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Effect of Voltage Unbalance on Adjustable Speed Drives and its Mitigation Using Supercapacitor

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Abstract. During the voltage unbalance, the resulting adverse effects on equipments such as induction motors and power electronic converters and drives on ASDs have been described. It has been observed that during unsymmetrical fault, the input rectifier slips into the single phase operation and draw heavy currents which may actuate the overload protection and trip the ASDs. The application of supercapacitors bank with boost converter to inject energy at DC-Link under voltage unbalance condition has been incorporated. The supercapacitor provides ride-through and reduces the current overshooting by injecting energy at DC-Link. Based on the designed topology, simulation model in MATLAB 7.5 (Sim Power Block set) has been developed for voltage unbalance conditions with supercapacitor as an energy storage device. The designed control technique is modeled, simulated and successfully implemented in the laboratory. The extensive simulation results supported by experimental results were provided to validate the proposed system

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Keywords: Speed Drives; Voltage Unbalance; Ride-through Capabilities; Energy Storage Devices; Supercapacitors

1 Introduction

The greatest effect of voltage unbalance is on three-phase induction motors. Three-phase induction motors are one of the most common loads on the network and are found in large numbers especially in industrial environments. When a three-phase induction motor is supplied by an unbalanced system the resulting line currents show a degree of unbalance that is several times the voltage unbalance. An excessive level of voltage unbalance can have serious impacts on mains connected induction motors. Although induction motors are designed to tolerate a small level of unbalance they have to be derated if the unbalance is excessive. Voltage unbalance also has an impact on ac variable speed drive systems where the front end consists of three-phase rectifier systems. The triplen harmonic line currents that are uncharacteristic to these rectifier systems can exist in these situations leading to unexpected harmonic problems. Although it is practically impossible to eliminate voltage unbalance it can be kept under control at both utility and plant level by several practical approaches.

Voltage unbalance is regarded as a power quality problem of significant concern at the electricity distribution level. Although the voltages are quite well balanced at the generator and transmission levels the voltages at the utilization level can become unbalanced due to the unequal system impedances and the unequal distribution of single-phase loads. The level of current unbalance that is present is several times the level of voltage unbalance. Such an unbalance in the line currents can lead to excessive losses in the stator and rotor that may cause protection systems to operate causing loss of production. [1-5]

Three-phase diode rectifier systems are an essential part of conventional Adjustable Speed Drives as shown in fig. 1 and uninterruptible power supplies. These rectifier systems draw non-sinusoidal current waveforms from the ac mains. If the ac supply system is balanced the line current waveform may take the “double pulse per half cycle” shape that contains characteristic harmonic orders given by:

$$h = kq \pm 1 \tag{1}$$

where h = harmonic order ,k = 1, 2,….and q=number of pulses of the rectifier system giving only 5th ,7th , 11th, 13th… order harmonics.

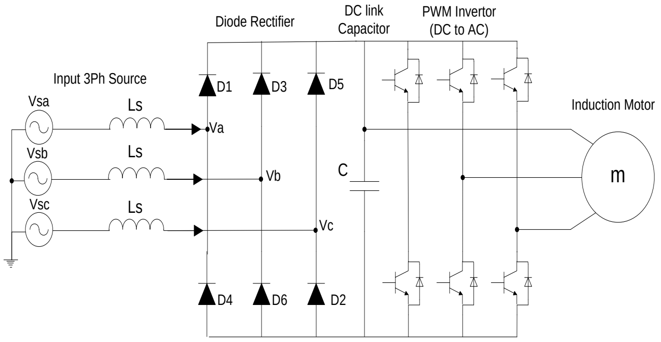

Fig.1. Typical adjustable speed drives (ASDs) system.

As the supply system becomes unbalanced the line current waveform deviates away from the double pulse formation to single pulse formation leading to uncharacteristic triplen harmonics. Supply voltage unbalance can lead to tripping of drive systems that is caused by excessive ac line currents on some phases and under voltage on the DC-Link. This can also lead to excessive thermal stress on diodes and dc link capacitor. Increase in the unwanted triplen harmonic currents can also lead to undesirable harmonic problems in the supply system.

