Journal of Zhejiang University SCIENCE A
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Dynamic voltage regulation and power export in a distribution system using distributed generation*

Aamir HANIF†, Muhammad Ahmed CHOUDHRY

(*Department of Electrical Engineering, University of Engineering and Technology, Taxila 47050, Pakistan*)

†E-mail: aamirhanif@uettaxila.edu.pk

Received Oct. 10, 2008; Revision accepted Feb. 17, 2009; Crosschecked Aug. 14, 2009

Abstract: The major aim of power quality (PQ) enhancing techniques is to maintain a specified voltage magnitude at a desired frequency for sensitive loads irrespective of faults on the power distribution network. The dynamic voltage restorer (DVR) is a device used to mitigate voltage sags to regulate load voltage. This paper presents a mathematical model for leading series voltage injection to mitigate sags thereby achieving the improvement of the utility power factor as well as power sharing between the DVR and utility. The power sharing will be as per requirement to compensate the sags considering the available distributed generation (DG). The approach of mitigating voltage sags using the concept of leading series voltage injection is suitable for those locations where phase shift in the voltage will not cause any problem. The MATLAB/SIMULINK SimPowerSystem toolbox has been used to obtain simulation results to verify the proposed mathematical model.

Key words: Power quality, Distributed generation, Voltage sags, Series injection
doi:10.1631/jzus.A0820699 **Document code:** A **CLC number:** TM712; TM74

INTRODUCTION

As the non-linear loads and complexity of control systems in industrial processes grow, the power quality (PQ) has emerged as an important issue in recent years. The ever-growing complexity of the power system (network connecting the generating stations in remote locations to load centers and industrial areas) and the faults concerned make it impossible to always maintain the desired specifications with regards to voltage magnitude, frequency and harmonic distortion at the consumer point of common coupling (PCC) at the desired level (Won *et al*., 2003). The utility network while viewed from a consumer side can be regarded as a Thevenin voltage source in series with Thevenin impedance (An *et al*., 2006). Faults on parallel distribution feeders and a definite time required by the circuit breakers momentarily change the Thevenin impedance thus resulting into a varied voltage drop across it and hence variations in supply magnitude and phase. These variations can be positive as well as negative; i.e., a positive variation in voltage magnitude mean voltage swell and a negative variation mean voltage sag.

Frequency variations are very rare as compared to the problems mentioned above (Hughes and Chan, 1996). The case of harmonic distortion is also an issue which is not that significant as against voltage sags (Fayyaz Akram and Mumtaz Bajwa, 2001).

Voltage sag is considered as one of the major power quality problems since the frequency of occurrence is very high (Ramasamy *et al*., 2007). Caused by a fault in the power system or by starting of large induction motors (Rai and Nadir, 2008) it is a momentary reduction in available supply for a short duration below 90% of the rated value (Bollen, 2000). Main characteristics of such voltage sag are its duration and magnitude of available utility voltage (Wang *et al*., 2004). Performance curves with regards to depth and duration of voltage sags provided by Information Technology Industry Council (ITIC) and

* Project (No. UET/ASR&TD-251/2006) supported by the Higher Education Commission of Pakistan

Semiconductor Equipment Manufacturers (SEM) are shown in Wang *et al*.(2005).

Voltage sags are very hazardous to control equipment in the process industry (McGranaghan *et al*., 1993). Any failure of control may result in the breakdown of process and therefore, loss of raw material and production time and even risk to human life. Thus it is of utmost importance to counter them. A dynamic voltage restorer (DVR) is a custom power device (CPD) being used as the active solution for voltage sag mitigation (Nguyen and Saha, 2004). It is connected in series between the utility bus/PCC and the load bus as shown in Fig.1 (which is a one phase equivalent).

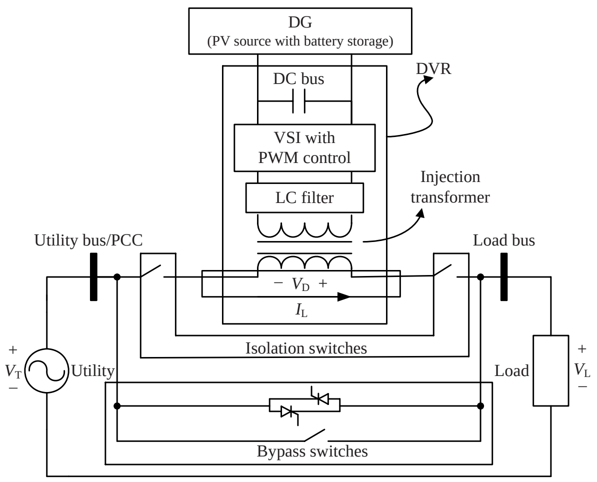

Fig.1 Conceptual diagram of one phase of a dynamic voltage restorer (DVR) with its protection components

