Application of Real-Time Rotor Current Measurements Using Bluetooth Wireless Technology in Study of the Brushless Doubly-Fed (Induction) Machine (BDFM)

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Abstract— **The Brushless Doubly-Fed Machine (BDFM) shows commercial promise as a variable speed drive or generator. However, for this promise to be realised, the design of the machine must be improved. Accurate machine modelling is therefore required for design optimisation. The measurement of rotor bar currents is of considerable benefit in the process of developing an accurate machine model. The authors present a system of measuring rotor bar currents in real time using a Rogowski coil to transduce the signal and recently available Bluetooth technology to transmit the data from the moving rotor to a standard PC. A coupled-circuit model has been developed for the BDFM to predict its dynamic and stead-state performance. The model has been verified using the proposed measurement system. The experiments were carried out on a frame size 180 BDFM with a nested-loop rotor design.**

I. Introduction

Potential applications for the BDFM have been the subject of research over the last decade. The machine has attracted attention as a variable speed drive [1] and as a generator [2] in applications where the prime mover speed is variable, such as in wind turbines. The rating of the inverter need only be a fraction of rating of the machine so there are potential savings in system cost. In wind turbines, the BDFM is being considered as an alternative to the doubly fed induction generator as using the BDFM eliminates the problems associated with brush gear, making the BDFM particularly attractive for offshore wind turbines.

The BDFM comprises two stators wound for different, non-coupling, pole numbers. The rotor is designed to couple both fields. In the normal mode of operation, one stator is connected to a source of fixed frequency, normally the mains or grid, and the other is fed with variable voltage at variable frequency from a converter. The machine operates in a synchronous mode and the shaft speed has a fixed relationship to the two supply frequencies. Details of machine construction and operation can be found in [3].

The design of the rotor is critical to good performance [4]. The nested loop type of rotor is the most widely used but the analysis of its performance is not straightforward. The ability to make direct measurements of rotor currents would help to build confidence in predictions from theory. Measurements of rotor currents would also facilitate the acquisition of parameter values for the equivalent circuit of the machine. In previous work, parameters have been obtained from terminal measurements at the two stators but it was not possible to obtain explicit values for all inductances [5]. The availability of rotor quantities in principle allows separation of these inductances. Furthermore, Roberts et. al. [6] presented a control strategy which requires knowledge of the rotor bar currents in real-time, so monitoring these currents during operation is of considerable advantage.

Rotor bar currents are difficult to measure. The design of a system to measure these currents is complicated because the rotor is moving and because of strong electro-magnetic fields in the machine air gap and end region. In the case of the BDFM, one winding will normally be fed from an inverter and this will introduce interference at frequencies related to the switching frequency of the inverter. Apart from the obvious difficulty of extracting data signals from a moving rotor, the centripetal acceleration acting on the transducer is around $1000m/s^2$ at $1000rpm$.

The authors have developed a system of measuring rotor bar currents directly with Rogowski coils, using the Bluetooth wireless technology to transmit the signal from the moving rotor back to a computer for logging and analysis [7], [8]. Bluetooth is one of a range of recently introduced protocols developed for the transmission of digital data. Measurements of rotor currents have been made to confirm predictions of rotor currents from the coupled-circuit model of the BDFM [9].

Table I gives the physical data for the machine used throughout this and the work described in [3]–[9]. The BDFM is shown in fig. 1 in the experimental rig.

II. Measurement System Design and Specification

The measurement system comprises the sections shown diagrammatically in fig. 2. Full details are given in [7].

A. Rogowski Transducers

A Rogowski coil is a low noise, air-cored current transducer. The Rogowski current transducer was chosen for the following reasons [7]:

TABLE I

PROTOTYPE MACHINE SPECIFICATIONS

Parameter	Value
Frame size	D180
Stator 1 pole-pairs	2
Stator 2 pole-pairs	4
Stator slots	48
Rotor slots	36
Rotor design	'Nested-loop' design consisting of 6 'nests' of 3 concentric loops of pitch $5/36$, $3/36$ and $1/36$ of the rotor circumference. Each nest offset by $1/6$ of the circumference, for the details see [10].