2 Impact of Electric Power Quality Disturbances on Adjustable Speed Drives (ASDs)

Steady-state voltage unbalance has a dramatic effect on input current unbalance and harmonics of PWM-VSI ASDs. Research to determine the electric power quality characteristics of ASDs demonstrates that, given a small voltage unbalance, the input current unbalance of the ASDs can be high. Generally, findings indicate that as the voltage unbalance increases, the ASDs input current unbalance increased from a nominal 10% to 50%, depending on the ASDs internal reactance and the electric supply impedance.

Moreover, the third harmonic component of the line current, which is an uncharacteristic harmonic of these drives, increased greatly. High input current unbalance can trigger overload protection and shut down critical processes. Many motor control centres are designed to trip for a current unbalance of only 5%. Also, the generation of different levels of harmonic components in each phase with the presence of triplen harmonics makes it difficult to design tuned harmonic traps for ASDs-generated harmonics. Applications of AC line reactors or DC-Link reactors can mitigate the adverse effects of phase-voltage unbalance on ASDs [6-10].

The different ride-through require energy storage devices injecting power at the DC-link during voltage sags as described in the literature[7-15]. Besides energy storage systems, some other devices Constant voltage transformers (CVT), DVR may be used to solve Electric Power Quality problems [9-12].

The sensitivity of AC ASD’s to voltage sags is presented in a voltage tolerance curve is defined by IEEE Std. 1346[5] as shown in Fig. 2. It may be seen that the ASD’s can withstand a reduction in the line voltage upto 85% of nominal value for an extended duration of time. For all points falling below the voltage tolerance curve, the drive will trip. SEMI F47-0200, Specification for Semiconductor Processing Equipment Voltage Sag Immunity [6], specifies the required voltage sag tolerance for semiconductor fabrication equipment. SEMI F47 requires that semiconductor processing equipment tolerate voltage sags connected onto their AC power line. They must tolerate sags to 50% of equipment nominal voltage for duration of up to 200 ms, sags to 70% for up to 0.5 seconds, and sags to 80% for up to 1.0 second.

It is observed from the literature survey that only theoretical analysis have been done by the different researchers in regards of providing ride-through to an Adjustable Speed Drives during voltage unbalance due to unsymmetrical fault conditions. Experimental work for improving upon the adverse effects of voltage unbalancing on Adjustable Speed Drives has not yet been proposed and implemented. Therefore in the present work, it is aimed to study the effectiveness of the supercapacitor as an energy storage device for providing ride-through to ASD's during symmetrical and unsymmetrical fault conditions [13-17].

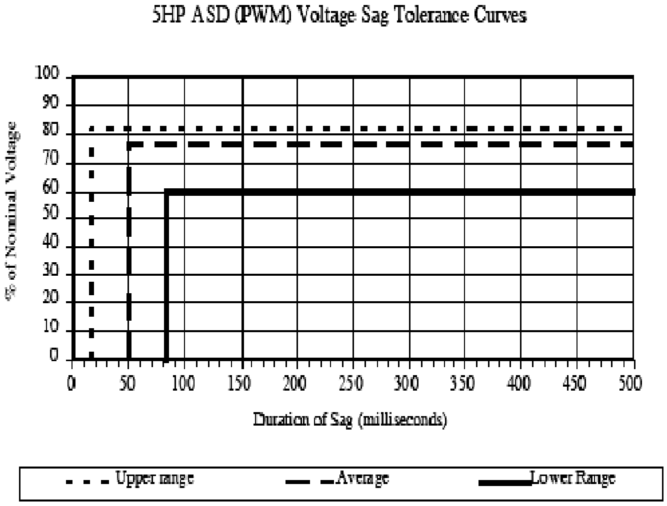

Fig.2 Voltage tolerance curve of an ASD's as per IEEE Std.1346

3 Analysis of Voltage Unbalance

A phase to ground fault will result in a type B. A phase to phase fault results in a type C. If the voltage sag is of Type B or Type C, the circuit will behave as a single-phase rectifier. Even 10% voltage sag will result in a single-phase operation of the three-phase diode rectifier. If there is a transformer that removes the zero-sequence between the fault location and the load for phase to ground fault, the voltage sag will be of type D. The voltage sags of type E, F and G are due to a two phase to ground fault [1-5].

