A Robust and Flexible Controller Based on Minimum Active Power Injection to Precise Tracking of Load Variation to Compensate Voltage Sag

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ABSTRACT
In viewpoint of technology-driven custom power apparatus, dynamic voltage restorer (DVR) is recognized as a most prominent device which can be implemented to compensate the voltage sag. On the other hand, this device has been customarily used in power distribution system to protect sensitive loads from sudden voltage sag. Owing to the restriction of energy storage in DVR's capacitors, it is essential that the active power injection by DVR to be reduced. As a consequence, this energy-saving strategy leads to the injecting the larger voltage magnitude and reactive power, shifting the phase, and cluttering the voltage wave shape. Meantime, this strategy is very sensitive respect to variation in load's power factor, so that the compensating operation will not be properly performed. In this regard, this paper suggests a flexible controller based on minimum active power strategy in order to perfectly correct the voltage sag notwithstanding variation in load's power factor. Likewise, the under-study DVR has been structured according to the cascaded H-bridge multilevel inverter topology.

KEYWORDS: H-bridge Multilevel Inverter, Voltage Sag, DVR, Minimum Active Power Strategy, Load Power Factor.

1. INTRODUCTION

Voltage sag is conventionally recognized as the prominent disturbance that affects the power quality. In fact, voltage sag is an instantaneous drop in voltage magnitude (typically defined between 0.5 and 30 cycles) which is commonly caused by occurrence of faults in transmission and distribution systems [1]. Increasing progresses in the field of power semiconductor devices provide an appropriate bed in order to using Distribution-Flexible AC Transmission System (D-FACTS) devices in distribution power system [2]. Dynamic Voltage Restorer (DVR) is one of series custom power D-FACTS devices to preserve sensitive loads against power quality issues namely: voltage sags, swells and distortion via injecting the appropriate voltage level [3-6]. Currently, DVR is recognized as premier and effective approach to compensate voltage sag in distribution system.

Many different sensitive loads are available in distribution systems that are at high risk of voltage sag, which may lead to creation of serious impacts for such the high-tech loads [7-9]. DVR can receive the required compensation power by means of whether an energy storages such as batteries, super-capacitors or the input supply from a rectifier. Regardless of benefits of

energy storages, these apparatuses are high-priced that restrict the implementation of DVRs [10]. Furthermore, owing to the limitation in energy storage capacity, DVR may inappropriately compensate the load voltage during the long term voltage sags. In this regard, a strategy based on minimized injection energy is introduced for DVR. In this strategy, active power injection during the shallow voltage sags will be zero, and also will be minimized for deep voltage sags [11]. Irrespective of the voltage sag's types i.e. balance or unbalance voltage sags, this strategy will perform the compensation operation. The presented controller in [11] has been constructed for only a predefined power factor. Hence, the compensation operation will be encountered with defeat for variation in load power factor. Hereof, this paper suggests a robust controller based on minimum active power strategy in order to perfectly correct the voltage sag notwithstanding variation in load power factor. Meantime, a 13-level cascade H-bridge inverter has been designed for this study. To sum up, the simulation results have transparently revealed the robust performance of suggested controller in order to perfect compensation of voltage sag against variation in load power factor.

2. DVR STRUCTURE

Fig. 1 presents a DVR deployed in the distribution system that is situated between sensitive load and upstream network. During occurrence of fault or disturbance in distribution system which lead to voltage sag in sensitive load, DVR injects a required voltage in series to retrieve the load voltage into its original status. As can be seen from Fig. 1, DVR is generally constructed by energy storage, coupling transformer, PWM inverter, filter unit, and control system in order to generate an essential 3-phase AC (balance or unbalance) voltage regarding to compensating the load voltage. In this paper, the designed 13-level cascade H-bridge inverter has been simulated in MATLAB/SIMULINK environment. The generated 3-phase voltage by presented H-Bridge Inverter is given in Fig. 2. Likewise, cascade H-bridge inverters model along with its firing circuit of IGBTs are displayed in "Figs. 3 and 4 ".
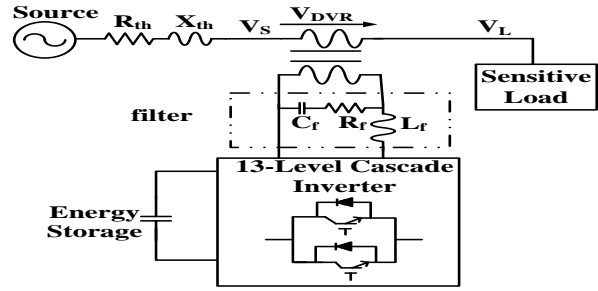

