Employing of Minimum Active Power Injection Strategy to Compensate Voltage Sag by DVR

A. D. Falehi [1], M. Rostami [2]
1-Department of Electrical Engineering, Izeh Branch, Islamic Azad University, Izeh, Iran.
Email: falehi87@gmail.com (Corresponding author)
2-Department of Electrical Engineering, Shahed University, Tehran, Iran.
Email: rostami@shahed.ac.ir

Received: December 2010 Revised: February 2011 Accepted: May 2011

ABSTRACT:
In this paper, voltage sag is compensated by the DVR (Dynamic Voltage Restorer) in distribution systems. This device is applied between the sensitive load and the supply in order to inject voltage in series to correct the voltage sag. Subsequently, all the other various DVR compensation techniques in the distribution system are explained. Due to the restriction of the energy storage in DVR's capacitors, it is essential to minimize the active power injected by the DVR. Thus, a minimum active power injection method is proposed to compensate the voltage sag. Performance of this method is evaluated under balanced and unbalance voltage sag in a distribution system.

KEYWORDS: Power quality, Voltage sag, DVR, Minimum active power injection, Control strategy, Compensation technique.

1. INTRODUCTION

Voltage amplitude is one of the significant factors that determines the power quality measures [1], and voltage sag is a critical power quality issue [2-4]. There are various sensitive loads in distribution systems that might be at risk while sag happens on load voltage [5, 6]. Occurrence of the voltage sag is perilous for high-tech industries [7]. Correcting the load voltage magnitude during the voltage sag is a challenging task. Therefore, the Dynamic Voltage Restorer (DVR) is used to correct the voltage sag in the distribution system [8-10] and also reduces the damaging effect of voltage sags on sensitive loads [11, 12]. Thus, the power quality can be improved by using DVR in the distribution system [13, 14]. If for any reason, a fault occurs in the system and severe voltage sag happened on sensitive load, it will cause an outage of sensitive load from the system [15]. One method for correcting the voltage sag is injection of series voltage by DVR. The DVR is basically controlled voltage source that has been installed between source and sensitive load. DVR must be able to detect voltage sag and control the inverter to restore the voltage properly [5]. There are three general strategies to compensate voltage sag and avoid tripping of the load, which includes: pre-sag, in-phase and minimal energy [16, 17].

The compensation capacity is one of the most important characteristics of DVR, which depend on the maximum injected voltage and produces active power by DVR. Due to the limitation in energy storage capacity, injected energy by DVR should be minimized [5]. Furthermore,, a new control methodology is proposed to control a single-phase capacitor-supported DVR [18]. A robust minimal energy strategy has been introduced to compensate the voltage sag [19-24]. In this strategy, DVR must absorb active power from network for shallow voltage sage, which is needed expensive additional equipment. Recently, minimum active power injection method has been proposed to the solution of this problem [25]. Also, a minimum energy compensation strategy by considering the voltage limitation of equipments [26] and optimal cost of energy [27] have been presented for analysis of the DVR structure.

In this method, active power injection became zero during the shallow voltage sags and minimized during the deep voltage sags.

In this study, minimum active power injection method has been applied to compensate voltage sag by DVR. Performance of this method is evaluated under balance and unbalance voltage sag in a distribution system.

2. DVR MODEL

In this paper, DVR has been designed by a 13-level cascade inverter having 6 H-Bridge Inverter blocks for each phase. Production of one cycle (three phase voltage) by H-Bridge Inverter blocks is presented in "Fig. 1". Also, cascade inverters model and its IGBT firing circuit presented in "Figs. 2 and 3 ". Designed

DVR is simulated by using MATLAB/SIMULINK software. The produced voltage after crossing the RLC filter converts to three phase sine wave voltages to compensate the voltage sag.

