

Comparing Schemes to mitigate the effect of symmetrical grid voltage sags on the operation of a Double-Fed Induction Generator

SANAA AMER, MONA N. ESKANDER
Electronics Research Institute
Cairo,
EGYPT

Abstract: - To lessen the negative impact of symmetrical voltage sag on the performance of a grid-connected wind-driven double-fed induction generator (WD-DFIG), four methods are suggested in this study. Adding RL impedance to the stator winding, adding RL impedance to the rotor winding, adding RL impedances to the stator and rotor windings simultaneously, and adding a passive filter to the stator windings are the four methods. At two voltage sag values at sub-sync and super-sync speeds, the response of the stator current, rotor current, rotor voltage, dc link current, dc link voltage, and electromagnetic torque under each suggested technique is compared at sub-sync & super-sync speeds.

Key-words: - DFIG, passive filter, voltage sag, voltage swell, stator added impedance, rotor added impedance.

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1 Introduction

The double-fed induction generator DFIG has a large share in wind energy conversion systems (WECS) due to its benefits of variable speed operation, lower-cost rotor converters, and active and reactive power independent control [1,2,16]. The stator is connected directly to the power grid, and the rotor is connected to the grid via a back-to-back voltage-source converter comprising a rotor-side converter (RSC) and a grid-side converter (GSC). Despite these benefits, the DFIG-based WECS is known for its limited fault-ride-through (FRT) capability due to the stator's direct connection to the grid. During grid voltage sags and swells, the stator and GSC are directly affected by the sudden change in the DFIG bus voltage. Stator perturbations will induce large voltages in rotor windings and lead to uncontrolled rotor current. The rotor overcurrent may cause a large increase in DC-link voltage. Both rotor inrush current and DC-link overvoltage can damage wind turbines and may lead to tripping of the wind-driven DFIG (WD-DFIG).

Several studies have been conducted to investigate the performance of DFIG-based WECS during grid faults and propose several techniques to mitigate the adverse effects of the grid faults [3-15].

Reviews on fault-ride-through (FRT) techniques for improving the transient stability of WD-DFIG were presented in [3-4], where FRT solutions were divided into protection circuits, Flexible Alternating Current Transmission System (FACTS) device-based methods, traditional control methods, and advanced control techniques. However, a comparative analysis

was not done to determine the benefits and drawbacks of each method. In [5], the stator voltage is kept constant at the nominal value by controlling the rotor-side converter of the DFIG. In [6], a dynamic voltage restorer (DVR) and high-power density of superconducting magnetic energy storage devices were applied for FRT of DFIG. In [7], superconducting magnetic energy storage (SMES) and a series transformer are incorporated for FRT. Using SMES for FRT is still expensive and costly. In [8] a modular multi-level inverter was applied, which leads to a complicated control system. In [9], a terminal-connected series dynamic braking resistor (SDBR) is applied to assist the low voltage ride-through of the DFIG. In [10] LCL filters are introduced in the wind turbine, which are of high power and hence high cost. In [11], the impact of the dynamic coupling between the dual-sequence PLLs on the dynamic stability during the steady-state stage of an asymmetric fault is analyzed. This analysis did not consider the symmetric fault. In [12] the authors proposed a control methodology for symmetrical and unsymmetrical FRT based on rotor components optimization called RCO tailored for the rotor side converter (RSC) within the DFIG. In [13], a non-linear forward power controller with an adaptive backstepping command using parametric estimation was designed to enhance fault ride-through (FRT) capacities in wind parks utilizing DFIGs. In [14] the effect of the DC link parameters on the FRT of DFIG was investigated. In [15] a coordinated control strategy for an integrated Battery Energy Storage System (BESS) and STATCOM, called BESS-

STATCOM, aimed at improving the FRT capability of DFIG-based WECSs.