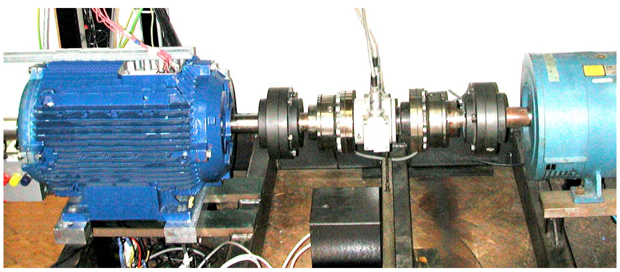

Fig. 1. Prototype BDFM machine (left) on test rig with torque transducer and DC load machine (right)

- It is air-cored and therefore, a small cross-section is possible. This is necessary as the coil is to be wrapped around a rotor bar.
- It can easily be made in an openable form, so it can be retro-fitted to a bar.
- Linear characteristic over a wide measuring range.
- High level of immunity to electromagnetic interferences.

High-performance, low-cost Rogowski transducers were constructed using the technique described in [11]. Fig. 3 shows the Rogowski coils installed on the rotor.

B. Bluetooth Wireless Technology

Bluetooth wireless standard was used for data communication between the instrumentation system installed on the rotor and a computer. It uses a $2.4GHz$ radio link for short-range connections. Bluetooth was chosen for this application, in preference to other wireless standards, because of its high

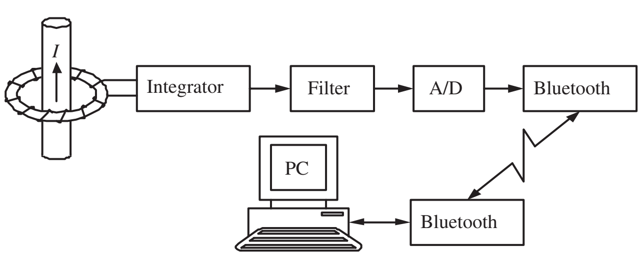

Fig. 2. Functional block diagram of the rotor instrumentation system

Fig. 3. Rogowski coils installed on the nested-loop prototype rotor to measure end-ring currents

interference immunity, low cost, and ease of implementation [7]. $BlueCore^{TM}$ RS232 cable replacement modules from Cambridge Silicon Radio (CSR) were used.

C. Electronic Circuitry

The circuitry is shown in fig. 4. The system is supplied by three rechargeable *AA* cells. Recharging *in situ* is possible via connections brought out through a hole in the shaft.

D. System Specification

The instrumentation system was constructed to measure rotor bar currents for the BDFM. The measurement setup was designed to measure bar currents up to $3000A$ peak-to-peak, with a resolution of $0.5A$, from $1Hz$ to $100Hz$. This frequency range is required for the BDFM as the machine runs with a wide range of slips in normal operation, unlike a standard induction motor. A high signal to noise ratio (SNR) of $50dB$ was achieved due to careful design and construction of the transducer and its accompanying circuitry

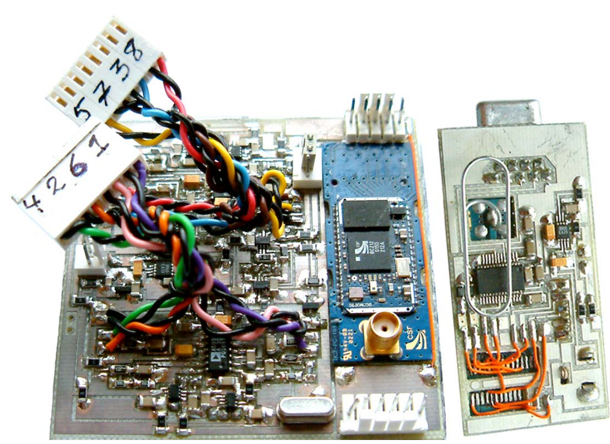

Fig. 4. Two electronic boards constructed for instrumenting the BDFM rotor. Left: Electronic circuitry mounted on the rotor shaft. Right: Electronic circuitry designed for logging data

