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Power Quality Analysis in a Distributed Power System Using D-SATACOM and DVR

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ABSTRACT: This paper describe the more reliable power electronic devices for a stability analysis of power by correcting the supply voltage sag, swell and interruption in a distributed power system. The use of sensitive electronic equipment has increased. Now days which have lead to power quality problems. To solve these power quality problems various custom power devices are used. At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications. Among these, the distribution static compensator (D-STATCOM) and the dynamic voltage restorer (DVR) both of them based on the VSC principle. DVR & D-STATCOM both are most effective devices,. A DVR injects a voltage in series with the system voltage and a D-STATCOM injects a current into the system to correct the voltage sag, swell and interruption. Simulation results using Matlab/Simulink are presented to verify the effectiveness of these devices.

I. INTRODUCTION

A Power quality problem is a manifest as an abnormal voltage, current or frequency that results in a failure or a misoperation of end user equipments. Power quality phenomena can be defined as the deviation of the voltage and the current from its ideal waveform voltage and the current it's ideal waveform. [1]. Utility distribution networks, sensitive industrial loads and critical commercial operations suffer from various types of outages and service interruptions which can cost significant financial losses. With the streamlining of power systems and with shifting trend towards distributed and isolated generation, the issue of power quality is going to take newer dimensions. Sensitive equipment and non-linear loads have become common for all consumers in sectors commercial, industrial and residential. In the past, most electrical equipment was insensitive to small supply voltage variations. Nowadays, since many industrial, commercial and even residential electrical loads have electronic logic circuits or microprocessors, they became very sensitive to voltage supply disturbances [9].

In developing countries like India, where the variation of power frequency and many such other determinants of power quality are themselves a serious question, it is very vital to take positive steps in this direction. In a general way, any disturbance in the voltage, current or frequency that results in fail or abnormal operation of an equipment can be classified as a power quality problem [9]. The present work is to identify the outstanding concerns in this area and hence the measures that can enhance the quality of the power are recommended. The increased amount of power from decentralized, renewable energy systems, as especially wind energy systems, requires determined grid code requirements to maintain a stable and safe operation of the energy network. Recent trend of industrial devices are based on electronic devices.

The electronic devices are very sensitive to disturbances and become less tolerant to power quality problems such as voltage sags, swells and harmonics. Voltage dips are considered to be one of the most severe disturbances to the industrial equipments. Voltage support at a load can be achieved by reactive power injection at the load point of common coupling [8]. The common method for this is to install mechanically switched shunt capacitors in the primary terminal of the distribution transformer.. The disadvantage is that, high speed transients cannot be compensated. Some sag is not corrected within the limited time frame of mechanical switching devices. Transformer taps may be used, but tap changing under load is costly. Another power electronic solution to the voltage regulation is the use of a dynamic voltage restorer (DVR) and distributed static compensator (D-STATCOM). DVRs are a class of custom power devices for providing reliable distribution power quality [3].

They employ a series of voltage boost technology using solid state switches for compensating voltage sags/swells. The DVR applications are mainly for sensitive loads that may be drastically affected by fluctuations in system voltage. The D-STATCOM is a shunt-connected, solid-state switching power converter that provides flexible voltage control at the point of connection to the utility distribution feeder for power quality improvements and also exchanges both active and reactive power with the distribution system by varying the amplitude and phase angle of the converter [8]. Since this device is utilized in steady-state condition for long term, because of limited capacity of energy storage system, it cannot inject active power to the system for long term. The effects of D-STATCOM on voltage improvement at other nodes are considered and the optimum location of D-STATCOM in the distribution network is determined. At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications. Among these, the distribution static compensator and the dynamic voltage restorer are most effective devices, both of them based on the VSC principle. A new PWM-based Control scheme has been implemented to control the electronic valves in the two-level VSC used in the D-STATCOM and DVR.

