Simulation of Unified Series Shunt Compensator for Power Quality Improvement

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ABSTRACT

This paper deals with the simulation of a unified series-shunt compensator (USSC) aimed at examining its capability in improving power quality in a power distribution systems. The USSC simulation model comprises of two 12-pulse inverters which are connected in series and in shunt to the system. A generalized sinusoidal pulse width modulation switching technique is developed in the proposed controller design for fast control action of the USSC. Simulation results verify the capabilities of the USSC in performing voltage sag compensation, flicker reduction, voltage unbalance mitigation, UPS mode, power-flow control and harmonics elimination. A comparison of the USSC with other custom power devices shows that the USSC gives a better performance in power-quality mitigation.

Keywords: Power Quality Mitigation, USSC , Simulation Model, Comparison with D-STATCOM and DVR

1. INTRODUCTION

An increasing demand for high quality, reliable electrical power and an increasing number of distorting loads have led an increased awareness of power quality both by customers and utilities. For power-quality improvement, the development of power electronic devices such as flexible ac transmission system (FACTS) and custom power devices have introduced an emerging branch of technology providing the power system with versatile new control capabilities. In general, FACTS devices are used in transmission control whereas custom power devices are used for distribution control. Since the introduction of FACTS and custom power concept , devices such as unified power-flow controller (UPFC), synchronous static compensator (STATCOM), dynamic voltage restorer (DVR), solid-state transfer switch, and solid-state fault current limiter are developed for improving power quality and reliability of a system . Advanced control and improved semiconductor switching of these devices have achieved a new era for power-quality mitigation.

Investigations have been carried out to study the effectiveness of these devices in power-quality mitigation such as sag compensation, harmonics elimination, unbalance compensation, reactive power compensation, power-flow control, power factor correction and flicker reduction.

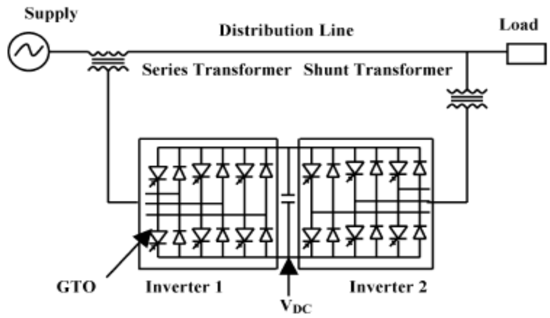

Fig.1(a) :. Basic Configuration of USSC

By using a unified approach of series-shunt compensators it is possible to compensate for a variety of power-quality problems in a distribution system including sag compensation, flicker reduction, unbalance voltage mitigation, and power-flow control. However, not much work has been carried out in the development of a USSC.

1.1 Model of USSC

The modeling of the USSC can be divided into three parts, namely equivalent circuit model, controller model and simulation model, respectively, as described below:

1.2 Equivalent circuit model:

In steady state analysis, the series and shunt inverters of the USSC are presented by two voltage sources Vdq and V_{sh}, respectively as shown in Fig. 3. Therefore, voltage equation of series and shunt inverter can be expressed as follows:

$$V_s = -V_{dq} + I_{se}(jX_{se}) + V_o$$
$$V_s + V_{dq} - I_{se}(jX_{se}) = V_{sh} + I_{dq}(X_{sh})$$

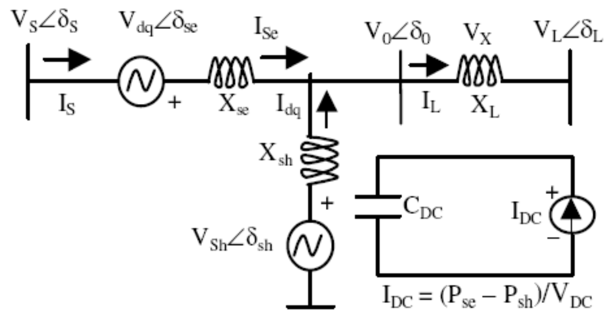

Fig.1(b): Equivalent circuit

Where, Ise and Idq are series and shunt inverter current, respectively.

