Dynamic Analysis of the Brushless Doubly-Fed Induction Generator during Symmetrical Three-Phase Voltage Dips

Shiyi Shao          Ehsan Abdi          Richard McMahon
Electrical Engineer Division
Cambridge University
9 JJ Thomson Avenue, Cambridge
CB3 0FA, United Kingdom
ram1@cam.ac.uk

Abstract – The Brushless Doubly-Fed Induction Generator (BDFIG) shows commercial promise as replacement for doubly-fed slip-ring generators for wind power applications by offering reduced capital and operational costs due to its brushless operation. In order to facilitate its commercial deployment, the capabilities of the BDFIG system to comply with grid code requirements have to be assessed. This paper, for the first time, studies the performance of the BDFIG under grid fault ride-through and presents the dynamic behaviour of the machine during three-phase symmetrical voltage dips. Both full and partial voltage dips are studied using a vector model. Simulation and experimental results are provided for a 180 frame BDFIG.

Index Terms—Brushless Doubly-Fed Induction Generator, voltage dips, vector model

I. INTRODUCTION

The Brushless Doubly-Fed Induction Generator (BDFIG), also known as the Brushless Doubly-Fed Machine (BDFM), promises significant advantages as a variable speed generator for wind power applications due to its fractionally rated converter and brushless operation [1], [2]. These advantages become even more important as there is continuous attempt to reduce the capital and operational costs of wind turbines as well as improve their reliability.

In order to realise the BDFIG’s advantages and deploy it in commercial wind farms, its performance at the system level such as inverter rating [3], system control [5] and grid code compliance have to be assessed. The latter is particularly important as the share of wind power generation has been increasing over the recent years and new grid codes are being introduced in countries with a large installed wind capacity such as Germany.

The grid fault ride-through capability of wind turbines with doubly-fed induction generators (DFIGs) has been studies in several publications, for example, [6], [7]. These have led to improvements in the performance of DFIG systems through utilising various methods such as crowbar solutions.

However, to date, no such studies exist for the BDFIG. This paper presents a preliminary study of the BDFIG performance under partial and full symmetrical three-phase voltage dips using the methods widely used for DFIGs [6], [7]. The analysis is based on a simplified vector model developed for the BDFIG with a nested-loop type of rotor. For this work, the multiple rotor loops in each nest are reduced to one effective loop in the vector model using the approach presented in [8].

The analysis presented in this paper for partial and full voltage dips can be utilised to assess inverter rating and grid code compliance for BDFIG-based wind turbines.

Fig. 1. BDFIG configuration

II. BDFIG OPERATION ANALYSIS

The BDFIG comprises two stator windings with different pole numbers to avoid direct coupling, and a special type of rotor which couples to both stator fields. The nested-loop type of rotor is the most well known [1]. One winding, called the power winding (PW), is connected to mains and the other, called the control winding (CW), is fed with a fractionally-rated power electronics converter as shown in Fig. 1. The shaft angular speed \( \omega_s \) is determined by the stator angular frequencies as:

\[
\omega_s = \frac{\omega_1 + \omega_2}{p_1 + p_2}
\]  

(1)

\( p_1, p_2 \) and \( \omega_1 \) and \( \omega_2 \) are the pole pair numbers and angular frequencies of the two stator windings respectively. The BDFIG is characterised by the so-called natural speed when the control winding is supplied with DC.
\[ \alpha_n = \frac{\alpha_1}{p_1 + p_2} \] (2)

A vector model aligned with the power winding stationary frame is used in this paper for the machine operation analysis [4], [8]. The model can be expressed as:

\[ v_1 = R_1 i_1 + \frac{d\psi_1}{dt} \] (3)
\[ v_2 = R_2 i_2 + \frac{d\psi_2}{dt} - j(p_1 + p_2)\omega_1 \psi_2 \] (4)
\[ v_r = R_s i_s + \frac{d\psi_r}{dt} - j p_r \omega \psi_r \] (5)
\[ \psi_1 = L_{s1} i_1 + L_{12} i_2 \] (6)
\[ \psi_2 = L_{s2} i_2 + L_{12} i_1 \] (7)
\[ \psi_r = L_{sR} i_1 + L_{12} i_2 + L_{2R} i_2 \] (8)