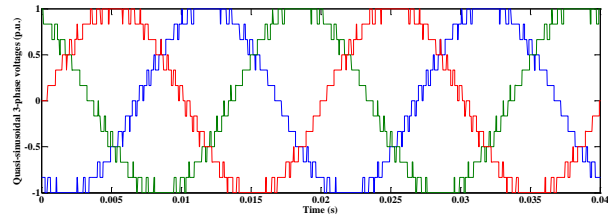**Fig. 1.** The DVR model connected to power distribution system

Fig. 2. The Quasi-sinusoidal three-phase voltages of the H-bridge multilevel inverter
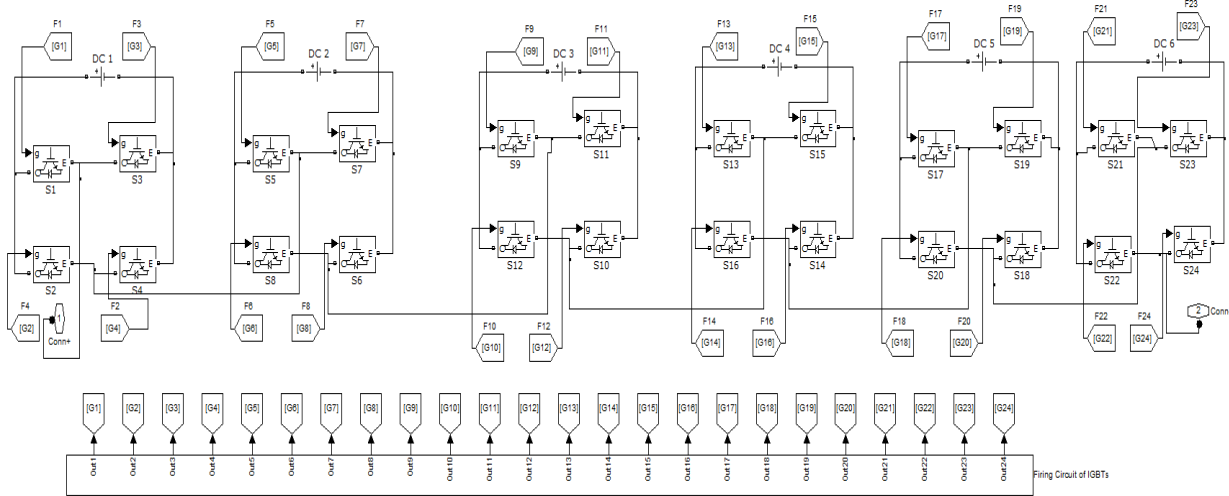

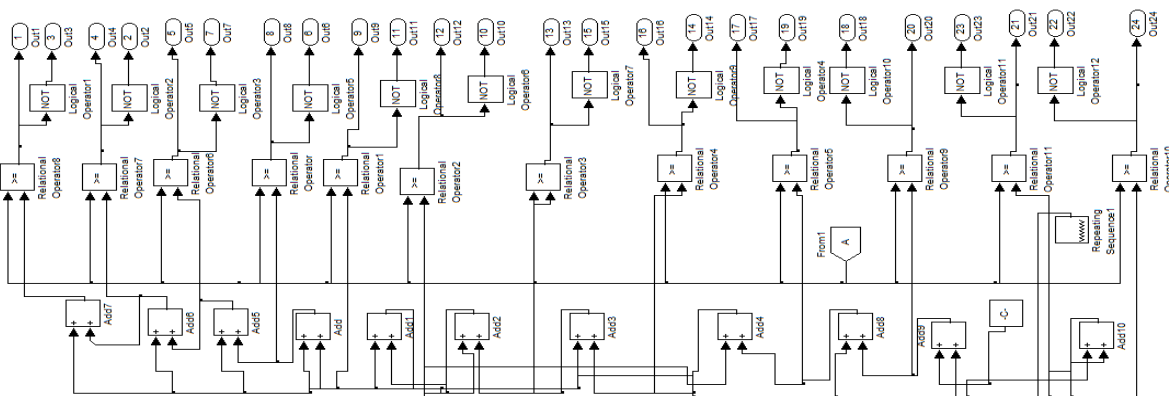**Fig. 3.** The 13-level cascade H-bridge inverter for phase "a"