The voltage across the distribution line reactance, XL, is:

$$V_X = V_s + V_{dq} - I_{se}(jX_{se}) - V_L = V_0 - V_L = I_L X_L$$

$$\frac{dV_{DC}}{dt} = \frac{1}{C_{DC}} I_{DC} = \frac{1}{C_{DC}V_{DC}}(P_{se} - P_{sh}) \qquad (8)$$

$$\text{where, } P_{sh} = \text{Re}\left[\frac{V_{sh}(V_s - V_{sh})}{jX_{sh}}\right]$$

$$P_{se} = \text{Re}\left[V_{dq}\left(\frac{V_s + V_{dq} - V_0)}{jX_{se}}\right]$$

2. PRINCIPLE OPERATION OF USSC

The USSC is a combination of series and shunt voltage source inverters and its basic configuration is shown in Fig. 1.

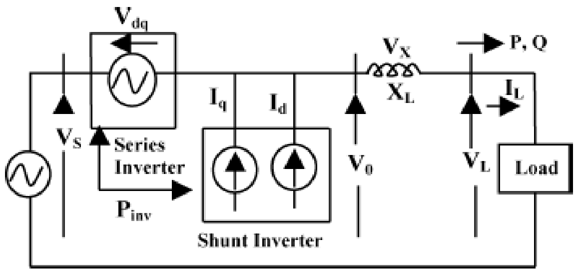

Fig.2 : Basic model of USSC

The principle operation of a USSC is described by first referring to the model shown in Fig. 2. The exchange of real power Pinv and reactive power Qinv can be written in terms of phase angle (the angle between the injected voltage Vdq and the line current I), the injected voltage Vdq , and the line current I, as

$$P_{inv} = V_{dq} I_{\cos\Phi}$$
$$Q_{inv} = V_{dq} I_{\sin\Phi}$$

The current injected by the shunt inverter has a real or direct component Id, which can be in phase or in opposite phase with the line and a reactive or quadrature component Iq , which is in quadrature with the line voltage, thereby emulating an inductive or a capacitive reactance at the point of connection with the distribution line. The reactive current can be independently controlled which in turn will regulate the line voltage.

The USSC behaves as an ideal ac-to-ac inverter, in which the exchange of real power at the terminal of one inverter to the terminal of the other inverter is through the common dc link capacitor. It should be noted that the shunt inverter is controlled in such a way as to provide precisely the right amount of real power at its dc terminal to meet the real power needs of the series inverter and to regulate the dc voltage of the dc bus. Thus, real power is absorbed from or delivered to the distribution line through the shunt connected inverter, which injects a current at the point of connection.

Thus, USSC includes the functions of both series and shunt connected inverters which generates or absorbs reactive power to regulate voltage magnitude and current flow at the ac terminal, respectively.

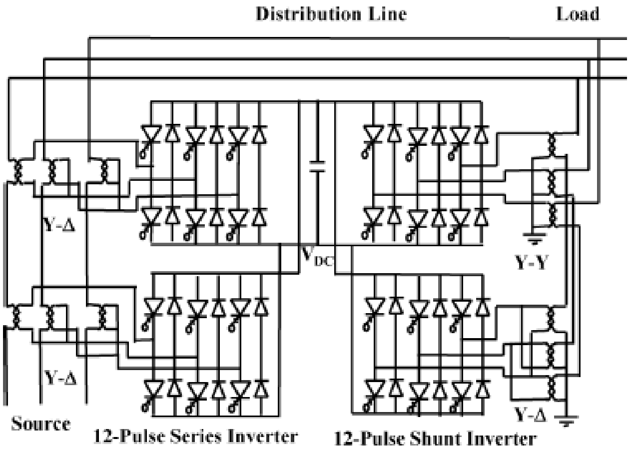

Fig.3 : Simulation model of USSC using 12-pulse series and shunt inverters

3. SIMULATION MODEL

The series and shunt combination of inverters consists of a two-level, three-phase, 24 self-commutated GTO switches with anti-parallel diodes. This valve combination and its capability to act as a rectifier or as an inverter with instantaneous current flows in positive or negative direction, respectively, is the basic voltage source converter concept. The shunt connected inverter is connected to the load by means of two sets of three single-phase transformers which are of Y-Y and Y- configurations to avoid phase shift of other than the order of harmonics in the secondary of the transformers, which may result in large circulating current due to common core of flux. The phase to neutral Harmonic voltages of Y-Y connected secondary, other than the order of $12n \pm 1$, i.e., 5th, 7th, 17th, 19th . are opposite to those of the phase to phase harmonic voltages of Y connected secondary and with 1/3 times the amplitude. Therefore, the output voltage of shunt inverter would be a 12-pulse wave form, with harmonic order of $12n \pm 1$. However, the series connected inverter is connected to the source by means of two sets of three single-phase transformers which are of Y configuration. The leakage reactance of the all the transformers are kept low so as to prevent a large voltage drop. The 22/4.6-kV step-down transformers with a leakage reactance of 0.01 per unit are considered. Two consecutive 6-pulse inverters are used to make up the 12-pulse inverter and the phase shift between these two inverters is calculated and found to be 30 degrees by using the phase shift displacement angle formula

