Comparing Methods to Mitigate the Effect of Grid Voltage Sag and Frequency Variation on the Operation of Variable Speed Drives

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Abstract: - In this paper, the effect of unsymmetrical grid voltage sag on the performance of a slip power recovery drive is studied, and two strategies to mitigate its effects are investigated. The first strategy consists of three phase parallel RL impedance connected to the rotor circuit. The second strategy consists of three phase LCL filter connected to the rotor circuit. A PI controller is tuned to test the drive at constant speed. Also, the effect of grid frequency drop on the drive performance is investigated with the same two protection strategies. The proposed systems are modeled with Matlab/Simulink and the simulation results are compared. The drive performance without any protection schemes are compared with its performance with the two proposed strategies. The compared results include the stator voltage and current, the rotor voltage and current, the DC link voltage and current, the electric torque, and the rotor speed.

Key-Words: - unsymmetrical voltage sag, three phase LCL filter, PI controller, grid frequency, three phase parallel RL impedance, protection.

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1 Introduction

The quality of electricity is an important issue for electricity distribution companies and end-users such as the industrial sector. Low power quality can disturb the customer's production process, and this, in turn, leads to loss of revenue. The variable speed drive (VSD) technology is vastly used in various industrial applications. The slip power recovery drive (SPRD) is one of the employed VSDs in industrial systems. It consists of a wound rotor induction machine with its rotor circuit connected to a 3-phase rectifier, a DC link, and a 3-phase inverter to provide speed and torque control. It employs low cost converters since the rotor power is a fraction of stator power. These drives may be subjected to power quality issues such as symmetrical and unsymmetrical voltage sag, unrated supply frequency, and harmonic distortion. Voltage sag causes a high current peak, high torque peak at the point of voltage recovery, and speed loss during the sag. In addition, unsymmetrical voltage sag results in increased losses, and therefore a rise in temperature, a decrease in the motor's efficiency, and a decrease in the lifetime of insulation, [1]

Several proposals for mitigating the effects of voltage sag on the performance of VSD have been proposed in the literature. Kinetic energy recovery [2], increasing the DC bus capacitor size [3], adding a boost converter [4], applying series dynamic braking resistors [5], and applying different Flexible AC Transmission System (FACTS) devices are examples of these proposals, [6], [7], [8], [9].

Another power quality problem is the decrease in supply frequency which causes a decrease in the speed of the rotating field on the stator, affecting the efficiency of the SPRD. Also, since the stator of the SPRD is directly connected to the grid without an electronic device, it is very sensitive to supply frequency deviation. The influence of supply frequency variation on the performance of induction motor drives was studied without giving specific solutions for such problems, [10], [11].

In this paper, the effect of unsymmetrical grid voltage sag on the performance of the drive is studied, and two strategies to mitigate their effects are investigated. The first strategy consists of three phase parallel RL impedance connected to the rotor circuit. The second strategy consists of three phase LCL filter connected to the rotor circuit. A PI controller is tuned to test the drive at constant speed.

The proposed systems are modeled with Matlab/Simulink and the simulation results are compared. The performance without any protection results are compared with the results of the two

proposed strategies. The compared results include the stator voltage and current, the rotor voltage and current, the DC link voltage and current, the electric torque, and the rotor speed. The decrease in transients at the starting and end of the symmetrical and unsymmetrical voltage sag in currents, voltages, and electric torque are noticed with better performance when using the LCL filter. Also, the effect of grid frequency drop on the drive performance is investigated with the same two protection strategies. The compared results include the stator voltage and current, the rotor voltage and current, the DC link voltage and current, the electric torque, and the rotor speed.
The paper's contributions are summarized as follows:

1. Investigating simple techniques for fault-ride-through of slip energy recovery drives during symmetrical and unsymmetrical voltage sags.
2. Investigating simple techniques to prevent the diverse effects of frequency variation on the slip energy recovery drives.

Hence improving the power quality of the grid-connected drives can be achieved.

2 System Description

The block diagram of the investigated system is shown in Figure 1, including the two proposed protection schemes.

