Supercapacitor a Ride-Through Alternative for an Adjustable Speed Drives During Voltage Sag

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***Abstract*-- This paper compares the experimental and simulation results to improve the voltage sag ride through capability of an adjustable speed drive using a supercapacitor as an energy storage device. The supercapacitor maintains the ASD dc bus voltage under voltage sag condition. Experimental results are presented, which show the effectiveness of the mitigation approach to voltage sags. The performance of ASD under healty and abnormal condition is first simulated in MATLab simulink and then the same are verified using designed hardware setup. The LABView (8.5) software and DAQ board has been used to record the generated waveforms during normal and abnormal conditions.**

***Index Terms*-- Adjustable speed drive, Low voltage ride-through capability, Voltage sag, Supercapacitor, Ultracapacoitor.**

I. Introduction

Adjustable Speed Drives (ASDs) used in a wide variety of industrial applications. The benefits that might be provided by the ASDs are the reason for their widespread use by the industry. Despite of its importance to the process operation, the ASDs are sensitive to voltage sags. Undervoltage and overcurrent often follow voltage sags which may cause the ASD trip bringing about the halt of the productive process and revenue losses. The ASD may also operate inappropriately resulting on load torque and load speed variations since the control of the current and of the output voltage are dependent on the inverter dc voltage level which decays during voltage sag [1], as shown in (1).

$$V_{dc} C \frac{dv_{dc}}{dt} = \frac{T_L \omega_r}{\eta_{mot} \eta_{inv}} \qquad (1)$$

Thus, the decrease rate of the dc bus voltage dV_{dc}/dt depends on the capacitance C, the voltage Vdc across the capacitor at the beginning of the voltage sag, the load torque T_L, the motor speed ω_r, the motor efficiency η_{mot} and the ASD efficiency η_{asd} . Different approaches to improve the ASD ride through by increasing the average voltage of the dc bus have been proposed [1], [6], [7], [8]. The methods include the addition of capacitors to the dc bus [6], the regenerativemitigation which converts the kinetic energy from the motor and load into electric energy transferring it to the ASD dc bus [1], the connection of the neutral conductor of the supply source to the midpoint of the dc bus through a controlled switch [8], and the application of boost converters [1], [7]. This paper presents a proposed topology to improve the low voltage ride-through capability of an adjustable speed drive via experimental and simulation results. The system is tested under symmetrical and asymmetrical voltage sag conditions in order to assess the contribution of the supercapacitor as an energy storage device to improve the ASD operation under voltage sags.

II. SUSCEPTIBILITY OF ASD TO VOLTAGE SAGS

The tolerance of an ASD to voltage sags depends on the characteristics of the voltage sag. Seven different types of voltage sags, classified as A, B, C, D, E, F, G, may come upon the terminals of an ASD as a result of symmetrical and asymmetrical faults. The voltage sags are classified according to the number of phases affected and the phase displacement, which are associated to the fault type. Table I presents the seven categories of voltage sags according to the fault type (three phase fault, single phase fault, double phase fault, and double phase-to-ground fault) and as seen by the phase voltage and the line voltage terminals. The voltage sag type C* has the same pattern of the voltage sag type C [9]. Voltage sag type A is caused by symmetrical faults, whilst the remaining cases are due to asymmetrical faults.

TABLE I
THE CATEGORIES OF VOLTAGE SAG ACCORDING TO THE FAULT TYPE.

Voltage Type	Fault Type						
	three phase	single phase	double phase		double phase-to-ground		
	Voltage Sag Categories						
Phase	A	B	C	D	E	F	G
Line	A	C*	D	C	F	G	H

Voltage sag severities are normally measured by their magnitude and duration. The voltage sag magnitude is usually measured by the smallest rms voltage among the sagged phases, while the duration is often measured from the instant the rms voltage of any phase drops to less than 0.9 pu until no phase voltage is under 0.9 pu. The drive is independent of line voltage sag as long as the dc bus holds up. During a voltage sag or short interruption, the diodes in an ASD rectifier bridge will not conduct if the peak line voltage drops below the dc bus voltage. While the ASD is still controlling the motor and its load, energy is drawn from the dc-bus capacitors, which will cause the dc bus voltage to decrease. When the dc-bus voltage drops below a pre defined set point before the line voltage returns, the control circuit will respond according to the drive's program, typically shutting down the drive. If the supply voltage recovers before the dc bus voltage reaches the undervoltage protection level, a high charging current is drawn from the supply which could end up in a shutdown of the drive, due to the activation of the over-current protection [1], [2].