In this paper, four techniques are proposed to mitigate the adverse effect of symmetrical voltage sag on the operation of a grid-connected wind-driven double-fed induction generator (WD-DFIG) at two values of grid voltage sags. In the first proposed method, a three-phase R-L impedance is connected between the grid and the stator coils. The same three-phase R-L impedance is connected between the rotor circuit and the RSC during the fault period in the second proposed method. The third proposal consists of adding the R-L impedances to the stator coils and rotor coils simultaneously. The fourth method comprises a stator-connected passive filter. Different values of the added impedance resistance and inductance are tested to determine the optimum values concerning the smaller current and voltage peaks, and the faster recovery to their steady-state values. The DFIG is modeled with each proposed mitigation scheme, and simulation results are compared. The response of the stator current, rotor current, rotor voltage, DC link current, DC link voltage, and the electromagnetic torque under each proposed technique is compared at two values of grid voltage sag. Results proved that when applying the R-L impedance to the stator and rotor simultaneously, lower current and voltage peaks and faster recovery times are obtained

2 System Description

2.1 DFIG mathematical equations

A wind-driven grid-connected DFIG system's basic setup is depicted in Figure 1. The system consists of an induction machine, a rotor side converter (RSC), a dc link, a grid side converter (GSC), and a filter.

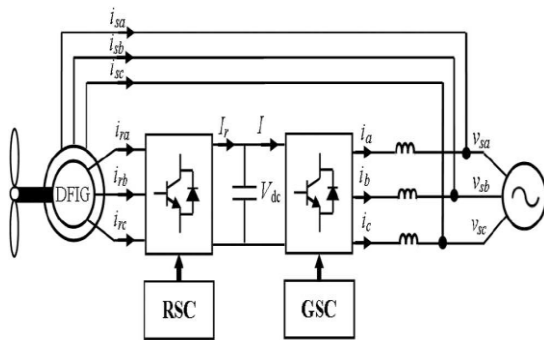


Fig. 1: Basic structure of wind-driven grid-connected (DFIG).

In the synchronous rotating reference frame (d-q), the DFIG stator and rotor voltages are represented by [16]:

$$v_{sd} = R_s i_{sd} - \omega_s \phi_{sq} + p \phi_{sd} \quad (1)$$

$$v_{sq} = R_s i_{sq} + \omega_s \phi_{sd} + p \phi_{sq} \quad (2)$$

$$v_{rd} = R_r i_{rd} - s \omega_s \phi_{rq} + p \phi_{rd} \quad (3)$$

$$v_{rq} = R_r i_{rq} + s \omega_s \phi_{rd} + p \phi_{rq} \quad (4)$$

where v_{sd} and v_{sq} are the d - q components of the stator voltage, i_{sd} and i_{sq} are the d - q components of the stator current, ϕ_{sd} and ϕ_{sq} are the d - q components of the stator flux, R_s is the stator resistance, v_{rd} and v_{rq} are the d - q components of the rotor voltage, i_{rd} and i_{rq} are the d - q components of the rotor current, ϕ_{rd} and ϕ_{rq} are the d - q components of the rotor flux, R_r is the rotor resistance, ω_s is the synchronous angular speed, ω_r is the rotational speed, and $s = (\omega_s - \omega_r)/\omega_s$.

$$\phi_{sd} = L_s i_{sd} + L_m i_{rd} \quad (5)$$

$$\phi_{sq} = L_s i_{sq} + L_m i_{rq} \quad (6)$$

$$\phi_{rd} = L_r i_{rd} + L_m i_{sd} \quad (7)$$

$$\phi_{rq} = L_r i_{rq} + L_m i_{sq} \quad (8)$$

The electromagnetic torque of the generator is given by:

$$T_{em} = -p \frac{L_m}{L_s} (\phi_{sd} i_{rq} - \phi_{sq} i_{rd}) \quad (9)$$

Where, suffixes s and r stand for stator and rotor parameters respectively, V is the voltage, I is the current, ϕ is the flux, L_m is the mutual inductance, L_s is the self-inductance, R is the resistance per phase, ω_s is the synchronous speed, P is the number of pole pairs, and "p" is the d/dt operator.

