A new control system for DVR to compensate voltage sag with minimized injection active power

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Abstract—**In this paper, voltage sag is compensated by DVR (Dynamic Voltage Restorer) in distribution system. This device is placed between sensitive load and supply in order to inject voltage in series to correct voltage sag. Subsequently, voltage sag compensation technique in distribution system is explained. Due to the restriction of storage energy in DVR's capacitors, minimization of active power injection by DVR is essential. Thus, minimum active power injection method applied to compensate voltage sag (balance & unbalance). Then a new control system for DVR based on minimum injection active power method is described. Finally voltage sag correction by proposed control system, in spite of variation in load power factor, is studied and evaluated.**

Keywords-Power Quality; Voltage Sag; DVR; System Control; Control Strategy; compensation

I. INTRODUCTION

Voltage amplitude is one of the most significant factors that determine power quality [1]. There are various sensitive loads in distribution systems that are affected by voltage sag. Occurrence of voltage sag for high-tech industries is hazardous [2]. Compensating the voltages sag and the load voltage magnitude voltage the disturbances is a challenging task. Therefore, the dynamic voltage restorer (DVR) is used for voltage sag correction in distribution systems [2]. Power quality is improved by DVR at distribution system [4, 5]. If for any reason, a fault occurs in system and severe voltage sag deployed on sensitive load will cause an outage of it from system [6]. One method for correcting the voltage sag is injection of compensating voltage in series, by DVR. A DVR is basically controlled voltage source that should be installed between source and sensitive load. The compensation capacity is one of the most important characteristics of DVR, which is depended on maximum voltage injected by DVR and active power produced by it. Due to the limit in energy storage capacity, energy injected by DVR should be minimized [7]. In minimum active power injection method, zero active power injection during the shallow voltage sags and minimum active power injection for deep voltage sags are targeted [7]. 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. Saturation disturbs control system presented in [7], which only has been designed for power factor 0.8. Thus, for the other power factors (load changing) DVR will not compensate voltage sag completely. This paper will present a new control system which is not limited to fix load power factor, and DVR will compensate voltage sag correctly in wide load power factor rang.

II. DVR MODEL

The DVR in this paper is a 12 pulse-Cascade inverter which has 6 HB-I (Half Bridge-Inverter). Inverters model is presented in Fig. 1. The produced voltage after passing through RLC filters, converts to three phase sine wave voltages to correct the voltage sag.

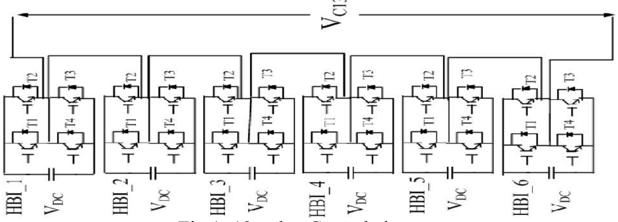

Fig 1. 12 pulse-Cascade inverter

III. PLACEMENT OF DVR IN DISTRIBUTION SYSTEM

Fig. 2 is shown a DVR in the distribution system that is located between critical load and the source. If a fault occurs in other lines, voltage sag occurs on sensitive load. Thus, DVR injected voltage in series to maintain nominal load voltage. DVR includes energy storage source, inverter, RLC filter and coupling transformer.

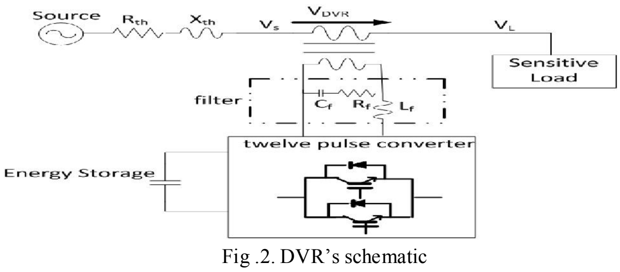

Fig .2. DVR's schematic

IV. MINIMUM ACTIVE POWER INJECTION STRATEGY

Active power Injection by the DVR in this method, for shallow voltage sag is zero and injected active power for deep voltage sag will be minimized. Diagrams P_{dvr}-V_{dvr} for power factor 0.8 and different voltage sag is presented in

Fig.3. It is obvious that for V_S=0.2^{pu} minimum active power injection becomes zero and for voltage sag less than 0.2 the minimum P_{dvr} is negative and for voltage sags higher than 0.2 minimum injected active power will not be zero. Considering the diagrams in Fig. 3, for voltage sag less than 0.2, minimum value of P_{dvr} becomes negative and active power should be absorbed by DVR from the system, which requires extra energy storage equipments, and which is costly [7].

