

Losses and Pulsating Torques in DFIGs with Unbalanced Stator and Rotor Excitation

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Abstract—This paper explores the operation of doubly fed induction generator (DFIG) under unbalanced supply conditions. Supply unbalance generally has a negative effect on induction machine operation, resulting in increased Joule loss and pulsating torques. The aim of this work is to quantify the effect that stator and/or rotor supply unbalance has on these aspects of DFIG performance.

I. INTRODUCTION

DOUBLY-FED induction machines continue to be the industry standard for wind generators, largely because power conditioning electronics are not required in the high power link between the stator and the grid. Like most machines, DFIGs are susceptible to unbalanced supply conditions, which result in unbalanced currents and excess Joule loss which reduce machine efficiency. Stator supply unbalance also gives rise to twice line-frequency torque pulsations which may cause mechanical damage to gearboxes and turbine blades and generally have an adverse effect on the wind turbine mechanical drivetrain. Furthermore pronounced asymmetries in the supply voltage can lead to removal of DFIG/turbine system from the grid in accordance with prescribed grid voltage characteristics. Some DFIGs are removed from the grid in the case when phase-to-phase voltage unbalance exceeds a prescribed value of 6% [1]. European/British standards [2] define supply voltage unbalance in terms of the percentage that the ten minute mean r.m.s. fundamental negative sequence component constitutes in the ten minute mean r.m.s. fundamental positive sequence component of supply voltage during a period of one week and set this limit to up to 3%. The UK national grid code [3] sets the limit for a maximum voltage unbalance at up to 2% at the transmission system level. These prescribed limits vary depending on the "plant or apparatus" operating voltage and the above values help in understanding what is typically perceived and defined as a supply unbalance. The fact that wind turbines are typically connected to weak grids in remote areas further intensifies the presence of supply unbalance in DFIGs.

In addition, recent trends [4,5] indicate that modern grid codes now require wind turbine systems to be able to ride through unbalanced supply conditions of operation in order

to improve grid stability. Maintaining DFIGs operational thus calls for improvements in DFIG control and in recent years several authors have devised control schemes which seek to reduce the undesired effects of unbalanced supply [1,6,7]. The work reported in literature regarding the effects of voltage unbalance in wind power generation is mainly focused on traditional induction generators and stator supply asymmetry [8,9]. However with DFIGs being the most ubiquitous type of generator in contemporary wind power applications there is a need for the analysis of their behaviour under unbalanced supply conditions. This paper presents such an analysis for steady-state DFIG operation, which is not confined to investigating the effects of stator supply unbalances only, but examines the effects of rotor supply asymmetry as well. Here attention is focused on the DFIG additional losses and pulsating torques that are introduced by unbalance in the stator and/or rotor supply with the aim of identifying the effects that these have on machine operation. The simulation and experimental results presented clearly show the existence of harmonic components in the generator torque signal that can be linked with stator and rotor supply unbalance.

II. MODEL

The behaviour of wound-rotor machines, such as DFIGs, may readily be analysed using a time-stepped coupled-circuit model. The data inputs to such a model include the self and mutual inductances of all machine windings as a function of rotor position, and it is upon the evaluation of these inductances that the accuracy of the whole simulation depends. The resulting set of circuit equations has the form

$$\mathbf{V} = \mathbf{R}\mathbf{I} + \frac{d\boldsymbol{\psi}}{dt} \quad (1)$$

and

$$\boldsymbol{\psi} = \mathbf{L}\mathbf{I} \quad (2)$$

where: \mathbf{V} - Vector of applied circuit voltages, \mathbf{R} - Circuit resistance matrix, \mathbf{I} - Circuit current vector, $\boldsymbol{\psi}$ - Flux linkage matrix and \mathbf{L} - Circuit inductance matrix. The mechanical behavior of the machine is governed by:

$$T_e - T_{MECH} = T_{F\&W} + J \frac{d\omega}{dt} \quad (3)$$

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$$\omega = \frac{d\theta}{dt} \quad (4)$$

$$T_e = \frac{1}{2} \mathbf{I}^T \frac{d\mathbf{L}}{d\theta} \mathbf{I} \quad (5)$$

where

- T_{MECH} externally-applied shaft torque;
- $T_{F\&W}$ friction and windage torque;
- J combined rotor inertia;
- T_e electromagnetic torque;
- ω rotor speed in mechanical radians per second;
- θ angular displacement of the rotor in mechanical radians.