2.2 Back to back converters

The dynamics of the dc-link voltage between the two converters is expressed by

$$C p V_{dc} = I - I_r \quad (10)$$

Where I_r is the current at the output of the RSC and I is the current input to the GSC.

2.3 Grid dynamics

The grid current dynamics in the (d-q) reference frame are given by:

$$p i_d = -\frac{R}{L} i_d + \omega i_q - \frac{v_s}{L} + \frac{1}{L} v_d \quad (11)$$

$$p i_q = -\frac{R}{L} i_q - \omega i_d + \frac{1}{L} v_q \quad (12)$$

Where v_d and v_q are the d-q components of the grid voltage, i_d and i_q are the d-q components of the grid current, R is the filter resistance, L is the filter inductance, and ω is the angular speed.

The active power and reactive power at the grid converter output can be approximated as:

$$P_g = \frac{3}{2} V_s i_q \quad (13)$$

$$Q_g = \frac{3}{2} V_s i_d \quad (14)$$

2.4 Three-phase harmonic filter

A three-phase passive filter is designed and connected to the stator circuit's input. Its function is to reduce voltage distortion caused by three-phase voltage sag or swell. Harmonic filters reduce distortion by diverting harmonic currents into low-impedance paths.

2.5 Ratio between stator parameters and R-L impedance

The value of the R-L impedance is chosen as a ratio of the stator resistance and stator self-inductance. Figures 2a, 2b, 2c show the stator current, rotor voltage and current, and the DC link voltage and current at three values of R-L impedance during voltage sag. It is clear that with $R=1000\ \Omega$ and $L=0.01\ \text{H}$, lower current and voltage peaks and faster recovery time are obtained. The ratio $R/R_s=1000$, while the ratio $L/L_s=0.01/0.006=1.67$.

Table 1 illustrates the settling time T_s for DFIG currents and voltages across three inductance values of the supplementary external impedances (0.0001H, 0.001H, and 0.01H), demonstrating that the optimal settling time for DFIG variables is achieved at $L=0.01\ \text{H}$.

Table 1

DFIG variables	T_s at $L=0.001\ \text{H}$	T_s at $L=0.01\ \text{H}$	T_s at $L=0.1\ \text{H}$
I_s	0.06 S	0.05 S	0.15 S
V_r	0.1 S	0.1 S	0.13 S
I_r	0.13 S	0.12 S	0.18 S
V_{dc}	0.18 S	0.18 S	0.22 S
I_{dc}	0.2 S	0.13 S	0.2 S

3 Simulation Results for 3-phase symmetrical voltage sag at sub synchronous speed

A 3-phase symmetrical voltage sag (460v-300v) is assumed for 0.2 seconds from (0.8- 1sec). The system is modeled and simulated using Matlab/Simulink for the four proposed protection techniques in addition to the DFIG without any protection devices, namely: the stator-connected impedance, the rotor circuit connected impedance, both stator and rotor added impedances, and the passive filter connected to the DFIG stator.

3.1 DFIG without any protection devices

Figure 3 shows the stator voltage, stator current, rotor voltage, and rotor current during a voltage sag without protection devices. The shown high currents' and voltages' peaks and oscillations cause damage to the machine and the power electronic devices [17].

3.2 DFIG with stator R-L impedance protection during voltage sag

Simulation results shown in Figure 4 are obtained when connecting the designed three-phase R-L impedance between the grid and the stator coils of the DFIG during a voltage sag (460-300V). The shown stator current, rotor current, rotor voltage, DC link voltage, DC link current, and electric torque peaks at the start and end of the voltage sag are diminished when comparing Figure 3 and Figure 4. .

3.3 DFIG with rotor R-L impedance protection during voltage sag

Simulation results shown in Figure 5 are obtained when connecting the proposed three-phase R-L impedance protection between the rotor coils and the RSC during the voltage sag. The peaks of the shown stator current, rotor current, rotor voltage, DC link voltage, DC link current, and electric torque at the start and end of the voltage sag are diminished when comparing Figure 3 and Figure 5. However when compared to Figure 4, it is clear that the current and voltage peaks and oscillations are almost the same.