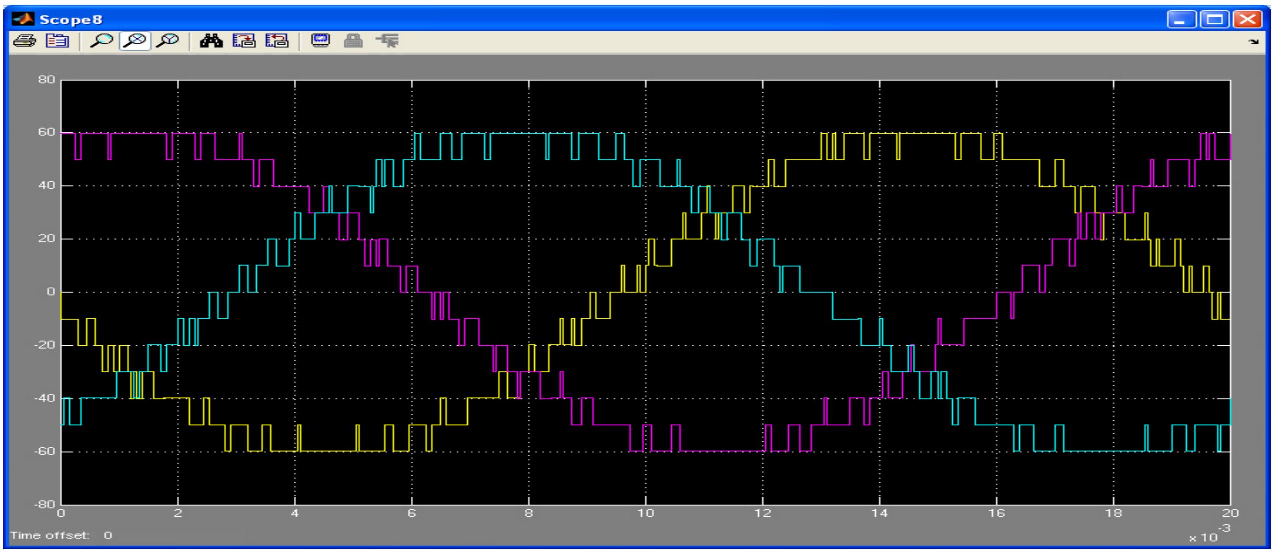

Fig. 1. Three phase voltage waveform of the cascaded inverters

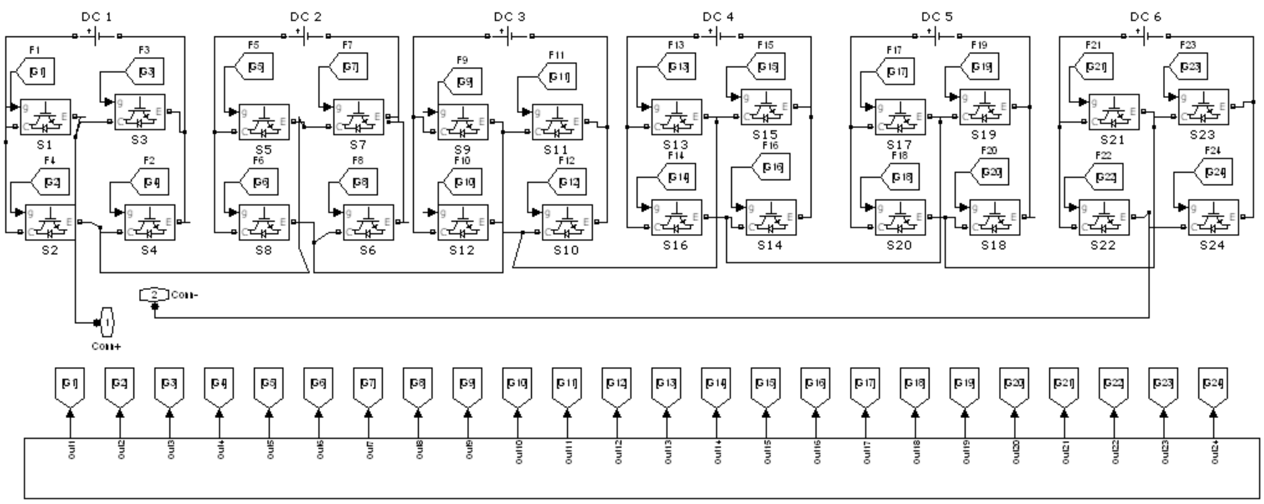

Fig. 2. 13-level cascade inverter of phase "a"

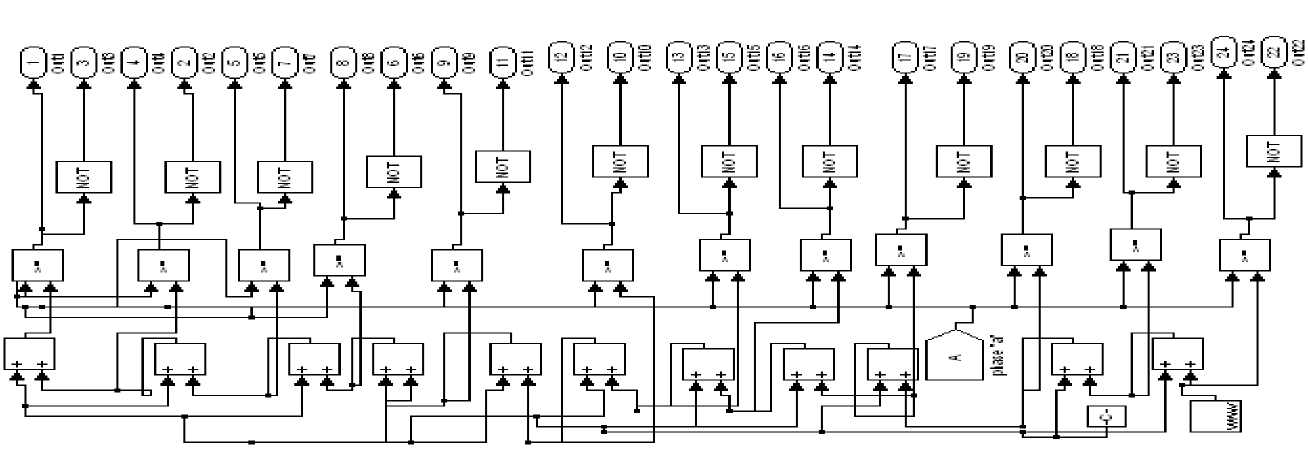

Fig. 3. Fire IGBT circuit of Cascade inverters

3. DVR IN DISTRIBUTION SYSTEM

"Fig. 4" shows a DVR in the distribution system that is located between critical load and the source. If a fault occurs in other lines, voltage sag happens on sensitive load. The probabilities of prevalence of the single line-to-ground faults, line-to-line faults, double line-to-ground faults, and three-phase faults are in 70, 15, 10, and 5 percent, respectively [28].

Thus, DVR injects voltage in series to maintain nominal load voltage. Basically, energy storage sources, inverter, RLC filter, and coupling transformer forming the structure of DVR as shown in "Fig. 4".