The series nature of the dynamic voltage restorer demands a dramatically fast and adequate mechanism to prevent its malfunction or destruction, in case of any short circuit occurring at the load side (Silva *et al*., 2004). An electromechanical bypass switch, associated with a fast static switch, can be used to remove the DVR from the system (through isolation switches) by supplying alternate path for the current under abnormal conditions as shown in Fig.1. The static bypass switch is capable of providing a path to short circuit currents until the operation of the electromechanical switch whose typical time of operation is in the order of 80 ms. When the supply current is in normal conditions the bypass switches will become inactive.

A DVR can mitigate voltage sags by injecting voltages of appropriate magnitude and phase angle so that the load bus voltage remains within the permissible limits. The injected voltage may or may not be in phase with any other variables of the main circuit, i.e., supply voltage, load current, load voltage, etc. (Piatek, 2006).

Small voltage sags can usually be restored through reactive power only, but for larger voltage sags, it is necessary to inject active power into the system by the DVR to correct the voltage sags (Hosseini *et al*., 2008). Therefore there are two main classifications as far as active power contribution from DVR is concerned. In the first type, only reactive power compensation is done by injecting a voltage in quadrature with the load current, which means no active power contribution. In the second case, active power available from any distributed generation resource is utilized to inject a voltage that compensates the load voltage to a required level. The phase angle between the injected voltage and load current hence does not need to be 90°. The reference voltage for the DVR to track (Fig.1) is given by the relationship (Zhang *et al*., 2000)

$$V_D^* = V_L^* - V_T, \tag{1}$$

where V_D^* is the reference voltage for DVR to track, V_L^* is the desired load voltage, and V_T is the utility/terminal voltage available at the point of a common connection.

The phase angle of desired load voltage in Eq.(1) can theoretically have any value. It is suggested in Ghosh and Ledwich (2002) with an example and without mathematical proof that the phase angle of desired load voltage should lag the phase of the available terminal voltage. Otherwise, reverse power flow through the rectifier-supported DVR may damage the rectifier unit.

This paper evaluates the possibility of leading voltage injection by a DVR with mathematical equations and then performs validations with the results obtained from MATLAB/SIMULINK SimPowerSystems simulations. The benefits of leading voltage injection are also discussed. In addition to exploring a possibility regarding power export using a DVR with calculations, simulation results for validation have been presented at length.

PROPOSED MATHEMATICAL MODEL FOR LEADING VOLTAGE INJECTION

The steady-state phasor diagram of a system in which a leading voltage is injected by the DVR is shown in Fig.2, where available terminal voltage and DVR injected voltage phasors add up to make load voltage phasor. Choi *et al.*(2000) have presented a similar approach with limitations on voltage rating of DVR and arbitrary phase-angle of utility voltage. However, choosing the utility voltage as a reference solves this problem as the reference generation for DVR can track the phase-angle of utility and generate reference waveform accordingly.

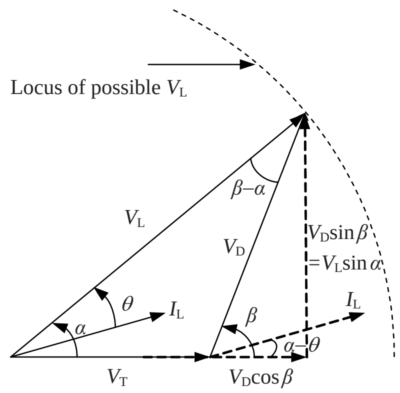

Fig.2 Phasor diagram of a system with leading voltage injection

In phasor notation, the load voltage can be written as

$$V_L = V_T + V_D, \tag{2}$$

where V_L is the load voltage phasor with phase angle α after injection, V_T is the utility voltage available at the point of a common connection taken as a reference (i.e., phase angle is zero), V_D is the DVR injected voltage with a phase angle β, and I_L is the load current which lags the load voltage by an angle θ.

The phase angle between the terminal voltage and load current is thus $\alpha-\theta$ and that angle between the DVR injected voltage and load current is $\beta-\alpha+\theta$.

