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DYNAMIC BEHAVIOR OF THE BRUSHLESS DOUBLY FED INDUCTION GENERATOR UNDER SYMMETRICAL AND ASYMMETRICAL FAULTS

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ABSTRACT

Wind energy has become ever more popular in recent decades. With its increasing penetration, requirements for grid connection have been established. Among these requirements, the low voltage ride through capability is regarded as the most challenging requirement found in wind generators which are integrated into the grid. The induction generators are behaving differently for symmetrical and asymmetrical faults. In this the brushless doubly fed induction generator (BDFIG) is used because of its lower cost and higher reliability when compared with DFIG. This paper explains about the dynamic behaviour of BDFIG under symmetrical and asymmetrical low voltage dips supported by MATLAB simulations is provided.

KEYWORDS: *BDFIG, Wind Energy*

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INTRODUCTION

The brushless doubly fed induction generator (BDFIG) is used for wind energy generation, especially offshore. Compared to DFIG, it has the advantage of being removal of brush gear and slip rings the maintenance cost of the system might get reduced and it has the high reliability [1] [2].

During recent decades wind energy generation has adept a rapid development. Wind energy commonly acknowledged as the clean and environmental friendly inexhaustible energy source that can reduce the usage of fossil fuels. With increasing access of wind power wind generators are required to remain connected and reactive current supply to the grid during grid voltage dips. Because of the advantages and the demand of wind energy most of the wind turbines are attached to the grid are operate at varying speed. At present the market for the variable speed wind turbines is increasing and these are capable of generating high power. And among the many requirements the low voltage ride through (LVRT)capability is the main requirement in grid code[3]-[5] which means the generators are remain connected to the grid to ride through the low voltage faults. There are two types of grid faults which are symmetrical and asymmetrical faults. When a symmetrical fault occus, wind turbines need to perform ride through of zero voltage and further grid voltage recovery also inject the reactive current to the grid up to the rated current during fault time. Asymmetrical faults are introducing a backward sequence to the generator but the current surge is less severe but these are more likely to happen. For such applications the Doubly Fed Induction Generator and Brushless Doubly Fed Induction Generators are used.

DFIG is the most widely used generator for wind turbines because it achieves the adjustable speed operation for a small rated power converter [6] [7].But the existence of brush gear and slip rings the maintenance cost of the system is getting higher. And in DFIG the flux from the stator is exposed directly to the grid so if there is any voltage dips then that will causes a sudden loss of the magnetization of the machine. DFIG also very sensitive towards asymmetrical faults [9] for which DFIG requires a crowbar protection equipment to take the control of transient over currents [11-13].

To overcome the above difficulties we are using the brushless doubly fed induction generator (BDFIG) in wind turbines. BDFIG has a larger series leakage reactance hence it experiences less transient current compared to the DFIG so as a result it is possible for BDFIG to ride through the low voltage fault without the need of an extra protecting equipment. So this paper is explained about the analysis of BDFIG in the symmetrical and also asymmetrical low voltage faults.

BDFIG OPERATION

The BDFIG stator has two windings with distinct pole pair numbers in order to prevent direct pairing between the windings. The rotor employs a special design enabling it to couple both stator windings. The stator windings are named as power winding (PW) and control winding (CW). The PW linked directly to the grid whereas the CW linked to the grid through the back to back converter which is variable voltage and variable frequency (VVVF) bidirectional converter that is handling a fraction of rated power [1].

The BDFIG is normally operated under synchronous mode i.e., in doubly fed mode in which shaft angular velocity determined by the excitation frequencies of the PW and CW of the stator, which is independent of the torque exerted on the machine, and can be expressed as the

$$\omega_r = \frac{\omega_1+\omega_2}{p_1+p_2} \tag{1}$$

$where\ \omega_1 and\ \omega_2$ are the excitation angular frequencies supplied to the two stator windings.