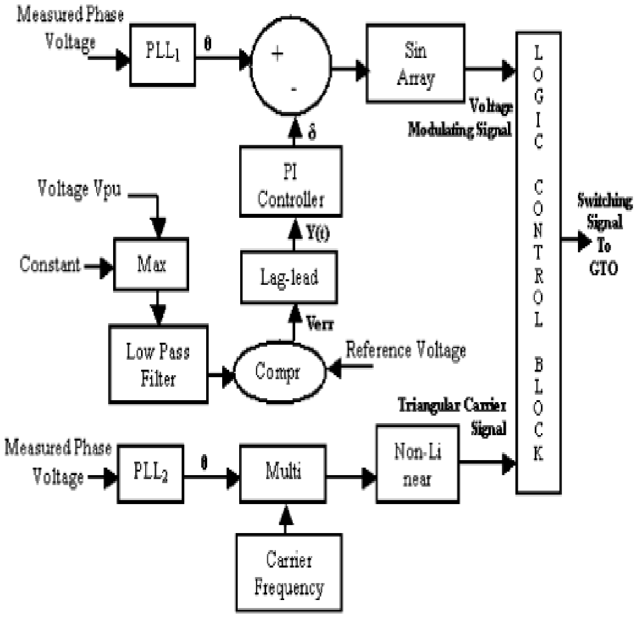

Fig. 4 Shunt inverter control system

which is given by , $2\pi/6m$ where m is the number of the 6-pulse inverters used. The capacitor plays an important role in the USSC operation by acting as a dc source to provide reactive power to the load and to regulate the dc voltage. The size of the dc capacitor considered in this simulation is 3340.

4. CONTROL SYSTEM OF USSC

The control system of the USSC can be divided into two parts, namely a shunt inverter controller and a series inverter controller, in which they control the shunt current and the series injected voltage, respectively. When the series and the shunt connected inverters operate as stand-alone devices, they exchange almost exclusively reactive power at their terminals. The series connected inverter injects a voltage in quadrature with the line current thereby emulating an inductive or a capacitive reactance in series with the line. The shunt connected inverter, however, injects a reactive current, thereby also emulating a reactance at the point of connection. While operating both series and shunt-connected inverters together as a USSC, the series injected voltage can be at any angle with respect to the line current. The exchange of real power flow can be between the terminals of series and shunt connected inverters through the common dc link capacitor.

4.1 Shunt Inverter Controller of USSC

If $\delta = 0$ the shunt inverter output voltage is said to be in phase with the ac system voltage. However, if there is an error between the reference voltage and the system voltage in per unit, that is Vp.u<Vref. then the displacement angle $\delta > 0$ and the shunt inverter voltage lags behind the ac system voltage thus causing real power flow into the shunt inverter. The increase in ac output voltage causes a reduction in the error voltage until Vp.u=Vref.If Vp.u>Vref. then the displacement angle $\delta < 0$ and the shunt inverter voltage leads the ac voltage thus causing real power flow into the system. Consequently, the dc Capacitor voltage will decrease, thus causing a decrease in the ac output voltage of the shunt inverter and a reduction in the error voltage Vp.u = Vref

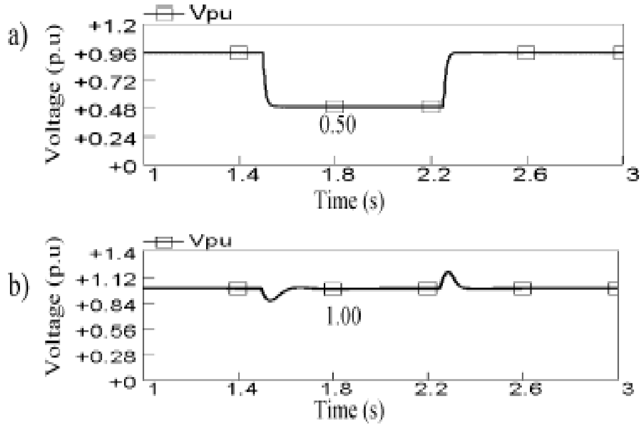

Fig. 5. Load voltages: (a) without USSC and (b) with USSC.