II. FACTS CONTROLLERS

Flexible alternating-current transmission systems (FACTS) are defined by the IEEE as "ac transmission systems incorporating power electronics-based and other static controllers to enhance controllability and increase power transfer capability" Similarly, a FACTS controller is defined as "power electronics based system or other static equipment that provides control of one or more ac transmission parameters" .In recent years, many different FACTS controllers have been proposed, performing a wide variety of functions [11].

A. Basic Types of FACTS Controllers

Basically the FACTS controllers are four types:-

1. Series controllers
2. Shunt controllers
3. Combined Series-Series Controllers
4. Combined Series -Shunt controllers

B. Series controller

By means of controlling impedance or phase angle or series injection of voltage a series FACTS Control can control the flow of current. Hence, the series controller could be variable impedance, such as capacitor, reactor or power electronics based variable source to serve the desired need. But generally all series controllers inject variable voltage in series with line. Even variable impedance multiplied by current flow through it represents an injected series voltage. As long as voltage is in quadrature with the line current, the series controller only supplies or consumes variable reactive power. Any other phase relationship will involve real power as well.

C. Shunt Controllers

As in the case of series controllers, shunt controllers may be variable impedance, variable source or a combination of these. In principle all shunt controller inject current into the system. Even variable shunt impedance causes a variable current injection in to the line. As long as injected current is in phase quadrature with the line voltage it supplies or consumes variable reactive power. Any other phase relationship will involve real power exchange also [8].

D. Combined series-series controller

This could be a combination of separate series controllers, which are controlled in a coordinated manner, or it could be a unified controller. The series controllers could provide independent series reactive compensation but also could transfer real power among the lines via the power link (D.C link) [2]. The real power transfer capability of the unified series- series controller, referred to as interline power flow controller, makes it possible to balance both the real and reactive power flow in the lines. And there by maximize the utilization of the transmission system. Note that the term “unified” here means that the DC terminals of all controller converters are all connected together for real power transfer.

E. Combined series-shunt controller

This is a combination of series and shunt controllers which are controlled in a coordinated manner or a unified power flow controller with series and shunt elements. In principle combined shunt and series controller inject current in to the system with the shunt part of the controller and voltage in series in the line with the series part of the controller [4]. However when the shunt and series controllers are unified, there can be a real power exchange between the series and shunt controllers via the power link.

III. DYNAMIC VOLTAGE RESTORER (DVR)

The series voltage controller is connected in series with the protected load as shown in Fig.1. Usually the connection is made via a transformer, but configurations with direct connection via power electronics also exist. The resulting voltage at the load bus bar equals the sum of the grid voltage and the injected voltage from the DVR. The converter generates the reactive power needed while the active power is taken from the energy storage [2].

The energy storage can be different depending on the needs of compensating. The DVR often has limitations on the depth and duration of the voltage dip that it can compensate. The system impedance Z_{th} depends on the fault level of the load bus. When the system voltage (V_{th}) drops, the DVR injects a series voltage V_{DVR} through the injection transformer so that the desired load voltage magnitude V_L can be maintained. The series injected voltage of the DVR can be written as [12].

$$V_{DVR} = V_L + Z_{th} I_L - V_{th}$$

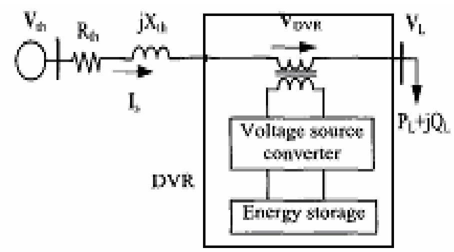

Fig. 1. Schematic diagram of a DVR.