When the CW angular frequency ω_2 equals to zero, the angular velocity of the shaft becomes the natural angular velocityω_n.

$$\omega_n = \frac{\omega_1}{p_1+p_2} \tag{2}$$

The vector model of the BDFIG aligned in an arbitrary rotating reference frame of ω is defined as [17]

$$V_1 = R_1 I_1 + \frac{d\phi_1}{dt} + j\omega\,\phi_1 \tag{3}$$

$$\phi_1 = L_1 I_1 + L_{1r} I_r \tag{4}$$

$$V_2 = R_2 I_2 + \frac{d\phi_2}{dt} + j(\omega - (p_1+p_2)\omega_r)\,\phi_2 \tag{5}$$

$$\phi_2 = L_2 I_2 + L_{2r} I_r \tag{6}$$

$$V_r = R_r I_r + \frac{d\phi_r}{dt} + j(\omega - p_1\omega_r)\,\phi_r \tag{7}$$

$$\phi_r = L_r I_r + L_{1r} I_1 + L_{2r} I_2 \tag{8}$$

Where $R_1, R_2, L_1, L_2, L_{1r}, L_{2r}, L_r$ are the PW resistance, CW resistance, PW self-inductance, CW self-inductance, mutual inductance between PW and rotor, mutual inductance between CW and rotor, rotor self-inductance respectively?

The active power and reactive power of the power winding (PW) of the stator are expressed as

$$P_1 = \frac{3}{2}\mathrm{Re}[V_1\bar{I_1}]$$

$$Q_1 = \frac{3}{2}\mathrm{Im}[V_1\bar{I_1}]$$

In the steady state all the vectors are rotate at the speedω_1, which is set by the grid frequency because the PW connected to the grid.

$$V_1 = |V_1|e^{j\omega_1 t} \tag{9}$$

Where $|V_1|$ is the magnitude of the PW voltage.

$$I_r = \frac{L_{1r}\phi_1 + L_{2r}L_1 I_2}{L_1L_r - L_{1r}^2 + \frac{L_1R_r}{s - jp_1\omega_r}} \tag{10}$$

From equations (4),(6),(7) &(8) the CW flux linkage can be represented in terms of PW flux linkage and CW current as

$$\varphi_2 = \frac{L_{1r}L_{2r}}{L_{1r}^2 - L_1L_r + \frac{L_1R_r}{s - jp_1\omega_r}}\varphi_1 + \frac{L_1L_2L_r - L_1L_{2r}^2 - L_2L_{1r}^2 + \frac{L_1L_2R_r}{s - jp_1\omega_r}}{L_1L_r - L_{1r}^2 + \frac{L_1R_r}{s - jp_1\omega_r}}I_2 \tag{11}$$

Where s is the differential operator $\frac{d}{dt}$

The term $s - jp_1\omega_r$ is very large so the reciprocal will be neglected. Then the control winding voltage will be

$$V_2 = I_2R_2 + \frac{L_1L_2L_r - L_1L_{2r}^2 - L_2L_{1r}^2}{L_1L_r - L_{1r}^2}(s - j(p_1 + p_2)\omega_r)I_2 + \frac{L_{1r}L_{2r}}{L_{1r}^2 - L_1L_r}(s - j(p_1 + p_2)\omega_r)\varphi_1$$

$$V_2 = V_{X2} + E_{\varphi 1} \tag{12}$$

Where

$$V_{X2} = (R_2 + L_l(s - j(p_1 + p_2)\omega_r)L_l)I_2 \tag{13}$$

$$E_{\phi 1} = \frac{L_{1r}L_{2r}}{L_{1r}^2 - L_1L_r}(s - j(p_1 + p_2)\omega_r)\phi_1 \tag{14}$$

$$L_l = \frac{L_1L_2L_r - L_1L_{2r}^2 - L_2L_{1r}^2}{L_1L_r - L_{1r}^2} \tag{15}$$

From above the CW voltage is split into two terms which are EMF induced by the PW flux it is referred as $E_{\varphi 1}$ and $V_{X2}$is defined as the voltage drop across the CW resistance and equivalent leakage inductance between the PW and CW which is caused by the CW currentI_2.

For simplicity the PW resistance is ignored for analysing the behaviour of the BDFIG under the faults. Hence the equation (3) can be written as

$$V_1 = \frac{d\varphi_1}{dt} = j\omega_1\varphi_1 \tag{16}$$

Substituting (9) and (16) in (14) gives

$$E_{\phi 1} = \frac{L_{1r}L_{2r}}{L_{1r}^2 - L_1L_r}\frac{\omega_1 - (p_1 + p_2)\omega_r}{\omega_1}|V_1|e^{j\omega_1 t}$$

$$= \frac{L_{1r}L_{2r}}{L_{1r}^2 - L_1 L_r} s_n |V_1| e^{j\omega_1 t} \quad (17)$$

Where s_n is the slip of the BDFIG?