Thus, the unsymmetrical faults lead to three major negative effects that unbalanced input voltages can have on ASD's performance. [18-22] :

i. Significant input current unbalances which stresses the diode bridge rectifiers and input protective devices such as fuses, contactors and circuit breakers.
ii. Injects a second harmonic voltage component on the DC-Link voltage which increases the electrical stresses on the DC-Link choke inductor (if used) and the DC-Link electrolytic capacitors. It potentially shortens the capacitor lifetime.
iii. May give rise to ripple torque of magnitude double the fundamental frequency of induction machine which increases the mechanical and thermal stresses.

4 Proposed Ride-through Topologies

The objective of this section is to investigate the performance of an ASD's under voltage unbalance condition leading to unbalanced voltage sag at PCC. Only the single line to ground fault (Type-B) has been considered. The performance of the proposed topology is identical for the remaining types of unsymmetrical faults. The proposed topology is designed by using supercapacitor as energy storage device along with boost converter across DC-Link as a ride-through alternative for ASD's.

The performance of ASD's under voltage unbalance condition has been simulated using MATLAB Simulink Power System Block set tool box. The functional block diagram is shown in Fig. 3. A three-phase programmable voltage source feeds the power bus to PCC through series impedance (taken as resistance of 0.1 ohm assuming the length of line to be very small). Two independent feeders are connected at this PCC bus; one feeds the ASD's and the other is connected to the load. The faults are created at the load feeder to study the impact of voltage sags on the ASD's connected at the same PCC. The shunt impedance method has been used to generate voltage sags[23-24]. At the time of faults the fault current flows through the impedance leading to a voltage drop across it, thereby causing voltage sags at PCC.

The ASD's used is a scalar controlled induction motor (specifications are given in Appendix) and is having a supercapacitors as an energy storage device at DC-Link. A buck-boost DC-DC converter converts the output of the connected energy storage device to the desired DC-Link voltage. The hardware set up consists of:

i. AC/DC converter section: This unit consists of uncontrolled three- phase diode bride rectifier.
ii. DC/AC inverter unit: This unit consists of MOSFET based inverter.
iii. Energy Storage Devices: The device is a supercapacitor bank of 12V modules. This 12V DC is converted to 220V DC (for experimental purpose) with the help of buck-boost converter
iv. Voltage Sag Generator Unit: The various types of faults were created in the lab using shunt impedance method by actually grounding/shorting the line terminals in order to represent the true voltage sag conditions as shown in Fig. 3.

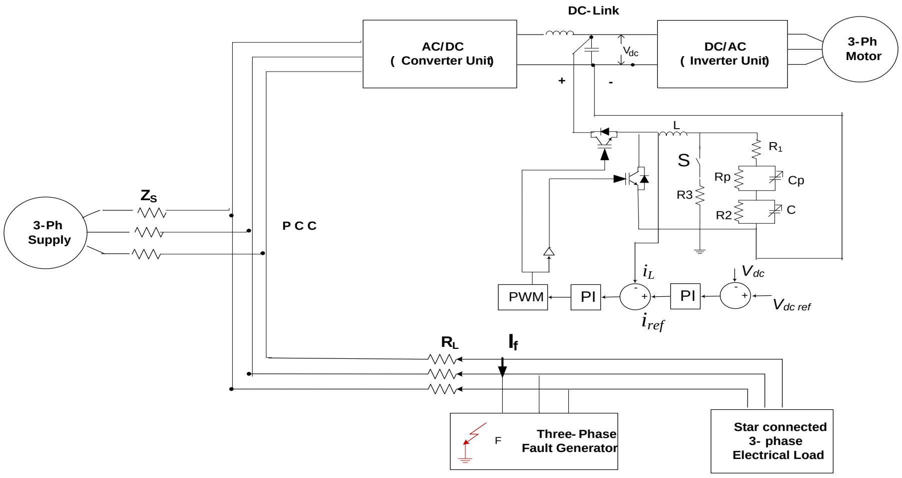

Fig.3 Block Diagram of Proposed Technique

5 Modelling of the System

5.1 Diode Rectifier Equations

The basic equations of a three-phase uncontrolled rectifier with input impedance in derivative form are given as:

$$pi_d = (V_{\max} - V_{dc}) / 2L_s \tag{2}$$

$$pV_{dc} = (i_d - i_o) / C_o \tag{3}$$

where, i_d is supply current and io is the current drawn by the inverter section.