The key to solving (1-5) is the calculation of the inductances, particularly the mutual inductances between stator and rotor windings, which vary with rotor position. One suitable method for accomplishing this is given in [10] which outlines an inductance calculation technique based on the harmonic analysis of conductor distributions. The method is fast, systematic and accurate, and includes the harmonic effects that are neglected in two-axis models which are based on fundamental fields only [11]. In this paper the authors will examine the effect of excitation unbalance under steady-state conditions, although the model developed in [10] is fully capable of simulating dynamic operation.

III. TEST RIG

Model predictions are verified through comparison with experimental results obtained from a purpose built test rig. The laboratory equipment comprises of a 30 kW four pole wound rotor induction machine coupled to a dc motor that

acts as a prime mover. Torque is regulated by means of an industrial dc drive employing an encoder feedback to provide closed-loop control. The induction machine rotor circuit is excited by means of a back-to-back converter which provides the rotor voltage necessary for experimentally achieving DFIG operation in various desired speed regimes. Dynamic measurement of induction generator's electromagnetic torque is achieved through mounting the generator on a highly sensitive commercial force measurement platform with piezo electric transducers, as shown in [12]. The DFIG speed signal is recorded by sampling the output voltage of the shaft mounted precision tachometer generator. DFIG terminal quantities are measured by using two three phase six channel power analyzers, one of which was installed on the primary and the other on the secondary side. Here total RMS values are measured on the stator and the fundamental of the PWM quantities on the rotor side. The DFIG shaft torque dc value is measured by means of an in-line torque transducer.

IV. RESULTS

A. Joule Loss

Table I gives a comparison of the measured and calculated values of total stator and rotor Joule loss for a typical set of DFIG operating points. The results are given for a DFIG operating with a supply unbalance present on both the stator and the rotor, and a series of four operating speeds, two in the super- and the other two in the sub-synchronous speed region. The supply unbalances present on the test rig during measurements were taken into account in the numerical model. The presented results show good agreement between the experimentally measured and predicted data sets thus demonstrating that the model is capable of accurate representation of DFIG behaviour under unbalanced

TABLE I
MODEL PREDICTIONS AND TEST RIG MEASUREMENTS FOR TOTAL STATOR AND ROTOR JOULE LOSS FOR A SET OF TYPICAL DFIG OPERATING POINTS

Operating point	Rotor line voltages [V]	Stator phase voltages [V]	Stator Joule Loss			Rotor Joule Loss		
			MEASURED [W]	PREDICTED [W]	ERROR [%]	MEASURED [W]	PREDICTED [W]	ERROR [%]
$n = 1622 \text{ rpm}$ $f_r = 4 \text{ Hz}$ $T_e = 25.2 \text{ Nm}$	13.7 14.0 13.9	130.5 132.5 131.5	188	183	2.7	164	166	1.2
$n = 1574 \text{ rpm}$ $f_r = 2.4 \text{ Hz}$ $T_e = 31.2 \text{ Nm}$	7.8 8.1 7.9	131.7 133.4 132.6	224	212	5.6	171	167	2.4
$n = 1381 \text{ rpm}$ $f_r = 4 \text{ Hz}$ $T_e = 23.5 \text{ Nm}$	14.0 13.9 14.0	127.6 129.7 129.0	339	315	7.6	42	45	7.1
$n = 1321 \text{ rpm}$ $f_r = 6 \text{ Hz}$ $T_e = 22.0 \text{ Nm}$	19.4 19.5 19.3	128.7 130.6 130.1	745	705	5.6	118	127	7.6

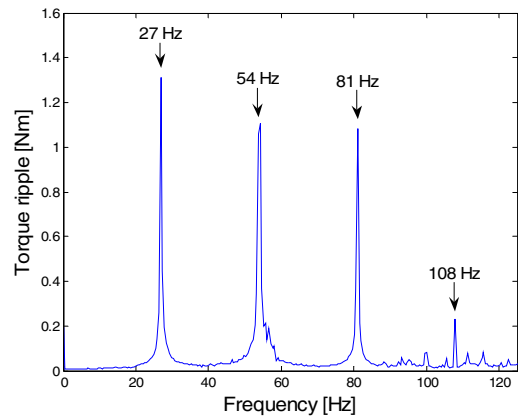
excitation conditions (stator and rotor).