From Fig.2 it is clear that

$$|V_L|^2 = (|V_T| + |V_D|\cos\beta)^2 + |V_D|^2 \sin^2\beta, \tag{3}$$

$$|V_L|\sin\alpha = |V_D|\sin\beta. \tag{4}$$

Eqs.(3) and (4) result into the following equations for the magnitude of injection voltage from DVR and the phase angle of load voltage:

$$|V_D| = -|V_T|\cos\beta \pm \sqrt{|V_L|^2 - |V_T|^2 \sin^2\beta}. \tag{5}$$

The negative sign within the 2nd term in the right-hand side of Eq.(5) is discarded as a magnitude should remain positive.

$$\alpha = \arcsin\left(\frac{|V_D|}{|V_L|}\sin\beta\right). \tag{6}$$

As sine is a dual value function in the range of 0° to 180°, Eq.(6) may produce invalid results. Another relationship for α from Fig.2 can be obtained as

$$\alpha = \arctan\left(\frac{|V_D|\sin\beta}{|V_T| + |V_D|\cos\beta}\right). \tag{7}$$

Note that inverse tangent algorithms catering for the sign of numerator and denominator values should be used; otherwise, Eq.(7) may also produce incorrect results.

Active and reactive power flow equations at utility bus (P_T, Q_T), load bus (P_L, Q_L) and power injected by DVR (P_D, Q_D) can be written as follows:

$$P_T=|V_T||I_L|\cos(-\alpha+\theta), \tag{8}$$
$$Q_T=|V_T||I_L|\sin(-\alpha+\theta), \tag{9}$$
$$P_D=|V_D||I_L|\cos(\beta-\alpha+\theta), \tag{10}$$
$$Q_D=|V_D||I_L|\sin(\beta-\alpha+\theta), \tag{11}$$
$$P_L=|V_L||I_L|\cos\theta, \tag{12}$$
$$Q_L=|V_L||I_L|\sin\theta. \tag{13}$$

The above equations are written using the active sign convention for sources and the passive sign convention for load. Therefore, positive values of active/reactive powers for sources mean power delivery and negative values imply absorption of active/reactive power.

Eq.(10) implies that active power contribution from DVR shall remain positive as long as the cosine term remains positive. Mathematically, this condition can be expressed as

$$-90 \le \beta - \alpha + \theta \le 90°. \tag{14}$$

The equations developed above clearly set out guidelines for dynamic voltage restoration using leading voltage injection.

The choice of β is driven by the active power available at the DVR input and its value can be increased or decreased accordingly.

It is evident that for a similar sag depth, an increase in β will result in a higher required injection voltage. However, this will reduce the requirement of active power from DVR and increase the reactive power contribution from DVR. This result is significant as distributed energy resources (DER) like solar and wind are dependent on the environment and available active power may change over a large range, provided that there is not enough storage capacity. The injection voltage phase angle can then be varied to achieve the saving of available active power and prevent the collapse of DVR voltage.

POWER EXPORT

If there is sufficient distributed energy capacity present and the load power factor is kept near unity with the help of power factor correction devices, phase-angle of the load current will become the same as that of the load voltage. Then the angle difference between injected voltage and load current will be β–α. To have β–α at 90° or greater, V_T has to be greater than V_L in magnitude, which is not possible. Hence, for a unity power factor load, no value of β will produce a phase angle difference of 90° or greater between injected voltage and load current, thereby ensuring a positive power injection every time. If β is increased, the magnitude of V_D increases and α also increases. A point will be reached when α attains the value of 90°, active power from the terminal side becomes zero, and DVR will be providing all the load active power as well as reactive power to the utility.

If β is further increased such that α becomes greater than 90°, the utility active power will become negative. It indicates that power is being supplied by the DVR to the utility which is also supplying complete load active power.

Maximum active power supplied to the utility by the DVR occurs when both α and β attain the value of 180°. At this point, some of the maximum power is picked up by the load and the rest is exported to the utility. This is a new concept on its own, as power export to utility is generally characterized by a shunt connection to the bus. Another point to emphasize is that current magnitude during the variation of power export by DVR remains the same; variation in power is obtained by changing the voltage magnitude and phase angle. Maximum voltage required during this variation is twice the rated load voltage minus the sag voltage on the terminal side.

This arrangement will also work even if there is no voltage sag; maximum voltage required to inject maximum power in the system will be twice the rated load voltage, and maximum power will be twice the rated load power, half of which will be taken up by the load and the other half will be exported to utility.

Active power contribution from DVR is possible only if energy storage reservoir is considered on the DVR side. The DC bus of DVR may be supplied with energy from the main supply through a rectifier-supported DVR or from engine-driven generators. Alternate energy resources like solar, wind or fuel cells can also be utilized as energy source at the DC bus in DG-supported DVR. In the absence of an energy reservoir, the DC bus includes capacitors in DVR which will have limited ability to mitigate power quality problems. However, we have assumed that PV source with battery storage is connected to the DC bus of DVR to have regulated DC voltage. PV source consists of solar panels with a charge control module which works in a voltage regulation mode of charging.