The EMF induced $E_{\varphi 1}$also written as when we are taking CW as a reference frame as subscript (2)

$$E_{\varphi 1}^{(2)} = \frac{L_{1r}L_{2r}}{L_{1r}^2 - L_1 L_r} s_n |V_1| e^{-j(\omega_1 - (p_1 + p_2)\omega_r)t} \quad (18)$$

And the voltage drop due to CW current with respect to CW reference frame is

$$V_{x2}^{(2)} = (R_2 + L_l(s - j(p_1 + p_2)\omega_r)L_l)I_2^{(2)} \quad (19)$$

Hence by combining equations (15) & (16) the CW voltage in terms of PW flux and the voltage drop caused by the CW current by considering the converter point of view is

$$V_2^{(2)} = E_{\varphi 1}^{(2)} + V_{X2}^{(2)} \quad (20)$$

The above equations (15), (16) and (17) shows that normal operation of BDFIG the CW voltage depends on the PW voltage and its gain is proportional to the CW frequency which is determined by the rotor angular velocity ω_r. The slip range for the fractionally rated converter is from -0.3 to 0.3.

BEHAVIOR OF BDFIG UNDER SYMMETRICAL VOLTAGE DIP

Based on the grid code the voltage dip occurs rapidly and grid faults are common in nature. In this symmetrical short circuit of the grid is considered during this the voltage collapse to zero. Consider the fault occurs at the time of t=t_0,

Then

$$V_1 = \begin{cases} V_1 e^{j\omega_1 t} & if\ t < t_0 \\ 0, & if\ t \geq t_0 \end{cases} \quad (21)$$

CW open circuit

Whenever the fault occurs the PW flux linkage is confined in the machine and the rotor windings continue to cut the trapped flux at the prefault speed and the larger EMF $E_{\varphi 1}$ which is observed at the CW though the rotor of the BDFIG.

In this we have to assume the CW is in open circuited. Hence the current flow through the winding is zero. The flux is a state variable and it cannot be discontinuous, hence the PW flux evolves from initial value to zero exponentially, then

$$\varphi_1 = \begin{cases} \frac{|V_1|}{j\omega_1} e^{j\omega_1 t}, & if\ t < t_0 \\ \frac{|V_1|}{j\omega_1} e^{j\omega_1 t_0} e^{\frac{-(t-t_0)}{\tau}} & if\ t \geq t_0 \end{cases} \quad (22)$$

By using the equations (5),(3) and (14) the time constant of flux decay is derived as

$$\tau = \frac{L_1 L_r - L_{1r}^2}{R_1 L_r} \quad (23)$$

By the (22) before the appearance of fault (t<t_0) the steady state flux vector rotates at the synchronous angular velocity $\omega_1$with constant magnitude. Whenever the fault appears then the flux vector stops at $t_0$and then it decays exponentially after that time period (t>t_0).

Then by substitute (21) and (22) in the (17) for t ≥ t_0, with respect to PW reference frame the EMF induced in the CW is

$$E_{\varphi 1} = \frac{L_{1r}L_{2r}}{L_{1r}^2 - L_1 L_r}\left(-j(p_1 + p_2)\,\omega_r\,\phi_1\right) \quad (24)$$

$$= \frac{L_{1r}L_{2r}}{L_{1r}^2 - L_1 L_r}\ (1\text{-}s_n)|V_1|\ e^{j\omega_1 t_0} e^{\frac{-(t-t_0)}{\tau}} \quad (25)$$

By considering the CW is open circuited the CW current is zero then CW voltage will be equal to the induced EMF. Because of the flux the CW voltage is a vector fixed to the PW stationary frame where the magnitude decays exponentially. Hence by the converter point of view the CW voltage vector reverses the rotation and has the angular velocity of $(p_1 + p_2)\omega_r$.

$$V_2^{(2)} = E_{\phi 1}^{(2)}$$

$$= \frac{L_{1r}L_{2r}}{L_{1r}^2 - L_1 L_r}(1\text{-}s_n)|V_1|\ e^{j\omega_1 t_0} e^{\frac{-(t-t_0)}{\tau}} e^{j(p_1+p_2)\omega_r t} \quad (26)$$

From the above equation the CW maximum voltage is obtained when the fault obtained is given by

$$|V_2| = \frac{L_{1r}L_{2r}}{L_{1r}^2 - L_1 L_r}(1\text{-}s_n)|V_1|. \quad (27)$$

The maximum voltage is directly proportional to (1-s_n). Meanwhile the slip of the BDFIG is usually ranging from -0.3 to 0.3, to a speed range of ±30% hence the maximum CW voltage when the fault happens and the machine is running at the rated speed is 130% of the natural speed. By considering the equation the voltage is directly proportional to the slip $|s_n|$ then the maximum voltage at the fault is 4.3 times the CW voltage before the fault.

