connection than is possible with the nested-loop.
- Rotor 5, applied to the D160 machine, is a 4 turn, two-layer, round-wire winding, which allowed rewinding, to investigate the effect of varying distribution factors and connections. A photograph of Rotor 5 is shown in [10].
- Rotor 6, applied to the D160 machine, Figure 2c shows a similar 5 turn, two-layer, round-wire winding giving an improved MMF distribution across the pole face.

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Figure 2a, A BDFM rotor with a 6-pole, 3 loop, nested winding. This is Rotor 1 in the D180 machine.

Figure 2b, Two D180 BDFM rotors with 6-pole, 4 turn, two-layer windings. The right hand example is Rotor 3 in the D180 machine.

Figure 2c, A BDFM rotor with a 6-pole, 5 turn, two-layer winding. This is Rotor 6 in the D160 machine.

III. ANALYTICAL METHODS

Roberts [5] developed a method for modelling the machine using an equivalent circuit, as shown in Figure 3, and described a method for extracting the parameters from the torque-speed curve measured during a cascade test. He also proposed a method for considering different winding designs and presented an analysis for an optimised rotor winding design.

The FEA permits visualisation of the detailed magnetic flux-plot in the rotor for different windings at different applied voltages, frequencies and rotor speeds, allowing the optimisation of rotor slot and yoke design. These methods have been used to predict the behaviour of the rotors described.

IV. EXPERIMENTAL WORK

Strong BDFM operation requires good coupling between each stator winding and the rotor winding, associated with no direct coupling between the stator windings. In order to test this coupling, and demonstrate the benefits of the different rotor and stator combinations, cascade operation of each motor was tested. That is each machine was supplied on one stator winding from the mains while the other stator winding was short circuited. The rotor torque was then measured at a variety of speeds throughout the speed range. This test was performed on the 4-pole winding and repeated on the 8-pole winding. The equivalent circuit in Figure 3 was extracted from these torque-speed curves.

Figure 4 shows a comparison between the cascade torque-speed curves of the 4 rotors studied. The curves also compare the experimental performance with that predicted using the extracted equivalent circuit. The flux-plots for the cascade performance were predicted using the FEA time-stepping method. The flux-plots shown in Figure 5 were each taken at the same point in time as the motor was running in 4-pole cascade at the Natural Speed, 500 rev/min. Therefore in each case the motor was running at zero torque on no-load. The Torque-speed curves were also predicted from the FEA and these are plotted alongside the experimental curves in Figure 4 and there is close agreement, confirming the validity of the FEA results.

These tests yield, for a range of rotor designs, the potential for a detailed comparison between:

- experimental performance,
- predictions using the equivalent circuit,
- predictions using time-stepping flux-plots.

V. DISCUSSION

The novelty of this work was the range of BDFM rotors investigated and the comparison between theory and experiment on these rotors. The torque-speed curves in Figure 4 and the parameters in Table 1 demonstrate that the equivalent circuit parameters can be extracted conveniently from the cascade test results and that the resultant circuits accurately represent the measured performance.

Study of the Torque-speed curves, particularly for Rotor 1 in the D180 and Rotor 6 in the D160 is instructive, because these rotors subsequently exhibited strong BDFM operation. Those curves both exhibit a steep torque transition through the natural speed of 500 rev/min and the synchronous speeds of 750 rev/min (8-pole) and 1500 rev/min (4-pole). In an induction motor that steep transition is achieved by a high \( L_r/R_r' \) ratio.
Study of Table 1 for the D180 machine shows that Rotor 1, with 3 nested-loops, had a low referred rotor resistance, $R_r'$, of 1.26 $\Omega$, and a high $L_r'/R_r'$ ratio, 27.9. This was higher than that for Rotor 3, with a 4 turn, two-layer winding. Similarly Rotor 6, with 5 turn, two-layer winding, had a low referred rotor resistance, $R_r'$, of 1.47 $\Omega$, and a high $L_r'/R_r'$ ratio, 19.0. This was higher than that for Rotor 5, with 4 turn, two-layer winding. In fact the two-layer winding in Rotor 6 of the D160 machine achieved almost as strong BDFM performance as the nested-loop winding in Rotor 1 of the D180 machine, which had a much larger volume of copper in its rotor circuit, compare the photographs in Figures 2a and 2c.