The input AC currents of the rectifier are computed as follows. When *VRY* is maximum (V_{max}), the current (i_d) flows from terminal '*R*' to '*Y*' through the concerned rectifier diode pair and the load. Where as for minimum value of *VYR* is maximum, the current flows from terminal 'Y' to 'R'. The current in line 'B' is zero when these conditions exist. Likewise the currents flowing through the lines are computed when VYB and VBR satisfy these upper and lower voltage conditions.

5.2 Scalar Control of Induction Motor Drive

An AC induction machine is scalar controlled, wherein, the ratio of stator voltage to frequency (V/F) is kept constant.

5.3 Modeling of Supercapacitor

A supercapacitor can be modeled using some standard circuit components as shown in Fig. 4. The two variable capacitances are nonlinearly varying with the voltage that is applied across the circuit. The capacitance *C* is responsible for the most important phenomenon in the model. The amount of energy stored and the rate of energy level variations are both determined mainly by the capacitance value. The resistance R_2 connected in parallel with the capacitor is meant to represent the self discharge effect.

The series resistance R_1 represents the losses during charge and discharge. The over voltage protection provided by R_3 and the switch controlling its connection to the circuit is necessary to prevent damage to the capacitor elements by balancing the voltage level. The resistance R_p and the capacitance C_p are included in the circuit to model some of the fast dynamics in the behavior of the supercapacitor [11].

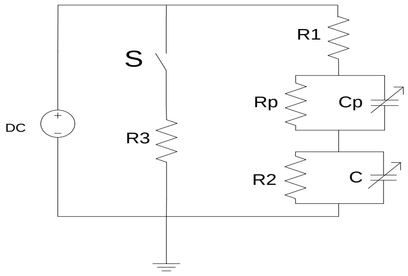

Fig.4 Basic circuit model of the supercapacitor.

Energy stored in the supercapacitor is given by the following equation:

$$E = \frac{1}{2} C V^2 \tag{4}$$

Where, C is the capacitance in farads, V is the voltage across C in volts; E is the energy stored in C in joules.

$$UsableEnergy = E = \frac{1}{2} C \left[V_1^2 - V_2^2 \right] \tag{5}$$

Where, V_1 is the rated charging voltage V_2 is the rated minimum operating voltage of supercapacitors.

6 Results and Discussion

The objective of this section is to investigate the performance of an ASD's under voltage unbalance of sag Type-B i.e. single line to ground (SLG) fault with and without different energy storage devices across DC-Link to provide ride-through. Fig. 5-8 show the performance of ASD's with the proposed scheme.

The simulations have been carried out to get the traces of three-phase source voltages (V_{sry}, V_{syb}, V_{sbr}), three-phase source currents (I_{sr}, I_{sy}, I_{sb}), Electromagnetic Torque(T_{eL}) , rotor speed (ω_r) and DC-Link voltage (V_{dc}) respectively.

6.1 Performance of ASD's during SLG without ride-through

The simulation and hardware results for ASDs during single line to ground fault without ride-through are shown in Fig. 5 and Fig. 6 respectively. The single line to ground fault was simulated where the three-phase source voltage amplitude drops to a value of about 40% of the pre-event voltage during 1.86 to 2.56 sec about 35 cycles as shown in Fig.5 and Fig. 6. After the event, voltage returns back to pre sag voltage. During the fault period the three-phase uncontrolled rectifier operates in single phase operation and draws almost, the double current which may actuate the over load protection and trips the ASDs. During the voltage sag the DC-Link voltage drops from 205V to 195 V which is well above the threshold setting at the DC-Link. The DC-Link voltage shows the voltage ripples of twice the fundamental frequency. The electromagnetic torque (T_e) and the speed (w_r) of the Induction motor drops slightly as shown in simulation and hardware results. The effective motor current during the fault period increases so as to maintain the desired torque. The experimental results match with the simulation results.