Analysis of BDFIG under Asymmetrical Voltage Dip

In this case also we are taking the CW is on open circuited which means the current through the CW is zero ($I_2 = 0$). For the analysis of asymmetrical faults we are considering the sequence component method [18][19]. Whenever a fault appears at t = appears at t = t_0 then the PW voltage will be defined as,

$$V_1 = \begin{cases} |V_1| e^{j\omega_1 t} if\ t < t_0 \\ |V_{1p}| e^{j\omega_1 t} + |V_{1n}| e^{-j\omega_1 t}, \quad if\ t \geq t_0 \end{cases} \quad (28)$$

Where then subscripts p, n represents the positive and the negative sequence which are decomposed as

$$\begin{bmatrix} |V_{1p}| \\ |V_{1n}| \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & e^{j\frac{2\pi}{3}} & e^{j\frac{4\pi}{3}} \\ 1 & e^{j\frac{4\pi}{3}} & e^{j\frac{2\pi}{3}} \end{bmatrix}\begin{bmatrix} V_{1a} \\ V_{1b} \\ V_{1c} \end{bmatrix} \quad (29)$$

Where
$$V_{1a} = V \sin \omega_1 t$$
$$V_{1b} = V \sin(\omega_1 t + \frac{2\pi}{3})$$
$$V_{1c} = V \sin(\omega_1 t + \frac{4\pi}{3})$$

The flux generated by the forward sequence is rotating at the synchronous speed and the flux generated by the backward sequence is rotating at the synchronous speed but it is in the reverse direction. The equation for the flux of positive and negative component is obtained as

$$\varphi_{1p} = \frac{|V_{1p}|}{j\omega_1} e^{j\omega_1 t} \tag{30}$$

$$\phi_{1n} = \frac{|V_{1n}|}{-j\omega_1} e^{-j\omega_1 t} \tag{31}$$

The positive and negative sequence components of the PW flux linkage in the steady state can be varied with the type of fault which is obtained. In this paper we will discuss about the three types of asymmetrical faults which are phase to phase short circuit (p-p), one phase to the ground short circuit (p-n) and phase to phase to ground short circuit (p-p-n). The PW of the BDFIG is connected in Δ then the PW voltage and flux linkage are expressed as

Phase to phase short circuit (p-p):

$$\begin{bmatrix} V_{1a} \\ V_{1b} \\ V_{1c} \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{\sqrt{3}}{2} V \sin(\omega_1 t + \frac{3\pi}{2}) \\ \frac{\sqrt{3}}{2} V \sin(\omega_1 t + \frac{\pi}{2}) \end{bmatrix} \tag{32}$$

$$\begin{bmatrix} \varphi_{1p} \\ \varphi_{1n} \end{bmatrix} = \frac{1}{j\omega_1} \begin{bmatrix} \frac{1}{2} V e^{j\omega_1 t} \\ \frac{1}{2} V e^{-j\omega_1 t} \end{bmatrix} \tag{33}$$

For phase to ground short circuit (p-n):

$$\begin{bmatrix} V_{1a} \\ V_{1b} \\ V_{1c} \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{3}}{3} V \sin(\omega_1 t + \frac{\pi}{6}) \\ V \sin(\omega_1 t + \frac{4\pi}{3}) \\ \frac{\sqrt{3}}{3} V \sin(\omega_1 t + \frac{\pi}{2}) \end{bmatrix} \tag{34}$$

$$\begin{bmatrix} \phi_{1p} \\ \phi_{1n} \end{bmatrix} = \frac{1}{j\omega_1} \begin{bmatrix} \frac{2}{3} V e^{j\omega_1 t} \\ \frac{1}{3} V e^{-j(\omega_1 t - \frac{4\pi}{3})} \end{bmatrix} \tag{35}$$