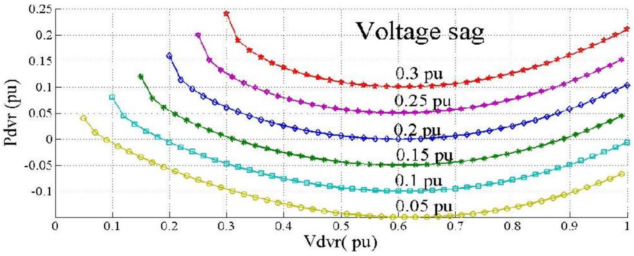

Fig. 3. Active power injection _ voltage injection

A Load power can be described in (1).

$$P_L = V_L.I_L.\cos(\varphi) \quad (1)$$

Bus power during sag can be expressed by (2):

$$P_S = V_S.I_L.\cos(\varphi - \delta) \quad (2)$$

So, injected active power by DVR will be calculated by (3):

$$Pdvr = P_L - P_S = \cos(\varphi) - V_S.\cos(\varphi - \delta) \quad (3)$$

According to the phasor diagram of Fig. 2, α can be expressed by (4) [7]:

$$\alpha = \sin^{-1}(V_L.\sin\delta / V_{dvr}) \quad (4)$$

Where, δ and α are angle of load voltage and DVR voltage respectively, and φ is the angle between the load current and voltage current. Also δ can be obtained from (5):

$$\delta = \cos^{-1}[(V_S^2 + V_L^2 - V_{dvr}^2)/(2V_L.V_S)] \quad (5)$$

If the value of $(V_S^2 + V_L^2 - V_{dvr}^2)/(2V_L.V_S)$ equals to D, by replacing (4) and (5) in (3), the active power injection will be obtained:

$$P_{dvr} = \cos(\varphi) - V_S.[\cos(\varphi).D + \sin(\varphi).\sqrt{(1-D^2)}] \quad (6)$$

In Fig. 4, diagrams of P_{dvr}_V_{sag} has been obtained from (6), based on S_{dvr}=0.37^{pu} for different cosφ values. Negative values of P_{dvr} are considered to zero as it doesn't need to absorb active power from DVR.

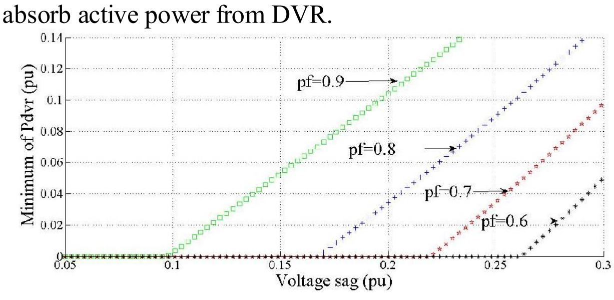

Fig .4 minimum active power injection-voltage sag (for S_{dvr}=0.37^{pu})

As its shown in Fig. 4, active power injection by the DVR for voltage sag less than 0.2 is considered to be zero and injected active power for voltage sag more than 0.2 will be minimized. For proposed block in [7], load power factor of 0.8 is assumed and thus, saturation block have been designed based on this assumption. Therefore, there isn't any control on load power factor changes. However, proposed strategy work freely from load power factor changes. In fact this control block can be used for different load angle and thus true compensation will be achieved. Upgraded control system and proposed block system concern the minimum active power injection method, presented in Figs (5 and 6) respectively.