4.2 B. Series Inverter Controller of USSC

In the series inverter, the SPWM technique is also used to control the magnitude and phase of the ac voltage by synchronizing the GTO's switching to the ac system voltages. The control for the series inverter are almost similar to that of the shunt inverter, but the only difference is that in the series inverter voltage control loop, the measured phase currents are input to the in order to generate the synchronizing signals. The series inverter injected voltages are kept in quadrature with the line currents to provide series compensation, whereas in the shunt inverter injected currents are kept in quadrature with the line voltage. In the series inverter control, the generation of the displacement angle and the generation of the triangular carrier signal and the voltage modulating signal is similar to that of the shunt inverter. In general, the overall controller function is the same to that of the shunt inverter controller.

5. SIMULATION RESULTS

The performance of the USSC model is evaluated by means of simulations using the PSCAD/EMTDC transient simulation program. The USSC is placed in a 22-kV distribution system with a static load of 5.2 MVA. There are twelve single-phase transformers with each rated at 1 MVA, 22/4.16 kV and a leakage reactance of 0.01 p.u., connecting the USSC to the distribution system. Simulations were carried out to illustrate the effectiveness of the USSC as a unified compensator for voltage regulation; voltage sag compensation, voltage flicker reduction, and voltage unbalance mitigation.

5.1 USSC for Voltage Sag Compensation

To illustrate the use of the USSC in compensating voltage sags, a voltage sag condition is simulated by creating a balanced three-phase fault using a three-phase generator. For the system without the USSC, the load voltage drops from 1.0 to 0.50 p.u., as shown in Fig. 5(a). This is a voltage sag condition which is due to a three-phase fault created at time t = 1.5s for a duration of 0.75 s. For the system with the USSC connected, the load voltage increases from 0.50 to 1.0 p.u., as shown in Fig. 5(b). The load voltage returns to its rated voltage due to the voltage sag compensation capability of the USSC. Comparing the voltage sag compensation capability of the USSC, D-STATCOM and DVR, the results are shown in Table I in terms of the minimum, maximum and steady-state voltage values.

TABLE I
COMPARISON OF VOLTAGE SAG COMPENSATION CAPABILITY OF USSC, DVR AND D-STATCOM

Device	Minimum Voltage	Maximum Voltage	Steady-State voltage
DVR	0.97	0.97	0.97
D-STATCOM	0.87	1.14	0.98
USSC	0.93	1.09	1.00

5.2 USSC for Voltage Flicker Reduction

Voltage flicker which is a phenomenon of annoying light intensity fluctuation caused by variable electric loads and arc furnaces have been a major power-quality concern. To illustrate the use of the USSC in reducing voltage flicker, simulations were carried out by first connecting a variable electric load of 5.2 MVA, 22 kV as the source of voltage flicker. Fig. 6(a) shows the flicker effect of a phase rms voltage for the system without the USSC connected. By connecting the USSC, it can be seen that the rms voltage of phase A is flicker free, as shown in Fig.6(b).