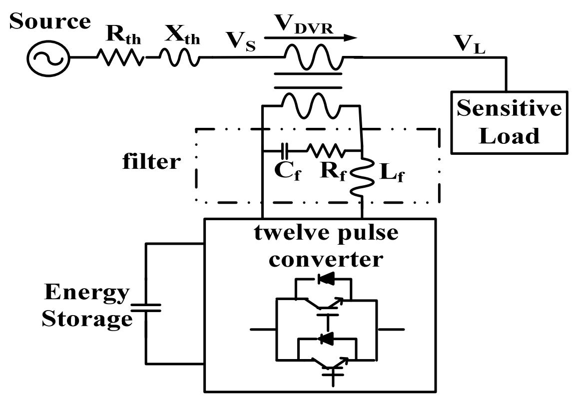

Fig. 4. Schematic of the DVR in distribution system

4. CONTROL STRATEGIES OF DVR

Generally, control strategies of DVR are divided into three main categories: 1- Pre-sag, 2- in-phase, and 3- Minimal energy

4.1. Pre-sag Control Strategy

In this method, load voltage is exactly regained into the same amount of voltage before the fault. Thus, improved voltage has same magnitude and phase of voltage before the fault [13]. Phasor diagram of this method is shown in "Fig. 5".

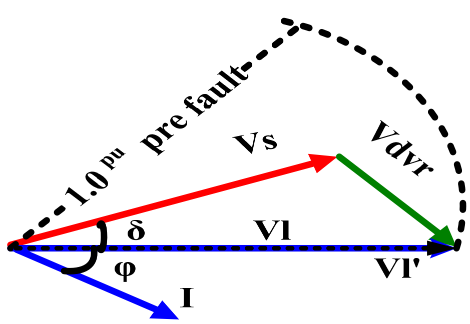

Fig. 5. Phasor diagram of pre-sag control

This Compensation method causes the least disturbance in the load, because the phase voltage did not change during the sag [5]. In this strategy, a PLL (Phase Locked Loop) should be synchronized to load voltage. As soon as fault occurs in the system, PLL is locked and phase of voltage can be restored. In this method, phase of voltage is returned before a fault. However, higher voltage should be injected by the DVR [5]. Equivalent circuit of DVR can be seen in "Fig. 4". V_{th}, V_S and Z_{th} indicate thevenin voltage, voltage sag and thevenin impedance of the system respectively.

4.2. In-phase Control Strategy

In this strategy, the voltage injected by DVR is minimized. In in-phase compensation strategy, the phase of voltage is jumped and creates the eddy and transient currents which cause the outage of sensitive loads from network. Therefore, this method can't be used for critical loads [5]. Phasor diagram of this method is shown in "Fig. 6". The only advantage of this method is the minimization of injected voltage amplitude and injected apparent power by DVR. However, injected active power by DVR is still higher than the pre-sag control strategy. In this method, the injected active power is presented in (1).

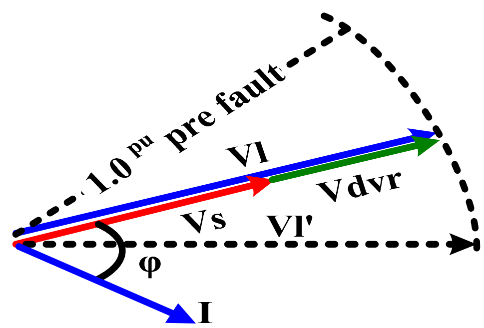

Fig. 6. Phasor diagram of in-phase control

$$P_{dvr} = 3\,(\mathrm{V_L} - \mathrm{V_S}).\,\mathrm{I_L}.\cos\varphi \qquad (1)$$

4.3. Minimal Energy Control Strategy

This method is based on the elimination of active injected power. In this strategy, voltage injected by DVR should be perpendicular to load current until the injected active power becomes zero. Phasor diagram of this method is shown in "Fig. 7". In this diagram δ and α are angles of V_L and V_{dvr} respectively, and also φ is the angle between the I_L and V_L. Subsequently, α is extracted with (2).

$$\alpha = \pi / 2 - \varphi + \delta \qquad (2)$$

Calculating the value of α, δ is obtained by following:

$$\delta = \varphi - \cos^{-1}(V_L.\cos\varphi / V_S) \quad (3)$$

Equation (3) leads the following inequality:

$$V_L.\cos\varphi \le V_S \quad (4)$$

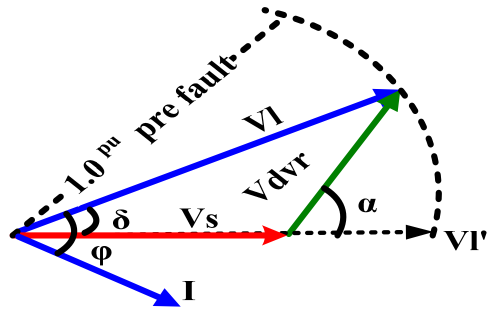

Fig. 7. Phasor diagram of minimal energy method

Reviewing (3), if cosφ is specified to be considered for special load and V_L is assumed 1^{pu} for shallow voltage sag, and then active power injection by DVR would be zero. However, considering inequality (4), injected active power by DVR cannot be zero for the deep voltage sag.

5. MINIMUM ACTIVE POWER INJECTION STRATEGY

In this method, active power Injection by DVR will be zero for shallow voltage sag and will be minimized for deep voltage sag. Diagrams of P_{dvr}-V_{dvr} (for power factor 0.8 and different voltage sag) are presented in "Fig. 8". It is obvious that minimum of active power injection is zero for $V_{sag}=0.2^{pu}$, and is negative about voltage sag less than 0.2. However, it is not zero for voltage sags higher than 0.2. Considering the diagrams in "Fig. 8", for voltage sag less than 0.2, minimum value of P_{dvr} becomes negative. Therefore, active power should be absorbed from the system by DVR. To absorb the active power by DVR, extra energy storage equipments are required, which is costly [27].

