Theoretical and experimental analysis of unbalanced doubly fed induction generators

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ABSTRACT

In this paper, a novel approach has been developed for the modeling and analysis of doubly fed induction generators operating under unbalanced load conditions. This comprehensive approach considers the derivation of the doubly fed induction generator's neutral voltage during unbalanced conditions. Using this innovative approach, important and extremely precise signatures on stator currents and voltages have been extracted during a rational simulation time. It has been shown that for unbalanced conditions, an abnormal operation is produced. It is characterized by unbalanced stator voltages, currents, and specific harmonics through the stator variables. These harmonics have been proposed to detect unbalanced conditions. The consistency and reliability of this approach for the analysis and modeling of unbalanced doubly fed induction generators are validated by the coherence and good correlation between experimental and simulation results.

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1. INTRODUCTION

Recently, the doubly-fed induction generator (DFIG) has been widely employed in wind energy conversion systems [1]–[5]. Many studies show that the DFIG stator windings are subject to mechanical, electrical, and thermal stresses [6]–[9]. These stresses produce stator asymmetry and severe effects such as noise, vibration, pulsating torque, and temperature rise [10]–[13].

For the diagnosis of asymmetrical DFIGs, several approaches have been used in the literature. In this context, Botha and Gule [14] investigate vibrational analysis. Wang *et al.* [15] suggest the use of current signature analysis for diagnosing the DFIGs. Shah *et al.* [16] use the rotor current signature analysis. Ma *et al.* [17] suggest the rotor power spectrum analysis. The challenge of these methods is to select the appropriate monitoring signal. In [18] and [19], adaptive observers are used to detect stator defects in DFIGs. The model-based approaches have the potential to produce false alarms and are sensitive to parametric variation. The advanced approach also relies on artificial intelligence techniques such as deep learning [20]. Another approach was also applied to detect and diagnose faults in DFIG, which is a fuzzy logic-based expert system [21]. In addition, a deep neural network (DNN) has been used for fault diagnosis in DFIG. Furthermore, the tree algorithm (DTA) has been applied to detect faults in the generator by identifying distinct characteristics within the stator current signals [22]. Despite the effective role of these advanced techniques in the diagnosis of DFIGs, they are complex and difficult to implement in practice.

For the modeling of unbalanced DFIG, the well-known approach is the finite element method (FEM) [23]. It is an integrated approach that accounts for a number of variables, including skin effects, the deflection of the rotor slots, and the spatial distribution of the rotor and stator windings. This allows for an accurate calculation of parameters and performance. The second strategy is predicated on the symmetrical components technique, which is used for the modeling of the steady state operation of unbalanced generators [24]. However, these methods require a long simulation time.

This paper proposes a novel approach to evaluate the DFIG operation under unbalanced load conditions, based on the state model approach [25]. This model accounts for the increase in stator currents and voltages under asymmetrical conditions. To detect unbalanced conditions, the spectrum analysis of the stator currents and voltages can be considered as an interesting tool. This approach has several advantages. Firstly, it can be expanded for the analysis of several faults in DFIG. In addition, it provides good accuracy and optimal simulation time comparison to symmetric components and finite element methods [26]–[29]. The simulation results by MATLAB and practical experiments demonstrate the accuracy and consistency of this novel approach for analyzing the DFIG operation under unbalanced load conditions.

2. EQUATIONS OF DFIG

2.1. Equations for stator voltage

To illustrate this approach, a star-connected DFIG has been considered as in Figure 1. Under asymmetrical conditions, the line to line voltages should be used as inputs in the stator state voltage [30]. Therefore, the stator voltage is expressed by (1),

$$\frac{d[\Phi_{sf}]}{dt} = [R_{sf}].[i_{sf}] + [u_{sf}] \quad (1)$$

with

$$[R_{sf}] = \begin{bmatrix} r_{as} & -r_{bs} & 0 \\ 0 & r_{bs} & -r_{cs} \\ -r_{as} & 0 & r_{cs} \end{bmatrix} \quad (2)$$

$[R_{sf}]$ is the matrix of stator resistances.