The typical duration of voltage sags are between 0.5 to 30 cycles or 8ms to 0.5s. Voltage sags, classified as type A, are the most severe ones as they cause the larger amount of energy withdraw from the dc bus, and are more likely to trip the ASD under voltage protection. The asymmetric voltage sags usually have at least one line supply voltage which keeps the dc link voltage above the under voltage protection level. Nevertheless, voltage sag type A is the least severe as far as the over current level is concerned. On the other hand, voltage sags type B, caused by one-phase faults, are accountable for the most severe sags as far as over current are concerned and the least severe as for the dc bus under voltage threshold level [10]. It has been withdrawn from [5] that tests with voltage sag type A can set the under voltage protection level and tests with voltage sag type B can set the over current protection level of an ASD.

III. Energy Storage Systems

The different ride-through require energy storage devices injecting power at the DC-link during voltage sags as described in the literature[5-6].

By adding capacitors to the DC-link, additional energy needed for full-power ride-through during voltage sag can be provided to the motor. It is a simple and rugged approach, which can provide limited ride-through for minor disturbances. However, its cost is relatively high and a large cabinet space is required.

The load inertia may be utilized to provide ride- through capability to ASD's. The inverter control software can be modified such that when a power disturbance causes the DC-link voltage to fall below a specified value, the inverter will adjust to operate at a frequency slightly below the motor frequency, causing the motor to act like a generator. The drive will absorb a small amount of energy from the rotating load to maintain the DC-link at a specified level and maintains the specified DC-link for few seconds during a sag that does not exceed 20%. Here, no additional cost is included only small software modification is required but may not be acceptable for certain loads.

Since the DC-link current varies with the frequency of the drive for variable-torque loads, such as fans and pumps, a reduction in the motor speed will result in a reduction in the DC-link current. Therefore, a fan and pump system running at 40 Hz will draw less current than a system running at 50 Hz and will, therefore, be able to operate for a longer period during a voltage sag situation. It provides ride-through without any additional hardware and cost but application may not tolerate reduced speed operation.

A boost converter can be used between the rectifier and the DC-link capacitors to maintain the DC-link voltage during voltage sag. Boost converter without energy storage provides ride-through with lower cost, upto 50% sag but fails during outages. Replacing the diode rectifier with an active PWM rectifier regulates the DC-link which offers immunity to voltage sags and transients and low input current harmonics. The range of ride through provided by this approach is limited only by the current rating of the rectifier. Active rectifier with lower cost provides ride-through up to 50% sag but fails during outages [7].

Battery backup systems operate similarly to adding capacitive energy storage, with the advantage that their energy per volume ratio is much higher than standard capacitors [6-9]. The batteries are easily available with low cost; provide ride-through for deep sags and full outages. These have low life and require additional space and maintenance.

Flywheels, which store kinetic energy in a rotating mass, are also showing promise for ASD's ride-through. Flywheels are suitable for 1kW–10 MW applications, and can provide full-power ride-through for up to 1 hr. Superconducting Magnetic Energy Storage (SMES) is based on the principle that energy stored in the field of a large magnetic coil can be converted quickly back to electric current as needed for various applications. A SMES unit can be applied directly connected to the DC-link of ASD's or to a number of ASD's which share a common DC-link. SMES with little maintenance provides good ride-through for long duration but it is costly and requires sophisticated cooling system to maintain cryogenic temperatures and the associated power loss. A fuel cell could be interfaced with the ASD's DC-link to provide appropriate backup power for an individual. However, the fuel cells are costly and may be used in near future.

Supercapacitors are new generation energy storage devices, which are true capacitors in the sense that energy is stored via charge separation at the electrode-electrolyte interface, and they can withstand a large number of charge/discharge cycles without degradation. The major advantages of Supercapacitors include higher capacitance density, higher charge-discharge cycles, reliable, long life, and maintenance-free operation, environmentally safe, wide range of operating temperature, high power density and good energy density, so they are a good alternative.[11-12]

Besides energy storage systems, some other devices may be used to solve EPQ problems [13-17]. Using proper interface devices, one can isolate the loads from disturbances deriving from the grid constant voltage transformers (CVT) were one of the first EPQ solutions used to mitigate the effects of voltage sags and transients. If not properly used, a CVT will originate more EPQ problems than the ones mitigated. It can produce transients, harmonics (voltage wave clipped on the top and sides) and it is inefficient (about 80% at full load).