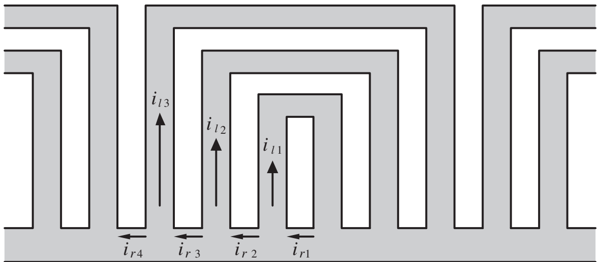

Fig. 5. End-ring and bar currents in a nested-loop rotor design

[11]. In practice, data rates of about $115.2Kbps$ were routinely achieved between the rotor mounted transmitter and the receiver, approximately $5m$ distant.

The nested-loop rotor consists of 36 slots, and as the prototype machine has stator windings with $p_1 = 2$ and $p_2 = 4$ poles respectively, the rotor has $S = p_1 + p_2 = 6$ nests terminated with a common end ring at one end only [4]. Each nest is allocated 6 slots. Therefore, three concentric loops are housed within each nest.

The Rogowski coils were installed to measure the end-ring currents as shown in fig. 3. Seven coils were used to acquire six loop currents in two consecutive nests and the current flowing between those nests. The relationship between the end-ring and loop currents may be simply derived from fig. 5, and is given by

$$\begin{aligned} i_{l1} &= i_{r1} - i_{r2} \\ i_{l2} &= i_{r2} - i_{r3} \\ i_{l3} &= i_{r3} - i_{r4} \end{aligned} \tag{1}$$

III. BDFM Coupled-Circuit Model

A generalised coupled-circuit model for a wide class of BDFM was developed by Roberts in [9]. The model can accurately predict the transient performance of the machine. It includes the effect of all space-harmonic components of inductance parameters. The proposed model is straightforward to implement on a computer, and allows a general interface for different machine windings or rotor designs.

The general electrical machine coupled-circuit equation is

$$v = Ri + \omega_r \frac{dM}{d\theta_r} i + M\frac{di}{dt} \tag{2}$$

where v and i are the voltage and current vectors, and R and M are the resistance and inductance matrices. ω_r and θ_r are respectively the rotor angular speed and position.

The torque generated by an electrical machine can be determined by considering instantaneous power transfer in the system [12] and is given by

$$T_e = \frac{1}{2} i^T \frac{dM}{d\theta_r} i \tag{3}$$

The mechanical differential equation is

$$J\frac{d\omega_r}{dt} = T_e - T_l \tag{4}$$

where J is the combined moment of inertia of the machine and load, and T_l is load torque.

The full dynamic equations may therefore be written as

$$\frac{d}{dt}\begin{bmatrix} i \\ \theta_r \\ \omega_r \end{bmatrix} = \begin{bmatrix} -M^{-1}\left(Ri + \omega_r \frac{dM}{d\theta_r} i\right) \\ \omega_r \\ \frac{1}{2J} i^T \frac{dM}{d\theta_r} i \end{bmatrix} + \begin{bmatrix} M^{-1}v \\ 0 \\ -\frac{T_l}{J} \end{bmatrix} \tag{5}$$