Hardware implementation of the scheme may be realized on a microcontroller through which the load and supply voltage parameter estimation and the proposed strategy of leading voltage injection can be implemented. Phase locked loop (PLL) software may be used to generate appropriate reference signals corresponding to the utility voltage. After the detection of the sag, the PLL records the pre-sag voltage phasor while the controller detects the sag voltage and phase shift. The reference signal goes to the pulse width modulator implemented in the microcontroller. The modulator will then direct the gate signals to the switching devices in the voltage source inverter (VSI) according to the modulated signal to have the regulated load voltage (Vilathgamuwa *et al*., 2002; Choi *et al*., 2005). In this study, the voltage sag mitigation strategy and the power export concept are illustrated by the simulation examples shown in the next section.

Table 1 gives a summary of design specifications and component values for the simulated examples.

Table 1 A summary of design specifications

Component/Parameter description	Value/Range	
	Case 1	Case 2
Rated voltage (V)	240	240
Maximum apparent power (kV·A)	707	500
Maximum load current (A)	2945.8	2083.3
Load power factor	0.707 lagging	unity
DC bus voltage (V)	500	500
System frequency (Hz)	50	50
Maximum sag depth	0.85	0.85
Sag detection and mitigation time (ms)	<20	<20
Injection transformer turn ratio (inverter side: power circuit side)	1:1	1:1
Control action	PWM	PWM
Filter type	LC low pass	LC low pass

PWM: pulse width modulator

SIMULATION RESULTS

The block diagram of simulation setup is shown in Fig.3. A simulation of one phase of a system compensated by DVR was carried out for 85% sag by keeping different injection voltage angles in the MATLAB/SIMULINK SimPowerSystems environment. The DVR consists of a pulse width modulated insulated gate bipolar transistor (IGBT) based inverter supplied from a DC bus with a filter connected at the output of the inverter. The filter output is connected to the primary winding of a 1:1 transformer whose secondary is connected in series between the point of common connection and load bus. Two different cases have been simulated:

Case 1 The load is assumed to be an inductive load with the 70.7% lagging power factor. Active power rating of the load is 500 kW and reactive power is also 500 kvar. The results are graphically presented in Figs.4a, 7a, 8a, and 11a, where all the concerned quantities are plotted against the injection voltage phase angle *β*.

Case 2 The load is assumed to be compensated by a power factor correction device and the power factor is 100%. Active power rating of the load is 500 kW. The results are shown in Figs.4b, 7b, 8b, and 11b, where all the concerned quantities are again plotted against the injection voltage phase angle *β*.

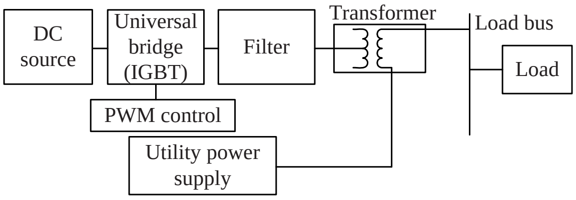

Fig.3 Block diagram showing DC source as DG injecting voltage in series with utility supply

Fig.4a shows the magnitude variation of required DVR voltage, and its effect on load voltage magnitude which is held almost constant at the required level of 240 V while the terminal voltage value is also indicated. Fig.4b shows the same quantities for Case 2.

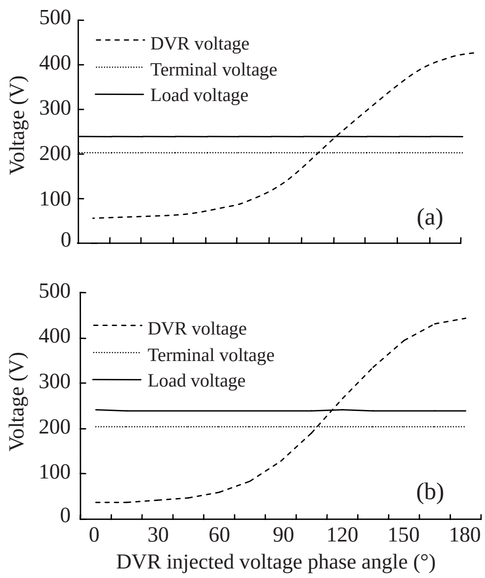

Fig.4 Voltage variation with injected voltage phase angles
(a) Case 1, inductive load; (b) Case 2, resistive load

In addition to the measurements taken for the steady state values of voltage and power for different injection voltage phase angles, the dynamic response of DVR, utility and load with respect to their voltage and power was also examined by considering 85% sag. However, time simulation of voltage dip and its mitigation with a 45° injection voltage phase angle is shown only in Figs.5a and 5b for Cases 1 and 2. Other plots for different injection voltage phase angles can be obtained on a similar analogy.