A dynamic voltage restorer (DVR) acts like a voltage source connected in series with the load. The output voltage of the DVR is kept approximately constant voltage at the load terminals by injecting active and reactive power in the output supply through a voltage source converter. A matrix converter may provide ride- through during power quality disturbance. However, these topologies are not cost effective till date and are at research stage.

In this paper, the performance of ASD's during voltage sag conditions has been simulated and experimentally verified using supercapacitor as an ride-through capabilitiy.

IV. PROPOSED RIDE-THROUGH TOPOLOGIES

The proposed topology uses capacitors/ battery/ supercapacitor across DC-Link. The proposed modification can be easily integrated into a standard adjustable speed drive. The hardware set up is shown in Fig. 1.

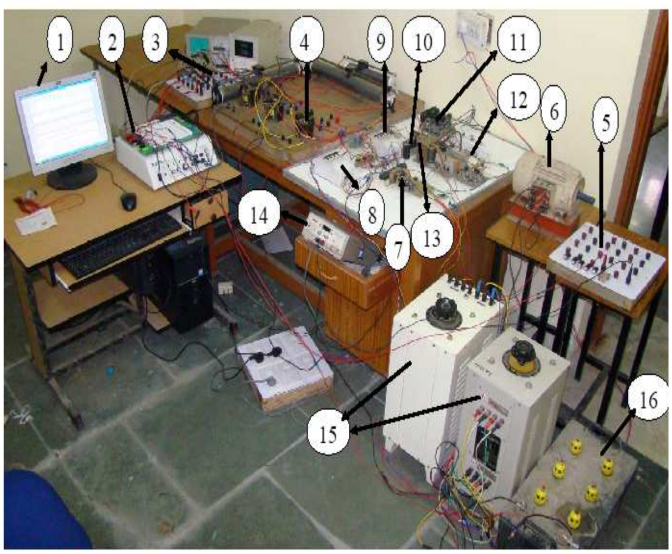

Fig. 1. View of Designed Hardware

1. Waveform in LabVIEW
2. DAQ board
3. DC isolation circuit
4. Isolation transformer
5. Supercapacitor
6. 3-phase induction motor
7. Sag generator
8. 3-phase supply
9. AC/DC converter section
10. Capacitor bank(DC- link)
11. Adjustable speed drives
12. Boost convereter
13. DC- link
14. Function generator
15. 3-phase Auto transformer
16. Battery

The ASD is a Field Oriented Controlled (FOC) induction motor (specifications are given in Appendix) .The designed hardware consists of:

A. *AC/DC converter section:* This unit consists of uncontrolled three- phase diode bride rectifier.

B. *DC/AC inverter unit:* This unit consists of IGBT based inverter.

C. Energy Storage Devices: These devices may be capacitor bank/ battery/ supercapacitor of 12Vmodules. This 12V DC is converted to 220 V DC (for experimental purpose) with the help of boost converter and the power is injected at the DC-link.

D. Voltage Sag Generation:

The various types of faults were created in the lab by actually grounding/shorting the line terminals in order to represent the true voltage sag condition as shown by single Line Diagram(SLD) in Fig.2.

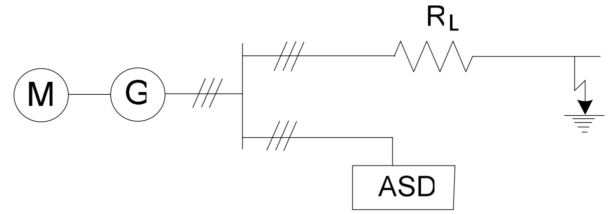

Fig. 2. SLD for voltage sag generation

V. MODELLING OF THE SYSTEM

1) Three-phase Converter

The first stage of proposed system is AC-DC conversion of a 3-phase AC power supply to a smooth DC voltage using uncontrolled/controlled rectifiers. In the system under consideration a simple 3-phase full bridge diode rectifier is used for AC-DC conversion as shown in Fig.3.