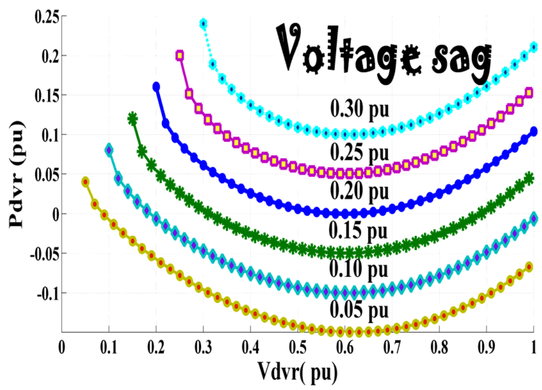

Fig. 8. Active power injection_voltage injection

Load power can be described in (5).

$$P_L = V_L.I_L.\cos(\varphi) \quad (5)$$

Bus power during sag can be expressed by (6):

$$P_S = V_S.I_L.\cos(\varphi - \delta) \quad (6)$$

So, active power injection will be calculated by the following:

$$P_{dvr} = P_L - P_S = \cos(\varphi) - V_S.\cos(\varphi - \delta) \quad (7)$$

According to the phasor diagram of Fig. (7), α can be expressed by the relationship (8):

$$\alpha = \sin^{-1}(V_L.\sin\delta / V_{dvr}) \quad (8)$$

Also value of δ can be obtained by (9):

$$\delta = \cos^{-1}[(V_S^2 + V_L^2 - V_{dvr}^2)/(2V_L.V_S)] \quad (9)$$

If the value of $(V_S^2 + V_L^2 - V_{dvr}^2)/(2V_L.V_S)$ equals to D, and replace (8) and (9) in (7), the active power injection will be obtained form of the (10):

$$P_{dvr} = \cos(\varphi) - V_S.[\cos(\varphi).D + \sin(\varphi).\sqrt{(1-D^2)}] \quad (10)$$

Diagrams of P_{dvr} _ V_{sag} based on $S_{DVR}=0.37^{pu}$ and cosφ=0.8 is shown in "Fig. 9", which has been resulted from (10). Negative values of P_{dvr} are considered to zero as it doesn't need to absorb active power from DVR.

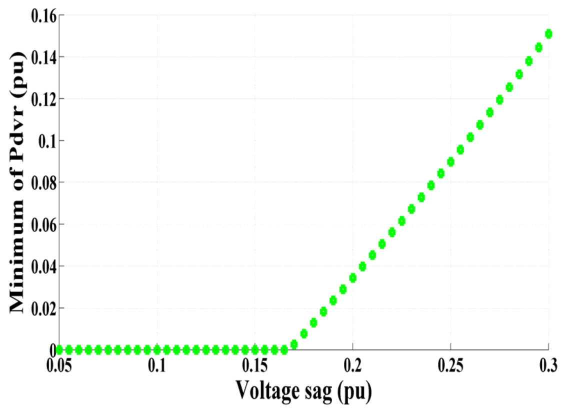

Fig. 9. The minimum active power injection_voltage sag (for $S_{DVR}=0.37^{pu}$)

However, as its shown in "Fig. 8", active power injection by the DVR is considered to be zero for voltage sag less than 0.2 and will be minimized injected active power for voltage sag more than 0.2.

For control block of minimum active power injection, PF=0.8 and $S_{DVR}=0.37^{pu}$ is considered in this study.

When sag occurs in the distribution system, for balanced voltage sags produce only a positive sequence but for unbalance voltage sags both positive and negative sequence is produced [29]. For the presented block diagram in Fig. 10, $V_{dvra,ref}$, $V_{dvrb,ref}$ and $V_{dvrc,ref}$ determine the required voltage that should be injected to the network by DVR. The firing pulses to the IGBTs are obtained by comparing the reference sine waveform ($V_{dvra,ref}$, $V_{dvrb,ref}$ and $V_{dvrc,ref}$) and the PWM triangular carrier signals.

Converting voltages to d-q axis, both positive and negative sequence components are existed for unbalance voltage sag:

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \sqrt{(2/3)} * T * \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \begin{bmatrix} V_{sd,dc} \\ V_{sq,dc} \end{bmatrix} + \begin{bmatrix} V_{sd,ac} \\ V_{sq,ac} \end{bmatrix} \quad (11)$$

where T is:

$$T = \begin{pmatrix} \cos(wt) & \cos(wt - 2\pi/3) & \cos(wt + 2\pi/3) \\ \sin(wt) & \sin(wt - 2\pi/3) & \sin(wt + 2\pi/3) \end{pmatrix} \quad (12)$$

The main frequency component of V_S is converted into $V_{sd,dc}$, $V_{sq,dc}$ while negative sequence component part of V_S is transferred to $V_{sd,ac}$, $V_{sq,ac}$. Then, after passed through HPF filters, their ac parts are extracted. Relevant dc part (V_{sq} and V_{sd}) can be taken out from the difference between output signals of HPF.

V_{Lm} can be obtained using the following:

$$V_{Lm} = \sqrt{[V_{sd}^{2} + V_{sq}^{2}]} \quad (13)$$

Subtracting V_{Lm} from $V_{Lm,ref}$ (usually is considered 1.0 pu) and passing through a controller PI, $V_{dvrd,ref}$ is obtained. To compensate voltage sag, DVR has both dc and ac active power components. The ac component is given into negative sequence part while the dc active power will be obtained using the (14) [27].

$$P_{dvr,dc} = V_{dvrd,dc} . I_d + V_{dvrq,dc} . I_q \quad (14)$$

$V_{dvrd,dc}$ and $V_{dvrq,dc}$ is as follows:

$$V_{dvrd,dc} = V_{Ld} - V_{sd,dc} \;,\; V_{dvrq,dc} = V_{Lq} - V_{sq,dc} \quad (15)$$