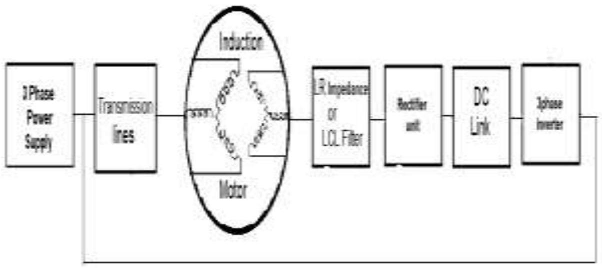

Fig. 1: System block diagram

2.1 Induction Machine Equations

The d-q axes equations describing the proposed system are given as [8];

$V_{ds} = R_s I_{ds} + p\lambda_{ds} - \omega\, \lambda_{qs}$ (1)

$V_{qs} = R_s I_{qs} + p\lambda_{qs} + \omega\, \lambda_{ds}$ (2)

$V_{dr} = R_r\, I_{dr} + p\lambda_{dr} - \omega_r \lambda_{qr}$ (3)

$V_{qr} = R_r I_{qr} + p\lambda_{qr} - \omega_r \lambda_{dr}$ (4)

$\lambda_{ds} = L_s I_{ds} + M I_{dr}$ (5)

$\lambda_{qs} = L_s\, I_{qs} + M\, I_{qr}$ (6)

$\lambda_{dr} = L_r\, I_{dr} + M\, I_{ds}$ (7)

$\lambda_{qr} = L_r\, I_{qr} + M\, I_{qs}$ (8)

Electromagnetic torque equation:
$T_e = 1.5\; P\; M\; (\lambda_{qs}\, I_{dr} - \lambda_{ds}\, I_{qr}) / L_s$ (9)

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

2.2 Rectifier

The three phase rectifier connected to the rotor circuit consists of 6 diodes. It is described by:

$$V_{dc} = V_{av} = \frac{\sqrt[3]{3V_{peak}}}{\pi} \quad (10)$$

Where V_{peak} is the rotor circuit voltage per phase.

2.3 The Three Phase Inverter

A three phase IGBT inverter is applied to change the DC rectifier voltage to a 60 Hz AC voltage fed back to the grid. It is controlled by a conventional PI controller.

2.4 Three Phase Dynamic Rotor Impedance

It is applied during voltage sag only via bypass switches, decreasing the rotor fault current and the torque oscillations.

2.5 The LCL filter

LCL filters are specially designed to reduce the harmonics of current absorbed by faults or power converters, which can be useful in reducing the effect of voltage sags. Mainly, they are made of a parallel-series combination of reactors and capacitors adapted to reduce the current harmonics. In this paper, it is connected to the rotor circuit.

3 Simulation Results for Un-Symmetrical Voltage Sag

A single phase unsymmetrical voltage sag (phase A drops voltage drops from 460 t0 250 V) is assumed for 0.2 seconds from (0.5- 0.7 sec.). The system is modeled and simulated using Matlab/Simulink for the three cases; namely, the SPRD without any protection devices, the SPRD with the rotor circuit added dynamic impedance, and the SPRD with the LCL filter.

3.1 SPRD Without any Protection Devices

Figure 2 and Figure 3 show the stator voltage and current, the rotor voltage and current the DC link voltage and current, the electric torque, and the rotor speed, during voltage sag without protection devices. The produced high current and voltage peaks, and the torque oscillations can cause damage to the machine and the power electronic devices.

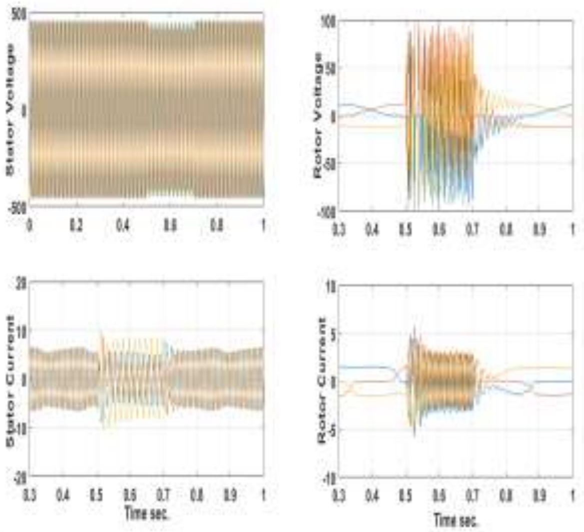

Fig. 2: stator voltage and current, rotor voltage and current during unsymmetrical voltage sag without any protection devices

3.2 SPRD with Rotor Impedance and Un-Symmetrical Voltage Sag

A 3-phase parallel RL impedance is connected to the rotor circuit to damp the effect of unsymmetrical voltage sag on the SPRD performance. The magnitude of the stator current during the voltage sag, shown in Figure 4, decreased to half of its value compared to the case without any protection, while the stator voltage profile was not affected. Also, a decrease in the transient rotor voltage and current peaks due to the unsymmetrical sag is obvious when compared to their magnitude without protection devices. The spike in Figure 4 is due to the sudden change in grid voltage at the beginning of the unsymmetrical fault. It takes a very short time, hence it does not cause damage to the rotor circuit.

