A coupled-circuit Model for a DFIG operating under unbalanced conditions

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Abstract-**The paper describes a time-stepped coupled-circuit model for a doubly-fed induction generator. The model, which is based on the summation of the harmonic winding inductances, is capable of representing both open- and short-circuit stator and rotor winding faults. The main purpose of this paper is to present evidence of the validity of this versatile and powerful technique and the advantages it offers when used for modeling and analysis of doubly-fed induction generator operation in unbalanced conditions.**

I. INTRODUCTION

One of the most commonly used types of machines in present day wind power generation is the doubly-fed induction generator (DFIG). In combination with power electronics in the rotor circuit, DFIGs offer significant advantages over other generating systems, primarily due to their ability to generate power at a speed that varies depending on the wind characteristic of the particular site while keeping the output frequency constant. As DFIGs are an essential part of typically isolated and remote wind power plants, having a competent condition monitoring system would significantly contribute to increasing the plant productivity and cutting down the cost of operation and maintenance.

The analysis of the machine primary current frequency content is an established means of dealing with induction machine asymmetry detection and is now recognized as a procedure that yields possible fault specific characteristics [1,2,3]. An effective condition monitoring technique may therefore be developed by investigating DFIG behaviour and identifying the means for discrimination between normal and fault conditions through examining the input current frequency content and identifying potential fault specific harmonic components. For this investigation to be achieved it is necessary to be capable of performing a detailed time/frequency domain analysis of machine behaviour under various healthy and faulty operating conditions. This requires an adequate dynamic machine model.

The *d-q* model based on two-axis theory is generally accepted as a means for dynamic DFIG analysis [4,5]. However it accounts for the fundamental m.m.f component only and assumes sinusoidally distributed windings, and is therefore not fully appropriate for the analysis of an arbitrarily connected machine in which asymmetries are present. This paper describes a novel DFIG dynamic model that is based on a coupled-circuit approach. The model facilitates dynamic analysis of a DFIG operating under arbitrary conditions, such as supply voltage unbalance and/or winding asymmetries. When frequency domain analysis of machine quantities is concerned the model is shown to offer a significant advantage over traditionally used two-axis approach. The procedure necessary to realize the proposed model, along with some typical model and experimental results is presented in this paper.

II. MODEL

A. Model Description

The DFIG model in this work is based on a coupled-circuit approach. Here a machine is analyzed as a system of magnetically coupled circuits, where a circuit is defined as any series connection of coils. Since the individual current carrying circuits within the machine can be clearly identified the proposed technique is particularly suitable for the analysis of DFIG operation with winding and/or supply asymmetries. The EMF induced in any machine circuit as the result of the currents flowing in other circuits is calculated using a technique based on the concept of complex conductor distributions and generalised harmonic analysis [6], and in this manner the harmonic circuit inductances are calculated. The total circuit inductance due to air-gap flux is established by summing a series of its harmonic components. Coupling inductances that link stator and rotor circuits are dependant on the angular orientation of the rotor and are calculated in real time from machine geometry data, conductor configuration and the rotor angle. Other machine parameters, such as resistances and leakage inductances, are evaluated using conventional methods described in more detail in [7].

B. Model Equations and Solving

Machine voltage and flux linkage equations in matrix form are given by:

$$\boldsymbol{V} = \boldsymbol{R}\boldsymbol{I} + \frac{d\boldsymbol{\psi}}{dt} \tag{1}$$

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$$\boldsymbol{\psi} = \boldsymbol{L}\boldsymbol{I} \tag{2}$$

where: $\boldsymbol{V}$ is the machine applied voltages matrix, $\boldsymbol{I}$ is the machine current matrix, $\boldsymbol{\psi}$ is the machine flux linkage matrix, $\boldsymbol{R}$ is the machine resistance matrix and $\boldsymbol{L}$ is the machine inductance matrix. Additionally, the machine torque balance equation is:

$$T_e - T_{LOAD} = J\frac{d\omega}{dt} \tag{3}$$

where

$$\omega = \frac{d\theta}{dt} \tag{4}$$

$$T_e = \frac{1}{2}\boldsymbol{I}^T\frac{d\boldsymbol{L}}{d\theta}\boldsymbol{I} \tag{5}$$