3.4 DFIG with both stator and rotor R-L impedances protection during voltage sag

Simulation results shown in Figure 6 are obtained when connecting the designed three-phase R-L impedance between the grid and the stator coils and a similar R-L impedance between the rotor coils and the RSC. It is evident that the currents' and voltages' peaks and the settling time are better than those in Figure 4 and Figure 5.

3.5 DFIG with stator-connected passive filter during voltage sag

A three-phase passive filter is connected at the input of the stator, between the stator coils and the ground. Results are shown in Figure 7. It is evident that the currents' and voltages' peaks and ripples are higher than in the case where the R-L impedance is added to both stator and rotor coils.

Table 2 presents the maximum variables magnitudes corresponding to each of the four proposed mitigation approaches at both the initiation and conclusion of the fault condition. Their reduced peaks illustrate the benefits associated with the concurrent incorporation of impedances in both the stator and rotor.

Table 2

Mitigation method	Stator impedance		rotor impedance		Stator & rotor impedances		Filter	
	Start of fault	End of fault	Start of fault	End of fault	Start of fault	End of fault	Start of fault	End of fault
I_s (amp)	15	14	12	10	12	10	12.5	11
V_r (volt)	200	400	250	400	210	400	220	400
I_r (amp)	10	6	10	6	9	6	10	6
V_{dc} (volt)	105	90	105	90	100	85	110	90
I_{dc} (amp)	11.5	6	12	6.5	10	6	11.5	6
T_e (N.m.)	20	-20	20	-20	15	-20	21	-21

4 Simulation Results for symmetrical deeper voltage sag at sub-synchronous speed

A 3- phase symmetrical deep voltage sag (460v-150v) is assumed for 0.2 seconds from (0.8- 1 second). The system is modeled and simulated using Matlab/Simulink for two of the four proposed protection techniques, namely: rotor-connected R-L impedance, and when R-L impedances are connected to both stator and rotor. These two cases are enough to prove the validity of the proposed protection schemes at different values of voltage sag.

4.1 DFIG with rotor R-L impedance protection during deep voltage sag

Simulation results shown in Figure 8 are obtained when connecting the designed three-phase R-L impedance between the rotor circuit and the RSC of the DFIG during a deep voltage sag. The shown stator current, rotor current, rotor voltage, DC link voltage, DC link current, and electric torque peaks at the start and end of the voltage sag are higher than the previous case due to the deeper voltage sag.