Phase to phase to ground short circuit (p-p-n):

$$\begin{bmatrix} V_{1a} \\ V_{1b} \\ V_{1c} \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{\sqrt{3}}{3} V \sin(\omega_1 t + \frac{3\pi}{2}) \\ \frac{\sqrt{3}}{3} V \sin(\omega_1 t + \frac{\pi}{2}) \end{bmatrix} \tag{36}$$

$$\begin{bmatrix} \phi_{1p} \\ \phi_{1n} \end{bmatrix} = \frac{1}{j\omega_1} \begin{bmatrix} \frac{1}{3} V e^{j\omega_1 t} \\ \frac{1}{3} V e^{-j\omega_1 t} \end{bmatrix} \tag{37}$$

Whenever the transient state happens the PW flux linkage is continuous from one state to the other state and also a transient zero sequence is introduced to connect these two states although there is step change in voltage[20] when the fault happens at t = t_0. So the flux linkage for zero sequence φ_{1z} is added then the PW flux linkage is expressed as

$$\phi_{1p} + \phi_{1n} + \phi_{1z} = \phi_1 \tag{38}$$

Substitute the equations (30),(31) in (38), then the zero sequence flux linkage written as PW reference frame is

$$\phi_{1z} = \left| \frac{(|V_1| - |V_{1p}|) e^{j\omega_1 t} - |V_{1n}| e^{-j\omega_1 t_0}}{j\omega_1} \right| e^{\frac{-(t-t_0)}{\tau}} (39)$$

Since we are considering the CW is open circuited then the CW current is zero, the CW voltage is the EMF induced From CW stationary reference frame from the equations (14),(20),(38) and (39) the voltage is

$$V_2^{(2)} = E_{\phi 1p}^{(2)} + E_{\phi 1n}^{(2)} + E_{\phi 1z}^{(2)} \quad (40)$$

Where

$$E_{\phi 1p}^{(2)} = \frac{L_{1r}L_{2r}}{L_{1r}^2 - L_1 L_r} s_n |V_{1p}| e^{j s_n \omega_1 t} \quad (41)$$

$$E_{\phi 1n}^{(2)} = \frac{L_{1r}L_{2r}}{L_{1r}^2 - L_1 L_r} (2 - s_n) |V_{1n}| e^{-j(2-s_n)\omega_1 t} \quad (42)$$

$$E_{\phi 1z}^{(2)} = \frac{L_{1r}L_{2r}}{L_{1r}^2 - L_1 L_r} (1 - s_n)\omega_1 |\phi_{1z}| e^{-j(1-s_n)\omega_1 t} e^{\frac{-(t-t_0)}{\tau}} \quad (43)$$

From converter side the open circuited voltage that contains all the three components during an asymmetrical fault at $t \geq t_0$

Steady state positive sequence of $E_{\phi 1p}^{(2)}$: In this sequence $E_{\phi 1p}^{(2)}$rotates at an angular velocity of $\omega_1 - (p_1 + p_2)\omega_r$,with slip of $|s_n|$. It is aligned with the prefault EMF but with a smaller magnitude due to forward sequence of grid voltage which is under fault $|V_{1p}|$ which is smaller than the rated voltage $|V_1|$. Usually the BDFIG is designed with a speed range of $\pm 30\%$, hence the slip is -0.3 to 0.3.

Steady state negative sequence of $E_{\phi 1n}^{(2)}$: In this sequence $E_{\phi 1p}^{(2)}$rotates at an angular velocity of $-\omega_1 - (p_1 + p_2)\omega_r$,with slip of $|2 - s_n|$.In this, the scaling factor is much larger than the positive sequence and maximum is the 2.3 when the BDFIG is running at high speed. That means the speed is 130 % of natural speed. The negative sequence component voltage $|V_{1n}|$ is smaller than the grid rated voltage.

Transient zero sequence of $E_{\varphi 1z}^{(2)}$: In this sequence $E_{\varphi 1p}^{(2)}$rotates at an angular velocity of $-(p_1 + p_2)\omega_r$,with slip of $|1 - s_n|$. In this case also the value is more than the positive sequence with a maximum value of 1.3. The magnitude of zero sequence of the CW voltage is obtained by the time whenever the fault occur and decays with the time constant of τ which can be obtained as $\frac{L_1 L_r - L_{1r}^2}{R_1 L_r}$.