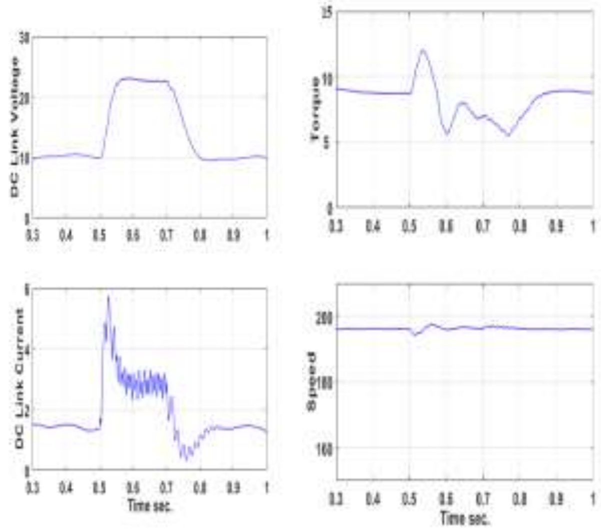

Fig. 3: DC voltage and current, the electric torque, and the rotor speed during unsymmetrical voltage sag without any protection devices

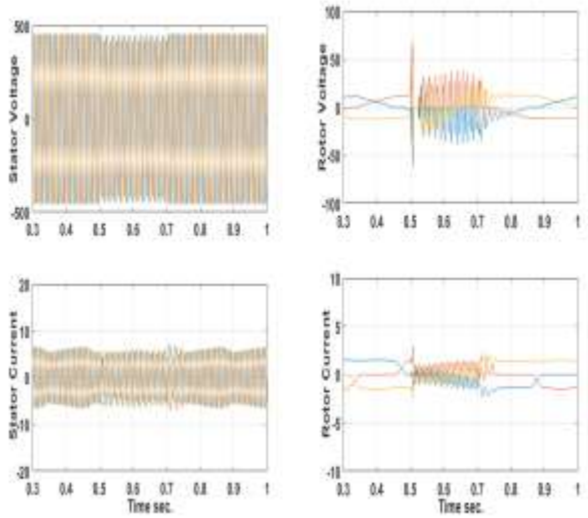

Fig. 4: Stator voltage and current, rotor voltage and current during unsymmetrical voltage sag with rotor impedance

Figure 5 shows a large drop in the magnitude of the DC link peak voltage and current during the voltage sag with fast recovery to their normal values as the sag ends. Also, lower ripples are noticed when compared to the case without a protection scheme. However, ripples are noticed in the electric torque profile due to the voltage sag but with smaller magnitudes than the case without the added RL impedance, while the drop in the rotor speed is minimized.

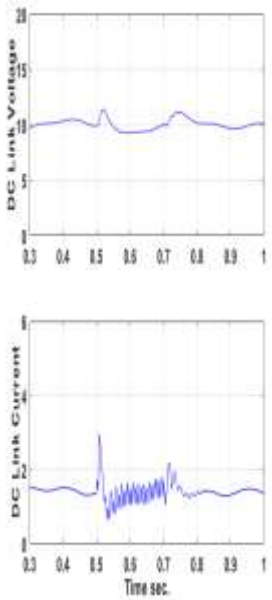

Fig. 5: DC voltage and current, electric torque, and rotor speed during voltage sag with rotor impedance

3.3 SPRD with Rotor LCL and Unsymmetrical Voltage Sag

A 3-phase LCL impedance is connected to the rotor circuit to damp the effect of unsymmetrical voltage sag on the SPRD performance. Results are shown in Figure 6 and Figure 7. The magnitude of the stator current during the voltage sag, shown in Figure 6, decreased as compared to its value without rotor LCL protection, but with a higher value when compared to rotor RL protection scheme. The stator voltage profile is not affected. Also, a decrease in the transient rotor voltage and current peaks due to the unsymmetrical sag is obvious when compared to their magnitude without protection devices. However, the rotor voltage and current during sag are higher when compared to the rotor RL protection scheme. The high frequency content in Figure 6 means that the system with an LCL filter needs a longer time to settle, which gives superiority to the rotor RL damping scheme. Figure 7 shows a large drop in the magnitude of the DC link peak voltage and current during the voltage sag with fast recovery to their normal values as the sag ends. Also, lower ripples are noticed when compared to the case without a protection scheme. Concerning the electric torque, ripples are higher than the case with the added RL impedance, while the rotor speed variation during the voltage sag is minimized. It is noticed that the DC voltage and current profiles as well as the electric torque during the voltage sag are similar to their profile when using the RL impedance, while the stator current and the rotor voltage and current are much better.