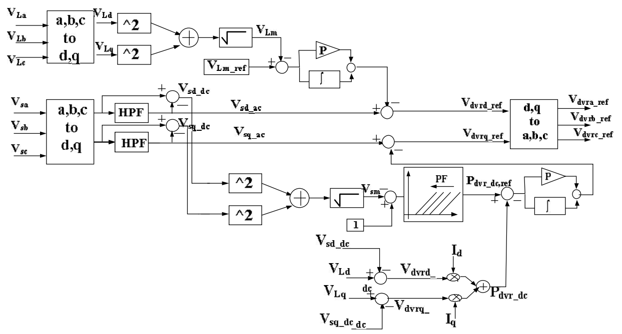

Fig 5 Upgraded control system of minimum active power injection method

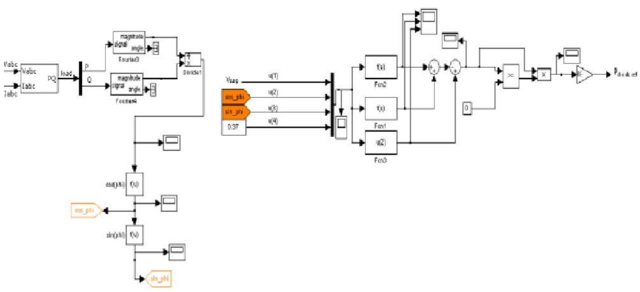

Fig. 6 non-linear control system block of minimum active power injection method

When sag occurs in distribution system, for balanced voltage sags produce only a positive voltage sequences but for unbalance voltage sags both positive and negative sequences are produced [8]. In block diagram, of Fig. 5, V_{a_ref}, V_{b_ref} and V_{c_ref} determine the required voltage to be injected to the network by DVR. These values are key parameters to determine amplitude and phase angle of injected voltage of DVR. Converting to d-q axis voltages vectors for unbalance voltage sag that has both positive and negative sequence components, we have:

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \sqrt{(2/3)} * T * \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \begin{bmatrix} V_{sd,dc} \\ V_{sq,dc} \end{bmatrix} + \begin{bmatrix} V_{sd,ac} \\ V_{sq,ac} \end{bmatrix} \quad (7)$$

Where T is:

$$T = \begin{pmatrix} \cos(wt) & \cos(wt-2\pi/3) & \cos(wt+2\pi/3) \\ \sin(wt) & \sin(wt-2\pi/3) & \sin(wt+2\pi/3) \end{pmatrix} \quad (8)$$

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, they are passed through HPF filters to extract their ac parts. 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:

$$V_{Lm} = \sqrt{[V_{sd}^{\;2} + V_{sq}^{\;2}]} \tag{9}$$

Subtracting V_{Lm} from $V_{Lm,ref}$ (usually is considered 1.0^{pu}) any 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 (10) [7].

$$P_{dvr,\,dc} = V_{dvrd,\,dc} \cdot I_d + V_{dvrq,\,dc} \cdot I_q \tag{10}$$

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

$$V_{dvrd,\,dc} = V_{Ld} - V_{sd,\,dc} \,,\; V_{dvrq,\,dc} = V_{Lq} - V_{sq,\,dc} \tag{11}$$

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

$$V_{sm} = \sqrt{[V_{sd,\,dc}^{\;2} + V_{sq,\,dc}^{\;2}]} \tag{12}$$

Vsm enter into the block that its function is obtained using (10).The control system block diagram is shown in Fig (10). The output of this block is $P_{dvr,\ dc,\ ref}$ which by subtracting it from Pdvr,dc and crossing the PI controller, $V_{dvrq,ref}$ will be achieved. All of the above quantities are based on per unit values.

V. SIMULATION RESULTS

Systems shown in the Figs 1 and 3 simulated modeled and in MATLAB environment. Magnitude of load voltage should be fixed on 1.0pu during the occurrence of sag in a system. In this simulation fault occurred at t=0sec and duration of voltage sag considered to be 0.16sec considered. System and DVR parameters are presented in Table I.

TABLE I. SYSTEM AND DVR PARAMETERS

C_S	R_S	L_S	Storage voltage	Base power	Load power	Load voltage
500µF	1 Ω	1.5mH	270volt	100KVA	100KVA	400volt

Balance voltage sag (V_S=0.9^{pu}) is shown in Fig 7.a which followed by voltage injection of 0.19pu by DVR Fig 7.b to compensate load voltage that is shown in Fig 7.c. Accordingly, for shallow voltage sags, injected active power by DVR becomes zero as can be seen in Fig 7.d. Real value of active power injection in this case is quite negligible.