Where
V_L is the desired load voltage magnitude
Z_{th} is the load impedance
I_L is the load current

V_{th} is the system voltage during fault condition
The load current I_L is given by,

$$I_L = [(P_L + J^* Q_L)/V_L]^* \quad \dots(1)$$

When
V_L is considered as a reference, eqn. can
Be rewritten as,

$$V_{DVR}\angle\alpha = V_L\angle 0 + Z_{th} I_L \angle(\beta - \theta) - V_{th}\angle\delta \quad \dots(2)$$

Here α, β and δ are the angle of V_{DVR}, Z_{th}, and V_{th} respectively, and θ is the load power factor angle,

$$\theta = \tan^{-1}\left(\frac{Q_L}{P_L}\right) \quad \dots(3)$$

The complex power injection of the DVR can be written as,

$$S_{DVR} = V_{DVR} I^*_L \quad \dots(4)$$

It may be mentioned here that when the injected voltage
V_{DVR} is kept in quadrature with I^*_L, no active power injection by the DVR is required to correct the voltage. It requires the injection of only reactive power and the DVR. Note that DVR can be kept in quadrature with I_L only up to a certain value of voltage sag and beyond which the quadrature relationship cannot be maintained to correct the voltage sag. For such a case, injection of active power into the system is essential. The injected active power must be provided by the energy storage system of the DVR.

V. TEST SYSTEM

Single line diagram of the test system for DVR is shown in Fig. 7 and the test system employed to carry out the simulations for DVR is shown in Fig. 2. Such system is composed by a 13 kV, 50 Hz generation system, feeding two transmission lines through a 3-winding transformer connected in Y/Δ/Δ, 13/115/15 kV. Such transmission lines feed two distribution networks through two transformers connected in Δ/Y, 15/11 kV.

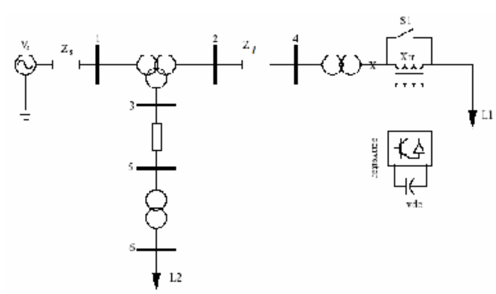

Fig. 2. Single line diagram of the test system for DVR.

Secondary side of the transformer. A two-level DSTATCOM is connected to the 11 KV tertiary winding to provide instantaneous voltage support at the load point. A 750 μF capacitor on the dc side provides the D-STATCOM energy storage capabilities. To show the effectiveness of this Controller in providing continuous voltage regulation, simulations were carried out with and with no DSTATCOM connected to the system.

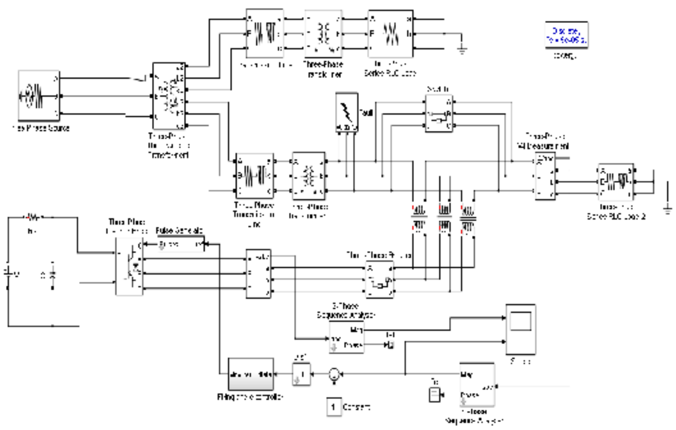

Fig. 3. Matlab/Simulink model of DVR.

VI. DISTRIBUTION STATIC COMPENSATOR (D-STATCOM)

The D-STATCOM (Distribution Static Compensator), which is a three-phase and shunt connected power electronics based device. It is connected near the load at the distribution systems. The major components of a D-STATCOM are shown in Figure 1. It consists of a dc capacitor, three-phase inverter (IGBT, thyristor) module, ac filter, coupling transformer and a control strategy [15]. A D-STATCOM is schematically depicted in Figure-4, consists of a two-level Voltage Source Converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the distribution network through a coupling transformer. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM and the ac system. Such configuration allows the device to absorb or generate controllable active and reactive power. The VSC connected in shunt with the ac system provides a multifunctional topology which can be used for up to three quite distinct purposes:

1. Voltage regulation and compensation of reactive Power
2. Correction of power factor; and
3. Elimination of current harmonics.