B. Frequency Spectrum Content of Torque and Speed Signal

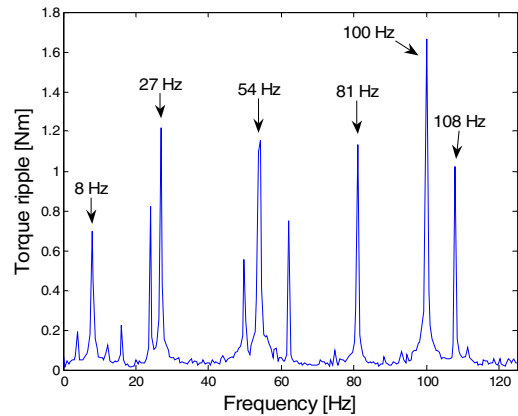
A further validation of the model predictions is obtained from examining and comparing the frequency spectrum content of the measured and calculated DFIG electromagnetic torque and mechanical speed signals. Measurements were conducted for a DFIG operating with balanced stator and rotor windings and asymmetries present in stator and rotor supply voltages. The existing operating conditions during the experimental measurements were simulated by using measured load torque and supply voltage values as model data inputs. Two sets of measurements were performed. For the first set the DFIG stator and rotor windings were open-circuited and the machine rotor was mechanically driven at constant speed using the dc motor; then, while maintaining the same operating speed, the DFIG primary and secondary circuits were appropriately excited and the generator synchronized to the grid and loaded after which the torque and speed measurements were taken. This procedure was followed in order to distinguish between the torque and speed harmonic components that arise from imbalances in the mechanical drive train and the mechanical system construction characteristics and those that originate from the DFIG electromagnetic system.

Speed ripple was measured experimentally by recording the output voltage of a shaft-mounted precision tachogenerator using a digital scope, which enabled the dc component of the generated voltage to be filtered out. Torque ripple measurements were performed using the force measurement platform installed on the test-rig. Measured torque and speed ripple signal data was then imported into MATLAB and processed using the built-in Fast Fourier Transform (FFT) function. The experimental data presented for speed and torque are average values of a series of measurements executed for identical DFIG operating conditions. These measurements were performed for an experimentally achieved mechanical speed of 1622 rpm and a load torque of 21.5 Nm.

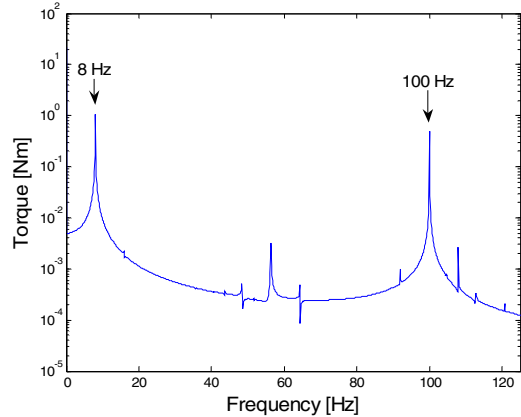
Measured torque ripple frequency content for a DFIG with open-circuited stator and rotor windings and the rotor driven at constant mechanical speed is given in Fig. 1a. The torque ripple spectrum measured under steady state DFIG operation at the same mechanical speed with a torque of 21.5 Nm is shown in Fig. 1b. The operating conditions that pertained when the results shown in Fig. 1a-b were recorded, were then replicated in the model. The predicted DFIG torque spectrum is presented in Fig. 1c. The harmonic components seen to exist in the spectrum on Fig. 1a arise from unbalances in the mechanical system and can be related to the shaft speed. The dominant components, labeled in the spectrum in Fig. 1a, have frequencies which are integer multiples of the fundamental shaft rotating frequency. Comparison with the torque ripple spectrum in Fig. 1b shows that these harmonic components are present in the spectrum at the same frequencies during DFIG operation and the same operating speed, with differences in



a) Measured torque ripple spectrum for DFIG rotor driven by the dc motor, with open-circuited stator and rotor windings



b) Measured DFIG torque ripple spectrum



c) Calculated DFIG torque spectrum

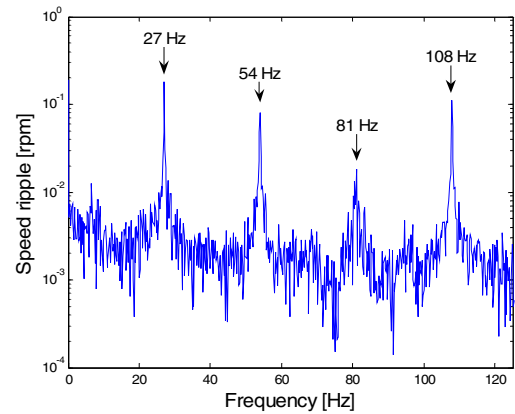
Fig. 1 Measured and predicted DFIG electromagnetic torque spectrum, 1622 rpm

their magnitudes due to different shaft loading conditions. Additionally to these there exist other pulsating torque