In (3-5): T_e is the machine electromagnetic torque, T_{LOAD} is the machine load torque including friction and windage losses, J is the effective inertia of the rotating parts, ω is the rotor mechanical speed and θ is the rotor mechanical angle. The mathematical model used in this work is defined by the set of equations given in (1-5). These equations may be used to model an arbitrary *n*-circuit machine, where the dimensions of the mathematical system are directly proportional to the total number of machine primary and secondary circuits.

Circuits within the machine are mutually interconnected forming loops and the voltage applied to each circuit is not usually known. It is therefore necessary to transform the model equations from circuit to loop variables, expressing the excitation in terms of the specified line voltages. This is achieved using the connection matrix method [8]. Model equations may now be solved for currents, speed, torque etc. in a time stepping numerical procedure. Reaching a steady state solution in the model typically requires several numerical transients. The model inputs that need to be defined are the line voltages, the load torque and the effective inertia.

A more detailed description of the methods employed for parameter estimation in this model and the solution procedure can be found in [7].

III. TEST RIG

A test rig was constructed for the purpose of experimental verification of the model predictions. The rig is designed to make it possible to simulate DFIG operation at various speeds and loading conditions. It consists of a 30kW DFIG that is mechanically coupled to a DC motor, which drives the DFIG as a generator. The DC motor is driven by an industrial drive system using encoder speed feedback. The DFIG rotor circuit back-to-back converter consists of two four-quadrant PWM converter units coupled by a DC link. The power flow through the rotor circuit is bi-directional, with the converter providing the appropriate excitation for the DFIG rotor circuit, depending on the generator operating regime that is desired. The test machine stator was specially wound to enable the investigators to switch between various balanced/unbalanced stator winding configurations. This was achieved by bringing the ends of each coil group and several other points of interest from the stator winding out to an external terminal box, where they can be connected to achieve the desired configuration. Machine currents, voltages and power were measured using LEM NORMA power analyzers, where total phase RMS values were measured on the primary and fundamental of the PWM line quantities on the secondary side. The torque on the shaft is measured using an in-line torque transducer and the machine speed is obtained from a stub shaft mounted incremental encoder. The test rig block diagram is shown in Fig. 1.