Here, such device is employed to provide continuous voltage regulation using an indirectly controlled converter. Figure 4 the shunt injected current I_{sh} corrects the voltage sag by adjusting the voltage drop across the system impedance Z_{th}.
The value of I_{sh} can be controlled by adjusting the output voltage of the converter. The shunt injected current I_{sh} can be written as,

$$I_{sh} = I_L - I_S = I_L - \left(\frac{V_{th} - V_L}{Z_{th}}\right) \qquad \ldots(5)$$

The complex power injection of the DSTATCOM can be expressed as,

$$S_{sh} = V_L I_{sh}$$

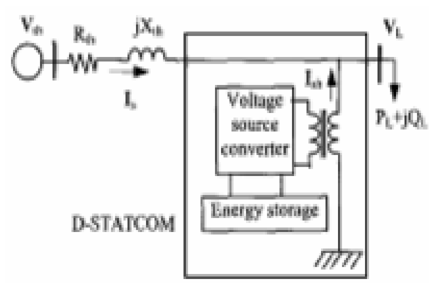

Fig. 4. Single line diagram of the test system for D-STATCOM.

It may be mentioned that the effectiveness of the D-STATCOM in correcting voltage sag depends on the value of Z_{th} or fault level of the load bus. When the shunt injected current I_{sh} is kept in quadrature with V_L, the desired voltage correction can be achieved without injecting any active power into the system. On the other hand, when the value of I_{sh} is minimized, the same voltage correction can be achieved with minimum apparent power injection into the system [14]. The control scheme for the DSTATCOM follows the same principle as for DVR. The switching frequency is set at 475 Hz.

A. Test system

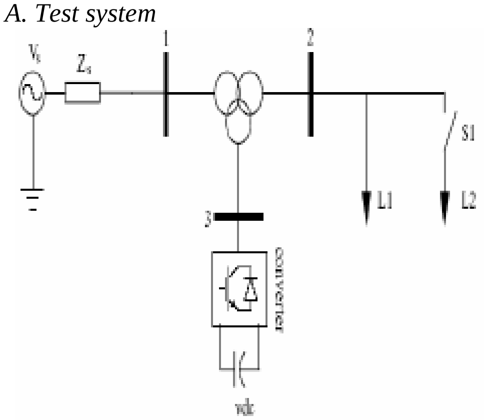

Fig. 5. Single line diagram of the test system for D-STATCOM.

Fig. 5 shows the test system used to carry out the various D-STATCOM simulations. Figure-6 shows the test system implemented in MATLAB SIMULINK. The test system comprises a 230KV, 50Hz transmission system, represented by a Thevenin equivalent, feeding into the primary side of a 3 winding transformer connected in Y/Y/Y, 230/11/11 KVA varying load is connected to the 11 KV, secondary side of the transformer. A two-level DSTATCOM is connected to the 11 KV tertiary winding to provide instantaneous voltage support at the load point. A 750 μF capacitor on the dc side provides the D-STATCOM energy storage capabilities. To show the effectiveness of this controller in providing continuous voltage regulation, simulations were carried out with and with no DSTATCOM connected to the system.

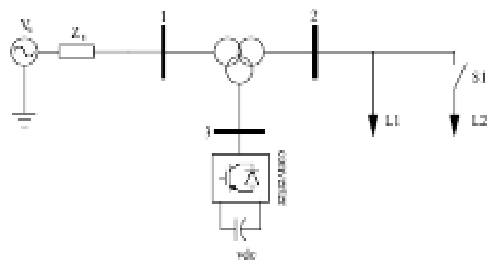

Fig. 6. Single line diagram of the test system for D-STATCOM.