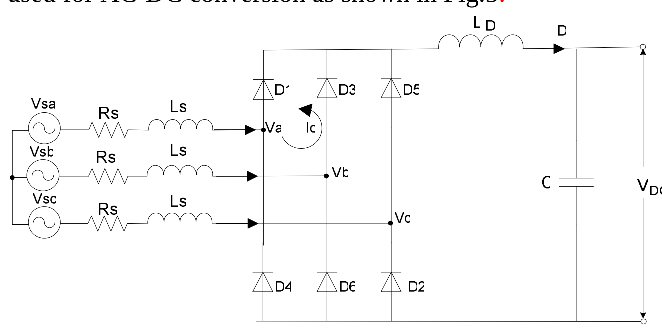

Fig.3. Three-Phase commutation with a 6-pulse diode bridge

The output DC voltage and operating sequence of the diode rectifier above is dependent on the continuous changes in the supply line voltages and is not dependent on any control circuit. This type of converter is called an uncontrolled diode rectifier bridge because the DC voltage output is not controlled and is fixed at $1.35 \times V_{rms}$ (2)

If the diodes are replaced with thyristors, it then becomes possible to control the point at which the thyristors are triggered and therefore the magnitude of the DC output voltage can be controlled. This type of converter is called a controlled thyristor rectifier bridge and requires an additional control circuit to trigger the thyristor at the right instant.

The three phase instantaneous input supply voltages v_{sa}, v_{sb}, and v_{sc} at PCC are expressed as:

$$v_{sa} = v_m \sin(\omega t) \quad (3)$$

$$v_{sb} = v_m \sin\left(\omega t - 2\pi/3\right) \tag{4}$$

$$v_{sc} = v_m \sin\left(\omega t + 2\pi/3\right) \tag{5}$$

Where, v_m is the peak value and $\omega = 2\pi f$ is the angular frequency of the supply.

Instantaneous voltages at PCC can be calculated as:

$$v_a = v_{sa} - R_s i_{sa} - L_s \frac{di_{sa}}{dt} \tag{6}$$

$$v_b = v_{sb} - R_s i_{sb} - L_s \frac{di_{sb}}{dt} \tag{7}$$

$$v_c = v_{sc} - R_s i_{sc} - L_s \frac{di_{sc}}{dt} \tag{8}$$

Where v_a, v_b, and v_c are three phase voltage at the input terminal of 3-phase rectifier, L_s and R_s are per phase source inductance and resistance respectively.

2) Field-Oriented Control of Induction Motor Drive

For the modeling and simulation of the IM drive system, the basic equations of IM are used in instantaneous form. By Park's transformation, the equations of the IM in a stationary reference frame, denoted by the superscript "*s*" in which d-axis aligned with the stator winding of phase "*a*" are shown in terms of voltage and flux as follows .

The stator voltage equation is as

$$v_s^s = i_s^s R_s + \frac{d}{dt}\varphi_s^s \tag{9}$$

The rotor voltage equation is as

$$0 = i_r^s R_r - \omega_r \varphi_r^s + \frac{d}{dt}\varphi_r^s \tag{10}$$

The stator flux equation is as

$$\varphi_s^s = L_s i_s^s + L_m i_r^s \tag{11}$$

The rotor flux equation is as

$$\varphi_r^s = L_r i_r^s + L_m i_s^s \tag{12}$$

The explicit expression of the flux linkage can be obtained from equation (9) and (10) are as

$$\varphi_s^s = \int (v_s^s - i_s^s R_s)dt \tag{13}$$

$$\varphi_r^s = \int (\omega_r \varphi_r^s - i_r^s R_r)dt \tag{14}$$

By solving equations (13) and (14), the explicit expressions of currents are as

$$i_s^s = \frac{1}{L_s L_r - L_m^2}\left(L_s \varphi_s^s - L_m \varphi_r^s\right) \tag{15}$$

$$i_r^s = \frac{1}{L_s L_r - L_m^2}\left(L_s \varphi_r^s - L_m \varphi_s^s\right) \tag{16}$$