6.2 Performance of ASD's during SLG with supercapacitor as ride-through

The simulation and hardware results shown in Fig. 7 and Fig. 8 respectively under voltage unbalance condition, are an example of voltage sag of Type-B (Line to Ground Fault) with supercapacitor as a ride-through capability connected across DC-Link through Boost Converter. A supercapacitor bank of 5 F, 13.5 V (25F, 2.7V , 5 Nos. connected in series)

The amplitude drops to a value of about 75% of the pre-event voltage during 2.05 to 2.58 sec about 27 cycles. The compensation provided by the supercapacitor bank is much faster as compared to other energy storage devices. The motor side three-phase voltages, currents, electromagnetic torque and rotor speed are also shown in Fig. 7 and Fig. 8.

The result shows the improvement in the current being drawn by the rectifier. A supercapacitor bank is able to provide required ride-through to ASDs by injecting power in the system during the fault and the same is also shown by DC-Link voltage which remains above the preset value.

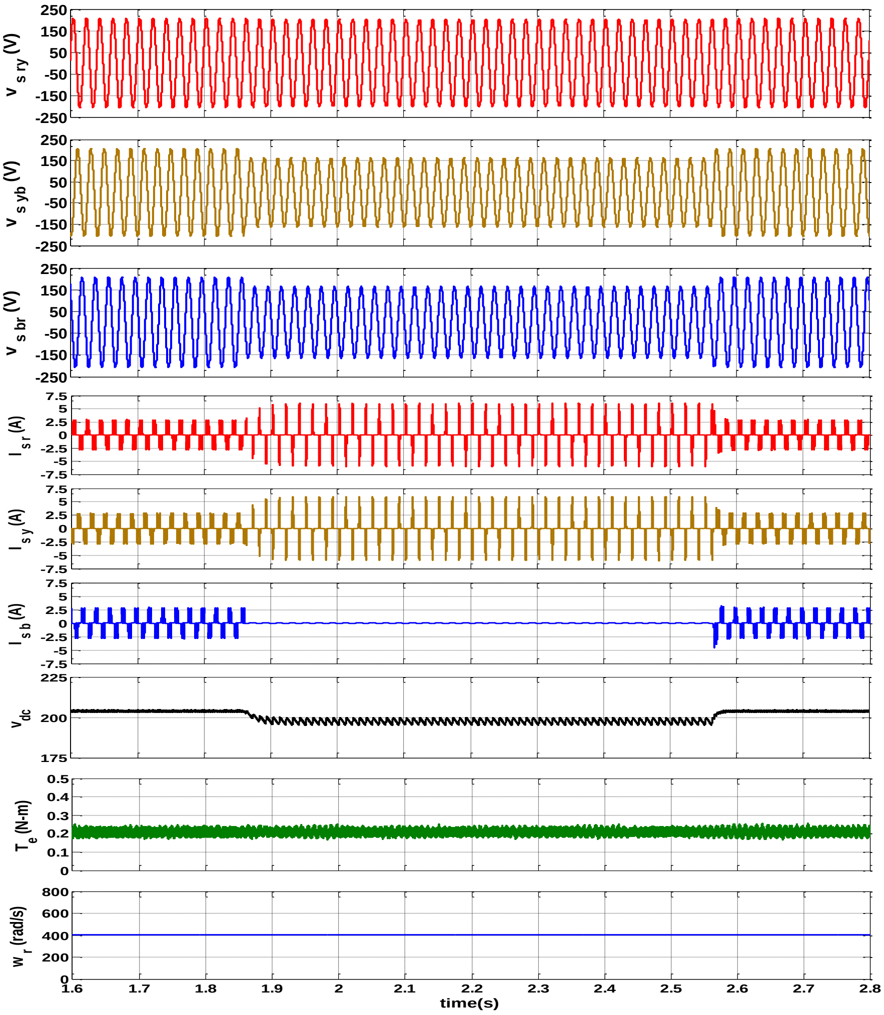

Fig.5 Simulation results showing three-phase source voltages, currents and DC-Link voltage during SLG fault (Type-B) without any ride-through.