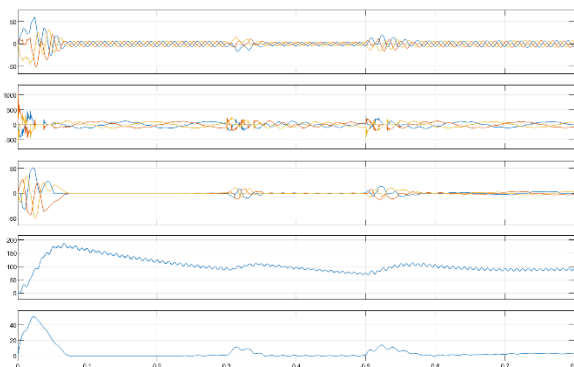


Fig. 2a. R=1000 Ω , L=0.001 H

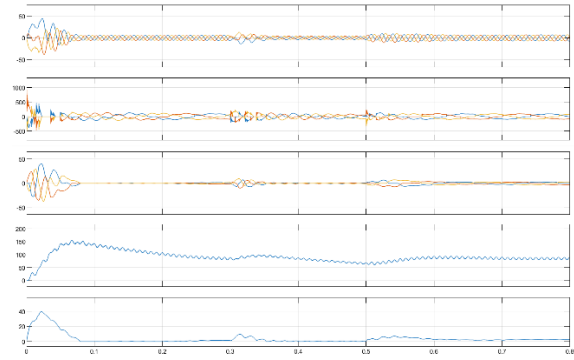


Fig. 2b. R=1000 Ω , L=0.01H

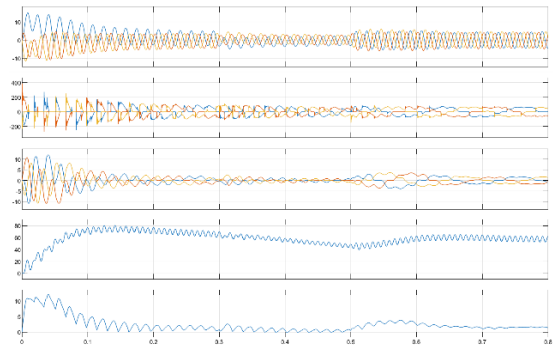


Fig. 2c. R=1000 Ω , L=0.1H

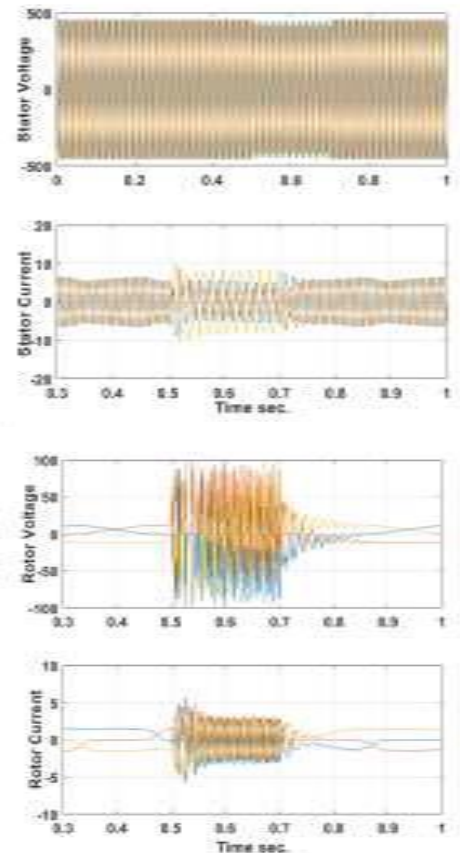


Fig. 3 stator voltage, stator current, rotor voltage, rotor current, during voltage sag without any protection devices

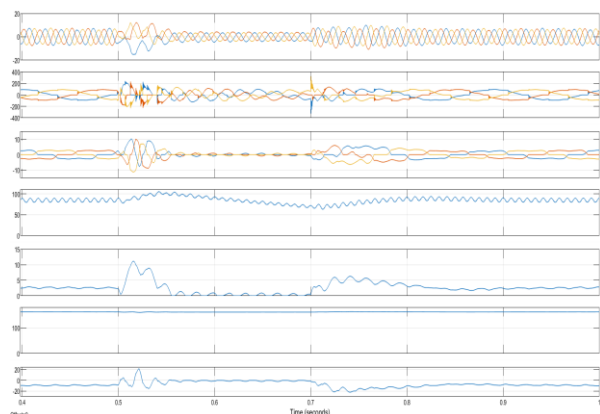


Fig. 4 stator current, rotor voltage, rotor current, DC link voltage, DC link current, rotor speed, & electric torque during symmetrical voltage sag with stator-connected R-L impedance at sub-synch speed

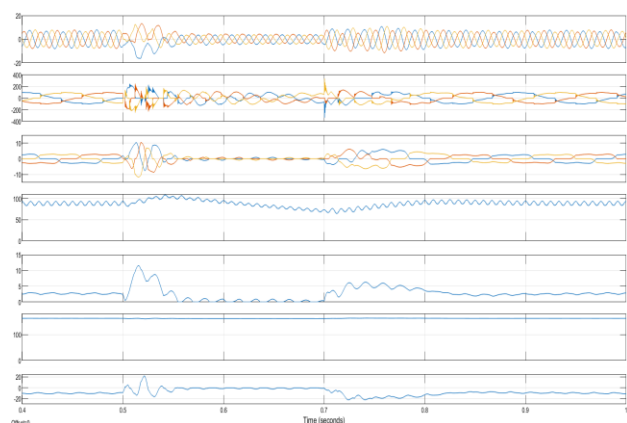


Fig. 5 stator current, rotor voltage, rotor current, DC link voltage, DC link current, rotor speed, & electric torque during symmetrical voltage sag with rotor-connected R-L impedance at sub-synch speed