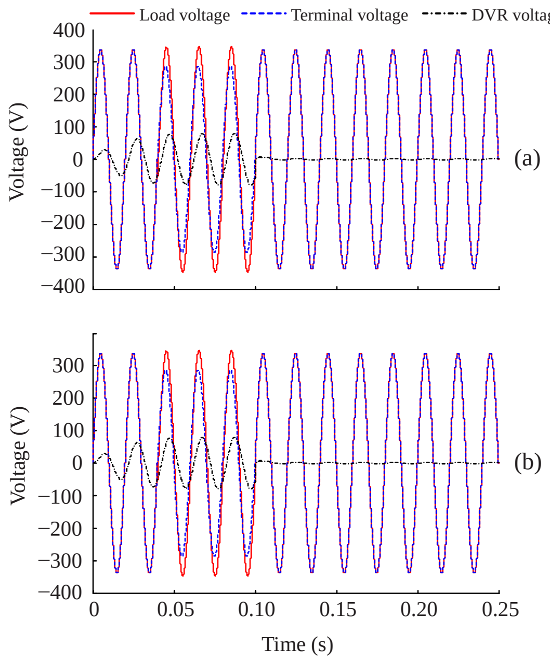

Fig.5 Dynamic voltages with a 45° injected voltage phase angle. (a) Case 1; (b) Case 2. 85% sag is initiated at 0.04 s in the utility voltage which is kept until 0.1 s, with a duration of 0.06 s

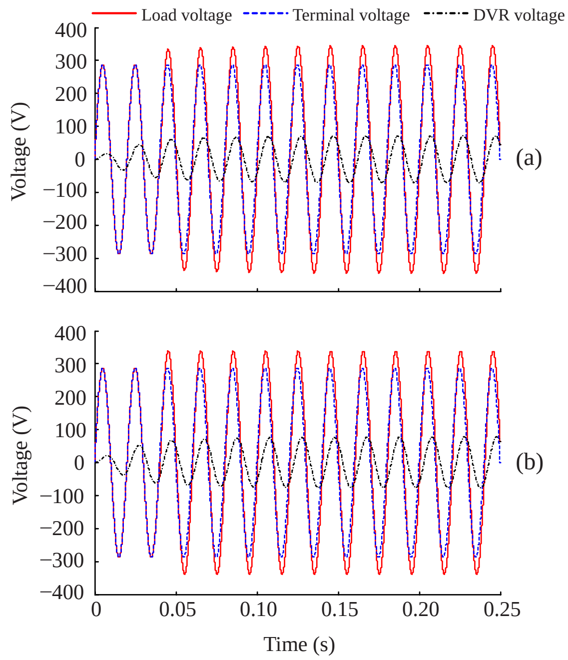

Fig.6 Dynamic voltages with a 45° injected voltage phase angle. (a) Case 1; (b) Case 2. 85% sag is initiated at 0 s and persists for 0.25 s (12.5 cycles)

Figs.5a and 5b show 85% sag initiated at 0.04 s in the utility voltage which is kept until 0.1 s, with a duration of 0.06 s. The peak value of utility voltage under normal circumstances is 339.4 V, whereas it is 288.4 V during sag. In case of leading voltage injection during sag, DVR responds by injecting 51 V to compensate the sag in the utility voltage.

Voltage injection after sag termination is zero as evidenced from Fig.5. DVR is connected between the utility and load to inject compensation voltage instantly to restore load voltage to its rated value. The first two cycles of injected voltage shown in Fig.5 are prior to the DVR connection. They are used to energize primary winding of the injection transformer of DVR circuit. According to the simulations, the load voltage is evidently restored in 10 ms against a target of 20 ms (one cycle); it is shown by equipment sensitivity curves (also known as power susceptibility curves) of control equipment supplied by ITIC and SEM.

Figs.6a and 6b also show time simulation of sag and its mitigation. In this case, 85% sag is initiated at 0 s which persists for 0.25 s (12.5 cycles). DVR was connected between utility and load at 0.04 s during sag to inject compensation voltage equal to 51 V to restore load voltage to its rated value. Again, the first two cycles of DVR injected voltage shown in Figs.6a and 6b are prior to the DVR connection.

Fig.7 indicates the phase angle of load voltage and current against the variation of injection voltage phase angles for Cases 1 and 2. Plots of load voltage and current phase angles coincide in Fig.7b as these are in-phase for a compensated load.