The parameters in the above equations are described in Table I.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>DEFINITION OF VECTOR MODEL PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Power winding</td>
</tr>
<tr>
<td>Resistance</td>
<td>( R_1 )</td>
</tr>
<tr>
<td>Self inductance</td>
<td>( L_{s1} )</td>
</tr>
<tr>
<td>Mutual inductance</td>
<td>( L_{12} )</td>
</tr>
<tr>
<td>Voltage vector</td>
<td>( i_1 )</td>
</tr>
<tr>
<td>Current vector</td>
<td>( v_1 )</td>
</tr>
<tr>
<td>Flux linkage vector</td>
<td>( \psi_1 )</td>
</tr>
</tbody>
</table>

The power winding is connected to the grid. Hence, in steady state, all vectors rotate at the power winding synchronous speed \( \omega_1 \), which is set by the frequency of the mains. For example, \( v_1 \) can be expressed as:

\[ v_1 = |V_1| e^{j\omega_1 t} \] (9)

where \( |V_1| \) is the magnitude of the power winding voltage.

From (5) and (8),

\[ v_r = -j \omega_1 L_{sR} i_1 = j \omega_2 L_{12} i_2 \]
\[ -(s - j p_2 \omega) L_{12} i_1 - j \omega_2 L_{2R} i_2 = 0 \] (10)

Considering (6) and (10), \( i_1 \) and \( i_2 \) can be expressed as:

\[ i_2 = \frac{L_{s1} \psi_1 + L_{12} \psi_2}{L_{s1} - L_{s2} - \frac{R_{s}}{s-jp_1\omega}} \] (11)
\[ i_1 = \frac{L_{s2} \psi_2 + L_{12} \psi_1}{L_{s2} - L_{12} - \frac{R_{s}}{s-jp_2\omega}} \] (12)

Substituting (11) to (7):

\[ \psi_2 = \frac{L_{s2} L_{12} L_{sR} - L_{2R} L_{12}^2 - L_{s2} L_{sR}^2}{L_{s2} - L_{12} - \frac{R_{s}}{s-jp_2\omega}} \psi_1 \]
\[ \psi_1 = \frac{L_{s1} L_{12} L_{sR} - L_{s1} L_{sR}^2 - L_{12} L_{sR}}{L_{s1} - L_{s2} - \frac{R_{s}}{s-jp_1\omega}} \psi_2 \] (13)

\[ \psi_r = \frac{L_{sR} L_{12} L_{sR} - L_{sR} L_{sR}^2 - L_{12} L_{sR}}{L_{sR} - L_{12} - \frac{R_{s}}{s-jp_2\omega}} \psi_1 \]
\[ \psi_r = \frac{L_{sR} L_{12} L_{sR} - L_{sR} L_{sR}^2 - L_{12} L_{sR}}{L_{sR} - L_{12} - \frac{R_{s}}{s-jp_2\omega}} \psi_1 \]

Noting that \( s-jp_1\omega_1 \) is larger both in steady state and transient, then its reciprocal can be neglected. Hence, substituting (13) to (4), \( v_2 \) can be expressed as:

\[ v_2 = R_2 i_2 + \frac{L_{s1} L_{s2} L_{sR} - L_{s1} L_{s2}^2 - L_{s2} L_{sR}^2}{L_{s1} - L_{s2} - \frac{R_{s}}{s-jp_1\omega}} (s-j(p_1 + p_2)\omega_1) \psi_2 \]
\[ + \frac{L_{s1} L_{s2}^2}{L_{s1} - L_{s2} - \frac{R_{s}}{s-jp_1\omega}} (s-j(p_1 + p_2)\omega_1) \psi_1 \]
\[ = v_2 + v_{Rs} + v_{R1} \] (14)