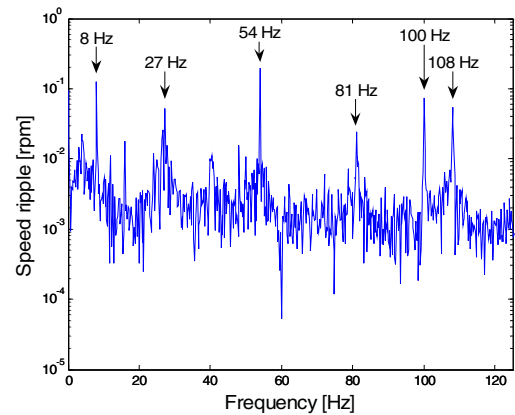
components, most noticeably at 8 Hz and 100 Hz , as indicated on the graph. Reference to the model results for DFIG electromagnetic torque FFT spectrum shown in Fig. 1c indicates that model simulations predict the existence of these two components, but do not yield the mechanical drive train components. This is expected as drivetrain unbalance is not taken into account in the model of the DFIG.

Experimental and model results for speed ripple frequency spectrum are shown in Fig. 2. The experimental data for DFIG operation with open-circuited stator and rotor windings and the rotor mechanically driven at constant speed and for conventional operation are given in Fig. 2a and 2b, respectively. The data in Fig. 2c are the corresponding model results for DFIG speed FFT spectrum. DFIG operating conditions when recording the corresponding experimental data shown in Fig. 1 and Fig. 2 were identical. Results in Fig. 2a show that, analogously to torque ripple data in Fig. 1a, there are harmonic components present in the speed ripple spectrum. The frequencies of these are labeled on the graph and can be correlated to a number of factors such as the steady value of the rotational speed and the number of tachogenerator collector segments. The mechanical drivetrain induced harmonic oscillations appear at frequencies in the speed ripple spectrum that coincide with those of drivetrain induced components found in the torque ripple spectrum for the same operating conditions. The frequencies of these components are integer multiples of the fundamental shaft rotational frequency. The measured steady-state DFIG speed ripple spectrum given in Fig. 2b shows the presence of the same harmonic components, together with addition of harmonic components at 8 Hz and 100 Hz , all of which are labeled in the graph. Model calculations for DFIG mechanical speed spectrum in the same operating conditions, given in Fig. 2c, also indicate the existence of these components but do not predict the presence of drivetrain induced harmonic components due to the fact that mechanical unbalances are not modeled in the theoretical considerations. The harmonic components that appear at 8 Hz and 100 Hz result from the DFIG electromagnetic system, unlike others found in the spectrum that are a consequence of the mechanical characteristic of the DFIG test rig drivetrain. The harmonic components found in the speed and torque spectra in Fig. 1 and Fig. 2 may therefore be summarized by their origin as is shown in Table II.

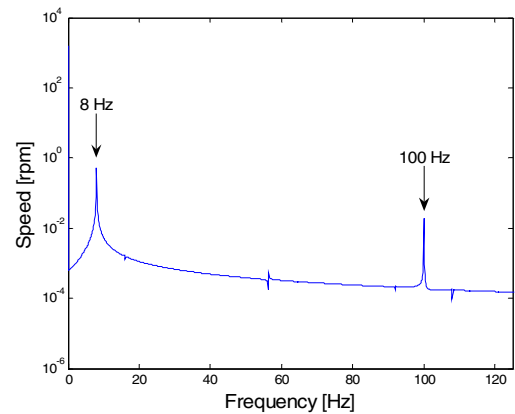
The experimental and measured data presented show good agreement in predicting the existence of harmonic components in the torque and speed signal spectra, which arise from unbalances in the DFIG electromagnetic system. The results of simulation do not exhibit the presence of harmonic components produced by mechanical unbalances in the drivetrain which do not form part of the model. The stated aim of this work is to explore the effects that supply unbalances have on DFIG operation in terms of additional pulsating torques and Joule loss and so the authors believe that the



a) Measured speed ripple spectrum for DFIG rotor driven by the dc motor, with open-circuited stator and rotor windings



b) Measured DFIG speed ripple spectrum



c) Calculated DFIG speed spectrum

Fig. 2 Measured and predicted DFIG mechanical speed spectrum, 1622 rpm

agreement between experiment and calculation is such that they can use their model with confidence to study these effects.