In the BDFM, it is convenient to partition v and i into stator 1, stator 2, and rotor quantities, noting that the rotor voltage will always be zero. The BDFM coupled-circuit equations can be therefore written as

$$\begin{aligned} \begin{bmatrix} v_{s1} \\ v_{s2} \\ 0 \end{bmatrix} &= \left(\begin{bmatrix} R_{s1} & 0 & 0 \\ 0 & R_{s2} & 0 \\ 0 & 0 & R_r \end{bmatrix} + \omega_r \begin{bmatrix} 0 & 0 & \frac{dM_{s1r}}{d\theta_r} \\ 0 & 0 & \frac{dM_{s2r}}{d\theta_r} \\ \frac{dM_{s1r}^T}{d\theta_r} & \frac{dM_{s2r}^T}{d\theta_r} & 0 \end{bmatrix} \right) \begin{bmatrix} i_{s1} \\ i_{s2} \\ i_r \end{bmatrix} \\ &+ \begin{bmatrix} M_{s1} & 0 & M_{s1r} \\ 0 & M_{s2} & M_{s2r} \\ M_{s1r}^T & M_{s2r}^T & M_r \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{s1} \\ i_{s2} \\ i_r \end{bmatrix} \end{aligned} \tag{6}$$

The torque equation from (3) and (6) is

$$T_e = \begin{bmatrix} i_{s1}^T & i_{s2}^T \end{bmatrix} \begin{bmatrix} \frac{dM_{s1r}}{d\theta_r} \\ \frac{dM_{s2r}}{d\theta_r} \end{bmatrix} [i_r] \tag{7}$$

v_{s1}, i_{s1}, v_{s2}, $i_{s2} \in \mathbb{R}^{3\times 1}$ are stator 1, stator 2 voltage and current vectors. i_r is the rotor current vector. For the nested-loop rotor with N nests of S loops, $i_r \in \mathbb{R}^{NS\times 1}$. R_{s1}, R_{s2} and R_r are respectively stator 1, stator 2 and rotor resistance matrices. The calculation of resistance matrices is straightforward and is presented in, for example [9].

The mutual inductance matrices M_{s1}, M_{s2} and M_r are all constant as they link circuits which are not moving relative to one another. The position varying parameters M_{s1r} and M_{s2r} are rotor-stator 1 and rotor-stator 2 mutual inductance matrices. For ease of implementation and to maximise running speed, the position dependent parameters M_{s1r} and M_{s2r} and their derivatives were computed off-line at one degree intervals and then values interpolated online.

A generalised method of calculating the mutual inductance matrices for the BDFM is presented in [9]. The method first calculates the flux density due to unit current flowing in a single coil. It then uses this result to determine the mutual inductance between any two coils in the machine. Since the machine is made up of interconnected groups of coils, the self and mutual inductance of the stator windings and rotor circuits may be derived by summing the single coil elements.

The authors have therefore developed a coupled-circuit model for the BDFM with a nested-loop design rotor. The inductance and resistance matrices were calculated using *MATLAB*. The model has been implemented in *Simulink*. A block diagram of the implemented model is shown in fig. 6.

IV. Experimental Verifications

The coupled-circuit model can predict the actual waveforms of voltages and currents in the BDFM, allowing both the dynamic and steady-state performance to be considered. The