From (14), the converter output voltage \( v_2 \) can be split into two terms: \( v_{Rs} \) that is the induced back EMP due to the rate of change of \( \psi_1 \), and \( v_{R1} + v_{R2} \) which is effectively the voltage drop across the control winding resistance and an equivalent leakage inductance. These terms are shown in an equivalent circuit in Fig. 2, in which:

\[ v_{Rs} = R_s i_2 \] (15)
\[ v_{R1} = -j \omega_1 L_{sR} i_1 = j \omega_2 L_{12} i_2 \] (16)
\[ L_{1} = \frac{L_{s1} L_{s2} L_{sR} - L_{s1} L_{s2}^2 - L_{s2} L_{sR}^2}{L_{s1} - L_{s2} - \frac{R_{s}}{s-jp_1\omega}} \] (17)

Ignoring the effect of the power winding resistance, (3) can be simplified as:

\[ v_1 = \frac{d\psi_1}{dt} = j \omega \psi_1 \] (18)

Substituting (18) to (14), then:

\[ v_{Rs} = \frac{L_{s1} L_{s2} L_{sR} - L_{s1} L_{s2}^2 - L_{s2} L_{sR}^2}{L_{s1} - L_{s2} - \frac{R_{s}}{s-jp_1\omega}} |V_1| e^{j\omega_1 t} \] (19)

In a well designed BDFIG, the voltage drops across the control winding resistance \( R_{s} \) and equivalent inductance \( L_{1} \) are relatively small, thereby, in normal operation \( v_{Rs} + v_{R1} \) can be neglected compared to \( v_{Rs} \). The control winding voltage can hence be derived by transferring (19) which is in the power winding stationary reference frame into the control winding stationary reference frame:

\[ v_2^{(2)} = \frac{L_{s1} L_{s2} L_{sR} - L_{s1} L_{s2}^2 - L_{s2} L_{sR}^2}{L_{s1} - L_{s2} - \frac{R_{s}}{s-jp_1\omega}} |V_1| e^{j(\omega_1 t + \theta_{p1})} \] (20)

Equation (20) shows that for normal operation of the BDFIG, the magnitude of \( v_2^{(2)} \) has a correlation with power winding voltage \( |V_1| \) and its gain is proportional to the control winding frequency which is determined by the rotor speed \( \omega_2 \). Therefore, only a partially-rated converter is needed if operating speed range is limited.
III. BDFIG PERFORMANCE UNDER FULL VOLTAGE DROP

In the following analysis, the control winding is assumed to be open-circuited, i.e. \( i_2 = 0 \). In literature, this mode is referred to as idle operation [9] which facilitates the investigation of the grid fault effects by decoupling the control winding supply.

The grid voltage profile can be expressed as below when a full voltage dip occurs at \( t = t_0 \):

\[
v_i = \begin{cases} 
|V_i| e^{j\omega t} & (t < t_0) \\
0 & (t \geq t_0)
\end{cases}
\]

(21)

Substituting (12) and (21) into (3) and setting \( i_2 = 0 \), \( \psi_1 \) can be calculated as:

\[
\psi_1 = \begin{cases} 
|V_i| e^{j\omega t} & (t < t_0) \\
|V_i| e^{j\omega t} e^{-j\omega t_0/\tau_1} & (t \geq t_0)
\end{cases}
\]

(22)

\( \tau_1 \) is a time constant defined as:

\[
\tau_1 = \frac{L_{1s} L_{2s} - L_{1s} L_{1t}}{R_{1s} L_{1t}}
\]

(23)