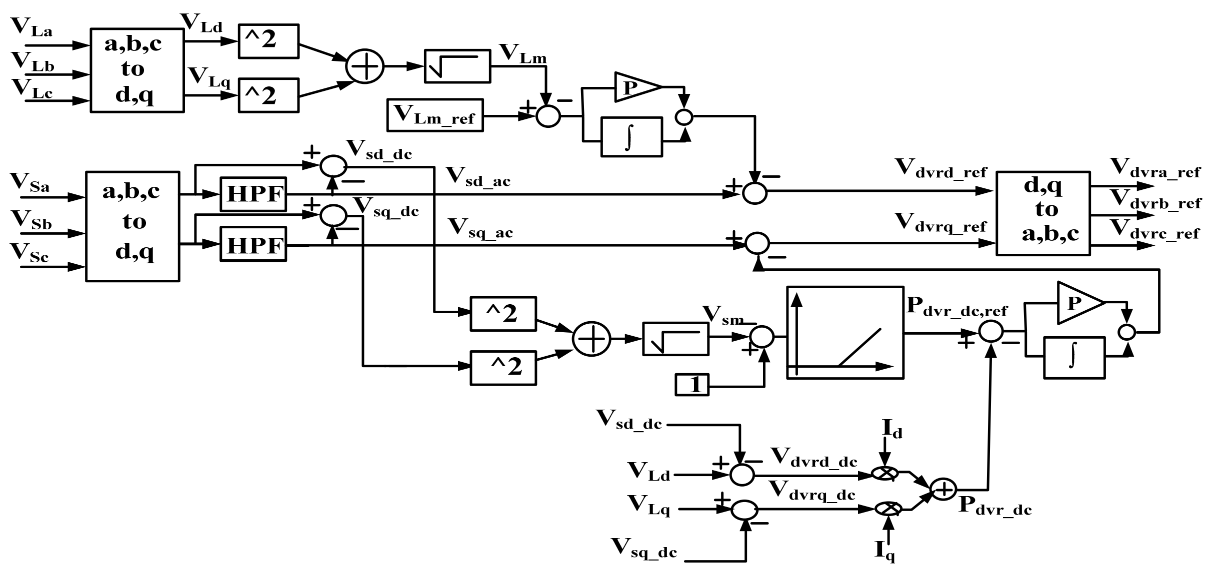

Fig. 10. Upgraded control system for minimum active power injection method

Magnitude of fundamental components of fundamental components (V_{sm}) is expressed by following:

$$V_{sm} = \sqrt{[V_{sd,dc}^{2} + V_{sq,dc}^{2}]} \quad (16)$$

All the the above quantities are based on per unit values.

6. SIMULATION RESULTS

Designed system and DVR are simulated by MATLAB/SIMULINK software.

Magnitude of load voltage should be maintained on 1.0^{pu} during the occurrence the sag in system voltage. In this simulation, fault occurred at $t=0^{sec}$ and duration of voltage sag is considered 0.16^{sec}. The relevant parameters of system and DVR are presented in Table1.

Table .1 Parameters of system and DVR

C_S	R_S	L_S	Stored voltage	Load power	Load voltage
$500^{\mu F}$	1^{Ω}	1.5^{mH}	270^{volt}	100^{KVA}	400^{volt}

Furthermore, Simulation results are divided to following sections:

6.1. Shallow Balance Voltage Sag

Balance voltage sag ($V_S=0.9^{pu}$) is shown in Fig.11.a which injects the voltage of 0.19^{pu} by DVR (Fig. 11.b) compensates the load voltage that is shown in Fig. 11.c. As mentioned above, injected active power by DVR becomes zero for shallow voltage sags that is presented in "Fig. 11.d". Real value of active power injection in "Fig. 11.d" is quite negligible.