Based on Ohm's law, we get:

$$[v_s] = -[R_l].[i_{sf}] \quad (3)$$

with

$$[R_l] = \begin{bmatrix} r_{la} & 0 & 0 \\ 0 & r_{lb} & 0 \\ 0 & 0 & r_{lc} \end{bmatrix} \quad 4()$$

$[i_{sf}] = [i_{as}\ \ i_{bs}\ \ i_{cs}]^T$

i_{as} , i_{bs} and i_{cs} are the line currents

r_{la} , r_{lb} and r_{lc} are the load resistances

The line-to-line voltages are expressed by (5):

$$[u_{sf}] = [T_f].[v_s] \quad (5)$$

where

$[v_s] = [v_{as}\ \ v_{bs}\ \ v_{cs}]^T$,

$[u_{sd}] = [u_{ab}\ \ u_{bc}\ \ u_{ca}]^T$,

v_{as} , v_{bs} and v_{cs} are the phase voltages, and

u_{ab} , u_{bc} and u_{ca} are the line-to-line voltages.

The stator flux vector is calculated using (6),

$$[\Phi_{sf}] = [T_f].[\Phi_s] \quad (6)$$

with

$$[T_f] = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \quad (7)$$

$$[\Phi_s] = -[L_{ss}].[i_s] - [L_{sr}].[i_r] \quad (8)$$

$$[L_{ss}] = \begin{pmatrix} L_{ms} + L_{ls} & -\frac{L_{ms}}{2} & -\frac{L_{ms}}{2} \\ -\frac{L_{ms}}{2} & L_{ms} + L_{ls} & -\frac{L_{ms}}{2} \\ -\frac{L_{ms}}{2} & -\frac{L_{ms}}{2} & L_{ms} + L_{ls} \end{pmatrix} \quad (9)$$

$[\Phi_s] = [\Phi_{as} \;\; \Phi_{bs} \;\; \Phi_{cs}]^T$
$[L_{ss}]$ is the matrix of the stator inductances.
L_{ls} , L_{ms} are respectively the leakage and magnetizing inductance of the stator windings.
$[i_r]$ is the vector of the rotor currents.

We define the stator-rotor mutual inductances by (10).

$$[L_{sr}] = L_{sr}.\begin{pmatrix} \cos(\theta) & \cos\left(\theta + \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \cos(\theta) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos(\theta) \end{pmatrix} \quad (10)$$

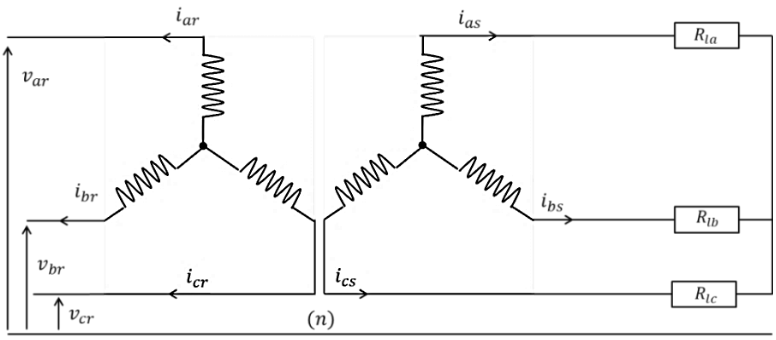


Figure 1. Star connected DFIG

2.2. Rotor voltage equations

The equation of rotor voltage is expressed by (11),

$$\frac{d[\Phi_r]}{dt} = [R_r].[i_r] + [v_r] \quad (11)$$

with

$$[v_r] = \begin{bmatrix} V_r \cos(\omega_r t) \\ V_r cos\,(\omega_r t - \frac{2\pi}{3}) \\ V_r \cos(\omega_r t + \frac{2\pi}{3}) \end{bmatrix} \quad (12)$$

$$[R_r] = \begin{bmatrix} r_{ar} & 0 & 0 \\ 0 & r_{br} & 0 \\ 0 & 0 & r_{cr} \end{bmatrix} \quad (13)$$

$[v_r]$, $[R_r]$ are respectively the matrices of rotor voltages and resistances.