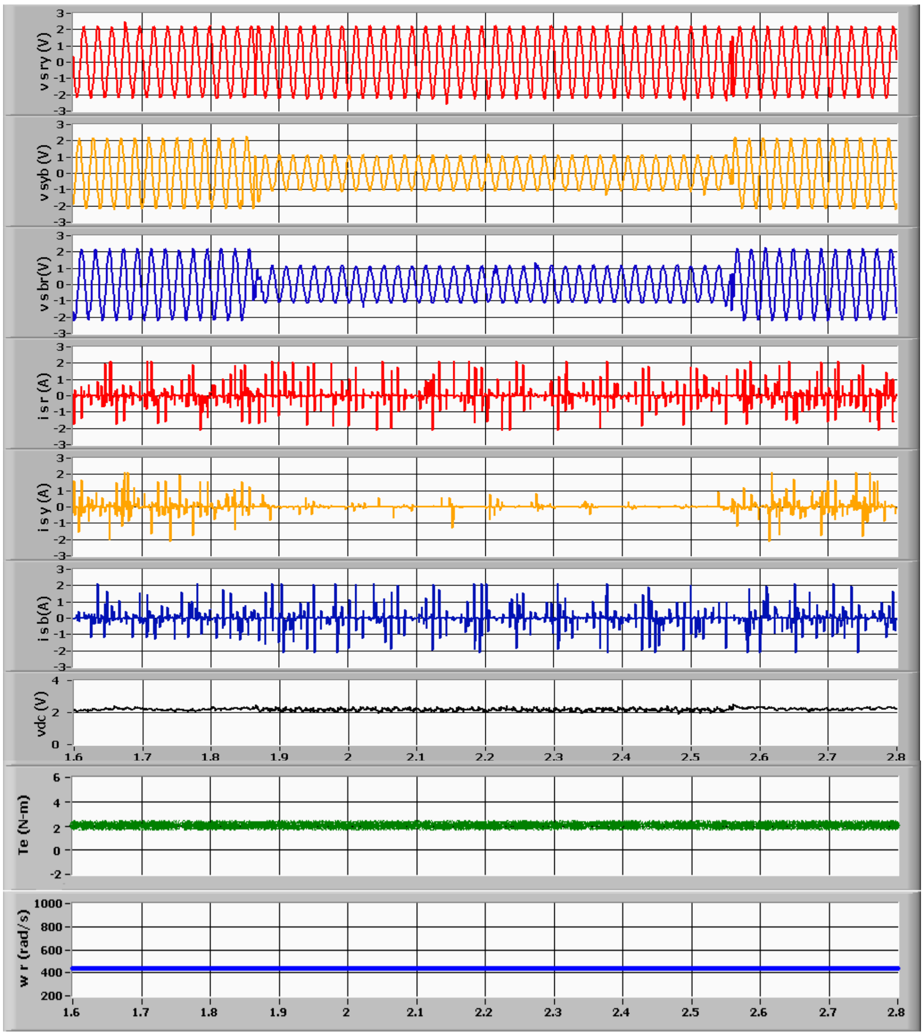

Fig.6 Experimental Results showing three-phase source voltages, currents and DC-Link voltage during SLG fault (Type-B) without any ride-through. Voltage scale: 100 V per division. Current scale: 2.25 A per division. DC-Link Voltage scale: 100 V per division.