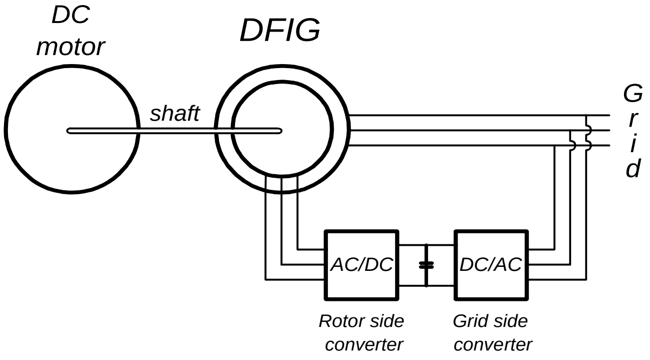


Fig.1 Test Rig block diagram

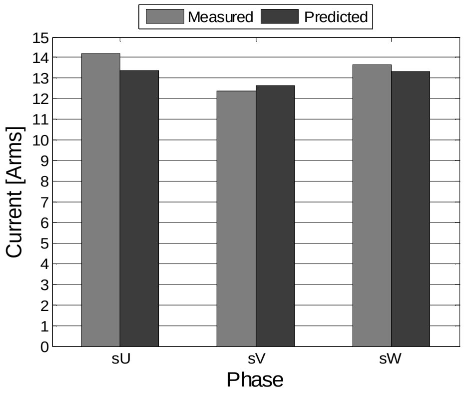
IV. SIMULATION AND EXPERIMENTAL RESULTS

A. DFIG Operation with Balanced Windings

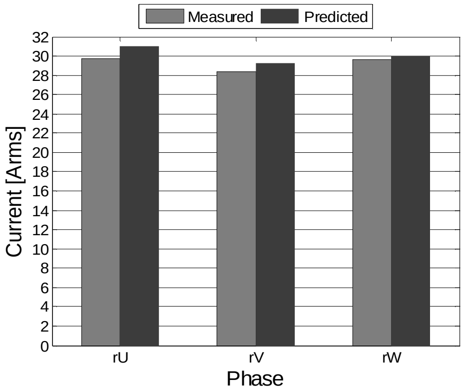
Measured current values are compared with model predictions for a series of experimentally achieved DFIG operating points in [7] as a means of demonstrating the model's capabilities. In addition to these and for the sake of completeness a comparison between measured and predicted stator and rotor current values for a DFIG operating at a speed of *1684 rpm* and with balanced windings is shown in Fig. 2. The test conditions were replicated in the model by using the measured line voltages and load torque values as data inputs to the model. The results show good agreement between model predictions and experimental data. The supply unbalances present during the test are taken into account in the model and their effect on machine currents is reflected in the simulation results.

B. DFIG Operation with a Stator Open-Circuit Fault

The results in Fig. 2 were obtained with the stator windings connected in star, with two parallel paths per phase, as shown in Fig. 3a. A typical stator winding asymmetry is introduced into both the test rig and the model by open-circuiting one of the parallels in a phase, as shown in Fig. 3b.



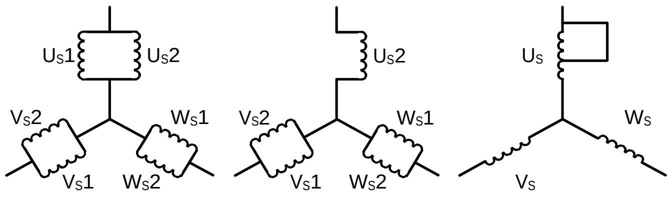
a) Stator currents



b) Rotor Currents

Fig. 2 Predicted and Measured current values for a DFIG operating at *1684 rpm* with balanced windings

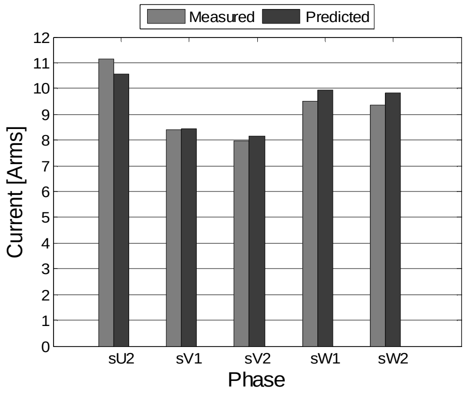
As with previous tests, machine voltages were measured during the experiment and then used as a data input for the numerical model. The comparison of current values measured for all stator groups and rotor phases against their corresponding predicted values and for a DFIG operating at *1556 rpm* is given in Fig. 4a-b, respectively.



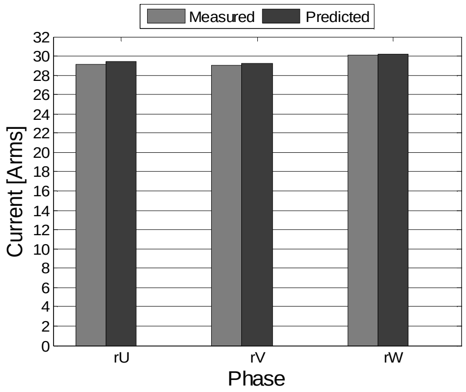
a) Healthy b) Stator open-circuit c) Stator short-circuit

Fig. 3 DFIG stator winding configuration

The faulty DFIG current measurements and model predictions are shown to be in good agreement. The results exhibit a fair degree of unbalance between different stator winding group currents. While some of the existing current unbalance results partly from that present in the laboratory grid supply, the pronounced unbalance seen here is in most part the effect of the existence of an open-circuit fault. The data presented provide a further evidence of the validity of the model and its ability to represent the operation of a DFIG with winding asymmetries.