TABLE II
TORQUE AND SPEED RIPPLE HARMONIC COMPONENTS SUMMARIZED BY THEIR
CAUSE FOR AN OPERATING SPEED OF 1622RPM

Harmonic Components		Origin
Torque	Speed	
8 Hz	8 Hz	DFIG
27 Hz	27 Hz	Drivetrain
54 Hz	54 Hz	Drivetrain
81 Hz	81 Hz	Drivetrain
100 Hz	100 Hz	DFIG
108 Hz	108 Hz	Drivetrain

V. SUPPLY UNBALANCE EFFECTS

In order to estimate DFIG losses and torque pulsations that arise from operating under unbalanced supply conditions a study is undertaken in which the effects of primary and secondary supply unbalances were investigated using the numerical model. DFIG operation at an arbitrary operating speed of 1600 rpm with a load torque of 25 Nm and under four different supply voltage unbalance scenarios is modeled. The four cases considered are:

1. balanced stator and rotor supply;
2. unbalanced stator and balanced rotor supply;
3. balanced stator and unbalanced rotor supply;
4. unbalanced stator and rotor supply.

Both stator and rotor windings are assumed to be balanced for the purpose of this investigation. The degree of supply unbalance that is introduced in either or both stator and rotor circuit in the model was set by relating to the European/British standards supply voltage unbalance limit definition [2]. The unbalance used in the study is therefore chosen as one where the fundamental negative sequence component of the supply voltage constitutes 3% of the fundamental positive sequence component.

Table III gives the calculated values for total stator and rotor Joule loss for the cases analyzed which illustrate the effects that supply asymmetries have on the increase of Joule losses in the DFIG. These results indicate that the presence of unbalance in either stator or rotor supply causes a rise in total Joule loss when compared to DFIG operation with balanced excitation. In the case considered in this study where unbalances are present in both primary and secondary excitation, it can be seen that there is a significant rise in Joule loss in both the stator

and the rotor circuit. Such an increase in machine Joule loss would represent a major decrease in the efficiency of DFIG operation.

Results for the calculated DFIG electromagnetic torque FFT spectrum are given for the four cases analyzed in Fig. 3. These clearly show that stator and rotor supply asymmetries have a different effect in terms of harmonic components induced in the torque spectrum, as would be expected. The results demonstrate that a stator supply asymmetry produces the double supply frequency harmonic component in the torque spectrum, shown in Fig. 3b. This is caused by the backwards rotating stator field fundamental interacting with the forward rotating rotor field fundamental. The rotor supply asymmetry is however shown in Fig. 3c to cause a $2sf$ component to exist in the torque spectrum, where s is the slip and f is the stator supply frequency. This torque component results from the interaction of the backwards rotating slip frequency fundamental and the forward rotating stator fundamental field. The overall effect of an asymmetry present in both stator and rotor supply is the existence of both a twice stator supply frequency component and a twice slip frequency component in the torque spectrum, as is shown in Fig. 3d. Additionally the harmonic fields generated by these asymmetries interact and give rise to sideband torque harmonic components such as those at $2(1\pm s)f$ Hz, as well as various other components present in the spectrum.

In general, unwanted rotating field components may arise from either the excitation unbalance or winding unbalance. The results presented here clearly identify supply voltage unbalance as one cause of pulsating torque components. In particular the presence of the twice supply frequency and twice slip frequency components in the torque spectrum may be caused by stator and rotor supply asymmetry, respectively. Results also indicate that the magnitudes of pulsating torque components are not negligible and suggest that minimizing these components would benefit the integrity of the DFIG drivetrain as well as the stability of DFIG operation.