Resolving all space vector equations (13-16) into their d-q axes components are as:

$$\varphi_{ds}^s = \int (v_{ds}^s - i_{ds}^s R_s)dt \tag{17}$$

$$\varphi_{qs}^s = \int (v_{qs}^s - i_{qs}^s R_s)dt \tag{18}$$

$$\varphi_{dr}^s = \frac{L_r}{L_m}\left(\varphi_{ds}^s - L_s i_{ds}^s\right) \tag{19}$$

$$\varphi_{qr}^s = \frac{L_r}{L_m}\left(\varphi_{qs}^s - L_s i_{qs}^s\right) \tag{20}$$

$$i_{ds}^s = \frac{1}{L_s L_r - L_m^2}\left(L_s \varphi_{ds}^s - L_m \varphi_{dr}^s\right) \tag{21}$$

$$i_{qs}^s = \frac{1}{L_s L_r - L_m^2}\left(L_s \varphi_{qs}^s - L_m \varphi_{qr}^s\right) \tag{22}$$

$$i_{dr}^s = \frac{1}{L_s L_r - L_m^2}\left(L_s \varphi_{dr}^s - L_m \varphi_{ds}^s\right) \tag{23}$$

$$i_{qr}^s = \frac{1}{L_s L_r - L_m^2}\left(L_s \varphi_{qr}^s - L_m \varphi_{qs}^s\right) \tag{24}$$

These equations (16)-(24) reveal the internal relations among voltage, current and flux of stator and rotor, which can be directly modeled by using Simulink blocks. However the above equations are not perfect to build the whole d-q axes motor model, another two equations to reflect the mechanical dynamics should be added.

The electromagnetic torque equation is as

$$T_e = \frac{3P}{4}(\varphi_{ds}^s i_{qs}^s - \varphi_{qs}^s i_{ds}^s) \tag{25}$$

The torque balance equation is as

$$\frac{d}{dt}\omega_m = \frac{T_e - T_L}{J_m} \tag{26}$$

where T_L load torque in the form of electric vehicle load.

3) Modeling of Voltage Source Inverter:

The voltage source inverter (VSI) consists of insulated gate bipolar transistors (IGBT) based three-phase voltage source inverter. The inverter output voltage can be obtained by following equations in terms of switching signals S_a, S_b and S_c and DC bus voltage, obtained from the current controller as

$$V_a = \left(V_{dc}/3\right)\left(2S_a - S_b - S_c\right) \tag{27}$$

$$V_b = \left(V_{dc}/3\right)\left(2S_b - S_a - S_c\right) \tag{28}$$

$$V_c = \left(V_{dc}/3\right)\left(2S_c - S_a - S_b\right) \tag{29}$$

where S_a, S_b and S_c are switching functions (which are either one or zero). V_a, V_b, V_c and V_{dc} are the voltage of phase winding *a*, *b*, *c* and DC link/ Battery voltage, respectively.

4) Energy Storage Devices

(a) Battery

The battery is modeled using well-known Thevenin equivalent circuit model as shown in Fig. 4. The battery side current is given as:

$$i_{bb} = (V_{dc} - V_{cb2} - V_{oc})/R_{b1} \tag{30}$$

and, its internal voltage derivative can be expressed as:

$$pV_{cb_2} = (i_{bb} - V_{cb_2}/R_{b_2})/C_{b_2} \tag{31}$$

where, V_{cb2} is the voltage across capacitor C_{b2} which gives the status of the charge of the battery. V_{oc} is the battery open circuit voltage and R_{b1} is the internal resistance of the battery and R_{b2} represents self-discharging of the battery.

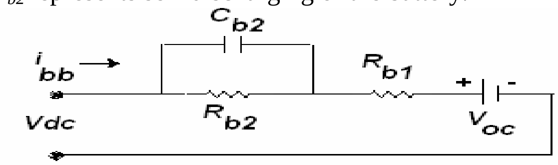

Fig. 4. Equivalent circuit of battery

(b) Supercapacitor

Energy stored in the supercapacitor is given by the following equation: [13]

$$E = \frac{1}{2} CV^2 \tag{32}$$

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

$$\text{Usable Energy} = E = \frac{1}{2} C\left[V_1^2 - V_2^2\right] \tag{33}$$

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

(c) Boost Converter

The boost converter, as shown in Fig. 5, converts an unregulated source voltage V_{in} into a higher regulated load voltage V_{out}. When the switch is closed as shown in Fig.6(a), the diode is reverse biased and the input voltage supplies energy to the inductor while the capacitor discharges into the load. When the switch is opened as shown in Fig.6(b), the diode conducts and both energy from the input voltage and energy stored in the inductor are supplied to the capacitor and the load; thus the output voltage is higher than the input voltage. During steady state operation, the ratio between the output and input voltage is $\frac{1}{1-D}$. The output voltage is controlled by varying the duty cycle. $\frac{V_{out}}{V_{in}} = \frac{1}{1-D}$