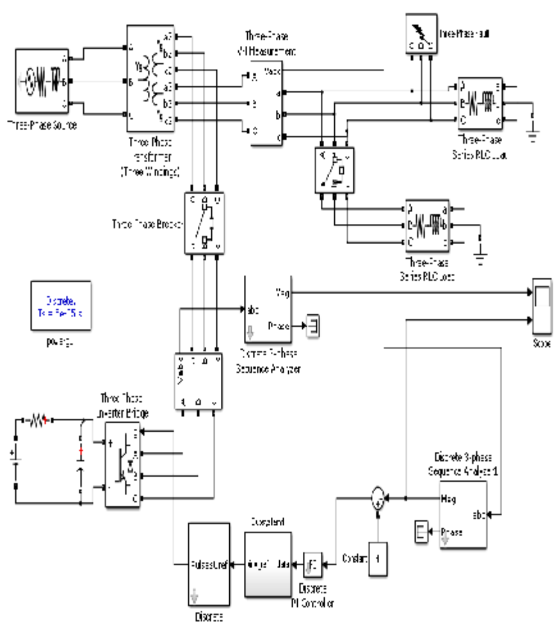

Fig. 7. Matlab/Simulink model of D-STATCOM.

VII. SIMULATION RESULTS

Case 1: Simulation results of voltage during single line to ground fault

The first simulation contains no DVR and single line to ground fault is applied, via a fault resistance of 0.09 Ω, during the period 400 to 600 ms. The voltage sag at the load point is 17% with respect to the reference voltage which is shown in Fig. 8. Energy storage of 7 KV, When the DVR is in operation the voltage sags mitigated almost completely, and the RMS voltage at the sensitive load point is maintained normal.

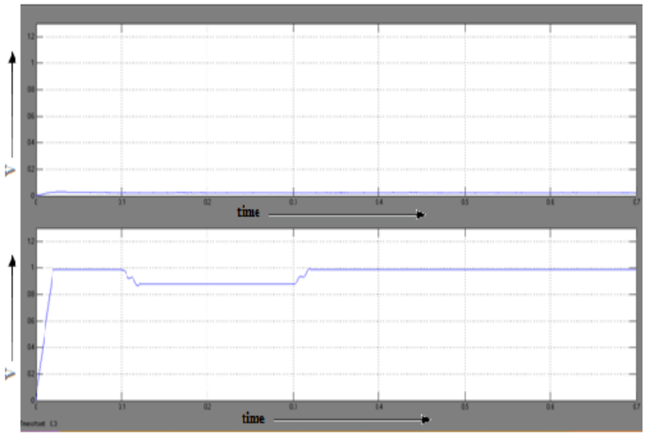

Fig. 8. Voltage V_{RMS} at load point after the occurrence of Single line to ground fault without DVR.

The PWM control scheme controls the magnitude and the phase of the injected voltages, restoring the RMS voltage very effectively. The swell mitigation is performed with a smooth, stable, and rapid DVR response.

Voltage at the sensitive load point is maintained normal. The second simulation is carried out using the same scenario as above but now with the DVR in operation as shown in Fig. 9. The total simulation period is 1000 ms.

Case 2: Simulation results of voltage during Double line to ground fault.The first simulation contains no DVR and double line to ground fault is applied, via a fault resistance of 0.09 Ω, during the period 400–600 ms. the voltage sags at the load point is 60% with respect to the reference voltage which is shown in Fig. 10. The second simulation is carried out using the same scenario as above but now with the DVR in operation as shown in Fig. 11. The total simulation period is 1000 ms.

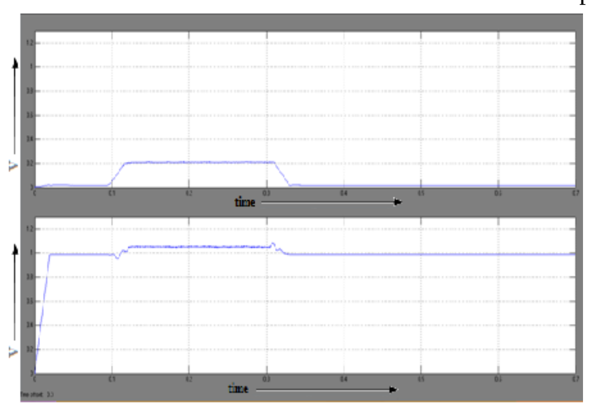

Fig. 9. Voltage V_{RMS} at load point after the occurrence of Single line to ground fault with DVR.