Table 1: Prototype Machine Specifications

Parameter-Value	Parameter-Value
Machine rating-250KW	L_1 -0.105 H
PW/CW pole pairs-2/4	L_2 -0.382 H
PW rated voltage-690V(50HZ)	L_{1r} -0.004 H
PW rated current-178A(line)	L_{2r} -0.006 H
CW rated voltage-620V(50HZ)	L_r -2.602$\times 10^{-4} H$
CW rated current-84A(line)	R_1 -0.079 ohm
Operating speed-350~650r/m	R_2-0.621 ohm
Rated torque-3670Nm	R_r -1.770$\times 10^{-4} ohm$

EXPERIMENTAL RESULTS

The results of the simulation which are constructed under the MATLAB/SIMULINK to verify the mathematical model of the brushless doubly fed induction generator under the symmetrical and asymmetrical low voltage faults. A 250KW rating BDFIG is taken for this analysis. When the fault happens at the time t=0 sec then the EMF induced in the control winding of the BDFIG is raised and after fault clearing it is decaying exponentially. The Figure shows the behaviour of the BDFIG under symmetrical fault the control winding EMF and flux waveforms. The Figure 2 shows the behaviour of the BDFIG under the asymmetrical fault which is one phase to ground fault the EMF induced in the control winding, EMF induced in the rotor winding of the machine. In figure 3 shows the behaviour of BDFIG under asymmetrical phase to phase fault in this also the EMF of the rotor winding is decreased exponentially after the fault clearing.

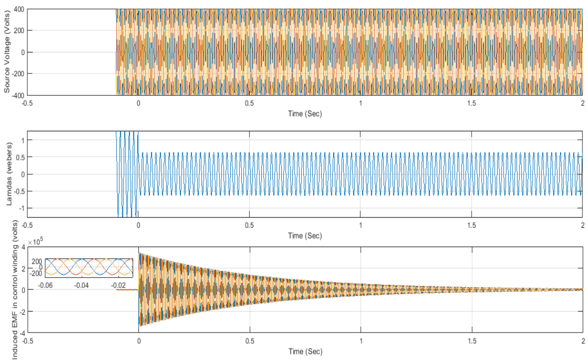

Figure 1: Symmetrical Fault.

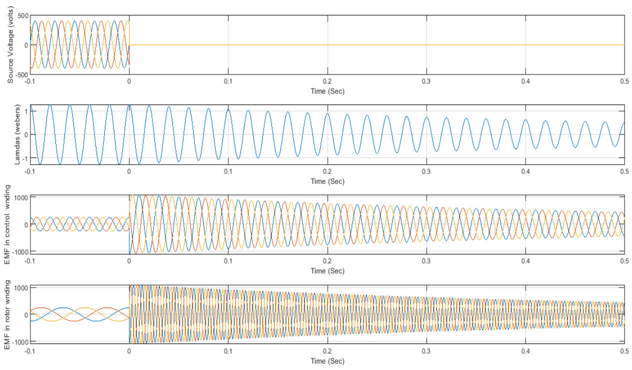

Figure 2: Asymmetrical Fault (Phase To Ground).

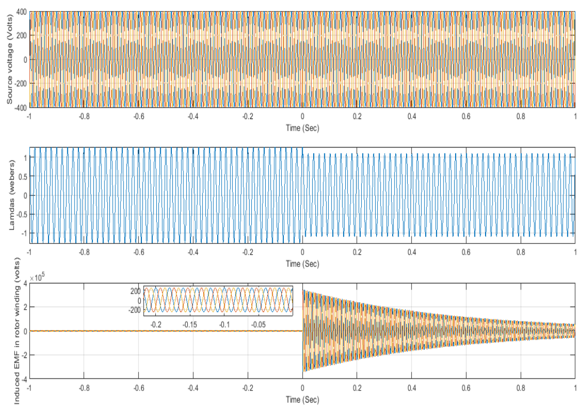

Figure 3 Asymmetrical Fault Phase To Phase.

CONCLUSIONS

This paper analysed the behaviour of the BDFIG under symmetrical and asymmetrical low voltage faults. The asymmetrical faults that consider here are phase to ground and phase to phase low voltage faults. The experimental results proved that the without any need of external hardware such as crowbar circuits BDFIG is able to meet the grid regulations.

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