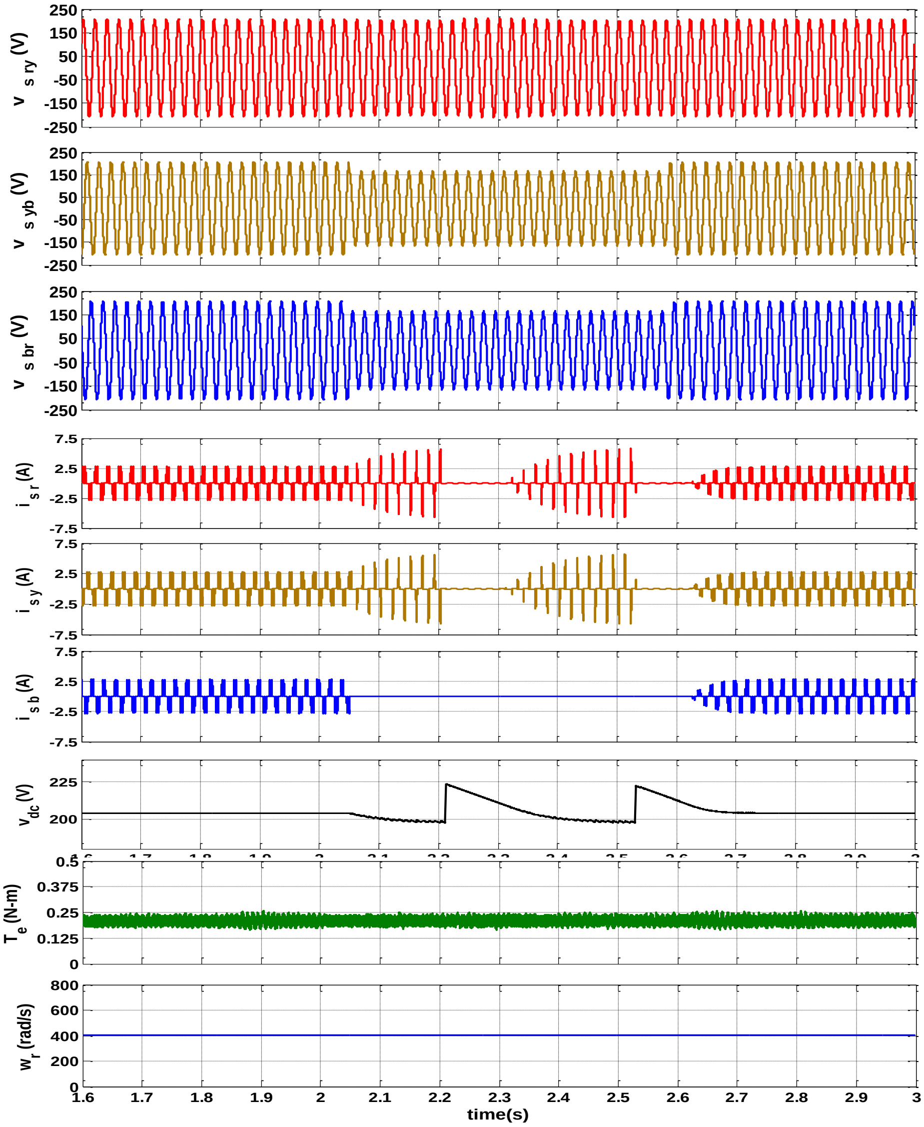

Fig.7 Simulation results showing three-phase source voltages, currents and DC-Link voltage during SLG fault(Type-B) with supercapacitor as ride-through alternative.