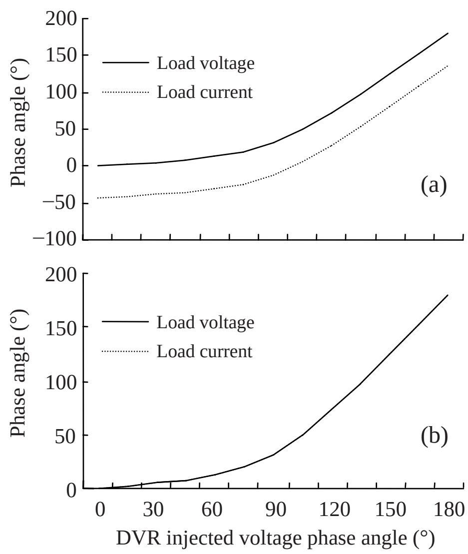

Fig.7 Phase angle variation of load voltage and current with injected voltage phase angles. (a) Case 1, inductive load; (b) Case 2, resistive load

Figs.8a and 8b present the active power plots for different DVR voltage phase angles for Cases 1 and 2, respectively. As clearly seen from Fig.8a, DVR active power becomes negative at a specific phase angle of injected voltage; this is the same interval during which terminal active power becomes greater than load active power. It is the point where reverse power flow occurs through the inverter. In contrast, Fig.8b shows that DVR active power never becomes negative and at a specific angle and beyond, supply active power to the terminal, whose power turns negative.

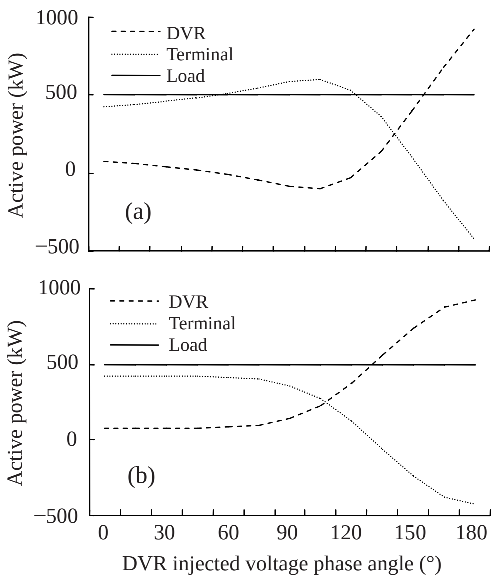

Fig.8 Active power variation with injected voltage phase angles. (a) Case 1, inductive load; (b) Case 2, resistive load

Usually in DC capacitor supported DVR and rectifier-supported DVR, the reverse power flow issue can raise the DC-link (bus) voltage large enough to damage the DC storage capacitors and/or switching devices (e.g., rectifier circuit in rectifier-supported DVR). To tackle reverse power in these two types of DVR, a discharge resistor or battery to the DC capacitor is usually shunted. As a result, connecting a discharge resistor or battery is a back-up solution to the unavoidable excess voltage rise when reverse power flows towards DVR. In our case we are using PV source with a battery storage system to supply regulated DC voltage to the DC capacitor. Hence we have already built the protection of reverse power flow.

Although voltage swell mitigation is not discussed in this paper, protection against its effect on the DC storage capacitor is provided in DG-supported DVR. Voltage swell causes the inverter of DC capacitor supported DVR and rectifier-supported DVR to absorb active power from distribution line, which charges up the DC storage capacitors and increases their voltage levels. An excess voltage rise will damage the DC storage capacitors of both types of DVR and switching devices of rectifier-supported DVR. In our case, battery (of PV source with a battery storage system) is connected in parallel with the storage capacitor and absorbs active power flowing from the utility/distribution line thus protecting the DC storage capacitor.

DVR in its compensation mode also helps in smoothing active and reactive power drawn by the load, as shown in Figs.9 and 10. Other plots for different injection voltage phase angles can be obtained on a similar analogy.