From (22), when a fault occurs at \( t = t_0 \), \( \psi_1 \) becomes frozen at the direction \( e^{j\omega (t)} \) and with a magnitude of \( |V_i|/j\omega t \), then decays exponentially with time constant \( \tau_1 \). From (20) and (22), the open-loop control winding voltage in the power winding stationary reference frame can be expressed as:

\[
v_{\psi_1} = \frac{L_{1s} L_{2s}}{L_{1s} L_{1t} - L_{1s} L_{1t}} \left( s - j(p_1 + p_2)\omega_0 \right) \psi_1
\]

\[
= \frac{L_{1s} L_{2s}}{L_{1s} L_{1t} - L_{1s} L_{1t}} \cdot \frac{1}{\tau_1 - j(p_1 + p_2)\omega_0} \cdot \frac{1}{j\omega_0} \cdot |V_i| e^{j\omega t} e^{-j\omega (t - t_0)/\tau_1}
\]

(24)

Generally, \( 1/\tau_1 \) is small relative to \( j(p_1 + p_2)\omega_0 \), hence (24) can be simplified as:

\[
v_{\psi_1} = \frac{L_{1s} L_{2s}}{L_{1s} L_{1t} - L_{1s} L_{1t}} \cdot \frac{1}{\tau_1} \cdot \frac{1}{j\omega_0} \cdot |V_i| e^{j\omega t} e^{-j\omega (t - t_0)/\tau_1}
\]

(25)

By transferring \( v_{\psi_1} \) to the control winding stationary frame, (25) becomes:

\[
v_{\psi_1} \stackrel{(2)}{=} \frac{L_{1s} L_{2s}}{L_{1s} L_{1t} - L_{1s} L_{1t}} \cdot \frac{1}{\tau_1} \cdot \frac{1}{j\omega_0} \cdot |V_i| e^{j\omega t} e^{-j\omega (t - t_0)/\tau_1} \]

(26)

From (26), the maximum transient voltage \( |v_{\psi_1}^{(2)}| \) occurs at \( t = t_0 \) and its amplitude is:

\[
|v_{\psi_1}^{(2)}|_{\text{max}} = \frac{L_{1s} L_{2s}}{L_{1s} L_{1t} - L_{1s} L_{1t}} \cdot \frac{1}{\tau_1} \cdot \frac{1}{j\omega_0} \cdot |V_i| e^{j\omega t}
\]

(27)

which is larger compared to its value before the grid fault, given by (20):

\[
|v_{\psi_1}^{(2)}|_{\text{pre-fault}} = \frac{L_{1s} L_{2s}}{L_{1s} L_{1t} - L_{1s} L_{1t}} \cdot \frac{1}{\tau_1} \cdot \frac{1}{j\omega_0} \cdot |V_i| e^{j\omega t}
\]

(28)

It should be noted from (27) that the maximum induced voltage is larger if the machine operates above the natural speed i.e. when \( \omega_2 > 0 \), as compared to the case that the shaft speed is below the natural speed i.e. when \( \omega_2 < 0 \). Moreover, (26) indicates that the post-fault induced voltage has a higher angular frequency \( (\omega_2 = (p_1 + p_2)\omega_0) \) than normal operation, which causes transient torque oscillations. Similar effects can be observed in DFIG systems [10].

The above analysis is based on the control winding being open circuit. However, in practical applications, the control winding is connected to a frequency converter and thereby \( i_2 \neq 0 \). If the converter is capable of providing the required \( v_2 \) in grid fault situations to balance the transient \( v_{\psi_1} \), the control winding currents would remain within their rating limit. Otherwise, the voltage difference between \( v_2 \) and \( v_{\psi_1} \) would cause increased currents.