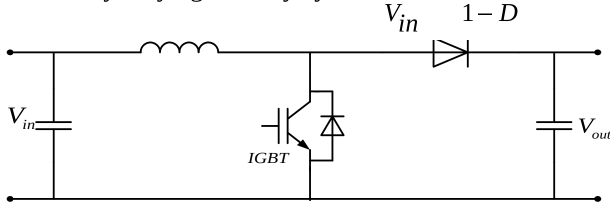

Fig.5. Boost Converter

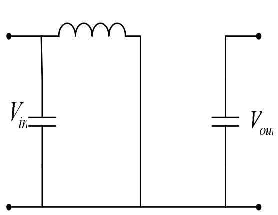

Fig. 6(a). S=1

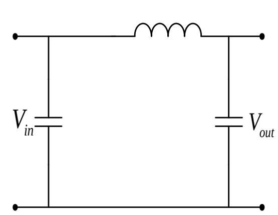

Fig. 6 (b). S=0

Control of DC-DC Converter: The output voltage of the switch-mode DC-DC converters are regulated to be within a specified range in response to changes in the input voltage and the load current.

DC-DC converters is used in current mode control as shown in Fig.7 for a DC-DC converter is a two-loop system. An additional inner current loop is added to the voltage loop. The current loop monitors the inductor current and compares it with its reference value. The reference value for the inductor current is generated by the voltage loop.

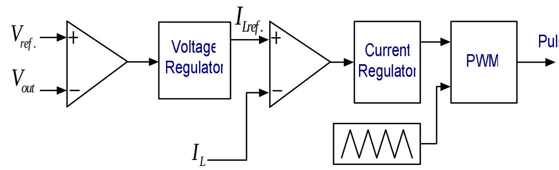

Fig.7. Current Control Mode

VI. Experimental Results and Discussion

The improved performance of ASD's was simulated in MATLAB Simulink Power System Block-set Toolbox. The objective of this section is to investigate the performance of an ASD's under various power system faults (EPQ disturbances). Figs. 8-13 show the performance of ASD's with the proposed scheme. The parameters V_{ry}, V_{yb}, V_{br}, I_{ry}, I_{yb}, I_{br}, V_{dc} show the line-line voltages, line currents, and DC-link voltage respectively.

A. Performance of ASD's during balanced voltage sag during balanced three-phase fault

Figs. 8-9 shows the theoretical and experimental results of ASD's during a voltage sag when supercapacitors as an energy storage device are applied. It can be seen that during a voltage sag of 20%, no source current is being drawn since the DC-link voltage remains higher than the line voltages. The DC – link voltage shows more oscilliations as the supercapacitors are faster in response. The ASD's rides-through and runs with desired torque and the speed with constant DC-link voltage as shown in Fig. 12.

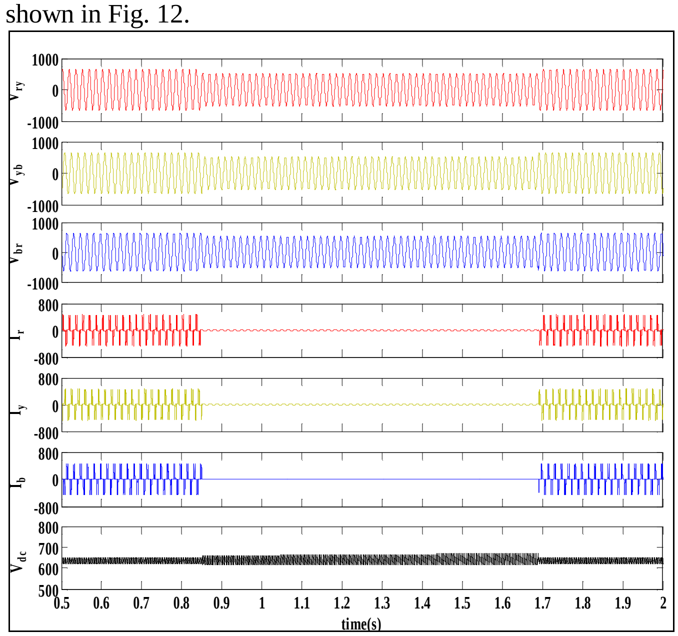

Fig. 8 Simulation results of ASD coupled with supercapacitor as an energy storage device during balanced voltage sag condition