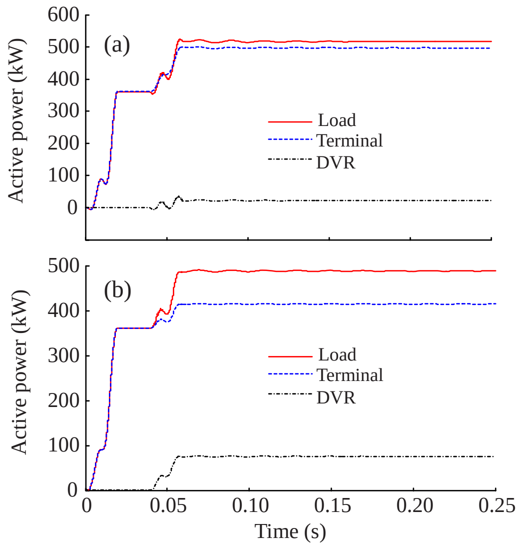

Fig.9 Active power variation with a 45° injected voltage phase angle. (a) Case 1; (b) Case 2

Fig.10a indicates that both the DVR and utility are contributing reactive power to meet load reactive power demand during sags as well as under normal circumstances. By contrast, Fig.10b shows that the load does not absorb reactive power because it is compensated by power factor correction measures and all the reactive power supplied by the DVR flows towards the utility to support the utility grid to meet its reactive power requirement.

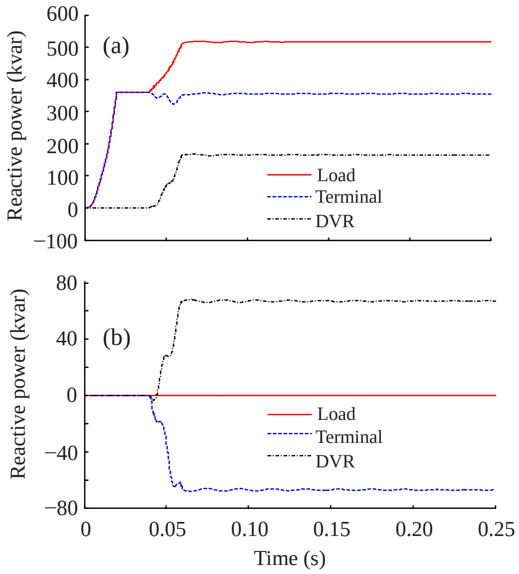

Fig.10 Reactive power variation with a 45° injected voltage phase angle. (a) Case 1; (b) Case 2

Fig.11 describes the reactive power contribution from all elements for Cases 1 and 2. Fig.11a indicates that any growth in injection voltage will increase the reactive power contribution from the DVR side till a specific angle, but a further increase will again bring about a reduction.

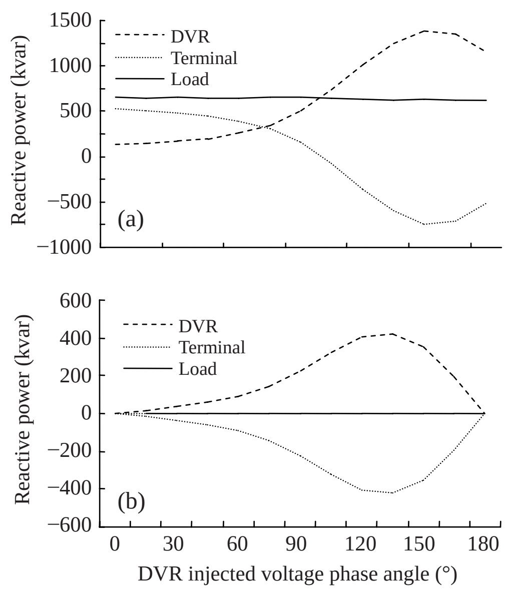

Fig.11 Reactive power variation with injected voltage phase angles. (a) Case 1, inductive load; (b) Case 2, resistive load

Fig.11b depicts the reactive power exchange between the DVR and terminal as the load reactive power is being compensated by power factor correction. DVR will always supply reactive power in the angle interval of interest; however, this will start to decrease after a certain angle has been achieved.

CONCLUSION

It is evident from the calculations and simulations that DVR can contribute towards the mitigation of sags as well as share power in a manner which suits a specific customer. In case of abundant availability of generated power from a distributed energy resource, maximum power can be shared, while in case of scarcity, minimum power sag mitigation can be managed.

In addition, a new concept of power export through a series generator is presented, whose power export capability is managed by injected voltage magnitude and phase angle instead of current. Note that the DVR current always remains constant in magnitude and is equal to the load current. This may act as a useful tool when there is power generated at consumer premises without adequate storage and the consumer may get the benefit of price obtained therein. In developing countries, where there is always shortage of power on the grid, electric utilities may benefit from injection of power from the consumer side. However, the approach of mitigating voltage sag using the leading series voltage injection concept is suitable for those locations where the phase shift in the voltage will not cause any problem.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the useful discussions with Prof. Dr. Khawar Islam, Prof. Dr. Saeed-ur-Rehamn and Prof. Dr. Khalid Munawar.