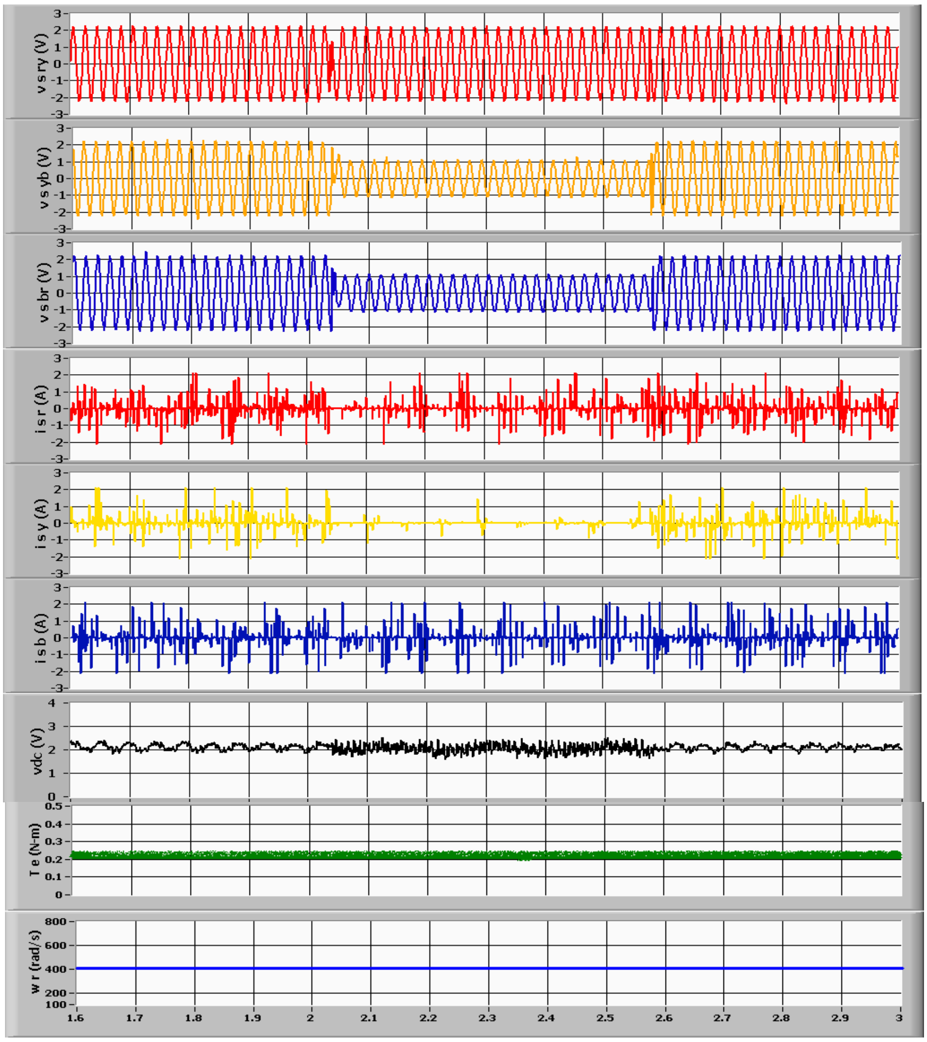

Fig.8 Experimental results showing three-phase source voltages, currents and DC-Link voltage during SLG fault(Type-B) with supercapacitor as ride-through alternative. Voltage scale: 100 V per division. Current scale: 2.25 A per division. DC-Link Voltage scale: 100 V per division.

7 Conclusion

During the unsymmetrical faults, the resulting adverse effects on equipments such as induction motors and power electronic converters and drives on ASDs have been described. It has been observed that during unsymmetrical fault, the input rectifier slips into the single phase operation and drew heavy currents which may actuate the overload protection and trip the ASDs. The observations are made on the basis of simulation and experimental work. It can be concluded that the supercapacitors are found to be the best alternative to provide ride-through to ASDs and also reduces the current overshooting by injecting energy at DC-Link during unsymmetrical fault conditions. Therefore it is concluded that among all the existing energy storage devices, supercapacitors appear to be a good option for applications that require high power densities and fast transient response such as to provide ride-through to ASDs, and all this in a reduced volume. The simulation results validated by experimental results have been provided under unsymmetrical fault condition.

8 Appendix

Induction Motor rating and parameters:
5 H.P, 415 volts(L-L), 3- Phase, 4 Poles, 50 Hz, 1444 rpm.
DC-link capacitor(supercapacitor) = 5 F / 13.5 V
(Supercapacitor 05 No’s connected in series of 25F/2.7V each)
DC-Link voltage (For Experimental Studies): 210 V
Lab View measurement Scale:
Three-phase source voltage : 1:300
Three-phase source current : 1:2.25
DC-Link Voltage : 1:100
Load Current (Motor Side) : 1:10
Electromagnetic Torque : 1:1
Rotor Speed : 1:1

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