Therefore good coupling from both stator windings to the rotor and strong BDFM performance seems to be consistent with a steep torque transition through the natural and synchronous speeds in the cascade test and a high $L_r'/R_r'$ ratio in the rotor.

Another important issue in the rotor magnetic design is the behaviour of the rotor magnetic flux under the complex BDFM excitation. A number of authors have noted the importance of the rated flux in the machine and this was considered in some detail in [7]. As in any electrical machine, saturation in the rotor teeth and yoke should be controlled but because of the superposition of fields in a BDFM, due to different pole numbers, this is complex to predict. This issue is central to consideration of the best design for a BDFM rotor and could be resolved by a study of the FEA flux-plots. The no-load 4-pole, cascade, flux-plots for each motor, in Figure 5, show a developed 6-pole field in the rotors. For the D180 machine the flux is well-developed in the Rotor 1. However, the width of the rotor tooth is too narrow but in Rotor 3 the rotor yoke is very restricted because of the extended depth of the rotor slots to accommodate the two layers.

The no-load flux-plots for the D160 machine show that it is hard to distinguish between Rotor 5 and Rotor 6, despite the substantial difference in the parameters and the marked differences in the torque-speed curves. The theoretical and experimental data collated from the variety of arrangements tested allows the reader to draw conclusions about the ideal arrangement of the rotor winding and the dimensions of the rotor slots in a BDFM.

VI. CONCLUSIONS

Analytical and experimental work has shown the following for the BDFM machine:

- Experimental results showed that rotors with strong BDFM performance had a high ratio of referred rotor winding inductance to resistance, $L_r'/R_r'$.
- The rotor air gap should be optimised to be as small practicable to achieve strong BDFM operation.
- The design of the BDFM should aim to reduce the referred rotor winding resistance, $R_r'$.
- Rotor slot cross-section needs to be large enough to achieve the low referred rotor winding resistance, $R_r'$.
- Rotor design needs to ensure that the rotor tooth width at the bottom of the slot is adequate to carry the rated flux of the machine.
- However in achieving an adequate rotor tooth width and rotor slot cross-section the slot depth must not restrict the depth of rotor yoke needed to carry the main flux.
- To date the best BDFM performance from machines at Cambridge and Durham has been achieved by Rotor 1 in the D180 machine, with a 3 loop nested rotor winding design, as proposed in [1].
- Two-layer rotor winding designs, as proposed in [11], allow more freedom to adjust winding connection and distribution, which could improve the rotor MMF, the air-gap flux form and therefore the output torque.
- In the D180 machine a low resistance 4 turn, two-layer rotor winding was achieved but at the expense of a deeper slot, reducing the rotor yoke below that acceptable for the rated flux. The BDFM performance of this rotor was not as good as that of Rotor 3 with the nested-loop rotor winding.
- In the D160 machine a 4 turn, two-layer rotor winding achieved a better balance between rotor slot width, slot cross-section and rotor yoke depth. A 5 turn, two-layer rotor winding achieved even better performance, however, the full benefits in BDFM operation were still not reached because of a low slot fill, due to the rewindable winding, resulting in a high rotor winding resistance.
- The tests suggest that a two-layer rotor winding can achieve BDFM performance at least as good, if not better than, a nested-loop if the above points are taken into consideration in the design.

VII. ACKNOWLEDGEMENTS

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VIII. REFERENCES


11. Schwarz K K, The design of reliable squirrel cage rotors, Publn 189, Laurence, Scott & Electromotors Ltd.
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Table 1, Parameters, showing the differences in values for for all 4 different rotor designs tested.

Figure 5a, No-load flux-plot from Rotor 1 in D180 machine
Figure 5b, No-load flux-plot from Rotor 3 in D180 machine
Figure 5c, No-load flux-plot from Rotor 5 in D160 machine
Figure 5d, No-load flux-plot from Rotor 6 in D160 machine