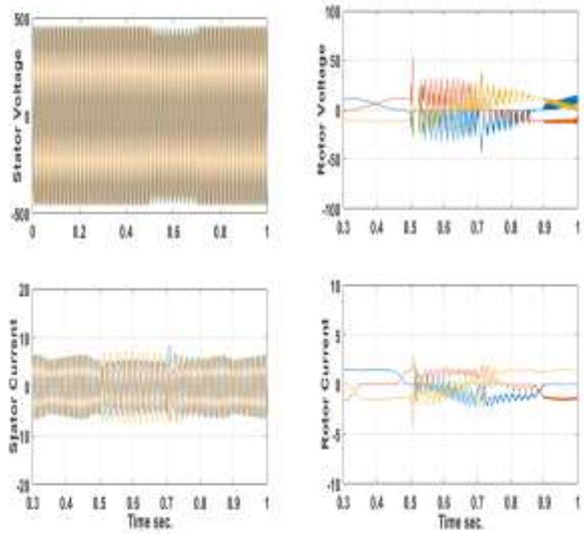

Fig. 6: Stator and rotor voltage and currents with LCL filter during unsymmetrical voltage sag

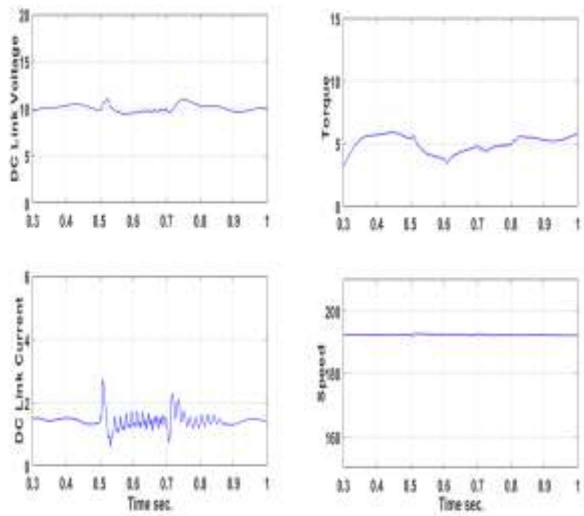

Fig. 7: DC voltage and current, electric torque, and rotor speed during voltage sag with rotor LCL filter

4 Effect of Supply Frequency Drop on the SPRD Parameters

Since the stator of the SPRD is directly connected to the grid without an electronic device, it is very sensitive to supply frequency deviation. A drop in the supply frequency from 60Hz to 50 Hz is assumed from 0.5-0.7 sec, and the effect of the proposed protection on the SPRD performance is studied.

4.1 SPRD during Supply Frequency Drop without Protection

Figure 8 and Figure 9 display the stator voltage and current, the rotor voltage and current, the DC voltage and current, the electric torque, and the rotor speed of the SPRD when the supply frequency dropped from 60 to 50 Hz from 0.5sec to 0.7 sec without protection scheme. It is noticed that the frequency drop drastically affects the performance of the SPRD.

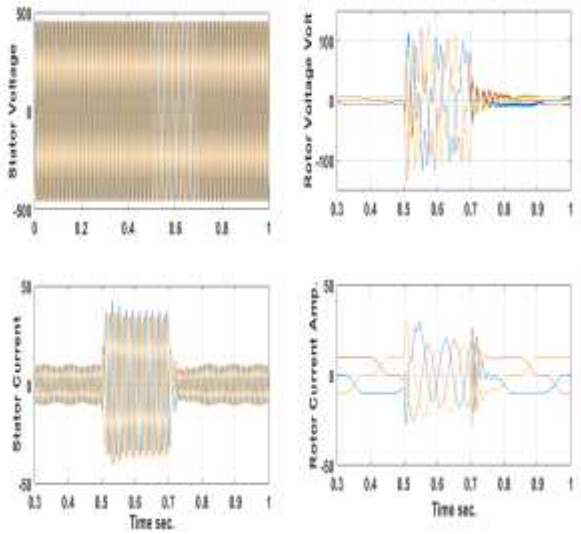

Fig. 8: stator voltage and current, rotor voltage and current due to frequency drop without any protection