a) Stator currents



b) Rotor Currents

Fig. 4 Predicted and Measured current values for a DFIG operating at *1556 rpm* with stator open-circuit fault

V. THE EFFECT OF HIGHER ORDER FIELD HARMONICS ON MODEL PREDICTIONS

A. Model Predictions for Currents and Joule Losses

The model outlined in this paper is based on generalized harmonic analysis in which machine inductances are evaluated on a harmonic-by-harmonic basis. This approach allows for the investigation of the number of space-harmonic fields accounted for in the calculations. In order to investigate the effect that the number of space harmonics has on model accuracy a study was undertaken where three different cases were analyzed:

Model 1. In the first case studied the higher order harmonics are taken into account when evaluating coupling inductances between all circuits within the machine;

Model 2. For the second case the evaluation of primary to secondary coupling is limited to considering the fundamental only while higher order harmonics are accounted for in all other stator-to-stator and rotor-to-rotor coupling;

Model 3. Finally, in the third case all coupling inductances within the machine are evaluated with the model calculations limited to taking into account the fundamentally-distributed field only.

TABLE I
NUMBER OD SPACE-HARMONIC FIELDS ACCOUNTED FOR IN THE MODEL CALCULATIONS FOR THE CASES ANALYZED

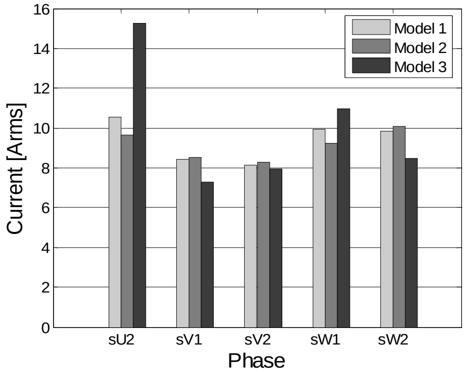
Harmonics considered	Coupling	
	Stator/Stator Rotor/Rotor	Stator/Rotor
Model 1	All harmonics	All harmonics
Model 2	All harmonics	Fundamental only
Model 3	Fundamental only	Fundamental only

The three cases considered are summarized by the number of harmonic fields accounted for in the calculations in Table I. The first case considered in the study was used for generating model results presented previously in this paper and is thus already proven to be of dependable accuracy. It may therefore be taken as a reference point, for the accuracy of the two other cases to be compared against. The DFIG operating conditions modeled in the study are for an open-circuit stator fault operating point already discussed in section *IVB*. A faulty operating condition was chosen because the authors found that the presence of winding asymmetry considerably intensifies the effect that the number of harmonic inductances accounted for has on model predictions. Model results are shown for machine currents in Fig. 5 where the corresponding data for the three cases examined is labeled with Model 1, Model 2 and Model 3 in the graphs, respectively.

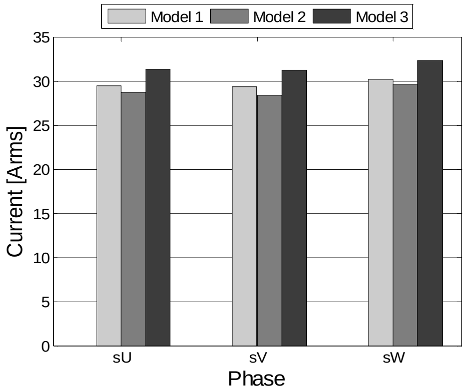
The study results clearly show that there are differences in model predictions for the three cases considered, and consequently that these are directly related to the number of inductance harmonics considered in the calculations. The difference in predicted current values is more evident on the primary side which is where the open-circuit fault is located. The comparison of results for cases *1* and *2* demonstrates that when limiting the stator to rotor coupling inductance calculations in the model to fundamental only, a change in the value of predicted currents can be expected. However the magnitude of this variation is not very significant. The accuracy loss is nevertheless much more apparent in the case where evaluation of all coupling inductances in the model is limited to fundamental only, as is seen in the data labeled Model 3 in the graphs. This is especially noticeable in the results for the faulty phase current. When rotor current predictions are concerned the model projections variation for the cases analyzed is more uniform and the results exhibit a relatively significant increase in predicted values for Model 3, while Model 1 and Model 2 are reasonably consistent. In addition to the results presented the model predictions for stator and rotor total Joule loss for the three cases analyzed are given in Table II. This data further substantiate that the model accuracy is most affected in the case when only the fundamental harmonic value of all coupling inductances is considered in the calculations. Again, it can be seen that accuracy loss is less significant when solely the primary-to-secondary coupling calculations are limited to accounting for fundamental only.