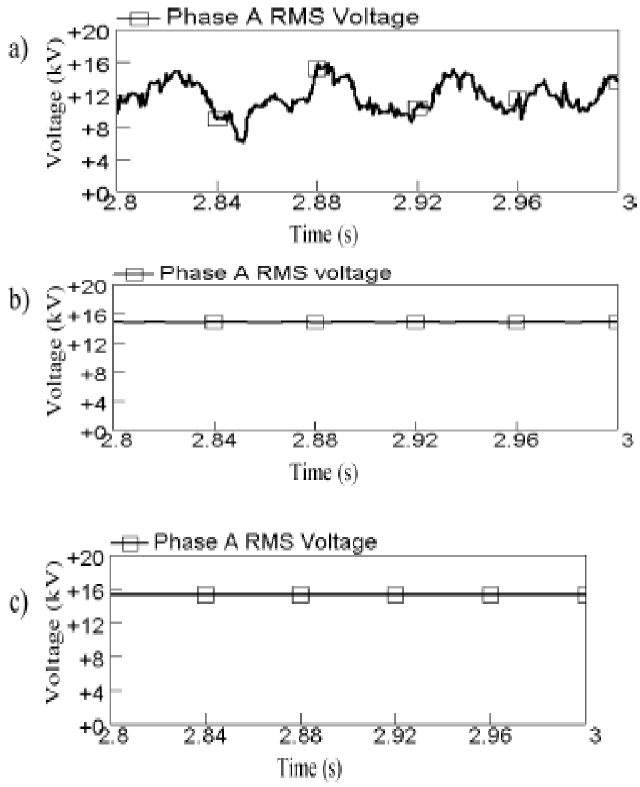

Fig.6.Rms Voltage flicker: (a) without USSC, (b) with USSC connected, and (c) with D-STATCOM connected.

5.3 USSC for Voltage Unbalance Mitigation

In this simulation, initially an unbalanced voltage condition is created by applying two single phase to ground faults on the phase A and phase C at time t = 0.5s for a fault duration of 100 ms. Fig. 7(a) shows the simulation results of the three-phase unbalanced voltages for the system without the USSC connected. It can be seen that during the fault condition, the maximum phase voltages are Va = 14.5 kv, Vb = 19.21kv, and Vc = 10.5kv , and . The percentage of voltage unbalance is calculated and found to be 28.7%. With the application of USSC, the three-phase load voltages are recorded as shown in Fig. 7(b). It is evident from Fig. 7(b) that in the presence of the USSC, the load voltage profile has improved in which the phase A and C voltages are increased and the phase B voltage is reduced, thus making the three phase voltages more balanced. The percentage of voltage unbalance decreases from 28.7% to 1.6%. For the cases with D-STATCOM and DVR connected the simulation results show that the percentage of voltage unbalance are reduced to 5.03% and 2.2%respectively as shown in fig.(c) and (d).

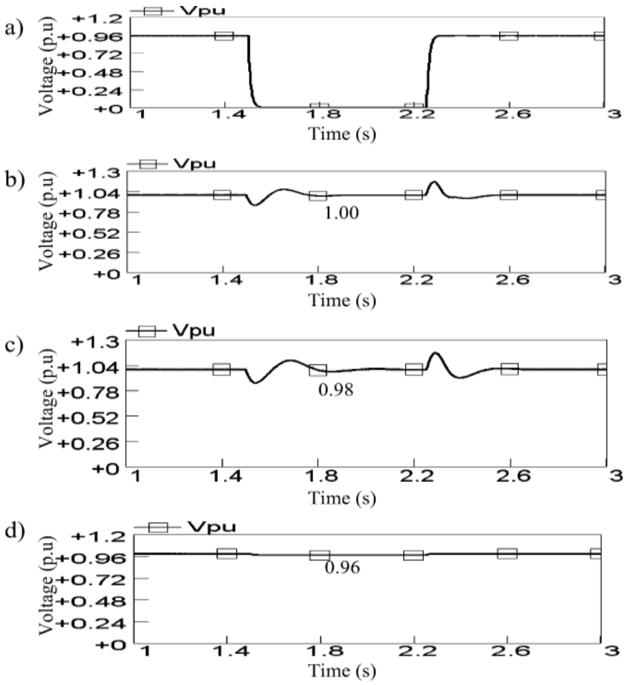

Fig.7.Waveforms for Voltage balance Mitigation

5.4 USSC Acting in UPS Mode

To show that the USSC can operate in uninterruptible power supply (UPS) mode, an outage is first created at time t = 1.5s for a duration of 0.75 s using a three-phase fault generator. The outage simulation result is as shown in Fig. 8(a). When the USSC is connected in the system, the USSC recovers the load voltage from 0.0 to 1.00 p.u. within a short time as shown in Fig. 8(b).