The rotor flux equation is expressed using (14) and (15).

$$[\Phi_r] = -[L_{rs}].[i_s] - [L_{rr}].[i_r] \tag{14}$$

$$[L_{rs}] = [L_{sr}]^t \tag{15}$$

with

$$[L_{rr}] = \begin{pmatrix} L_{mr} + L_{lr} & -\frac{L_{mr}}{2} & -\frac{L_{mr}}{2} \\ -\frac{L_{mr}}{2} & L_{mr} + L_{lr} & -\frac{L_{mr}}{2} \\ -\frac{L_{mr}}{2} & -\frac{L_{mr}}{2} & L_{mr} + L_{lr} \end{pmatrix} \tag{16}$$

where $[L_{rr}]$ is the matrix of the rotor inductances, L_{lr} , L_{mr} are respectively the leakage and magnetizing inductance of the rotor windings, and $[L_{rs}]$ is the rotor-stator mutual inductances.

2.3. Machine currents

Using (17) to (19), two independent components can be calculated i_{as} and i_{bs}, to obtain the stator currents defined by (17),

$$[i_{sf}] = [B_f][i_{abs}] \tag{17}$$

with

$$[B_f] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ -1 & -1 \end{bmatrix} \tag{18}$$

$$[i_{abs}] = \begin{bmatrix} i_{as} \\ i_{bs} \end{bmatrix} \tag{19}$$

We define stator flux of two independent components by (20),

$$[\Phi_{abs}] = [A_f][\Phi_s] \tag{20}$$

with

$$[A_f] = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \tag{21}$$

Using (20), the stator and rotor fluxes are expressed as illustrated by (22) to (26),

$$[\Phi_{abs}] = -[L_{sf}][i_{abs}] - [L_{srf}][i_r] \tag{22}$$

$$[\Phi_r] = -[L_{rsf}][i_{abs}] - [L_{rr}][i_r] \tag{23}$$

with

$$[L_{sf}] = [A_f][L_{ss}][B_f] \tag{24}$$

$$[L_{srf}] = [A_f][L_{sr}] \tag{25}$$

$$[L_{rsf}] = [L_{rs}][B_f] \tag{26}$$

Using (22) and (23), we get the equation of stator and rotor currents as illustrated by (27) and (28),

$$[i_{abs}] = [C_{sf}]\left([\Phi_{abs}] - [L_{srf}][L_{rr}]^{-1}[\Phi_r]\right) \tag{27}$$

$$[i_r] = [C_{rf}]\left([\Phi_r] - [L_{rsf}][L_{sf}]^{-1}[\Phi_{abs}]\right) \tag{28}$$

with

$$[C_{sf}] = -\left([L_{sf}] - [L_{srf}][L_{rr}]^{-1}[L_{rsf}]\right)^{-1} \tag{29}$$

$$[C_{rf}] = -\left([L_{rr}] - [L_{rsf}][L_{sf}]^{-1}[L_{srf}]\right)^{-1} \tag{30}$$

2.4. The state model of unbalanced DFIG

Using (1), (11), (27) and (28), the DFIG state model operation under unbalanced load conditions can be represented by (31),

$$\begin{cases} \dfrac{d[\Phi_{sf}]}{dt} = [R_{sf}][B_f][C_{sf}]\left([\Phi_{abs}] - [L_{srf}][L_{rr}]^{-1}[\Phi_r]\right) + [u_{sf}] \\ \dfrac{d[\Phi_r]}{dt} = [R_r][C_{rf}]\left([\Phi_r] - [L_{rsf}][L_{sf}]^{-1}[\Phi_{abs}]\right) + [v_r] \\ \dfrac{d\Omega}{dt} = \dfrac{1}{J}(T_m - T_e - f_v\Omega) \end{cases} \tag{31}$$

where J is the rotor and the connected load inertia, f_v is the viscose friction coefficient, Ω is the mechanical angular speed, T_e is the electromagnetic torque, and T_m the motorized torque.

We determine the electromagnetic torque by (32).

$$T_e = p[i_s]^t \frac{\partial[L_{sr}]}{\partial\theta}[i_r] \tag{32}$$

Here, p and θ are respectively the poles pairs number and mechanical angle.