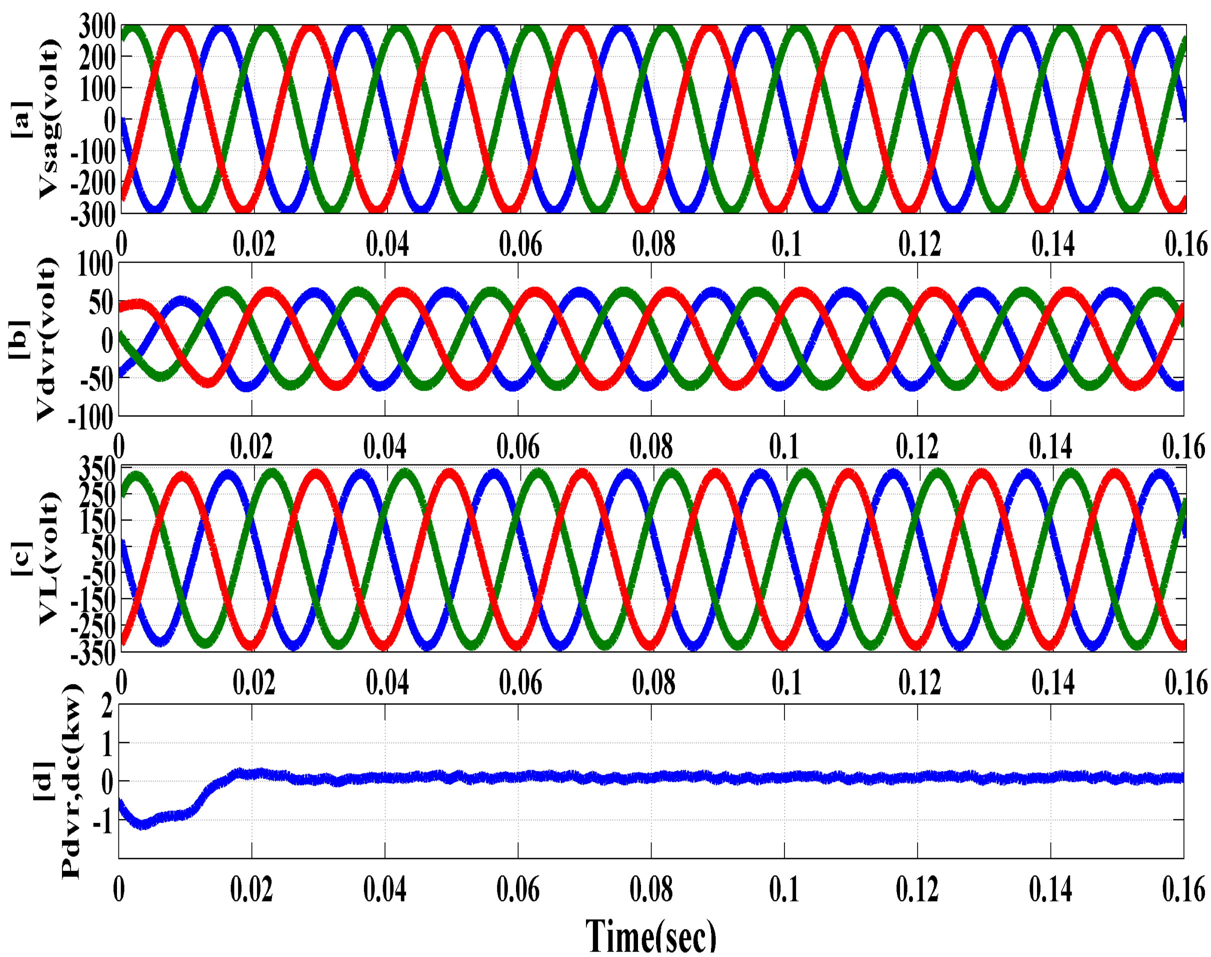

Fig. 11. Shallow Balance Voltage Sag
(a) Voltage sag (b) injected voltage (c) compensated load voltage (d) active power injection

6.2. Deep Balance Voltage Sag

As other cases, balanced voltage sag of 0.75pu is presented in "Fig. 12.a". For deep voltage sag, zero active power injection is impossible (for $S_{DVR}=0.37^{pu}$). Nevertheless, by injecting the maximum voltage by DVR, injected active power is minimized as displayed in "Fig. 12.b". Furthermore, compensated load voltage is shown in "Fig. 12.c". In this case, total active power injection is about 9.2^{KW} which is shown in "Fig. 12.d".

6.3. Shallow Unbalance Voltage Sag

For Fig. 13.a, unbalance voltage sag occurred on sensitive load in which voltage phase of ‘a’ dropped to 0.21^{pu} and voltage phase of ‘b’ and ‘c’ falling down to 0.11^{pu}. To compensate unbalance voltage sag, required injecting voltage by DVR can be seen in Fig. 13.b. Plot of Fig. 13.d confirms that for unbalance shallow voltage sag, active power injection got to be zero.

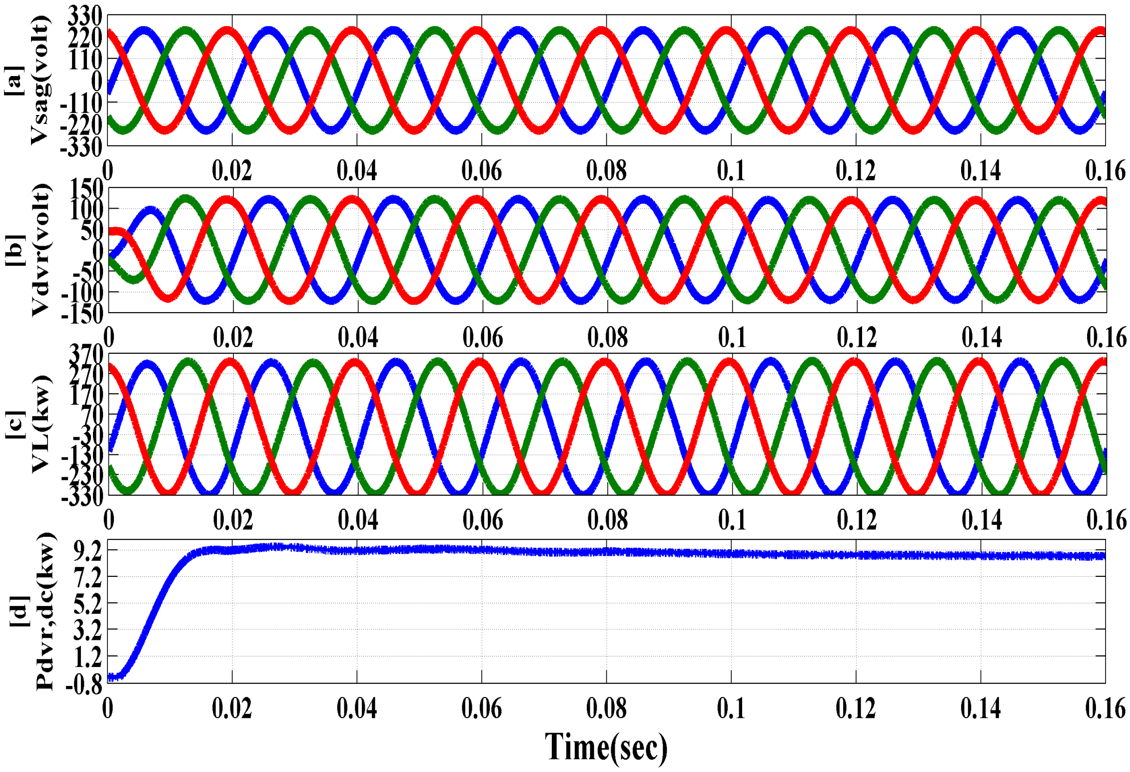

Fig. 12. Deep Balance Voltage Sag
(a) Voltage sag (b) injected voltage (c) compensated load voltage (d) active power injection

