Vibration monitoring for wound rotor induction machine winding fault detection

DOI:

[10.1109/ICEIMach.2012.6350142](https://doi.org/10.1109/ICEIMach.2012.6350142)

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Durovic, S., Vilchis-Rodriguez, D., & Smith, S. (2012). Vibration monitoring for wound rotor induction machine winding fault detection. In *Proceedings - 2012 20th International Conference on Electrical Machines, ICEM 2012|Proc. - Int. Conf. Electr. Mach., ICEM* (pp. 1906-1912). IEEE.
<https://doi.org/10.1109/ICEIMach.2012.6350142>

Published in:

Proceedings - 2012 20th International Conference on Electrical Machines, ICEM 2012|Proc. - Int. Conf. Electr. Mach., ICEM

Citing this paper

Please note that where the full-text provided on Manchester Research Explorer is the Author Accepted Manuscript or Proof version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version.

General rights

Copyright and moral rights for the publications made accessible in the Research Explorer are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Takedown policy

If you believe that this document breaches copyright please refer to the University of Manchester's Takedown Procedures [<http://man.ac.uk/04Y6Bo>] or contact uml.scholarlycommunications@manchester.ac.uk providing relevant details, so we can investigate your claim.

Vibration Monitoring for Wound Rotor Induction Machine Winding Fault Detection

S. Djurović, D. Vilchis-Rodriguez, A.C. Smith

Abstract -- This paper investigates wound rotor induction machine winding fault detection by vibration monitoring. The influence of stator open-circuit faults on machine operation is first examined using a time-stepped circuit model. The calculations indicate that fault specific changes exist in the machine torque and therefore the vibration signal. Model predictions are validated by torque and vibration signals measurements on a commercial 30kW machine. The paper establishes closed form expressions that enable the evaluation of torque and vibration signals spectral frequencies and linking these to healthy and faulty operating conditions.

Index Terms-- Condition monitoring, Electrical fault detection, Induction generator, Torque spectrum, Vibration spectrum, Winding fault, Wind power generation

I. INTRODUCTION

Wind energy is the dominant form of sustainable electricity generation today. With a significant increase in wind energy penetration levels projected in the near future for a number of national markets [1], competent condition monitoring of wind power plants will become crucial in order to minimize the downtime and maintenance cost of production systems. The development of effective non-invasive wind turbine (WT) condition monitoring techniques is increasingly gaining importance in this respect.

A considerable proportion of installed and currently manufactured commercial high power (>1MW) variable-speed WTs use wound rotor induction generator (WRIG) drives for electromechanical energy conversion. Recent fault surveys [2-6] indicate that generator faults form a high contribution to turbine downtime. In addition, [2,5,6] highlight the high rates of winding failures in WT generators.

The traditional approach to ac machinery non-invasive electrical fault detection is based on spectral analysis of machine electrical signals [7]. Vibration and torque signal analysis for electrical fault detection has received significantly less attention in available literature due to claimed lower sensitivity, but was however shown to be feasible [8,9]. Consequently a number of authors have recently investigated WRIG winding fault detection and the reported findings demonstrate that winding fault specific spectral changes can be identified in WRIG currents [10-13]. However, most commercially available WT condition monitoring systems today are almost exclusively focused on generator vibration data monitoring and processing [14] and high fidelity current measurements may introduce unnecessary complexity to the existing monitoring systems.

This work builds on previous research [10,11] to

investigate the possibility of WRIG winding fault detection based on vibration signal spectral analysis. The presented analysis employs an advanced numerical model [10] to predict and investigate the WRIG electromagnetic torque signal spectrum under healthy and faulty operating conditions with a view to examining the possibility of detecting the identified fault induced torque pulsations in the machine frame vibration signal. The model predicted torque frequencies are shown to be clearly detectable in torque and vibration signals data measured on the laboratory WRIG test rig. In addition, the paper provides a theoretical analysis of the WRIM electromagnetic torque signal spectral content yielding closed form analytical expressions that link torque frequencies to machine operating conditions and thus enable real time monitoring of reported torque/vibration frequencies of interest. Finally, the consistency of identified fault effects is investigated on the laboratory machine over its rated operating range.