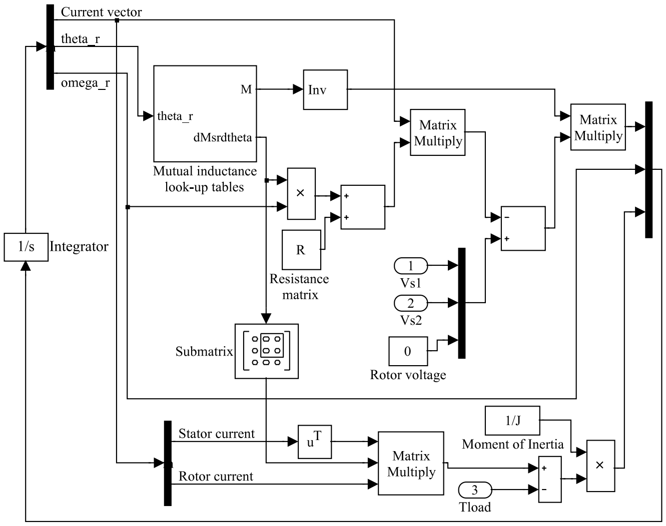

Fig. 6. The BDFM coupled-circuit model implementation in Simulink

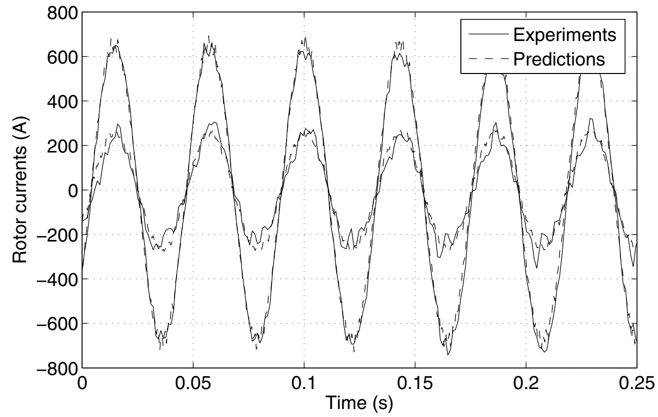

Fig. 7. Middle and inner loop currents within one nest for the nested-loop rotor. The middle loop current clearly has a greater amplitude.

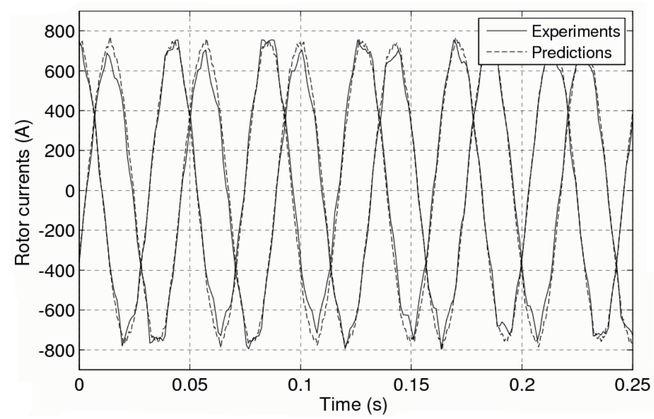

Fig. 8. Outer loop currents for two consecutive nests of the nested-loop rotor.

measurement system similarly enables the actual waveforms of rotor bar currents to be observed. Comparisons are made between predicted and measured current waveforms and further comparisons are made in steady-state operation between the magnitudes of predicted and measured currents. The tests were performed at relatively low supply voltages in order to avoid saturating the iron circuit.

A. Comparison of current waveforms

Experimental tests were carried out in the synchronous mode of operation, the normal running mode and the one for which the design of the machine is to be optimised [3]. The machine 4-pole and 8-pole stator windings were supplied at $90V$ and $50Hz$, and $170V$ and $30Hz$ respectively. The machine was operating at its synchronous speed, that is $800rpm$. The mechanical torque applied to the machine shaft was $30Nm$.

Fig. 7 and 8 show the measured rotor loop currents with the simulation results from the coupled-circuit model overlaid. The currents in all loops of a nest have the same phase (see fig. 7). The loop currents of two consecutive nests have $\frac{2\pi}{3}$ phase difference (see fig. 8). This is in agreement with the consideration of the nested-loop rotor with N sets of S loops as N S-phase systems.

B. Comparison of current magnitudes in steady-state operation

The BDFM was run in steady state in the normal synchronous mode and also in the cascade mode which is used for parameter extraction purposes. A description of BDFM operating modes is given in [3].