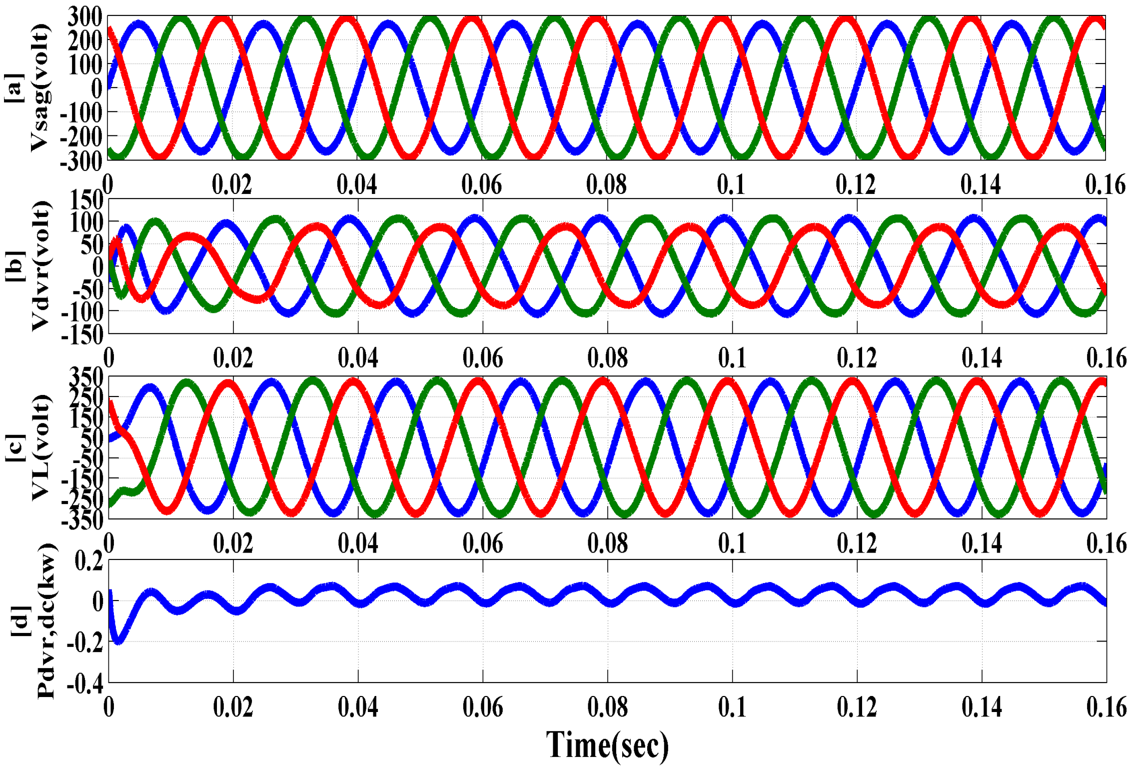

Fig. 13. Shallow Unbalance Voltage Sag
(a) Voltage sag (b) injected voltage (c) compensated load voltage (d) active power injection

7. CONCLUSION

While sag occurs in distribution systems, DVR can be employed to compensate the load voltage. Basically, DVR injects voltage in series to compensate sag in a voltage. There are three different control methods to correct the load voltage for DVR, but minimization of active power injection by DVR is essential due to the restriction of storage energy in DVRs capacitors. Thus, in this paper, minimum active power injection strategy is proposed to control the injected active power by DVR. In this method, active power injection became approximately zero during the shallow voltage sags and is minimized during the deep voltage sags. The nonlinear simulation results approve the performance of this method under balanced and unbalance voltage sag in a distribution system.

REFERENCES

[1] M.H. Haque, **"Compensation of distribution system voltage sag by DVR and D-STATCOM,"** *IEEE Power Tech Conference*, Vol. 1, 5 pp. Porto Portugal, September 2001

[2] D. J. R. S. S. Kumar, S. Sasitharan, M. K. Mishra, B. Kalyan Kumar, **"Unbalanced Voltage Sag Correction with Dynamic Voltage Restorer Using Particle Swarm Optimization,"** *IEEE India Conference*, pp.400-405, Kanpur, 11-13 December 2008

[3] P. Wang, N. Jenkins, M. H. J. Bollen, **"Experimental Investigation of Voltage Sag Mitigation by an advanced static var compensator,"** *IEEE Trans. Power Delivery*, Vol. 13, No. 4, 1461–1467, October 1998.

[4] K. Perera, D. Salomonsson, A. Atputharajah, S. lahakoon, **"Automated control technique for a single phase dynamic voltage restorer,"** *International Conference on Information and Automation*, pp. 63-68, Shandong, December 2006.

[5] C. Meyer, R.W. De Doncker, Y. WeiLi, F. Blaabjerg, **"Optimized Control Strategy for a Medium-Voltage DVR—Theoretical Investigations and Experimental Results,"** *IEEE Transaction on Power Electronics*, Vol. 23, No. 6, 2746-2754, November 2008.

[6] H.M. Wijekoon, D.M. Vilathgamuwa, S.S. Choi, **"Interline dynamic voltage restorer: an economical way to improve interlines power quality,"** *IEE Proceeding Generation, Transmission. Distribution.*, Vol. 15,No. 5, 513-520, September 2003.

[7] A. Sannino, M. G. Miller, M. H. J. Bollen, **"Overview of voltage sag mitigation,"** *IEEE Power Engineering Society Winter Meeting*, Vol. 4, pp. 2872–2878, January 2000.