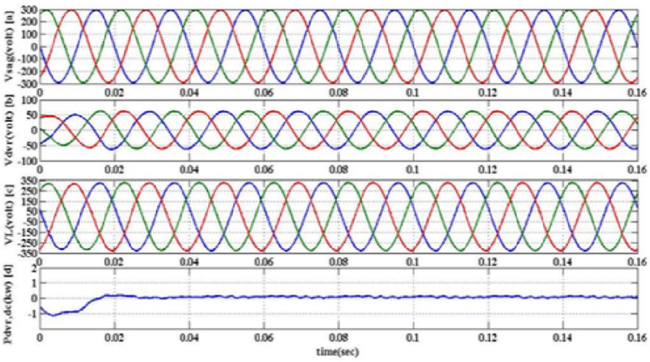

Fig. 7 (a) voltage sag (b) injected voltage (c) compensated load voltage (d) active power injection

As another cases, balanced voltage sag of 0.75^{pu} is presented in Fig 8.a. Because of almost deep voltage sag, zero active power injection is impossible (for S_{dvr}=0.37^{pu}). Nevertheless, injection of the maximum voltage by DVR, injected active power is minimized which is displayed in Fig 8.b. Furthermore, compensated load voltage is shown in Fig 8.c. In this case total active power injection is about 9.2^{KW} which is shown in Fig 8.d.

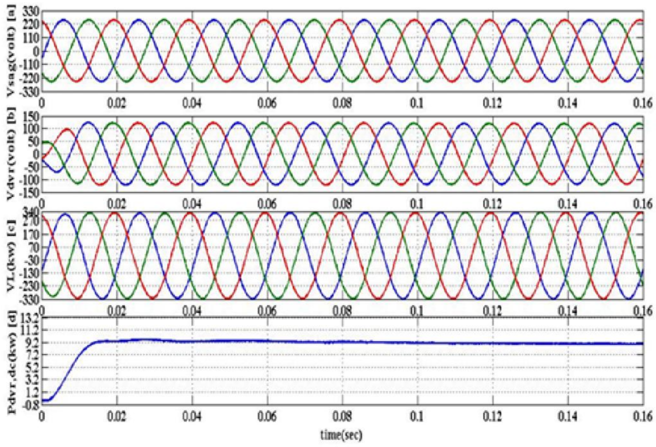

Fig. 8 (a) voltage sag (b) injected voltage (c) compensated load voltage (d) active power injection

For Fig 9.a, unbalance voltage sag occurred on sensitive load which phase voltage 'a' dropped to 0.21pu and phase's voltage 'b' and 'c' falling down to 0.11pu. Required injection voltage by DVR to compensate unbalance voltage sag can be seen in Fig 9.b. plot of in Fig 9.d confirms that for unbalance shallow voltage sag, active power injection got to be zero.

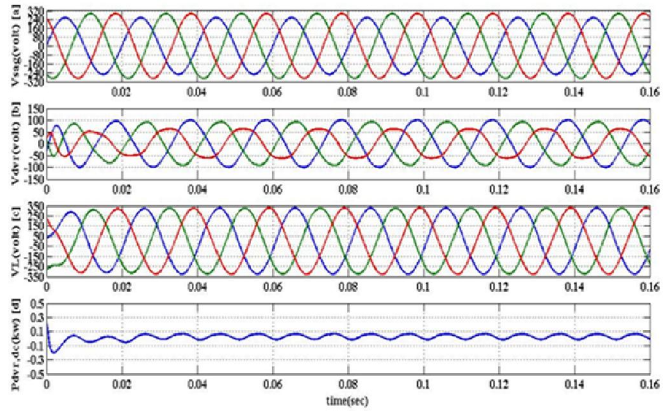

Fig. 9 (a) voltage sag (b) injected voltage (c) compensated load voltage (d) active power injection

As mentioned, if the non-linear block in Fig. 5 designed to operate only for specific power factor compensation, for other loads factors, will not act correctly. Balance voltage sag of 0.75^{pu} is shown in Fig 10.a. If this block is designed for power factor 0.9 while power factor changes to 0.8 (considering Fig 4). Value of $P_{dvr\_dc,\ ref}$ increases and subsequently the reference values of V_{aref} and V_{bref} and V_{cref} decrease consequently to reduce the injected voltage by

DVR as shown in Fig 14.b. Finally, a little compensation will be done which is in adequate as shown in Fig 10.c.

Balance voltage sag of 0.75^{pu} is shown in Fig 11.a. In this case, if control block is designed for fixed power factor of 0.7, changing power factor to 0.8 (considering Fig 4), and follows by decrease in $P_{dvr\_dc,\ ref}$ decreases and the reference values of V_{aref} and V_{bref} and V_{cref} will be increased. As DVR is not able to generate a sine wave voltage, magnetite of voltage becomes more than 0.37^{pu}, thus DVR generate a non-sinusoidal voltage with magnitude more than 0.37^{pu} (Fig 11.b). Consequently, compensated load voltage isn't true sine wave and also magnitude of compensated load voltage will be more than 1.0^{pu}.