IV. BEHAVIOUR OF THE BDFIG UNDER A PARTIAL VOLTAGE DROP

In this section, the performance of the BDFIG under a partial voltage dip is analysed. Similar to the preceding analysis, it will be assumed that control winding is open circuit. The profile of a voltage dip occurring at \( t = t_0 \) is given as:

\[
v_i = \begin{cases} 
|V_i| e^{j\omega t} & (t < t_0) \\
(1 - a) |V_i| e^{j\omega t} & (t \geq t_0)
\end{cases}
\]

(29)

where \( a \) is defined as dip depth. When \( a = 1 \), (29) is equivalent to the full voltage dip which is a special case of the partial voltage dip. The power winding flux linkage can be obtained from (3) as:

\[
\psi_i = \begin{cases} 
|V_i| e^{j\omega t} & (t < t_0) \\
\frac{1}{j\omega_0} \cdot \frac{1}{j\omega_0} \cdot |V_i| e^{j\omega t} e^{-j\omega (t - t_0)/\tau_1} & (t \geq t_0)
\end{cases}
\]

(30)

From (30), the post-fault flux linkage comprises two components: the first term has fixed amplitude and rotates at the synchronous speed \( \omega_0 \), and the second term is frozen in the power winding stationary frame and decays exponentially.

Substituting (30) into (20), the control winding open-loop voltage can be obtained as:

\[
v_{\psi_1} = \frac{L_{1s} L_{2s}}{L_{1s} L_{1t} - L_{1s} L_{1t}} \cdot \frac{1}{\tau_1} \cdot \frac{1}{j\omega_0} \cdot \frac{1}{j\omega_0} \cdot \frac{1}{j\omega_0} \cdot \frac{1}{j\omega_0} \cdot |V_i| e^{j\omega t}
\]

(31)

\[
+ \frac{L_{1s} L_{2s}}{L_{1s} L_{1t} - L_{1s} L_{1t}} \cdot \frac{1}{\tau_1} \cdot \frac{1}{j\omega_0} \cdot \frac{1}{j\omega_0} \cdot \frac{1}{j\omega_0} \cdot \frac{1}{j\omega_0} \cdot \frac{1}{j\omega_0} \cdot |V_i| e^{j\omega t}
\]

(32)

If (31) is expressed in the control winding stationary reference frame, then:

\[
v_{\psi_1} = \frac{L_{1s} L_{2s}}{L_{1s} L_{1t} - L_{1s} L_{1t}} \cdot \frac{1}{\tau_1} \cdot \frac{1}{j\omega_0} \cdot \frac{1}{j\omega_0} \cdot \frac{1}{j\omega_0} \cdot \frac{1}{j\omega_0} \cdot |V_i| e^{j\omega t}
\]

(32)
has a fixed amplitude determined by the depth of the voltage dip and rotates at the same frequency as the pre-fault condition, i.e. \( \omega = (p_1 + p_2) \omega_r \).

The second term
\[
\frac{L_{Ls}L_{Lr}}{L_{Ls}L_{Lr} - L_{Lr}^2} \omega_1 + \omega_2 \left| V_L \right| \quad (34)
\]
decays exponentially with an oscillation frequency of \((p_1 + p_2) \omega_r\).

Therefore, the steady-state value of the post-fault control winding open-loop voltage is:
\[
v_{\psi_2(\alpha = 1)} = \frac{L_{Ls}L_{Lr}}{L_{Ls}L_{Lr} - L_{Lr}^2} \omega_1 \left| V_L \right| e^{(\omega_1 - (p_1 + p_2) \omega_r) t} \quad (35)
\]

From (33) and (34), if the machine is operating above the natural speed i.e. \( \omega > 0 \), both vectors have the same initial phase, hence (32) reaches its maximum value at \( t = t_0 \).

However, when the shaft speed is below the natural speed, i.e. \( \omega < 0 \), (33) and (34) have opposite direction at \( t = t_0 \). Since (34) rotates faster than (33), at \( t = t_0 + \pi / \omega_r \), the two vectors will be aligned, but the amplitude of (33) has reduced by a damping factor of \( e^{-\tau \omega_r} \).