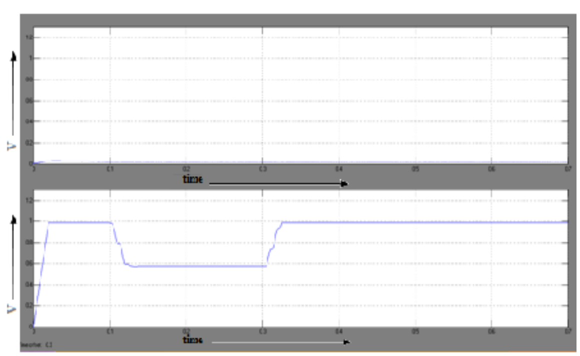

Fig. 10. Voltage V_{RMS} at load point after the occurrence of Double Line to ground fault without DVR.

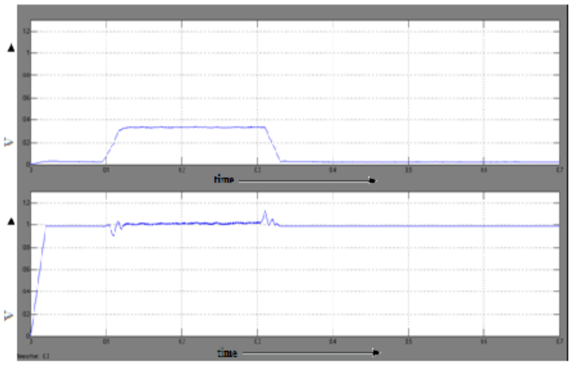

Fig. 11. Voltage V_{RMS} at load point after the occurrence of Double Line to ground fault with DVR Energy storage of 7 KV.

Case 3: Simulation results of voltage during three phases to ground fault. The first simulation contains no DVR and three phase to ground fault is applied, via a fault resistance of 0.09 Ω, during the period 400–600 ms. The voltage sags at the load point is 75% with respect to the reference voltage which is shown in Fig. 12.

The second simulation is carried out using the same scenario as above but now with the DVR in operation as shown in Figure 13. The total simulation period is 1000 ms.

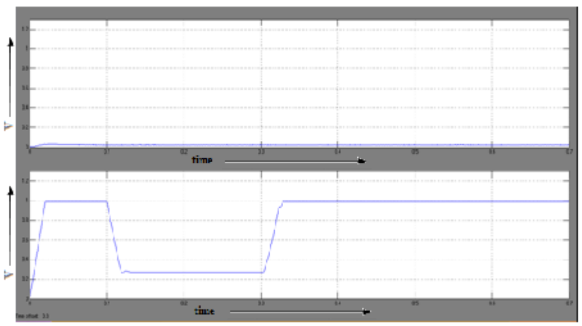

Fig. 12. Voltage V_{RMS}at load point after the occurrence of three phase fault without DVR.

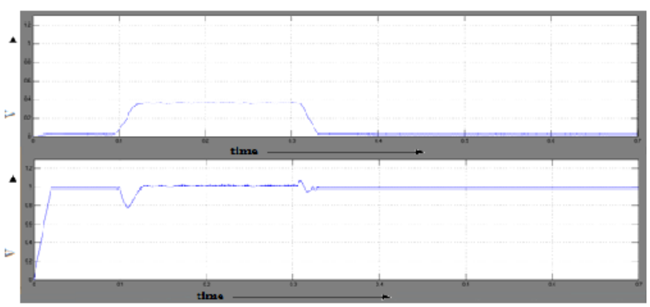

Fig. 13. Voltage V_{RMS} at load point after the occurrence of three phase fault with DVR Energy storage of 7 KV.