II. MODELING AND EXPERIMENTAL TOOLS

The WRIG model used in this work is based on the principles of generalized harmonic analysis and is presented in [10]. The model accounts for higher order harmonic effects when evaluating machine parameters and is particularly appropriate for frequency domain analysis of machine quantities, as demonstrated in [10,11,15]. In order to emulate the behavior of the laboratory machine used for experimental research in this work, the machine design and operational data were used as model inputs.

The laboratory test rig comprises a four pole 30kW wound rotor induction machine coupled by a common shaft to a 40kW DC motor. The DC motor torque and speed are controlled by a commercial DC speed drive to operate the induction machine (IM) as a generator. For the purpose of this research the IM rotor windings were short circuited and the stator windings were connected to the grid via a three-phase variable transformer. To enable the experimental emulation of winding faults, the IM stator was wound with the individual coil connections taken out to an external terminal box where healthy and faulty winding configurations were achieved by appropriate connection of the coil terminals [10,11].

Effects of a common open-circuit fault in stator phase windings with two parallel paths are investigated in this work. The healthy machine stator and rotor winding configuration corresponding to the manufacturer's specifications, along with the investigated stator winding fault scenarios, are shown in Fig. 1. Power analyzers were used in IM stator and rotor circuits to monitor and record currents and voltages. The rotational speed was measured by a stub shaft mounted 1024ppr incremental encoder. Electromagnetic air-gap torque signal for a balanced machine was estimated from stator voltage and current measurements [9,19]. The motor was also mounted on a force measuring platform containing three-axis piezoelectric transducers which was

This work was supported by UK EPSRC Supergen Wind Energy Technologies programme, EP/D034566/1.

S. Djurović, D. Vilchis Rodriguez and A. C. Smith are with the Power Conversion Group, School of Electrical and Electronic Engineering, The University of Manchester, Manchester M13 9PL, UK. (e-mail: Sinisa.Durovic@manchester.ac.uk).

Fig. 1. Machine winding configurations

used for obtaining dynamic shaft torque measurements for unbalanced machine operation [16]. The vibration signal was recorded by installing an accelerometer on the top of the drive end bearing in the radial direction. The accelerometer output signal was conditioned using the Bruel&Kjaer Pulse vibration analysis platform [17]. The vibration signal FFT analysis was performed using the Pulse platform proprietary routine at 6400 line resolution for the investigated 0-1kHz bandwidth. The air-gap and shaft torque FFT measurements were performed for the identical bandwidth with the resolution of ≈ 0.1 Hz.

III. ELECTROMAGNETIC TORQUE SIGNAL

This work builds on the analysis presented in [11] and considers a three-phase four-pole wound rotor induction machine. The air-gap of the wound rotor induction machine contains the following rotating magnetic fields [11]:

- stator-driven fields produced by the stator excitation;
- rotor-driven fields produced by currents induced in the rotor.

The respective angular speeds of the two air-gap fields can be expressed in the stator reference frame as [11]:

$$\omega = 2\pi f \quad (1)$$

$$\omega_i = (1 + \frac{v-\mu}{p}(1-s))2\pi f \quad (2)$$

where: f is the supply fundamental frequency, s is the fractional slip, p is the number of pole-pairs and v and μ are the field harmonic pole numbers relating to the stator and rotor windings and excitation, respectively. A general case is considered initially where v and μ can take any integer value.

The interaction of any two stator and rotor driven magnetic fields with identical pole numbers will establish an electromagnetic torque signal frequency. The torque angular frequency established by two fields with identical pole numbers travelling in the same direction is given by the absolute value of the relative difference between their respective angular speeds, i.e. $|\omega - \omega_i|$ (3). Similarly, for identical pole number fields travelling in opposite directions, the resulting torque angular frequency will be given by the absolute value of the sum of the individual field angular velocities, i.e. $|\omega + \omega_i|$ (4).