As a conclusion, when the BDFIG operates at below natural speed and a partial voltage dip occurs, (32) may reach its maximum transient value at either \( t_0 \) or \( t_0 + \pi / \omega_r \), depending on the dip depth \( \alpha \).

It should be noted that (32) is a general expression which can be used to analyse full voltage dip by setting \( \alpha = 1 \) (identical to (26)), as well as pre-fault operation by setting \( \alpha = 0 \) (identical to (20)).

\section*{V. EXPERIMENTAL AND SIMULATION RESULTS}

Please use automatic hyphenation and check your spelling. Additionally, be sure your sentences are complete and that there is continuity within your paragraphs. Check the numbering of your graphics (figures and tables) and make sure that all appropriate references are included.

\subsection*{A. Experimental setup}

In order to verify the analysis presented in previous sections, an experimental rig has been set up on a 180 frame size BDFIG with specifications shown in Table II. Tests were carried out under the following conditions:

1) The power winding was connected to a PWM-driven converter which can simulate balanced three-phase voltage dips.
2) The control winding was open circuited and \( \psi \) was measured from the control winding terminals.
3) A DC machine was mechanically coupled to drive the BDFIG at constant speeds.

\subsection*{B. Full voltage dip test}

The BDFIG was first tested under a full voltage dip. As shown in Fig. 3(a), when the power winding is disconnected at \( t = 0.2 \) s, the power winding voltages disappear immediately. However, due to the inductive nature of the windings, the power winding currents vanish with a time constant as shown in Fig. 3(b).

\begin{table}[h]
\centering
\caption{Prototype Machine Specifications}
\begin{tabular}{|c|c|c|}
\hline
Parameter & Value & Parameter & Value \\
\hline
Frame size & DI80 & L1 & 0.3498 H \\
PW pole-pairs & 2 & \( L_{Lr} \) & 0.3637 H \\
CW pole-pairs & 4 & \( L_{Ls} \) & 0.0031 H \\
Natural speed & 500 rpm & \( R_{Lr} \) & 2.3 \( \Omega \) \\
PW rated voltage & 240 (at 50 Hz) & \( R_{Ls} \) & 4 \( \Omega \) \\
CW rated current & 7 A & \( I_{2(\psi_2)} \) & \( 1.2967 \times 10^{-5} \) H \\
Rated current & 7 A & \( F_{2(\psi_2)} \) & 0.53 kgm
\end{tabular}
\end{table}

When \( N_r = 400 \) rpm, from (20) the steady-state control winding open-loop voltage is:
\[
\left| V_{\psi_2} \right|_{(\omega_2;\alpha=\text{max})} = 0.23 \left| V_L \right| = 43.7 \text{ V}
\]

and its angular frequency, from (1), is:
\[
\omega_2 = -2x \times 10 \text{ rad/s}
\]

During the voltage dip, the maximum \( \psi \) can be calculated from (26):
\[
\left| \psi_{\psi_1} \right|_{(\alpha=\text{max})} = 0.91 \left| V_L \right| = 172.9 \text{ V}
\]

with the angular frequency calculated from (26):
\[
\omega_1 = 2x \times 0.4 \text{ rad/s}
\]

For the operation above the natural speed when \( N_r = 600 \) rpm, \( \left| V_{\psi_2} \right|_{(\omega_2;\alpha=\text{max})} \) and \( \omega_2 \) have the same values as calculated above, but the maximum transient induced control winding voltage during full voltage dip is:
\[
\left| V_{\psi_2} \right|_{(\omega_2;\alpha=\text{max})} = 1.333 \left| V_L \right| = 252.7 \text{ V}
\]

and its angular frequency is \( \omega_2 = 2x \times 40 \text{ rad/s} \). Both are larger than their equivalent values in below-natural speed operation. The simulated waveforms of \( \psi \) are shown in Fig. 3(c) and 3(d).