3. RESULTS AND DISCUSSION

3.1. Simulation results

The state model described above is simulated using the MATLAB software. The DFIG of 220/380 V–50 Hz–4 kW, is rotated at 3020 tr/mn in order to get 50 Hz as fundamental frequency for the stator variables. During time $t = 0 - 0.15\ s$, the DFIG supplies a balanced load of $45\ \Omega$ and at time $t = 0.15\ s$, an unbalanced load of $R_{la} = 70\ \Omega$, $R_{lb} = R_{lc} = 45\ \Omega$ is selected. These values are selected to get significant effects of unbalanced load conditions. The stator currents and voltages are depicted in Figure 2. Figure 3 shows the spectrum analysis of the stator current I_{as} and voltage V_{as} respectively for balanced load, and unbalanced load in Figure 4.

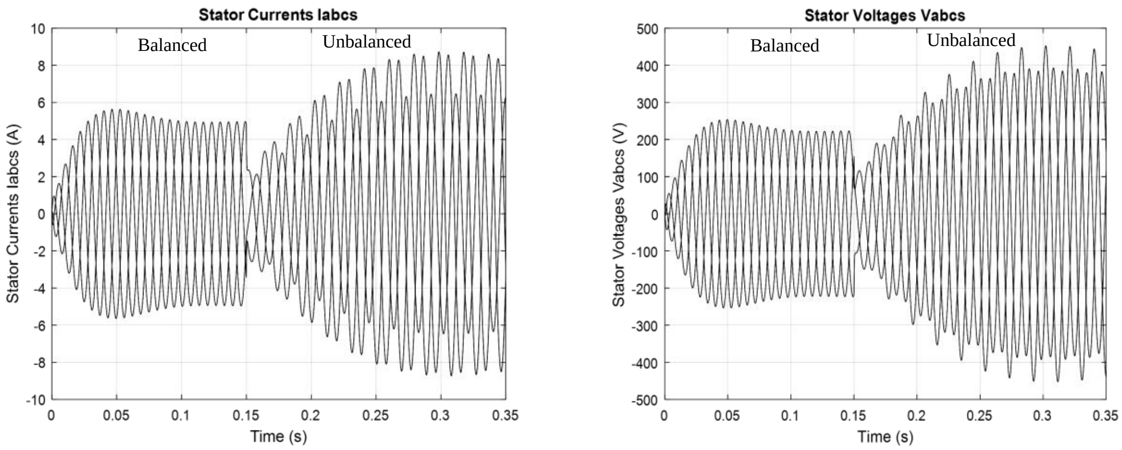