1) Synchronous operation: The machine 4-pole stator winding was supplied from a constant voltage and frequency supply at $90V$ and $50Hz$. The machine 8-pole stator winding was fed with a variable voltage, variable frequency inverter. However, the 8-pole supply frequency was fixed to $30Hz$ throughout the experiment and therefore the synchronous speed was $800rpm$. The test was performed at a constant torque of $30Nm$. Fig. 9 shows the predictions made by the coupled-circuit model overlaid with the experimental results.

2) Cascade operation: Two cascade tests over a wide speed range were carried out: one with 4-pole winding supplied with a constant $90V_{rms}$, and 8-pole winding shorted, and one with 8-pole winding excited by a constant $110V_{rms}$ supply, and 4-pole winding shorted. All tests were performed at $50Hz$ supply frequency. In order to limit currents to acceptable values throughout the range of the machine rating, reduced supply voltages were applied. The outer loop currents are plotted against the rotor speed in fig. 10.

V. CONCLUSIONS

The paper presents the design and evaluation of the real time rotor bar current measurement system which uses a Rogowski coil as a current transducer and a Bluetooth wireless link to transmit data back to the bench. The measurement system has high accuracy, good immunity to noise, and low power consumption. By using commercially available Bluetooth modules the cost is moderate.

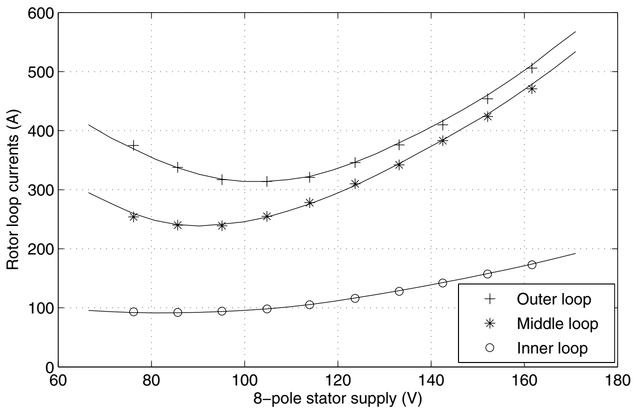

Fig. 9. The rotor loop currents at synchronous mode of operation. Solid lines are the coupled-circuit predictions and marks indicate the experimental results.

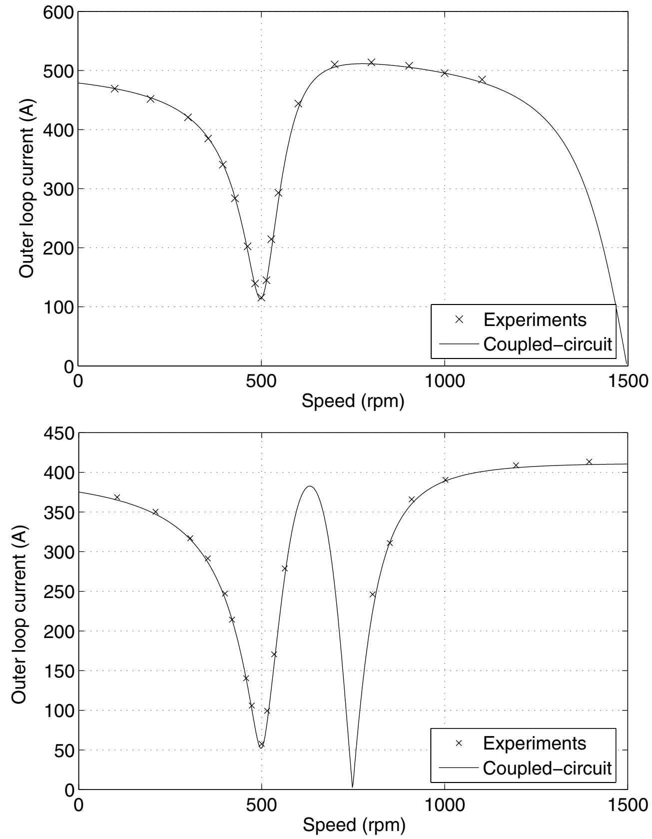

Fig. 10. Rotor outer-loop current in the cascade mode of operation.