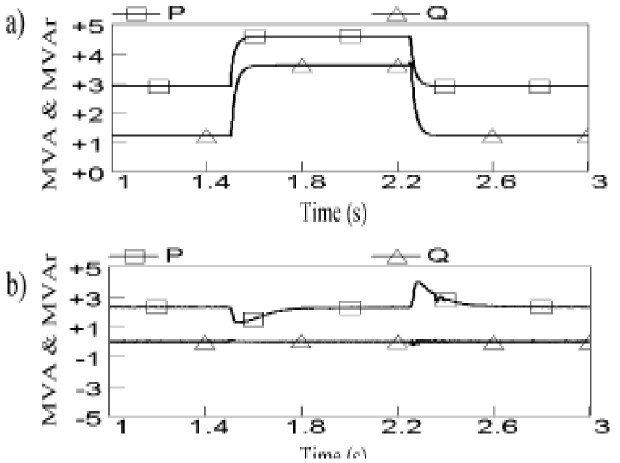

Fig.8.Active and reactive power flows: (a) without USSC and (b) with USSC
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Waveform of USSC in UPS mode

5.5 USSC for Power-Flow Control

The flow of instantaneous active and reactive powers into or out of the USSC are investigated using the transient simulation. When a fault occurs at time t = 1.5s for a duration 0.75 s, the active and reactive powers into the system are as shown in Fig. 8(a). The simulation result indicates that during the fault period, both the active and reactive powers of the system increase. The exchange of real power can be made in either direction between the series and shunt inverters of the USSC. With the USSC connected in the system, the reactive power of the system is reduced from 1.2 MVAr to zero in order to achieve a steady-state value of active power, as shown in Fig. 8(b). Thus, the active and reactive power flows are controlled and maintain at a pre-fault levels.

5.6 Harmonic Elimination

Simulation results in Fig. 10 show that the USSC inverters generate a voltage total harmonic distortion (THD) of 78%. Due to high frequency switching losses, the inverters have generated a THD which is higher than the acceptable level of 5%. Therefore, filtering is indispensable so as to eliminate the harmonics generated by the USSC. Several methods can be used for reducing the harmonics produced by the USSC. To illustrate the effect of using an inductance–capacitance (*LC*) passive filter, simulations were carried out and the THD of the system without and with the filter inserted into the system are recorded as shown in Fig.9(a) and (b), respectively.

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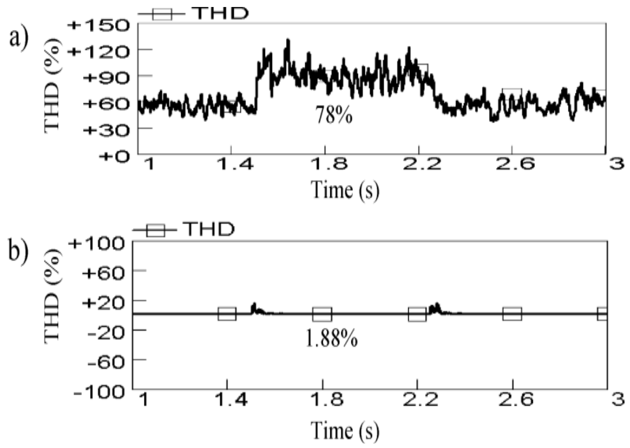

Fig.9.Total harmonic distortion:(a) without filter and (b) with filter

TABLE II
PQ MITIGATION OF USSC VS. D-STATCOM AND DVR

PQ Mitigation	DVR	D-STATCOM	USSC
Sag Compensation	Yes	Limited	Yes
Voltage Flicker	No	Yes	Yes
Unbalance	No	Yes	Yes
UPS Mode	Yes	Yes	Yes
Power Flow Control	No	No	Yes
Harmonic Elimination	No	Yes	Yes

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5.7 Capabilities of USSC versus D-STATCOM and DVR

Usually individual custom power devices such as D-STATCOM and DVR are concentrated on solving definite power-quality problems in a distribution system, as shown in Table II. However, by using USSC, it is possible to compensate a variety of power-quality problems as compared to D-STATCOM and DVR as stated in Table II. It is noted that in the UPS mode, mitigated load voltage by the DVR is a steady state value, where as in the D-STATCOM and the USSC have minimum and maximum values at the starting and the ending of the fault.

6. CONCLUSION

A unified approach to the mitigation of multiple power quality problems has been investigated by using USSC. Simulation results prove that the USSC can perform voltage sag compensation, flicker reduction, voltage unbalance mitigation, and UPS mode and power-flow control. It was also observed that harmonics generated by the USSC can be significantly reduced by inserting a passive filter into the system. A comparison is made between the USSC and the other custom power devices such as D-STATCOM and DVR in terms of their capabilities in power-quality mitigation. It is shown that the USSC gives a better performance in power-quality mitigation, especially in voltage sag compensation and power-flow control, and also provide more power-quality solutions as compared to the D-STATCOM and DVR.

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