A single frequency excited stator three-phase winding system will give rise to a range of air gap-fields with pole numbers v determined by the existing stator windings and supply arrangement. Each individual stator current driven harmonic field will induce emf in the rotor three-phase windings, and each of these can in turn create a range of fields in the stator reference frame at frequencies given by (2) and with pole numbers μ defined by the rotor winding arrangements [11]. Consequently, every stator driven field

Fig. 2. Stator and rotor air-gap fields for unbalanced operation

with pole number v at frequency given by (1) can interact with the range of air-gap fields with identical pole numbers rotating at frequencies given by (2) and created by the induced rotor currents. The resulting electromagnetic torque signal angular frequencies can then be established directly from expressions in (1) and (2) by investigating the healthy and introducing appropriate constraints for possible values of μ and v . This analysis neglects the effects of supply higher order harmonics which will be investigated separately. The presented derivations also neglect the influence of the machine mechanical system on the torque signal spectrum. This work assumes an unbalanced stator/grid supply as is generally the case for on-line operating machines.

Torque frequencies can now be derived for the operating conditions investigated in this work.

A. Balanced windings and unbalanced supply

When operating with an unbalanced stator supply, for each harmonic order of the machine stator field there will exist a forward and a backward rotating field component. These will in turn give rise to forward and backward rotating components of the rotor driven fields, respectively, resulting in a range of magnetic fields in the air-gap traveling in the same and opposite directions at speeds $\omega^+, \omega^-, \omega_i^+$ and ω_i^- . The air-gap rotating fields for these operating conditions are illustrated in Fig. 2. For unbalanced supply conditions the pole numbers μ and v will have the form: $\mu = \pm p(1 - 6m)$ and $v = \pm p(1 - 6n)$, where $m, n = 0, \pm 1, \pm 2, \pm 3...$ Substituting these constraints into (2) and considering (3) and (4), the possible torque angular frequencies for machine operation with unbalanced supply and balanced windings are derived from the following interactions of air-gap fields:

$$|\omega^+ - \omega_i^+|; |\omega^+ + \omega_i^-|; |\omega^- - \omega_i^-|; |\omega^- + \omega_i^+|, \quad (5)$$

yielding the expressions:

$$|6k(1-s)|2\pi f \text{ and } |2 \pm 6k(1-s)|2\pi f, \quad (6)$$

where $k=0,1,2,3...$

B. Unbalanced windings and supply

A winding fault will give rise to air-gap field components identical to those discussed in section III.A and shown in Fig. 2, however the open-circuit faults in Fig. 1 considered here will induce a severe air-gap field distortion resulting in the loss of field half-cycle symmetry and periodicity over the pole-pair pitch as shown in [18]. The harmonic effects of this field distortion are profound and result in the presence of all harmonic orders over the air-gap perimeter of the analyzed four pole machine [18].

Consequently, μ and ν will take a different form to III.A and in this case all pole values can be assumed to be possible, i.e. $\mu, \nu = \pm 1, \pm 2, \pm 3, \dots$. A general expression can therefore be derived, by substituting the above condition into (2) and evaluating the field interactions given by (5) resulting in the expressions for torque angular frequencies for a machine operating with an open-circuit winding fault:

$$\left| \frac{k}{p}(1-s) \right| 2\pi f \text{ and } \left| 2 \pm \frac{k}{p}(1-s) \right| 2\pi f, \quad (7)$$

where $k=0, 1, 2, 3, \dots$. Expressions in (7) are derived under the assumption that all fault induced harmonic fields will be equally manifested in the air-gap and gives all possible frequencies in the torque signal that can originate from the considered faulty conditions. However, not all frequencies given by (7) will necessarily be detectable or present in the torque signal, as how each of these is manifested will be highly dependent on a particular machine winding layout design and how it responds to the fault induced air-gap field distortion.

The derived expressions for possible torque signal frequencies under the investigated operating conditions are summarized in Table 1.

IV. TORQUE SIGNAL MODEL STUDY

A model study was undertaken to investigate the spectral content of the electromagnetic torque signal for the laboratory wound-rotor induction machine under healthy and faulty winding operating conditions. An arbitrarily chosen super-synchronous operating speed of 1590rpm was simulated in the calculations. The simulations also assume a stator excitation unbalance representative of that found in the laboratory grid supply. Model results for the electromagnetic torque were analyzed in a bandwidth of 1kHz with a 2^{13} data point resolution. It is important to point out that the model calculations [10] neglect any time-varying interactions between electromagnetic torque and the machine mechanical system (inherent rotor and/or shaft unbalance, natural/resonant frequencies etc.) and therefore any pulsating torque damping or excitation that may result from these.