The application to the BDFM shows the feasibility of the approach, which may find application in the wider field of electrical machines. The approach can also be used when electrical isolation is required, as in high voltage machines.

Applying the system to the BDFM allows the rotor current to be monitored. This is valuable both in verifying theoretical predictions and in obtaining machine parameters for equivalent circuits. The system has the potential to be part of a control system of the type proposed in [6].

The measurement system was used to verify predictions of rotor bar currents in the BDFM in the machine's synchronous and cascade modes of operation. The agreement between the experimental and predicted results was good and within the limitations of measurement accuracy.

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REFERENCES

[1] M. Boger, A. Wallace, and R. Spee, "Investigation of appropriate pole number combinations for brushless doubly fed machines as applied to pump drives," *IEEE Transactions on Industry Applications*, vol. 31, no. 5, pp. 1022–1028, 1996.

[2] S. Bhowmik, R. Spee, and J. H. R. Enslin, "Performance optimization for doubly fed wind power generation systems," *IEEE Transactions on Industry Applications*, vol. 35, no. 4, pp. 949–958, 1999.

[3] R. A. McMahon, P. C. Roberts, X. Wang, and P. J. Tavner, "Performance of bdfm as generator and motor," *Electrical Power Applications, IEE Proceedings*, vol. 153, no. 2, pp. 289–299, March 2006.

[4] P. C. Roberts, R. A. McMahon, P. J. Tavner, J. M. Maciejowski, T. J. Flack, and X. Wang, "Performance of rotors for the brushless doubly-fed (induction) machine (bdfm)." 16th International Conference on Electrical Machines (ICEM2004), September 2004, pp. 450–455.

[5] P. C. Roberts, R. A. McMahon, P. J. Tavner, J. M. Maciejowski, and T. J. Flack, "Equivalent circuit for the brushless doubly fed machine (bdfm) including parameter estimation and experimental verification," *IEE Proceedings*, vol. 152, no. 4, pp. 933–942, July 2005.

[6] P. C. Roberts, T. J. Flack, J. M. Maciejowski, and R. A. McMahon, "Two stabilising control strategies for the brushless doubly-fed machine (bdfm)." First IEE International Conference on Power Electronics, Machines and Drives, June 2002, pp. 341–346.

[7] E. Abdi-Jalebi, P. C. Roberts, and R. A. McMahon, "Real-time rotor bar current measurement using a rogowski coil transmitted using wireless technology," vol. 5. 18th International Power System Conference (PSC2003), October 2003, pp. 1–9.

[8] P. C. Roberts, E. Abdi-Jalebi, R. A. McMahon, and T. J. Flack, "Real-time rotor bar current measurements using bluetooth technology for a brushless doubly-fed machine (bdfm)," vol. 1. 2nd IEE International Conference on Power Electronics, Machines and Drives (PEMD2004), March 2004, pp. 120–125.

[9] P. C. Roberts, "A study of brushless doubly-fed (induction) machines," Ph.D. dissertation, University of Cambridge, 2005.

[10] A. R. W. Broadway and L. Burbridge, "Self-cascade machine: A low-speed motor or high frequency brushless alternator," *IEE Proceedings*, vol. 117, pp. 1277–1290, 1970.

[11] E. Abdi-Jalebi and R. A. McMahon, "Simple and practical construction of high performance, low cost rogowski transducers and accompanying circuitry for research applications," vol. 1. 22nd IEEE Conference on Instrumentation and Measurement Technology (IMTC2005), May 2005, pp. 354–358.

[12] P. C. Krause, O. Wasynczuk, and S. D. Sudhoff, *Analysis of Electric Machinery and Drive Systems*, 2nd ed. New York: IEEE Press Wiley, 2002.