TABLE II
MODEL PREDICTIONS FOR TOTAL STATOR AND ROTOR JOULE LOSSES FOR A DFIG OPERATING AT *1684RPM* WITH STATOR OPEN-CIRCUIT FAULT

Joule Losses	STATOR		ROTOR	
	PREDICTED	PERCENTAGE INCREASE	PREDICTED	PERCENTAGE INCREASE
case 1	80.13	--	175.14	--
case 2	75.86	-5.6%	166.69	-5.1%
case 3	97.32	+21.4%	199.85	+15.7



a) Stator currents



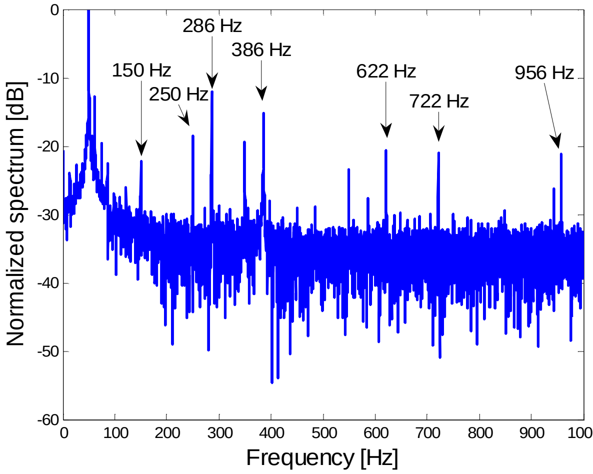
b) Rotor Currents

Fig. 5 Predicted current values for a DFIG operating at *1684 rpm* with stator open-circuit fault

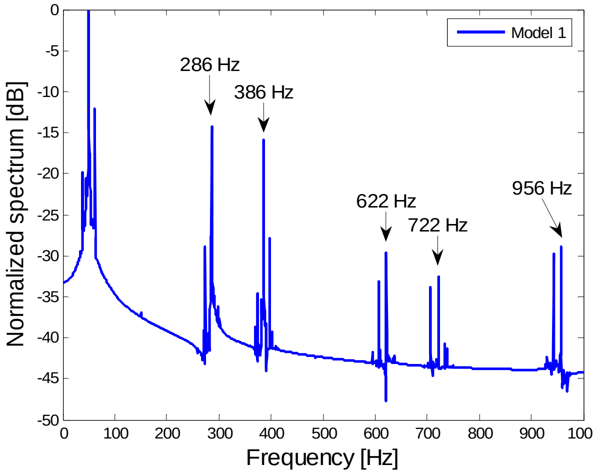
The data presented in this section demonstrates that modeling the existence of higher order air-gap field space harmonics is necessary if accurate analysis of DFIG operation with winding asymmetry is to be achieved. Through comparison of experimental data against model predictions it was shown that the proposed model is capable of replicating these effects and credibly predicting DFIG operation where winding and excitation asymmetries exist.