Machine operation with balanced windings and unbalanced supply was first simulated and model predictions for the steady-state torque signal spectrum are shown in Fig. 3. The presented data indicate that in addition to a clearly defined DC torque component there exist a range of significant torque pulsations at 100Hz , 218Hz , 318Hz , 418Hz , 536Hz , 636Hz , 736Hz , 854Hz and 954Hz .

TABLE I
ELECTROMAGNETIC TORQUE SIGNAL FREQUENCIES

WINDINGS	SUPPLY	TORQUE FREQUENCIES
BALANCED	UNBALANCED	$ 6k(1-s) f$ $ 2 \pm 6k(1-s) f$
UNBALANCED	UNBALANCED	$\left \frac{k}{p}(1-s) \right f$ $\left 2 \pm \frac{k}{p}(1-s) \right f$

Model predictions for the torque spectrum when the machine is operating with an open-circuit winding fault, shown in Fig. 1b, and an unbalanced supply are presented in Fig. 4. The data shows that the presence of stator open-circuit fault gives rise to additional fault-specific components in the torque spectrum at the following frequencies: 59Hz , 159Hz , 259Hz , 377Hz , 477Hz , 577Hz , 695Hz , 795Hz and 895Hz . Torque spectrum predictions for machine operation with multiple winding faults from Fig. 1c are presented in Fig. 5. The data confirm that the previously observed fault-specific components in the torque spectrum remain and no new frequencies are produced. The data also indicate that the magnitudes of a number of identified frequency components are directly linked to the fault severity.

The pulsating torques identified in the model study results in Figs. 3-5 can be calculated for the corresponding operating conditions using the appropriate closed form expressions in Table I and knowledge of the operating speed and the supply frequency. Table II lists the related equation parameters that yield the numeric values of the observed torque frequencies.

Fig. 3. Predicted torque spectrum for balanced windings and unbalanced supply, 1590rpm

Fig. 4. Predicted torque spectrum for a single stator open-circuit fault and unbalanced supply, 1590rpm

Fig. 5. Predicted torque spectrum for multiple stator open-circuit faults and unbalanced supply, 1590rpm

TABLE II
ELECTROMAGNETIC TORQUE SIGNAL FREQUENCIES AND THEIR
CORRESPONDING CLOSED-FORM EXPRESSION PARAMETERS

Healthy Windings		Winding Fault	
k	Frequency[Hz]	k	Frequency[Hz]
0	100	6	59
1	218	6	159
1	318	6	259
1	418	18	377
2	536	18	477
2	636	18	577
2	736	30	695
3	854	30	795
3	934	30	895

V. TORQUE AND VIBRATION MEASUREMENTS

The analysis in the previous sections indicates that stator winding faults produce torque pulsations at predictable frequencies that can be estimated by analytic expressions. The identified electromagnetic torque pulsations for healthy and faulty conditions will be transferred to the machine shaft but will also be manifested mechanically on the machine frame as vibration. The vibration signal spectrum will therefore carry the same pulsating frequencies as those reported in the torque signal. To verify the observed spectral phenomena, a series of experiments were undertaken on the laboratory test rig during generator on-line operation. The generator was driven at a super-synchronous speed of $1590rpm$ and vibration, shaft-torque, stator voltage and stator current signals recorded in order to directly compare the presented model predictions with corresponding experimental data.

The estimated air-gap torque, obtained from stator voltage and current measurements for the practical condition of unbalanced supply and balanced machine operation is shown in Fig. 6. The frequencies predicted by the model simulation for identical operating conditions in Fig. 3 and calculated using the corresponding closed-form expressions are seen to be present in the experimental results, thus confirming the validity of the approach. There are also additional components in the measured air-gap torque signal which are believed to mostly originate from the supply harmonic effects that this work neglects. The estimated air-gap torque signal does not however account for the mechanical interactions in the system and, more importantly, the estimation principles do not hold for asymmetric machine conditions [19] therefore the measured shaft torque signal is used in further analysis.