B. Simulation Results of D-STATCOM

Case 1: Simulation results of voltage during single line to ground fault.The first simulation contains no D-STATCOM and single line to ground fault is applied, via a fault resistance of 0.09 Ω, during the period 400–600 ms. The voltage sag at the load point is 30% with respect to the reference voltage which is shown in Fig.14.

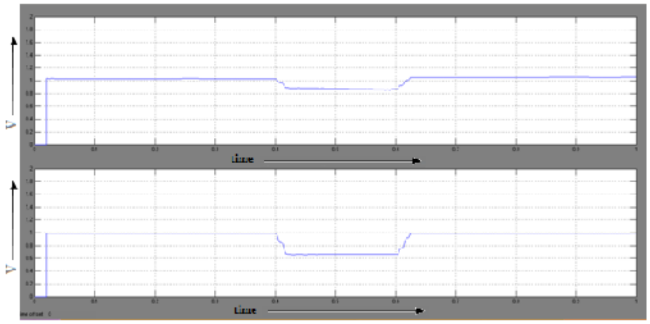

Fig. 14. Voltage V_{RMS} at load point after the occurrence of Single Line to ground fault without DSTATCOM.

When the D-STATCOM is in operation the voltage sag is mitigated almost completely, and the RMS voltage at the sensitive load point is maintained normal. The PWM control scheme controls the magnitude and the phase of the injected voltages, restoring the RMS voltage very effectively.

The second simulation is carried out using the same scenario as above but now with the D-STATCOM in operation as shown in Figure 15. The total simulation period is 1000 ms.

Case 2: Simulation results of voltage during Double line to ground fault.The first simulation contains no D-STATCOM and double line to ground fault is applied, via a fault resistance of 0.09 Ω, during the period 400–600 ms. The voltage sag at the load point is 55% with respect to the reference voltage which is shown in Figure 16.

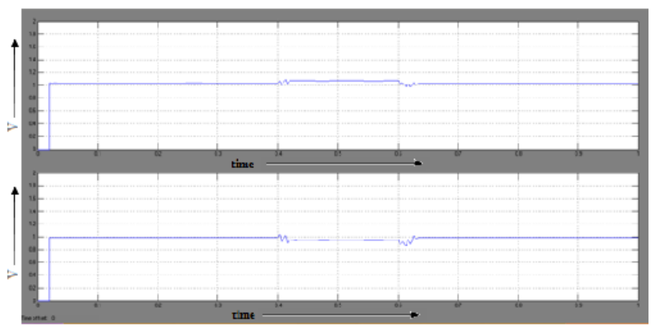

Fig. 15. Voltage V_{RMS} at load point after the occurrence of Single Line to ground fault with D-STATCOM, Energy storage of 25 KV.

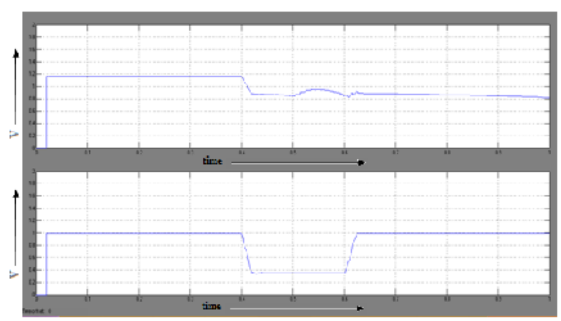

Fig. 16. Voltage V_{RMS} at load point after the occurrence of Double Line to ground fault without D-STATCOM.

The second simulation is carried out using the same scenario as above but now with the DSTATCOM in operation as shown in Fig. 17 the total simulation period is 1000 ms.

Case 3: Simulation results of voltage during three phase to ground fault. The first simulation contains no DSTATCOM and three phase to ground fault is applied, via a fault resistance of 0.2 Ω, during the period 400–600 ms. The voltage sag at the load point is 85% with respect to the reference voltage which is shown in Fig. 18. The second simulation is carried out using the same scenario as above but now with the D-STATCOM in operation as shown in Figure 19 the total simulation period is 1000 ms.