The power winding time constant can be calculated from (23) as:
\[
\tau = 0.033 \text{ s}
\]

Indicating that the transient regime disappears in 3 s, which can also be observed from Fig. 3(c) and 3(d).

The experimental results are shown from Fig. 3(e) to 3(h), demonstrating close agreement with simulation results.

\subsection*{C. Partial voltage dip test}

A 50 % voltage drop at \( t = 0.2 \) s is generated by the converter as shown in Fig. 4(a). The power winding currents are shown in Fig. 4(b).

At \( N_r = 400 \) rpm, the control winding has the same steady

\footnote{R_{Lr} was set to 4.055 \( \Omega \) in simulation. The additional value of 1.755 \( \Omega \) is due to the converter output resistance which is connected in series with the power winding.}
state value and frequency as the previous test. During the voltage dip, as discussed in the previous section, the maximum value of \( v_{\psi_1}^{(2)} \) may occur at either \( t_0 \) or \( t_0 + \pi / \alpha_1 \) and can be calculated from (32):

\[
|V_{\psi_1}\big|_{t_{\psi_1}=t_0}=0.91\alpha |V_i| - 0.23(1-\alpha)|V_i| = 64.6 \text{ V}
\]

\[
|V_{\psi_1}\big|_{t_{\psi_1}=t_0+\pi/\alpha_1} = 0.56\alpha |V_i| + 0.23(1-\alpha)|V_i| = 75.45 \text{ V}
\]

Therefore,

\[
|V_{\psi_1}\big|_{t_{\psi_1,max}} = |V_{\psi_1}\big|_{t_{\psi_1}=t_0} = 75.45 \text{ V}
\]

From (34), the angular frequency of the transient regime is \((p_1 + p_2)\omega_0 = 2\pi \times 40 \text{ rad/s} \) and from (33), the angular frequency of the post-fault steady-state control winding voltage is \(-\omega_1 + (p_1 + p_2)\omega_0 = -2\pi \times 10 \text{ rad/s} \).

For above-natural speed test, \( N_r = 600 \text{ rpm} \) and

\[
|V_{\psi_1}\big|_{t_{\psi_1,max}} = 1.33\alpha |V_i| + 0.23(1-\alpha)|V_i| = 148.2 \text{ V}
\]

The transient and steady-state angular frequencies are \(2\pi \times 60 \text{ rad/s} \) and \(2\pi \times 10 \text{ rad/s} \) respectively.

In both under and above natural speed operations, the damping time constant \( \tau_1 \) is the same as calculated for the previous test with full voltage dip.

The simulated control winding voltage waveforms are shown in Fig. 4(c) and 4(d). Experimental results are provided in Fig. 4(e) and 4(h).

\[D. \text{ Voltage dip test when control winding is supplied} \]

In normal BDFIG operation, the control winding is fed from a converter. The voltage dip leads to a high induced \( v_{\psi_1} \) on the control winding terminals. If the converter is capable of generating enough voltage \( v_2 \) to balance the induced \( v_{\psi_1} \), then \( i_2 \) would be restricted ensuring safe operation. Otherwise, high currents will be induced in the control winding as a result of the voltage difference between \( v_2 \) and \( v_{\psi_1} \) exerted on \( R_g \) and \( L_b \), shown in Fig. 2. This is similar to the case for DFIG systems. However, the BDFIG typically has a larger \( L_b \), so the transients in the converter may not be as severe as for the DFIG.

The short-circuit currents are shown from simulation in Fig. 5. The BDFIG is equipped with a vector controller [5],
The transient and steady-state behaviour of such voltages have been derived in detail. It has been shown that the induced voltage is large, particularly at over-natural speed operation, leading to large currents induced in the control winding. Hence, the system will require an increase in the inverter rating. The amplitude of the induced currents is limited by the effective series impedance of the machine. In the BDFIG, this impedance is typically larger than an equivalent DFIG, hence the currents may have lower magnitudes.

**REFERENCES**