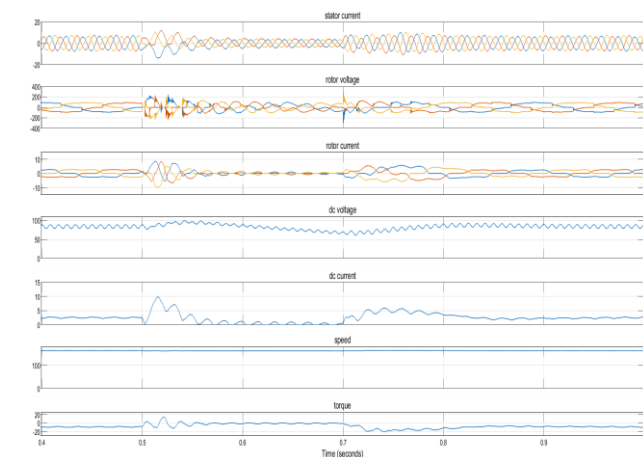


Fig. 6 stator current, rotor voltage, rotor current, DC link voltage, DC link current, rotor speed, & electric torque during symmetrical voltage sag with connected stator and rotor R-L impedance at sub-synch. speed

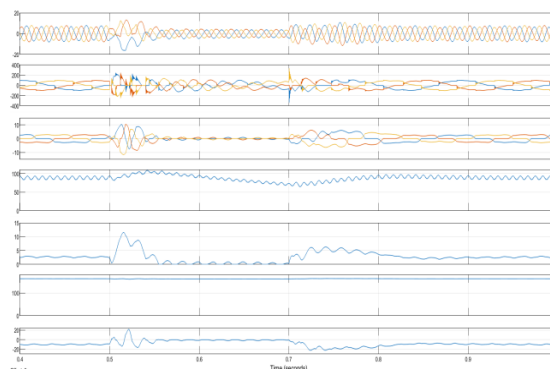


Fig. 7 stator current, rotor voltage, rotor current, DC voltage, DC link current, rotor speed, & electric torque during symmetrical voltage sag with connected stator passive filter at sub-synch. speed

Table 3 displays the peak current and voltage values for each of the two recommended mitigation techniques at sub-synchronous speed for the deep voltage sag. The benefits of the concurrently added external stator and rotor additional impedances are seen in the lower peaks of these variables.

Table 3

Variables	Rotor impedances		Stator & rotor impedances	
	Start of fault	End of fault	Start of fault	End of fault
I_s (amp)	20	30	20	26
V_r (volt)	400	600	400	550
I_r (amp)	25	23	20	18
V_{dc} (volt)	140	150	130	135
I_{dc} (amp)	30	27	22	18
T_e (N.m.)	50	75	25	50

4.2 DFIG with both stator and rotor R-L impedances protection during deep voltage sag

Simulation results shown in Figure 9 are obtained when connecting the designed three-phase R-L impedance between the grid and the stator coils and a similar R-L impedance between the rotor coils and the RSC. It is evident that the currents' and voltages' peaks and ripples are higher than in the case of a small voltage sag. Also, the settling time is longer. Comparing Figure 8 and Figure 9 proves that connecting impedances to the stator and the rotor simultaneously gave better results in both cases of light and deep voltage sag.

5 Simulation Results for symmetrical deep voltage sag at super synchronous speed

A 3- phase symmetrical deep voltage sag (460v-150v) is assumed for 0.2 seconds from (0.8- 1 second) at super synchronous speed. The system is modeled and simulated using Matlab/Simulink for two of the four proposed protection techniques, namely: rotor-connected R-L impedance, and when R-L impedances are connected to both stator and rotor. These two cases are enough to prove the validity of the proposed protection schemes at different values of voltage sag.