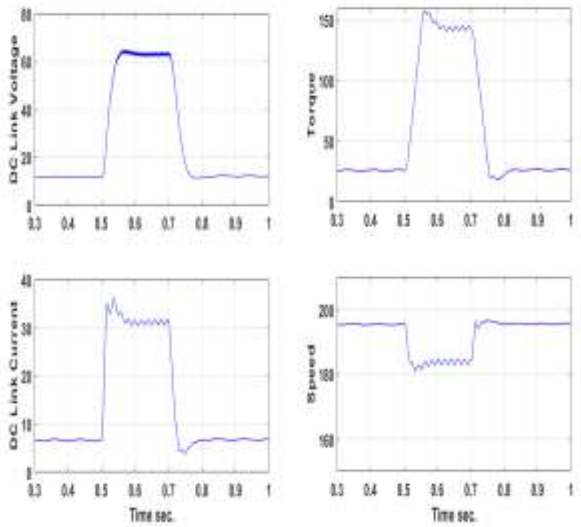

Fig. 9: DC link voltage and current, electric torque and speed during grid frequency drop without protection device

4.2 SPRD during Supply Frequency Drop with Rotor RL Protection

Figure 10 and Figure 11 display the stator voltage and current, the rotor voltage and current, the DC voltage and current, the electric torque, and the rotor speed of the SPRD when the supply frequency dropped from 60 to 50 Hz from 0.5sec to 0.7 sec with rotor RL protection. A drop in the stator current transient during the fault is obvious. The transient dropped from 40 amps without RL impedance to approximately 20 amps. A small decrease in the rotor voltage transient during the fault took place, while a large decrease in the rotor current transient is obvious. This behavior is due to the added rotor inductance.

Figure 11 reveals the effect of the protection scheme in decreasing the DC voltage and current transients that occurred due to the frequency drop, from 65 to 23 Volt. and from 35 Amp. without any protection to 13 V with RL impedance. Consequently, a large drop in the electric torque transients is obvious, dropping from more than 150 Nm to 24 Nm, which is nearly its steady state value. In addition, minimum ripples took place in the rotor speed during the fault compared to the large speed drop resulting from the frequency drop without protection RL scheme.

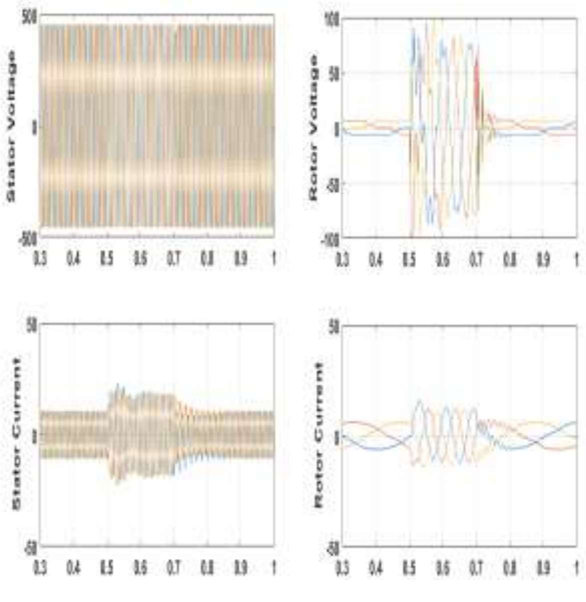

Fig. 10: Stator and rotor voltages and currents during frequency drop with added rotor RL impedance

4.3 SPRD during Supply Frequency Drop with Rotor LCL Protection

Figure 12 and Figure 13 display the stator voltage and current, the rotor voltage and current, the DC voltage and current, the electric torque, and the rotor speed of the SPRD when the supply frequency dropped from 60 to 50 Hz from 0.5sec to 0.7 sec with rotor LCL protection. The stator current transient during the frequency drop slightly decreased when compared to its value without protection. Similarly, a small decrease in the rotor current transients occurred, while the rotor voltage transients are still large. The DC link voltage and current, the electric torque, and the rotor speed shown in Figure 12, improved as compared to the case without any protection. However, these transients are higher when compared to the added RL impedance.