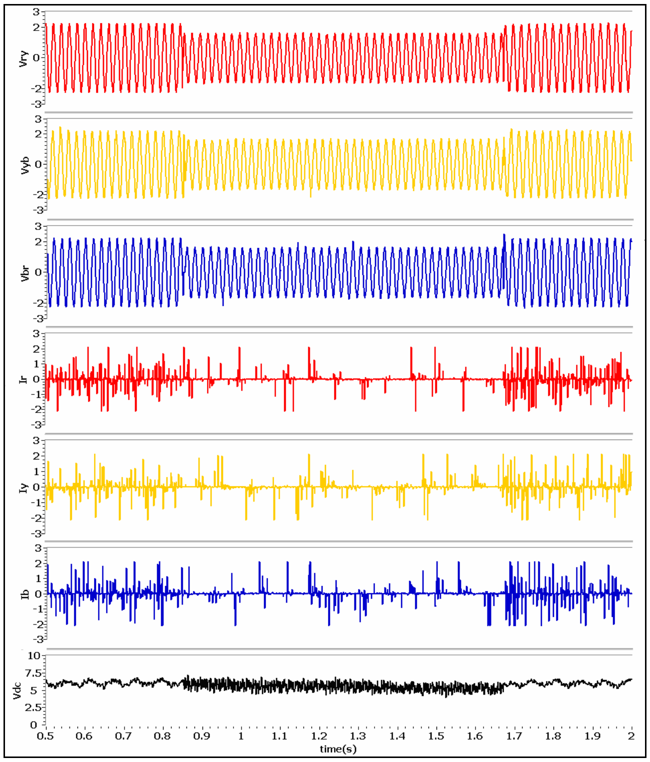

Fig. 9 Experimental results of ASD coupled with supercapacitor as an energy storage device during balanced voltage sag condition

B. Performance of ASD's during unsymmetrical fault condition

Figs. 10-11 show the theoretical and experimental results of ASD's with an unsymmetrical fault (single phase operation) with supercapacitors as an energy storage device acting separately. With the application of an energy storage device as a ride-through, the performance of the machine improves keeping the DC-link voltage almost constant as shown in Fig. 13.

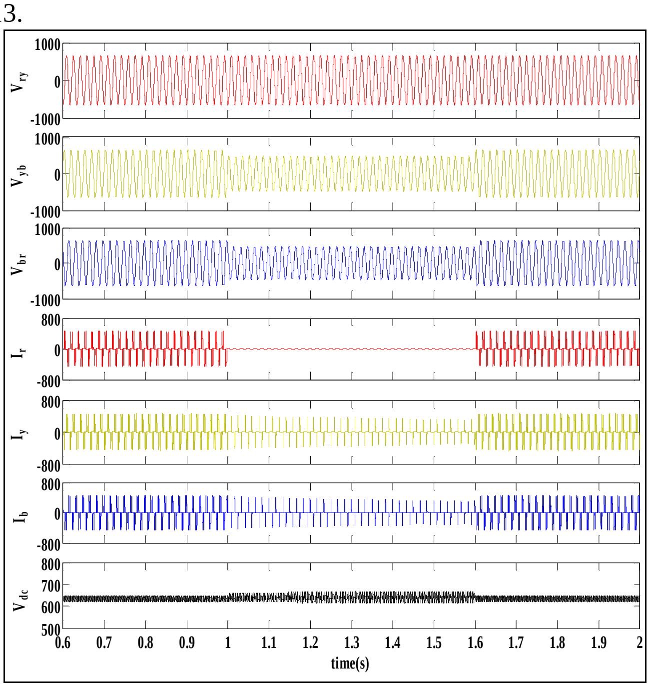

Fig. 10 Simulation results of ASD coupled with supercapacitor as an energy storage device during voltage unbalance condition