References

An, T., Zhou, S., Yu, J., Zhang, Y., 2006. Tracking of Thevenin Equivalent Parameters on Weak Voltage Load Bus Groups. IEEE PES Power Systems Conf. and Exposition, p.1570-1576. [doi:10.1109/PSCE.2006.296147]

Bollen, M.H.J., 2000. Understanding Power Quality Problems. Voltage Sags and Interruption. IEEE Press, New York, USA, p.14-19.

Choi, S.S., Li, B.H., Vilathgamuwa, D.M., 2000. Dynamic voltage restoration with minimum energy injection. *IEEE Trans. Power Syst.*, **15**(1):51-57. [doi:10.1109/59.852100]

Choi, S.S., Li, J.D., Vilathgamuwa, D.M., 2005. A generalized voltage compensation strategy for mitigating the impacts of voltage sags/swells. *IEEE Trans. Power Del.*, **20**(3): 2289-2297. [doi:10.1109/TPWRD.2005.848442]

Fayyaz Akram, M., Mumtaz Bajwa, S., 2001. A Sample Power Quality Survey for Emerging Competitive Electricity Market in Pakistan. Proc. IEEE Int. Multi Topic Conf., p.38-44. [doi:10.1109/INMIC.2001.995311]

Ghosh, A., Ledwich, G., 2002. Power Quality Enhancement using Custom Power Devices. Kluwer Academic Publishers, The Netherlands, p.335-339.

Hosseini, M., Shayanfar, A., Firuzabad, M.F., 2008. Modeling of static series voltage regulator (SSVR) in distribution systems for voltage improvements and loss reduction. *Leonardo Electron. J. Pract. Technol.*, **12**:61-82.

Hughes, M.B., Chan, J.S., 1996. Canadian National Power Quality Survey Results. Proc. IEEE Transmission and Distribution Conf., p.45-51. [doi:10.1109/TDC.1996.545912]

McGranaghan, M.F., Mueller, D.R., Samotyj, M.J., 1993. Voltage sags in industrial systems. *IEEE Trans. Ind. Appl.*, **29**(2):397-403. [doi:10.1109/28.216550]

Nguyen, P.T., Saha, T.K., 2004. Dynamic Voltage Restorer against Balanced and Unbalanced Voltage Sags: Modelling and Simulation. IEEE Power Engineering Society General Meeting, p.639-644. [doi:10.1109/PES.2004.1372883]

Piatek, K., 2006. A New Approach of DVR Control with Minimised Energy Injection. Proc. IEEE 12th Int. Power Electronics and Motion Control Conf., p.1490-1495. [doi:10.1109/EPEPEMC.2006.283400]

Rai, A., Nadir, A.K., 2008. Modeling and simulation of dynamic voltage restorer (DVR) for enhancing voltage sag. *Sens. Transd. J.*, **87**(1):85-93.

Ramasamy, A., Kumaran, R., Iyer, R.K., Liu, L.Z., 2007. Control of Dynamic Voltage Restorer Using TMS320-F2812. Proc. 9th IEEE Int. Conf. on Electrical Power Quality and Utilization, p.1-6. [doi:10.1109/EPQU.2007.4424233]

Silva, S.M., Eleuterio, F.A., de Souza Reis, A., Filho, B.J.C., 2004. Protection Schemes for a Dynamic Voltage Restorer. 39th IAS Annual Meeting Conf. Record of the Industry Applications Conf., **4**:2239-2243. [doi:10.1109/IAS.2004.1348787]

Vilathgamuwa, D.M., Perera, A.A.D.R., Choi, S.S., 2002. Performance improvement of the dynamic voltage restorer with closed-loop load voltage and current-mode control. *IEEE Trans. Power Electron.*, **17**(5):824-834. [doi:10.1109/TPEL.2002.802189]

Wang, J., Chen, S., Lie, T.T., 2004. Estimating Economic Impact of Voltage Sags. Proc. IEEE Int. Conf. on Power System Technology, p.350-355.

Wang, J., Chen, S., Lie, T.T., 2005. System voltage sag performance estimation. *IEEE Trans. Power Del.*, **20**(2): 1738-1747. [doi:10.1109/TPWRD.2004.834341]

Won, D.J., Ahn, S.J., Chung, Y., Kim, J.M., Moon, S., 2003. A New Definition of Voltage Sag Duration Considering the Voltage Tolerance Curve. Proc. IEEE Power Tech Conf., **3**:5-9. [doi:10.1109/PTC.2003.1304432]

Zhang, Y.H., Viathgamuwa, D.M., Choi, S.S., 2000. An Experimental Investigation of Dynamic Voltage Restorer (DVR). IEEE Power Engineering Society Winter Meeting, **4**:2745-2750. [doi:10.1109/PESW.2000.847317]