[8] N. H. Woodley, L. Morgan, A. Sundaram, **"Experience With An Inverter-based Dynamic Voltage Restorer,"** *IEEE Transaction on Power Delivery* ,Vol. 14, No. 3, 1181–1186, July 1999.

[9] S. Chen, G. Joos, **"Series and shunt active power conditioners for compensating distribution system faults,"** *Canadian Electrical and Computer Engineering Conference on*, Vol. 2, pp. 1182-1186, Halifax, Mar 2000.

[10] Y.H. Song, A.T. Johns, **"Flexible AC Transmission Systems (FACTS),"** *IEEE Power and Energy Series 30*, London, UK, 1999.

[11] J. G. Nielsen, F. Blaabjerg, **"A Detailed Comparison of System Topologies for Dynamic Voltage Restorers,"** *IEEE Transaction on Industry Applications,* Vol. 41, No. 5, 1272–1280, September/October 2005.

[12] M. J. Newman, D. G. Holmes, J. G. Nielsen, F. Blaabjerg, **"A Dynamic Voltage Restorer (DVR) With Selective Harmonic Compensation at Medium Voltage Level,"** *IEEE Transaction on industry application*, Vol. 41, No. 6, 1744-1753, November/December 2005

[13] Y. W. Li, D. M. Vilathgamuwa., P. C. Loh, F. Blaabjerg, **"A Dual-Functional Medium Voltage Level DVR to Limit Downstream Fault Currents,"** *IEEE Transaction on Power Electronics,* Vol. 22, no. 4, pp. 1330-1340, July 2007

[14] M. Hojo, T. Funabashi, **"Unified Power Quality Conditioner for Dynamic Voltage Restoration and Fault Current Limitation,"** *IEEE International Harmonics and Quality of Power Conference* , pp. 1-5, Wollongong, Oct 2008

[15] X. Lei, D. Retzmann, M. Weinhold, **"Improvement of power quality with advanced power electronic equipment,"** *IEEE Electric Utility Deregulation and Restructuring and Power Technologies*, pp. 4–7, London, April 2000.

[16] J. G. Nielsen, F. Blaabjerg, **"Control strategies for dynamic voltage restorer compensate voltage sags with phase jump,"** *in Proc. Annu.Appl. Power Electron. Conf. Exposition*, 2001, no. 2, pp. 1267–1273.

[17] M. Vilathgamuwa, R. Perera, S. Choi, K. Tseng, **"Control of energy optimized dynamic voltage restorer,"** *in Proc. IECON*, 1999, vol. 2, pp.873–878.

[18] C. N. M. Ho, Henry S. H. Chung, **"Fast Transient Control of Single-Phase Dynamic Voltage Restorer (DVR) Without External DC Source"** *Power Electronics Specialists Conference, 2006, PESC 37th IEEE Publication*, pp.1-7.

[19] S.H. Hosseini, M.R. Banaei, **"A new minimal energy control of the DC link energy in four-wire dynamic voltage restorer"** *IEEE Industrial Conference of Electronics Society*, Vol. 3 pp. 3048-3053, 2004.

[20] H. K. Al-Hadidi, A. M. Gole, D. A. Jacobson, **"Minimum Power Operation of Cascade Inverter-Based Dynamic Voltage Restorer"** *IEEE Transactions on Power Delivery*, Vol. 23, No. 2, pp. 889- 898, 2008.

[21] G.J. Li, X.P. Zhang, S.S. Choi, T.T. Lie, Y. Z. Sun, **"Control strategy for dynamic voltage restorers to achieve minimum power injection without introducing sudden phase shift"** *IET Generation, Transmission & Distribution*, Vol. 1, No. 5, pp. 847-853, 2007.

[22] S. Zhe, G. ChunLin, X. YongHai, X. XiangNing, L. Yingying, T. Shun, **"A new analysis method for compensation strategy of DVR and minimum energy control"** *IEEE Conference on Industrial Electronics and Applications,* pp. 1321-1325, 2010.

[23] J. G. Nielsen, F. Blaabjerg, **"A detailed comparison of system topologies for dynamic voltage restorers",** *IEEE Transactions on Industry Applications,* Vol. 41, No. 5, pp. 1272-1280, 2005.

[24] S. S. Choi, B. H. Li, D. M. Vilathgamuwa , **"Dynamic voltage restoration with minimum energy injection"** *IEEE Transactions on Power Systems,* Vol. 15 , No. 1, pp. 51-57, 2000.

[25] A. D. Falehi, M. Rostami, **"Verification of a Novel Proposed Control System for DVR to Correct the Voltage Sag"** *International Review on Modelling and Simulations*, Vol. 3, No. 6, pp. 1461–1467, December 2010.

[26] Y. Liu, Y. Xu, X. Xiao, C. Guo, **"Minimum Energy Compensation Strategy and Characteristic Analysis for Dynamic Voltage Restorer"** *ICEET International Conference on Energy and Environment Technology*, Vol. 2 pp. 172-175, 2009.

[27] D. Pan, C. Zhongming, J. Peng, A. Benchaib, G. De Preville, **"Optimal compensation algorithms for a Dynamic Voltage Restorer"**, *International Conference on Electrical and Control Engineering*, pp. 3937-3940, 2010.

[28] P. Kirawanich, R. M. Oconnell, **"Experimental verification of an active power line conditioner with a fuzzy logic switch controller"**, *IEEE Conference on Power Electronics Specialist,* Vol. 1, pp. 315-320, 2003.

[29] J. Gu, D. Xu, H. Liu, M. Gong, **"Unified power quality conditioner (UPQC) the principle of control and application,"** *IEEE Power Conversion Conference*, Vol. 1, pp. 80–85, PCC-Osaka, Aug 2002.