5.1 DFIG with rotor R-L impedance protection during deep voltage sag at super synchronous speed

Simulation results shown in Figure 10 are obtained when connecting the designed three-phase R-L impedance between the rotor circuit and the RSC of the DFIG during a deep voltage sag at super synchronous speed. The shown stator current, rotor current, rotor voltage, DC link voltage, DC link current, and electric torque peaks at the start and end of the voltage sag are higher than the previous case due to the deeper voltage sag.

5.2 DFIG with both stator and rotor R-L impedances protection during deep voltage sag at super synchronous speed

Simulation results shown in Figure 11 are obtained when connecting the designed three-phase R-L impedance between the grid and the stator coils and a similar R-L impedance between the rotor coils and the RSC. Comparing Figure 10 and Figure 11 proves that the simultaneous connection of R-L impedances leads to lower transient currents and voltage peaks and lower recovery time for sub- and super-synchronous speed at light and deep voltage sag. Table 4 displays the peak current and voltage values for each of the two recommended mitigation techniques at super-synchronous speed for the deep voltage sag. The benefits of the concurrently added external stator and rotor additional impedances are seen in the lower peaks of these variables.

Table 4

Variables	Rotor impedances		Stator & rotor impedances	
	Start of fault	End of fault	Start of fault	End of fault
I_s (amp)	20	25	19	21
V_r (volt)	400	600	500	500
I_r (amp)	25	22	21	20
V_{dc} (volt)	140	115	60	100
I_{dc} (amp)	30	23	21	18
T_e (N.m.)	50	110	30	75

6 Conclusion

In this paper four methods are proposed to lessen the impact of symmetrical voltage sag on the performance of a grid-connected wind-driven double-fed induction generator (WD-DFIG). Adding RL impedance to the stator winding, adding RL impedance to the rotor winding, adding RL impedances to the stator and rotor windings simultaneously, and adding a passive filter to the stator windings are the four methods. At two voltage sag values, at sub-sync and super-sync speeds, the WD-DFIG system is modeled, and simulation results are obtained using Matlab- simulink software. The simulation results include the response of the stator current, rotor current, rotor voltage, dc link current, dc link voltage, and electromagnetic torque under each suggested protection technique. The responses are examined at two values of voltage sag (% and .%). Comparing these responses proved that adding the designed RL impedance to the stator windings and another RL impedance to the rotor windings simultaneously led to lower current and voltage peaks during voltage sags at sub-synchronous as well as super-synchronous DFIG speeds.

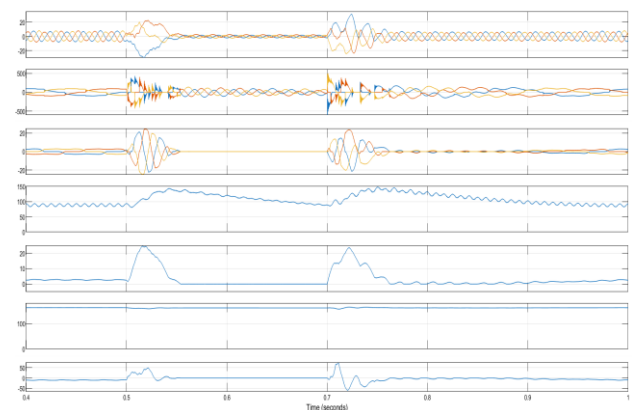


Fig. 8 stator current, rotor voltage, rotor current, DC link voltage, DC link current, rotor speed, &electric torque during deep voltage sag with rotor-connected R-L impedance at sub-sync speed