The measured vibration and shaft torque signals spectra for machine operation with balanced windings, single open-circuit fault (Fig 1b), and multiple open-circuit faults (Fig. 1c) are shown in Figs. 7-9, respectively. Frequencies of interest corresponding to the previously identified electromagnetic torque signal spectral components are labeled in the graphs. The measured vibration and shaft torque signals data are seen to be in good agreement with the previously observed spectral content patterns in the model air-gap torque predictions. The frequencies present in the model predictions and the estimated air-gap torque spectrum for healthy machine operation with unbalanced supply are clearly observable in the measured healthy machine vibration and shaft torque spectrum for the same operating conditions,

Fig. 6. Estimated torque spectrum for balanced windings and unbalanced supply, $1590rpm$

shown in Fig. 7. The measured vibration and shaft torque data account for the mechanical effects in the machine drivetrain and are therefore significantly noisier than the estimated air-gap torque signal. The fault-specific changes in the electromagnetic torque signal spectrum predicted by the model in Figs. 4 and 5 can also be clearly identified in the measured shaft torque spectra for the same operating conditions shown in Figs. 8 and 9. Winding fault-specific changes in the corresponding vibration signal spectra in Fig. 8 and 9 are seen to be consistent with those observed in the simulated air-gap torque signal and the measured shaft torque. The fault-specific component magnitude dependency on fault severity is illustrated by comparison of the measured vibration and torque spectra in Fig. 8 and Fig. 9, and although clearly manifested for a number of components, it is less pronounced than in the model predictions. The mechanical response of the motor frame, not considered in presented model predictions, is seen to have a moderate damping effect on fault frequencies.

The measured vibration frequencies of interest can be predicted by using the closed form expressions derived in Section III. Minute discrepancies between the numerical data presented in Table II and measured frequencies in Fig. 7-9 are due to an assumed ideal $50Hz$ supply and $1590rpm$ speed while the actual measured values of these two quantities are slightly different and time varying due to inherent supply frequency oscillations and speed measurement precision limitations. The consistency of reported spectral effects was examined for healthy and faulty operating conditions on a number of additional machine steady-state operating points and was found to be satisfactory and in agreement with the previously presented data. The counterpart pulsating torque and vibration frequency components for different steady-state operating speeds were found to follow the relationships to equation parameters set out in Table II.

The measured vibration and shaft torque spectra presented in Figs. 7-9 are seen to be noisy and contain a large number of frequency components. For the purpose of the analysis undertaken in this paper, only the signal spectral frequencies that relate directly to electromagnetic torque spectral components are labeled in the graphs. The identified winding fault specific torque and vibration signals components of interest are clearly defined and are significantly above the noise level in the presented measurements with the shaft torque signal data exhibiting a clearer harmonic signature of fault effects. In addition, a number of components seen in the vibration and shaft torque spectra originate from inherent mechanical

unbalances in the machine rotor/shaft system and are found at frequencies equal to integer multiples of the operating speed. A zoom-in of the measured vibration and shaft torque signal spectra for the machine running at $1590rpm$ and operating with no excitation and on-line with balanced windings or with a single open-circuit fault are presented for a low-frequency narrow bandwidth in Fig. 10 for illustration purposes. The vibration and shaft torque spectrum with no excitation were measured with no current flowing in the windings and the rotor driven at $1590rpm$ by the DC motor. The data in Fig. 10 demonstrate that, for all the considered operating conditions, the spectral components at multiples of the rotational speed can be clearly identified in the measured vibration and shaft torque signals and are interspersed with components originating from the electromagnetic torque signal. The data also

indicate that in comparison with non-excited conditions, a significantly larger number of spectral components can be identified in the vibration and torque signals of an excited machine and it is believed that some of these components arise due to pulsating torques induced by higher order supply harmonics and inherent machine electrical unbalance.