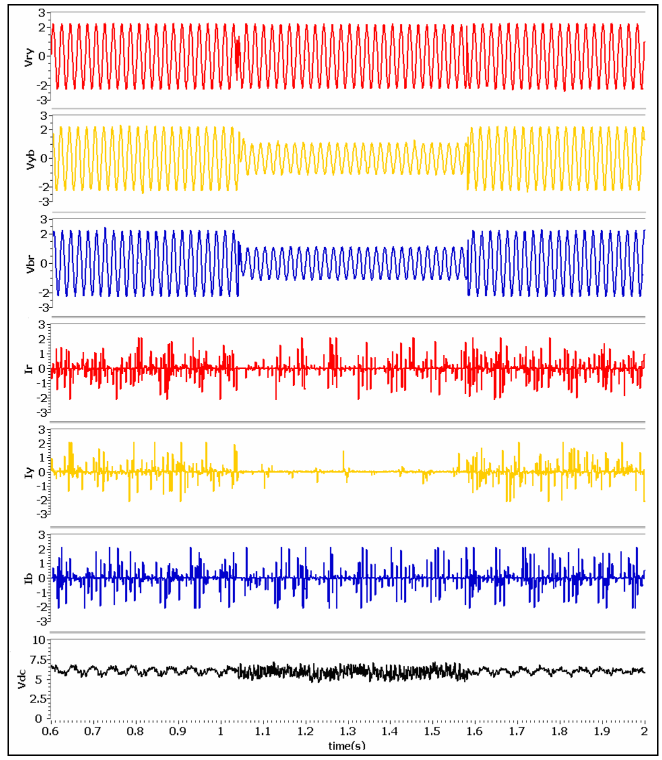

Fig. 11 Experimental results of ASD coupled with supercapacitor as an energy storage device during voltage unbalance condition

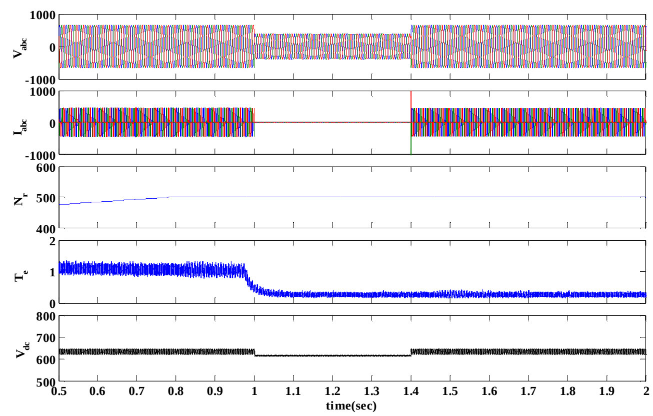

Fig. 12. Rotor Speed and Electromagnetic Torque Characteristics of ASD coupled with supercapacitor as an energy storage device during balanced voltage sag condition

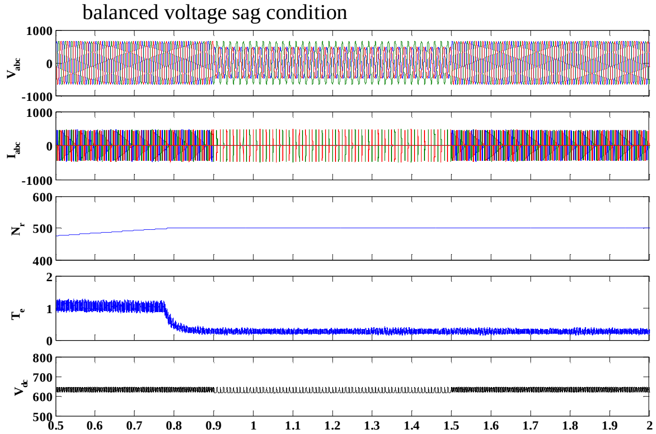

Fig. 13. Rotor Speed and Electromagnetic Torque Characteristics of ASD coupled with supercapacitor as an energy storage device during voltage unbalance condition

VII. .CONCLUSIONS

From the discussion it is clear that Super-capacitors, due to high power density and low ESR, are a very convenient energy storage component to be used in power quality applications. A proposed topology using Supercapacitors as an energy storage devices is developed and tested. The proposed topology is capable of providing ride through for deep voltage sags. All this, while maintaining the dc link voltage level constant during the duration of the transient disturbance. The effectiveness of the proposed ride through topology is shown by means of simulations based on MATLAB and experimental results obtained on a laboratory prototype. From these results it is clear that the supercapacitor's dynamic response is fast enough to respond to the load transient requirements and avoid

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) = 220 volts

LabView measurement scale:

Source Voltage and Current : 1: 300

DC-link Voltage : 1: 36

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