B. Frequency Content of Predicted DFIG Current

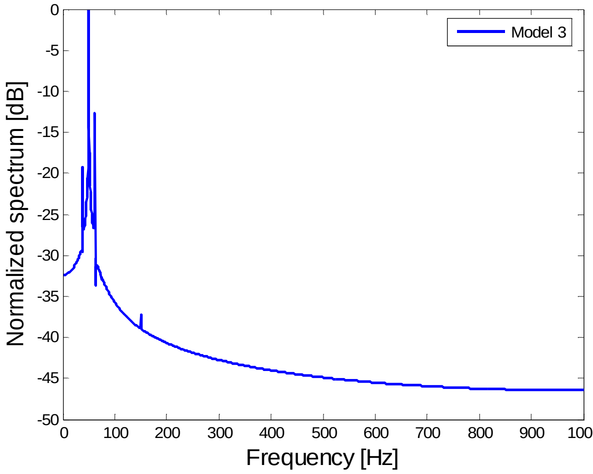
The credibility of frequency domain analysis is reliant on being capable of reliably predicting the existence of various slot harmonic components in the current spectra, as the appearance of some of these may potentially be linked to a particular unbalanced operating condition and may be used as a fault indicator. The model presented in this paper is primarily designed to be used for frequency domain analysis of machine quantities and it is here that it demonstrates its capabilities fully. A typical set of experimental and model results for a



a) Spectrum of experimental stator currents for a healthy DFIG

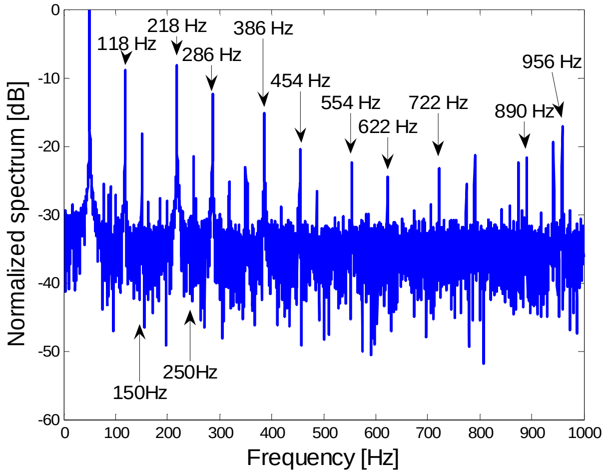


b) Spectrum of predicted stator currents for a healthy DFIG, *Model 1*

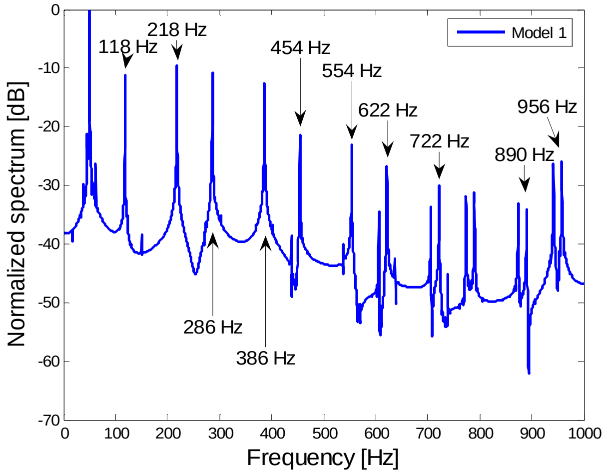


c) Spectrum of predicted stator currents for a healthy DFIG, *Model 3*

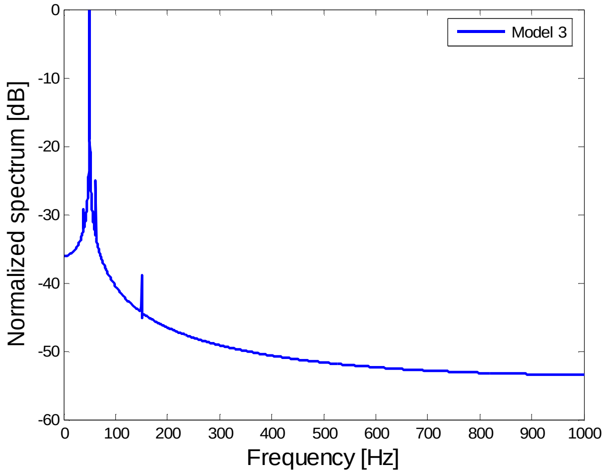
Fig. 5 Measured and predicted DFIG stator current spectra. *1684 rpm*



a) Spectrum of experimental stator currents for a healthy DFIG



b) Spectrum of predicted stator currents for a DFIG operating with stator short-circuit fault, *Model 1*



c) Spectrum of predicted stator currents for a DFIG operating with stator short-circuit fault, *Model 3*