The potential of using the identified fault specific vibration frequencies as fault indicators in a condition monitoring system was evaluated in an experimental load dependency study. A series of vibration signal measurements were taken in uniform steps within the machine rated operating region, i.e. from no load conditions until rated current ($\approx 59A$ stator) was achieved. For each different steady-state load level, three separate vibration measurements were taken for a single stator

Fig. 7. Measured vibration (top), torque (bottom) signals spectrum for machine on-line operation with balanced windings and unbalanced supply, $1590rpm$

Fig. 8. Measured vibration (top), torque (bottom) signals spectrum for machine on-line operation with single stator open-circuit fault, $1590rpm$

Fig. 9. Measured vibration (top), torque (bottom) signal spectrum for machine on-line operation with multiple stator open-circuit faults, 1590rpm

Fig. 10. Measured vibration (top) and torque (bottom) signals spectra for machine operation at 1590rpm

Fig. 11. Measured load dependency of the fault-specific vibration frequencies

open-circuit fault and averaged in order to minimize the sensitivity to variations in the supply. Nine fault specific frequencies were considered in the study, corresponding to the frequency components identified in the analysis in

section III and consistent with the frequency equations parameter data presented in Table II.

The study results are presented in Fig. 11. The data show a general rising trend in fault frequency magnitude

with increasing load. The vibration fault frequencies are also seen to be manifested at different magnitudes for different load levels and not all are present in the spectrum at similar magnitude levels either. The components showing the largest sensitivity to fault at considered load levels are the 2nd, 3rd and 9th fault frequency, as shown in Fig. 11.

VI. CONCLUSIONS

This paper investigates the possibility of winding fault detection in wound rotor induction machines based on vibration signal spectral analysis. The presented experimental data validate the numerical model predictions for the machine electromagnetic torque signal. The presented torque and vibration signals measurements indicate that winding faults result in a range of clearly defined spectral components in the respective signal spectra. Generalized derivations are provided that establish closed-form analytic expressions defining the spectral content of both torque and vibration signals for healthy and faulty operating conditions. This research demonstrates that it is possible to link each identified fault-specific frequency in the examined vibration bandwidth to the machine operating conditions and thus sets a base for real time monitoring of the observed frequencies. Load dependency of the identified fault components was examined and it was shown that not all are manifested equally in the spectrum for different load levels as some components exhibit higher sensitivity to loading. All reported components were however shown to be clearly defined and detectable for the rated operating region of the wound rotor machine investigated in this work.

VII. REFERENCES

- [1] "EU Energy Policy to 2050," The European Wind Energy Association Report, EWEA, March 2011.
- [2] "UpWind: Design Limits and Solutions for Very Large Wind Turbines," The European Wind Energy Association Report, EWEA, March 2011.
- [3] F. Spinato, P. J. Tavner, G. J. W. Van Bussel, E. Koutoulakos, "Reliability of Wind Turbine Subassemblies," *IET Renewable Power Generation*, Vol. 3, Iss. 4, pp. 1-15, 2009.
- [4] M. Wilkinson, B. Hendriks, F. Spinato, E. Gomez, H. Bulacio, J. Roca, P. Tavner, Y. Feng, H. Long, "Methodology and Results of the Reliawind Reliability Field Study," Scientific Proc. European Wind Energy Conference. (EWEC), Warsaw, Poland, March 2010.
- [5] K. Alewine, W. Chen, "Wind Turbine Generator Failure Modes Analysis and Occurrence," Windpower 2010, pp. 1-6, Dallas, Texas, May, 2010.
- [6] K. Alewine, W. Chen, "A review of Electrical Winding Failures in Wind Turbine Generators," Proc. of IEEE Electrical Insulation Conference (EIC) 2011, pp. 392-397, June 2011.
- [7] P. J. Tavner, "Review of Condition Monitoring of Rotating Machines," *IET Renewable Power Generation*, Vol. 2, Iss. 4, pp. 215-247, July 2008.
- [8] W. Li, C. K. Mechefske, "Detection of Induction Motor Faults: A Comparison of Stator Current, Vibration and Acoustic Methods," *Journal of Vibration and Control*, Vol. 12, no. 2, pp. 165-188, Feb. 2006.
- [9] J. S. Hsu, "Monitoring of Defects in Induction Motors Through Air Gap Torque Observation," *IEEE Trans. on Ind. App.*, Vol. 31, Iss. 5, pp. 1016-1021, Sep/Oct 1995.
- [10] S. Djurović, S. Williamson, A. Renfrew, "Dynamic model for Doubly-fed Induction Generators with Unbalanced Excitation, both

With and Without Faults," *IET Electric Power Applications*, Vol. 3, Iss. 3, pp. 171-177, 2009.