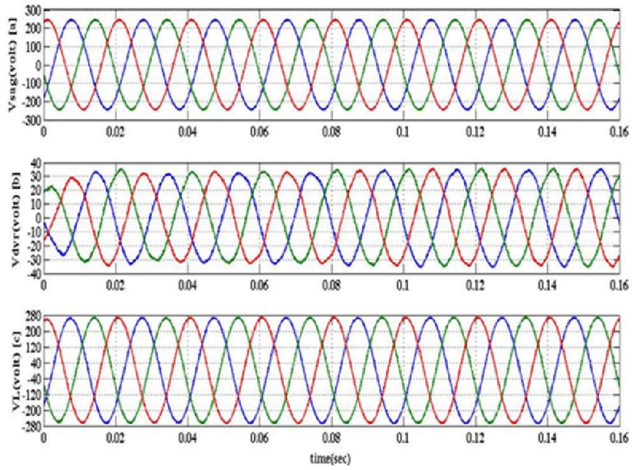

Fig. 10 (a) voltage sag (b) injected voltage (c) compensated load voltage

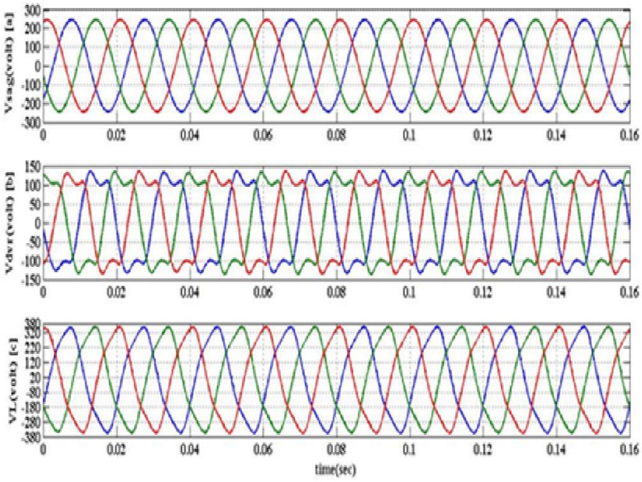

Fig. 11 (a) voltage sag (b) injected voltage (c) compensated load voltage

However, for presented control system in this paper, the phase angle is measured (as one of the block inputs), so by changing the load power factor, compensation will be done correctly. Fig 12.a shows a balance voltage sag 0.75^{pu} which in this case, the load power factor is reduced from 0.8 to 0.7. As mentioned before, while the real value of $P_{dvrdc,ref}$ is measured, then injected voltage by DVR will be the exact voltage required to compensate the load voltage (Fig 12.b).

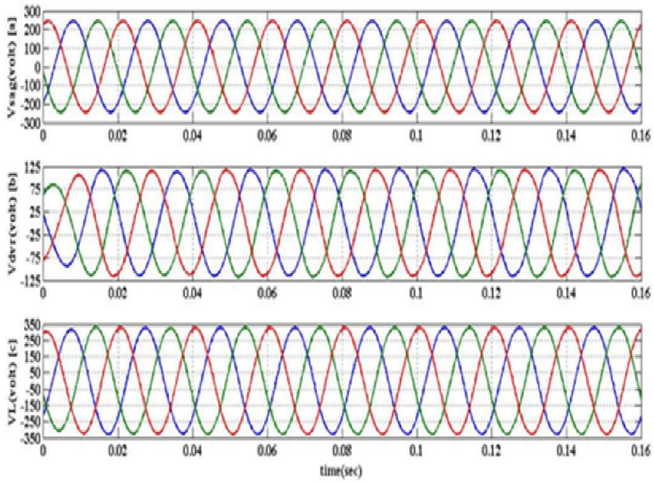

Fig. 12 (a) voltage sag (b) injected voltage (c) compensated load voltage

VI. Conclusion

While sag occurs in distribution systems, DVR can be used for correcting the sensitive load voltage level. DVR injects voltage in series to compensate load voltage. There are different voltage sag compensation techniques, but due to the restriction of storage energy in DVRs capacitors, minimization of active power injection by DVR is essential. In minimum active power injection method, for shallow voltage sag, injected active power by the DVR will be zero and for deep voltage sag, injected active power by DVR will be minimized. As load angle variation is inevitable, upgraded DVR controller works flexible this variation and properly compensate load voltage level especially for sensitive loads. Fixed load angle control strategy fouls in this case.

VII. References

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