Fig. 6 Measured and predicted DFIG stator current spectra. *1684 rpm*

DFIG stator line current frequency spectrum is given in Fig. 5a and 5b, respectively. Higher order field harmonics were taken into account when estimating all coupling inductances in the model calculations. Results shown are for a healthy DFIG with unbalanced supply and operating at *1684 rpm*, corresponding to the time domain data shown in Fig. 2a. The test machine current frequency spectrum was obtained by sampling the machine currents using a precision digital scope and then importing the measured data into MATLAB and processing it using the Fast Fourier Transform (FFT) tool. The same tool was used for frequency analysis of the predicted current data. All the results are normalized with respect to the fundamental component. The data shown exhibit good agreement between predictions and measurements when it comes to the slot harmonic component content in the spectra and thus verify the model predictions in frequency domain. The most dominant components are labeled in the graphs and can clearly be distinguished in both experimental and model results. The model calculations differ from measured data in predicting the existence of harmonic components that arise due to magnetic saturation (multiples of line frequency) and the general noise level, since saturation and rotor PWM excitation are not taken into account in the model considerations. This is discussed in detail in [7]. In addition to the data presented, model results for stator line current FFT spectrum and the same DFIG operating point where only the fundamental coupling inductance is accounted for in the calculations is shown in Fig. 5c. There is an obvious difference in the frequency spectrum content between these and model predictions given in Fig. 5b. The slot harmonic components found in the model predictions in Fig. 5b are not present in the calculated current spectra in Fig. 5c. This difference is directly related to the various number of harmonics considered in the model calculations when generating these results. The results show that, when frequency domain analysis of machine currents is concerned, there is a significant advantage to be gained from incorporating the existence of higher order field harmonics in the model considerations. This is especially noticeable when analyzing DFIG operation where a winding asymmetry is present. Model and experimental results are shown in Fig. 6 for a DFIG operating at *1684* rpm with a stator winding short-circuit fault configuration from Fig. 3c. The machine parameters measured on the laboratory test rig during short-circuit fault experiments were used as data inputs to the numerical model. The destructive nature of short circuit fault due to high current was eliminated in the experiments by limiting the short circuit current. This was achieved by using variable resistors in the short circuit path, and is taken into account in the model by setting the short circuit branch resistance to the same value as the one used in the experiments ($\approx 1\Omega$). The experimental and model results presented in Fig. 6 are for a short circuit current limited to *30A*. It can be seen that the differences between model and experimental results are consistent with the ones commented upon previously for the data shown in Fig. 5. Similarly to before two different scenarios are considered, where first the higher order harmonics and then only the fundamental are accounted for in the model calculations. Again, the benefits of modeling higher order harmonics are clearly evident, with the results in Fig. 6b showing a current spectrum rich in harmonic components. Comparison with results shown in Fig. 5c demonstrates that, when limited to fundamental only, model calculations fail to predict the existence of harmonic components of interest. An additional dimension is given to this study by the fact that the *d-q* model, a traditionally used tool for DFIG dynamic analysis, is, similarly to results presented where fundamental only is considered in the calculations, limited when it comes to modeling the effects of higher order field harmonics. The time domain analysis of unbalanced DFIG operating conditions based on the two-axis method would therefore suffer the drawback of decreased accuracy as was pointed out previously. The frequency domain analysis will in this case yield only the harmonic components that result from the interaction of primary and secondary field fundamentals. This may represent a handicap from the perspective of the model usability for developing frequency domain based condition monitoring techniques.

VI. CONCLUSIONS

A detailed analytical model is developed in this work where higher order field harmonics are taken into account in model calculations. The proposed technique is capable of modeling any supply and/or machine winding unbalance and is verified through comparison of model predictions against experimental data. The study presented outlines the importance of considering the influence that the higher order field harmonics have on machine operation and sets a robust base for further in-depth analysis of the effects that various asymmetries have on DFIG operation.

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