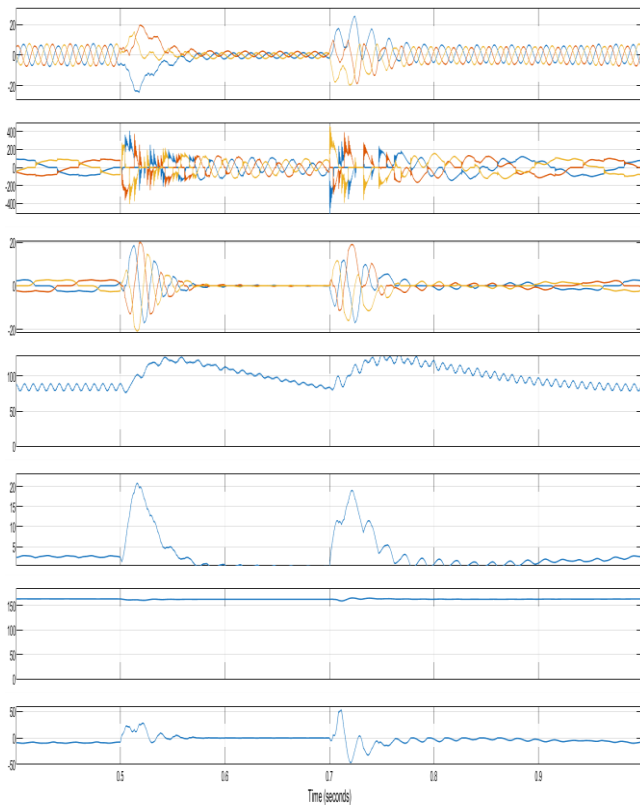


Fig. 9 stator current, rotor voltage, rotor current, DC link voltage, DC link current, rotor speed, & electric torque during deep voltage sag with stator and rotor-connected R-L impedances at sub-syn speed and deep voltage sag

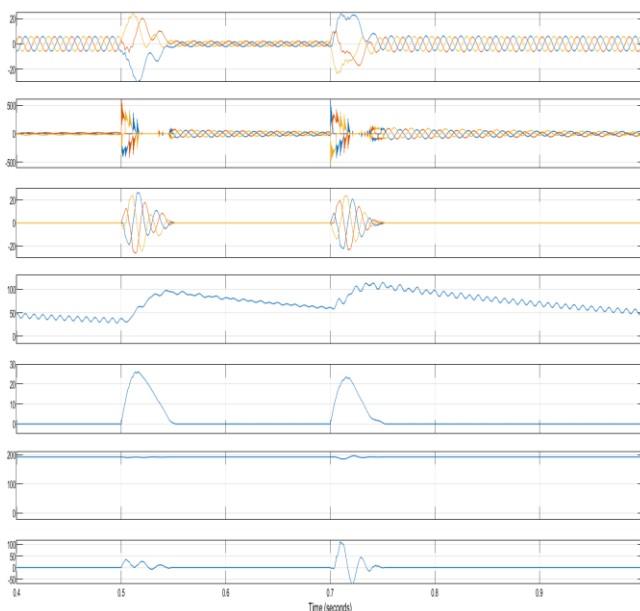


Fig. 10 stator current, rotor voltage, rotor current, DC link voltage, DC link current, rotor speed & electric torque during deep voltage sag with rotor-connected R-L impedance at super synchronous speed

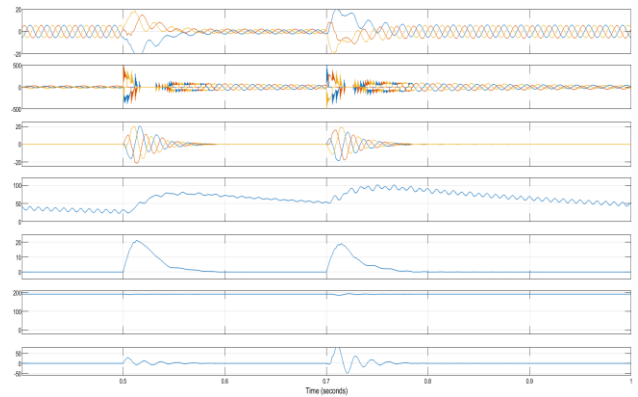


Fig. 11 stator current, rotor voltage, rotor current, DC link voltage, DC link current, rotor speed, & electric torque during deep voltage sag with stator and rotor-connected R-L impedances at super-syn speed

Declaration of Generative AI and AI-assisted Technologies in the Writing Pro

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

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The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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