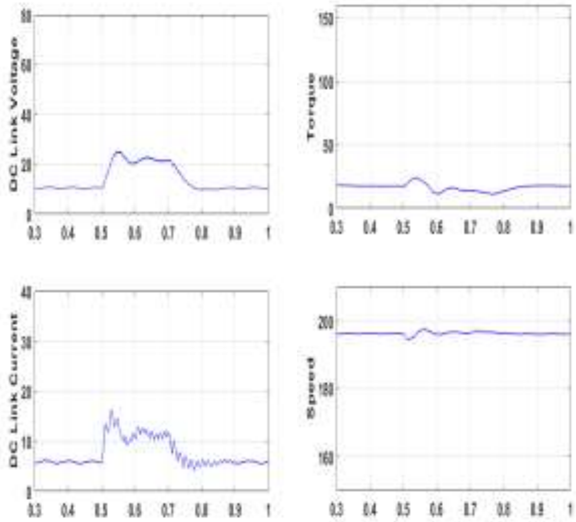

Fig. 11: DC voltages and currents, electric torque, and speed during frequency drop with added rotor RL impedance

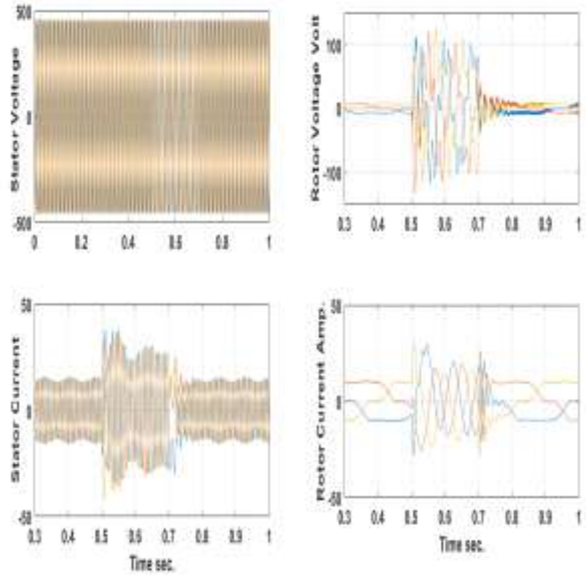

Fig. 12: Stator and rotor voltages and currents during frequency drop with added rotor LCL filter

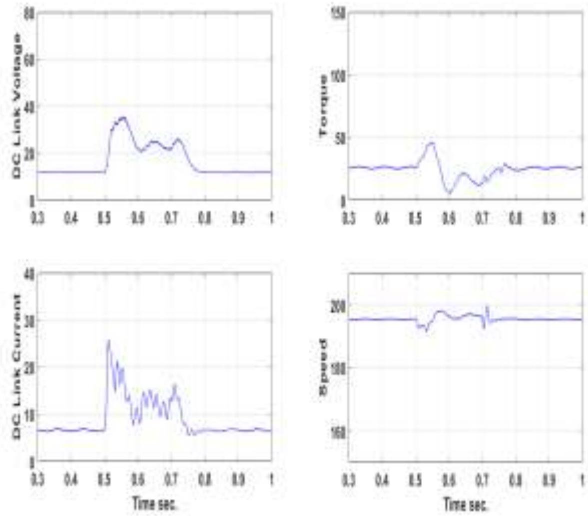

Fig. 13: DC voltages and currents, electric torque, and speed during frequency drop with added rotor LCL filter

5 Conclusion

In this paper, the effect of unsymmetrical grid voltage sag on the performance of a slip power recovery drive (SPRD) is studied, and two strategies to mitigate its effects are investigated. The first strategy consists of a phase parallel RL impedance connected to the rotor circuit. The second strategy consists of three phase LCL filter connected to the rotor circuit. A PI controller is tuned to test the drive at constant speed. Also, the effect of grid frequency drop on the drive performance is investigated with the same two protection strategies. The proposed systems are modeled with Matlab/ Simulink and the simulation results are given. The drive stator voltage and current, rotor voltage and current, DC link voltage and current, electric torque, and the rotor speed are calculated and their values are compared for three cases, namely, without any protection scheme, with the rotor added RL impedance, and with the added LCL filter. It is concluded that the added rotor RL impedance decreased the transients that took place due to the unsymmetrical voltage sag and those due to the frequency drop, drastically while a moderate decrease in these transients resulted when connecting the rotor LCL filter.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

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

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Conflict of Interest

The authors have no conflicts of interest to declare.