- [11] S. Williamson, S. Djurović, "Origins of Stator Current Spectra in DFIGs with Winding Faults and Excitation Asymmetries," Proc. of IEEE IEMDC 2009, pp. 563-570, Miami, USA, 2009.
- [12] A. Yazidi, H. Henao, G.A. Capolino, F. Betin, "Rotor Inter-turn Short Circuit Fault Detection in Wound Rotor Induction Machines," Proc. of IEEE ICEM 2010, pp. 1-6, Rome, Italy, 2010.
- [13] D. Shah, S. Nandi, P. Neti, "Stator Inter-Turn Fault Detection Of Doubly-Fed Induction Generators Using Rotor Current and Search Coil Voltage Signature," *IEEE Trans. on Ind. App.*, Vol. 45, Iss. 5, pp. 1831-1842, 2009.
- [14] C. J. Crabtree, "Survey of Commercially Available Condition Monitoring Systems for Wind Turbines", SuperGen Wind Energy Technologies Consortium, November 2010.
- [15] S. Djurović, S. Williamson, "Influence of Supply Harmonic Voltages on DFIG stator Current and Power Spectrum," Proc. of IEEE ICEM 2010, pp. 1-6, Rome, Italy, 2010.
- [16] R. C. Healey, S. Lesley, S. Williamson, and P. R. Palmer, "The measurement of transient electromagnetic torque in high performance electrical drives," Proc. of 6th Int. Conf. on Power Elec. and Variable Speed Drives, Nottingham, UK, 1996, pp. 226-229.
- [17] <http://www.bksv.com>
- [18] P. Tuohy, S. Djurović, A.C. Smith, "Finite element analysis of winding fault effects in a wound rotor induction machine with experimental validation," Proc. of IET PEMD 2012, pp. 1-6, Bristol, UK, 2012.
- [19] J. S. Hsu, H. H. Woodson, and W. F. Weldon, "Possible errors in measurement of air-gap torque pulsations of induction motors", *IEEE Trans. Energy Conversion*, vol. 7, pp.202 -208 1992.

VIII. BIOGRAPHIES

Siniša Djurović (M'07) received his Dipl. Ing. degree in Electrical Engineering from University of Montenegro in 2002 and his Ph.D. degree from The University of Manchester in 2007.

Dr. Djurović is currently a Lecturer in the School of Electrical and Electronic Engineering at The University of Manchester, UK. His current research interests are in the area of induction machine modelling and fault analysis, condition monitoring of machines and application of electrical machines in renewable generation systems.

Alexander C. Smith (M'89–SM'02) received the B.Sc.Eng. and Ph.D. degrees from Aberdeen University, Aberdeen, U.K., in 1977 and 1980, respectively.

He has had academic appointments at Imperial College, London, U.K. (1983–1990), and at the University of Cambridge, Cambridge, U.K. (1990–1997). In 1997, he joined Invensys Brook Crompton as Head of Research responsible for motor technology. Since 2000, he has been with The University of Manchester (formerly UMIST), Manchester, U.K., where he has been a Professor of electrical machines in the School of Electrical and Electronic Engineering since 2007. He has been the Director of the Rolls-Royce University Technology Centre on Electrical Systems for Extreme Environments, The University of Manchester, since 2004. His research interests include design and modelling of motors, generators, and drives. He is currently Editor-in-Chief of the IET journal *Electrical Systems in Transportation*.

Prof. Smith is a Fellow of the Institute of Engineering and Technology (formerly IEE) and past Chairman of the IEE Professional Network—Power Conversion and Applications.

Damian S. Vilchis-Rodriguez graduated from the Universidad Autonoma del Estado de Morelos in 1992 and gained his PhD degree from University of Glasgow, UK in 2010. He worked as a power quality consultant in Mexico for the period 1993-2004.

Dr. Vilchis-Rodriguez is currently a Research Associate in the Power Conversion Group at the University of Manchester, UK. His current research interests include electrical machines, condition monitoring, power systems dynamic simulation and embedded generation.