Figure 2. The stator currents and voltages

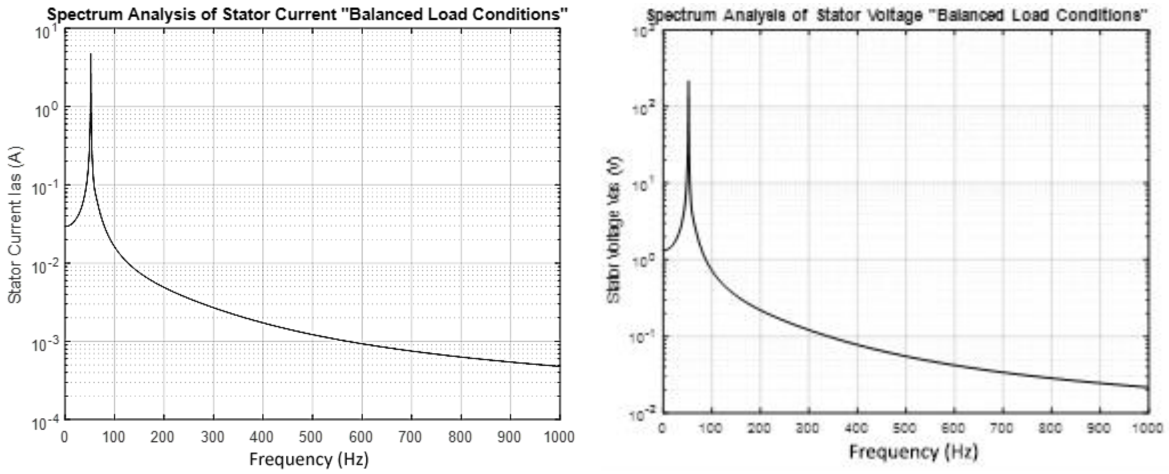
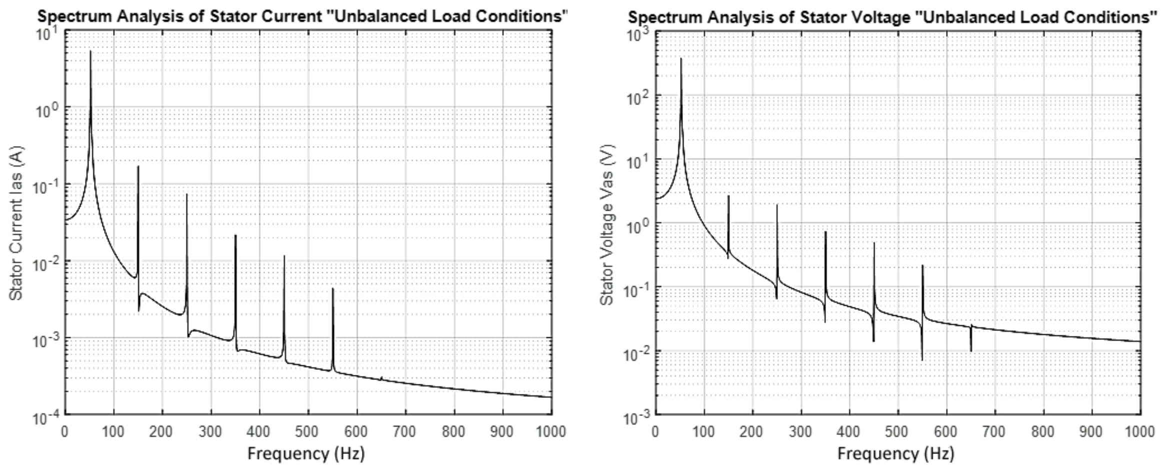


Figure 3. Spectrum analysis of stator current and voltage for balanced load



Stator current I_{as} Stator voltage V_{as}

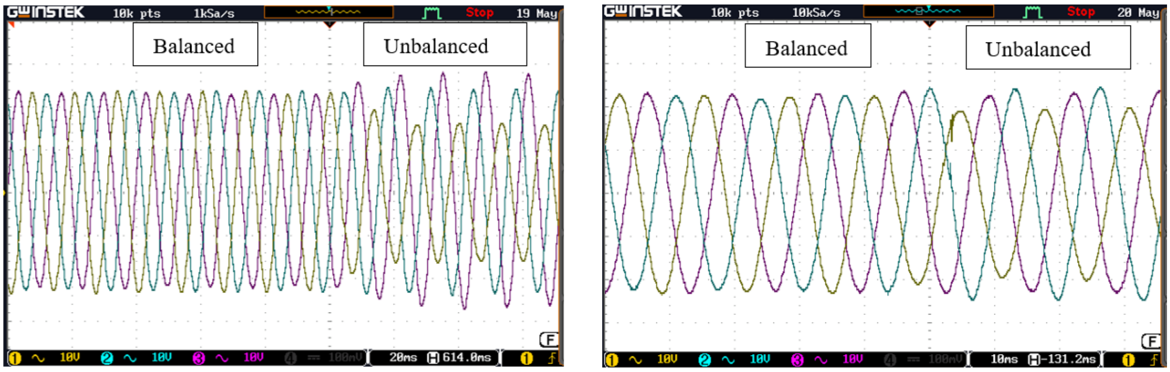
Figure 4. Spectrum analysis of stator current I_{as} and stator voltage V_{as} for unbalanced load

The simulation results indicate that the stator currents and voltages are unbalanced as shown in Figure 2. Specific harmonics ($f_1 = 50Hz$, $f_3 = 250Hz$, $f_5 = 350Hz$, etc.) are also detected through the stator currents and voltages, as given in Figure 4 in contrast to the balanced conditions, as shown in Figure 3. These harmonics generate undesirable defects on the DFIG, such as noise, vibrations, overheating and increased losses.