VI. CONCLUSION

A detailed analysis of DFIG electromagnetic torque signal and Joule loss for operation under unbalanced supply conditions is presented in the paper. Stator supply unbalance

TABLE III
CALCULATED TOTAL STATOR AND ROTOR JOULE LOSS FOR VARIOUS UNBALANCED SUPPLY OPERATING CONDITIONS

Stator voltage	Rotor voltage	Stator Loss [W]	Percentage increase [%]	Rotor Loss [W]	Percentage increase [%]
Balanced	Balanced	514	0	345	0
Unbalanced	Balanced	532	3.5	412	19.4
Balanced	Unbalanced	630	22.6	342	-0.9
Unbalanced	Unbalanced	656	27.6	421	22.0

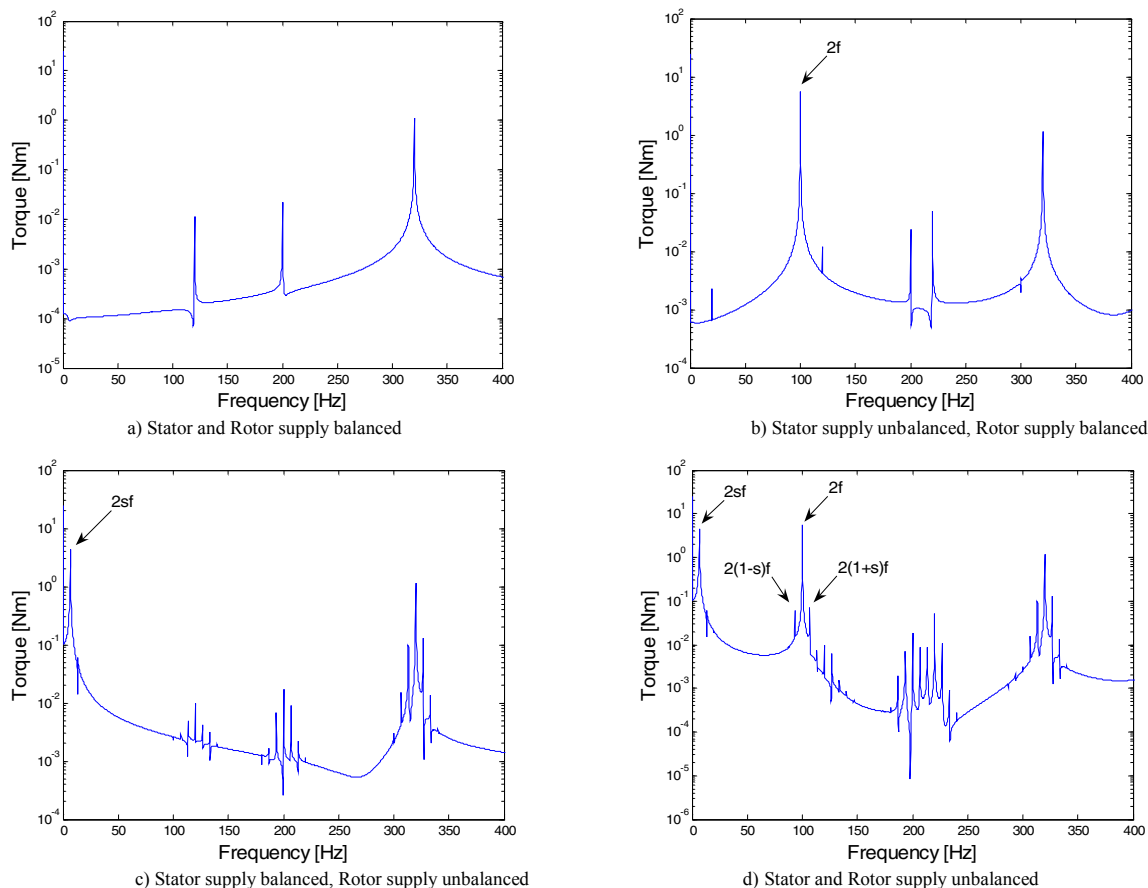


Fig. 3. Predicted DFIG Electromagnetic torque spectrum

has been shown to produce a twice supply frequency pulsating torque, and rotor supply unbalance a twice slip-frequency pulsation. However, these torque pulsations may also arise from other causes (such as winding faults) and so their presence cannot be solely attributed to supply unbalance. It was also shown that the presence of asymmetries in the DFIG primary and secondary supply significantly increases the machine total Joule loss. The effect of a typical voltage supply unbalance on DFIG steady-state operation was shown to be negative, inducing harmful torque components and decreasing the efficiency of operation.

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