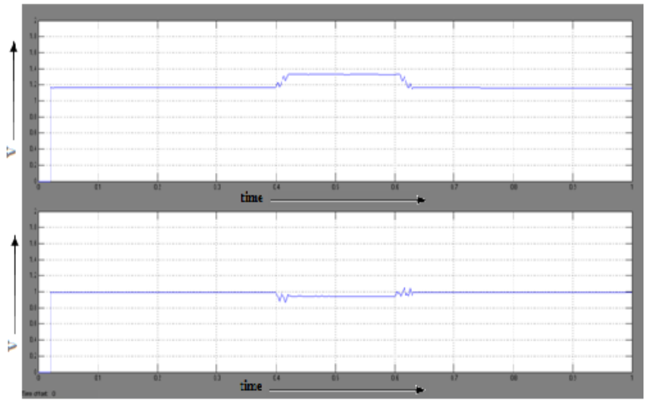

Fig. 17. Voltage V_{RMS} at load point after the occurrence of Double Line to ground fault with D-STATCOM Energy storage of 35 KV.

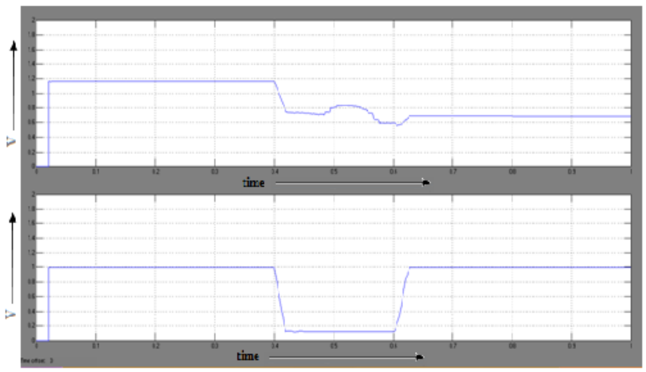

Fig. 18. Voltage V_{RMS} at load point after the occurrence of three phase fault without D-STATCOM.

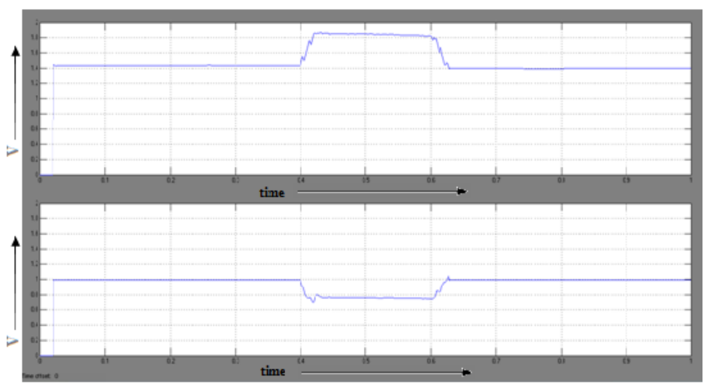

Fig. 19. Voltage V_{RMS} at load point after the occurrence of three phase fault with D-STATCOM Energy storage of 35 KV.

VII. CONCLUSION

In this paper, the power quality problems such as voltage dips, swells, distortions and harmonics. Compensation techniques of custom power electronic devices DVR & D-STATCOM are presented. The DVR & D-STATCOM handles both balanced and unbalanced situations without any difficulties and injects the appropriate voltage component to correct rapidly any deviation in the supply voltage to keep the load voltage balanced and constant at the nominal value. From the simulation results, the designed DSTATCOM & DVR responded well in mitigating voltage sag caused by three phase balanced fault. The DC capacitor value is dependent on the percentage of voltage sag. The difference of step drop load current during sag is the amount of reactive current needed to be compensated.

A PWM based control scheme has been implemented. As opposed to fundamental frequency switching schemes already available in the MATLAB/SIMULINK, this PWM control scheme only requires voltage measurements. This characteristic makes it ideally suitable for low voltage custom power applications.

It was observed that the capacity for power compensation and voltage regulation of DVR and D-STATCOM depends on the rating of the dc storage device.

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