3.2. Experimental results

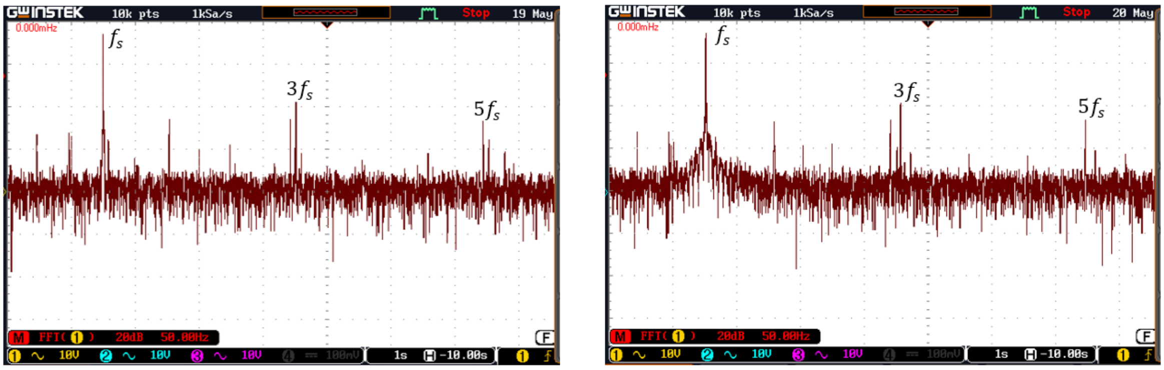
In order to verify the validity of the theoretical analysis, an experiment study has been conducted on a DFIG of 4 kW and 220/380 V-50 Hz. The DFIG is mechanically coupled to a direct motor rotated at 3020 tr/mn to get 50 Hz as fundamental frequency for the stator variables. The DFIG starts with no load and then a balanced load of 45 Ω has been introduced. After that, an unbalanced load R_{la}=70 Ω, R_{lb}=R_{lc}=45 Ω is selected. Shunt resistors are used for measuring the stator currents. The stator voltages and currents are given in Figure 5. Figure 6 illustrates the spectrum analysis of the stator voltage V_{as} and current I_{as} respectively for unbalanced load conditions.

As illustrated by Figure 5, experimental results during unbalanced load conditions show unbalanced stator voltages and currents, as well as a rise in voltage values. Specific harmonics ($f_1 = 50Hz$, $f_3 = 250Hz$, $f_5 = 350Hz$, etc.) are also detected through the stator voltages and currents, as given in Figure 6. It is noteworthy that the harmonic components of the stator currents generate pulsating torques that causes overheating, noise and vibrations. As a result, the DFIG will gradually be destroyed under unbalanced load conditions. Therefore, stator voltages and currents are important signals for detecting unbalanced load conditions and ensuring the DFIG’s safe operation. Experimental results, which correspond to simulation results, reveal that unbalanced and increased stator voltages are created during unbalanced load conditions, whereas load asymmetry produces harmonic components of stator currents.



Stator voltages Stator currents

Figure 5. Experimental results of DFIG for unbalanced load conditions: stator voltages and currents



Stator voltage V_{as} Stator current I_{as}

Figure 6. Experimental results of DFIG for unbalanced load conditions: stator voltage spectrum analysis V_{as} and stator current spectrum analysis I_{as}

4. CONCLUSION

Both theoretical and experimental research have been conducted to analyze the operation of the DFIG under unbalanced load conditions and extract various electromagnetic characteristics such as stator currents and voltages. Furthermore, anomalous operation has been highlighted during unbalanced conditions. It is characterized by unbalanced stator voltages, currents, and specific harmonics through the stator variables. To detect this abnormal operation, the stator variables spectrum analysis can be used. This method provides accurate results during reasonable simulation time. This work should be conducted in future research to explicitly distinguish unbalanced load conditions from other stator asymmetries, as all cases have identical current and voltage signatures.

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