Fig. 4. The firing circuit of IGBTs

3. CONTROL STRATEGIES FOR DVR

There are four prominent strategies up to now: 1-Pre-sag 2-In-phase 3-Minimal energy 4- Minimum active power injection [11].

In minimum active power injection strategy, the injected active power by DVR will be zero like minimal energy control strategy. According to Fig. 5, injected voltage by DVR is perpendicular to load current in order to zeroing the injected active power. Due to restriction of energy storage in DVR's capacitors, this plan will be valid for shallow voltage sags. Accordingly, the injected active power by DVR will be minimized for dip voltage sags.
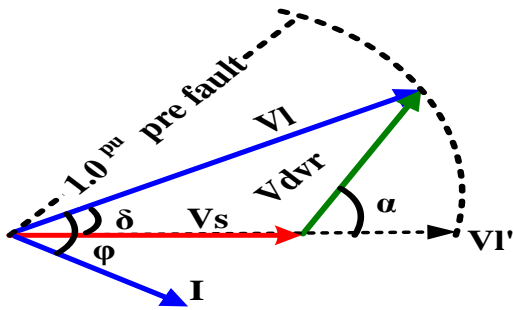

Fig. 5. The phasor diagram of minimal energy method

Fig. 6 presents the minimum injected active power by DVR (P_{dvr}) in terms of injected voltage by DVR (V_{dvr}) for different voltage sag and power factor 0.8. What is certain, the injected active power is zero for voltage sag 20%, and also, for values of lower and upper than 20% voltage sag less than 0.2 the minimum injected active power will be negative and positive, respectively. Owing to DVR has no ability to absorb negative active power, the lower values of 20% become zero i.e. compensating operation will be performed via reactive power (elimination of active power).
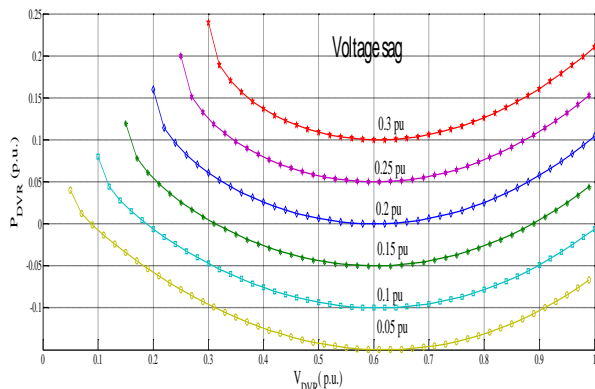

Fig. 6. Active power injection versus Voltage injection

4. DESIGN OF FLEXIBLE CONTROLLER BASED ON MINIMUM ACTIVE POWER INJECTION STRATEGY

In order to construct this controller the relevant equations regarding to this strategy must be figured out which are calculated as follows:

Must be noted that, δ and α are phase angles of load voltage and DVR voltage, respectively, and also, φ is the phase angle between the load current and load voltage. α is cab be defined:

$$\alpha = \pi/2 - \varphi + \delta \tag{1}$$

As well as δ:

$$\delta = \varphi - \cos^{-1}(V_L.\cos\varphi/V_S) \tag{2}$$

Eq. 2 will lead to the following inequality:

$$V_L.\cos\varphi \leq V_S \tag{3}$$

The active power of load can be presented by:

$$P_L = V_L.I_L.\cos(\varphi) \tag{4}$$

Also, the bus active power during occurrence of voltage sag can be given:

$$P_S = V_S.I_L.\cos(\varphi - \delta) \tag{5}$$

So, injected active power by DVR will be calculated by the following equation:

$$P_{DVR} = P_L - P_S = \cos(\varphi) - V_S.\cos(\varphi - \delta) \tag{6}$$

According to Fig. 5, α can be presented by following relationship:

$$\alpha = \sin^{-1}(V_L.\sin\delta / V_{dvr}) \tag{7}$$

And, as more comprehensive:

$$\delta = \cos^{-1}[(V_S^2 + V_L^2 - V_{dvr}^2)/(2V_L.V_S)] \tag{8}$$

If the value of $(V_S^2 + V_L^2 - V_{dvr}^2)/(2V_L.V_S)$ is taken γ, by substituting (7) and (8) into (6), the injected active power by DVR will be:

$$P_{dvr} = \cos(\varphi) - V_S.[\cos(\varphi).D + \sin(\varphi).\sqrt{(1-D^2)}] \tag{9}$$

Fig. 7 has been elicited from Eq. 9 based on $S_{DVR}=0.37^{pu}$ considering various power factor. It must be noted that, the negative values of injected active power are taken zero, because it does not need to be absorbed by DVR.
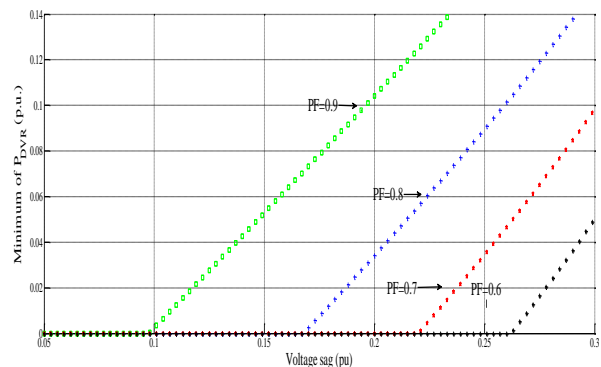

Fig. 7. Minimum active power injection versus Voltage sag

The presented controller in [11] has compensated voltage sags (balance or unbalance) without variation in load power factor. Therefore, the accurate compensation will not be carried out whenever power factor to be changed. Hereof, the suggested controller for DVR will accurately perform the compensation operation in spite of variation in load power factor. The improved control system based on minimum injected active power strategy is presented in Fig. 8. In block diagram of Fi.g 8, V_{a_ref}, V_{b_ref} and V_{c_ref} define the required voltage to be injected to the network by DVR. For balance voltage sags only positive sequences of reference signal will be generated, and also for unbalance voltage sags both the positive and negative sequences of reference signals will be generated [12]. These reference values are prominent signals to determine amplitude and phase angle of injected voltage of DVR. d-q axis of voltages vectors can be obtained from:

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \sqrt{(2/3)} * T * \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \begin{bmatrix} V_{sd,dc} \\ V_{sq,dc} \end{bmatrix} + \begin{bmatrix} V_{sd,ac} \\ V_{sq,ac} \end{bmatrix} \quad (10)$$

Where T is:

$$T = \begin{pmatrix} \cos(wt) & \cos(wt - 2\pi/3) & \cos(wt + 2\pi/3) \\ \sin(wt) & \sin(wt - 2\pi/3) & \sin(wt + 2\pi/3) \end{pmatrix} \quad (11)$$

Also, magnetite of voltage can be presented:

$$V_{Lm} = \sqrt{[V_{sd}^2 + V_{sq}^2]} \quad (12)$$

Subtracting V_{Lm} from $V_{Lm,ref}$ (commonly is considered 1.0pu) by passing through a PI controller, $V_{dvrd,\ ref}$ is obtained. To compensate voltage sag, DVR has both dc and ac active power components. The ac part is given into negative sequence part when the dc active power will be acquired.

$$P_{dvr,dc} = V_{dvrd,dc} \cdot I_d + V_{dvrq,dc} \cdot I_q \quad (13)$$

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

$$V_{dvrd,dc} = V_{Ld} - V_{sd,dc} , V_{dvrq,dc} = V_{Lq} - V_{sq,dc} \quad (14)$$

Magnitude of fundamental parts of supply voltage (V_{sm}) is given as follows:

$$V_{sm} = \sqrt{[V_{sd,dc}^2 + V_{sq,dc}^2]} \quad (15)$$

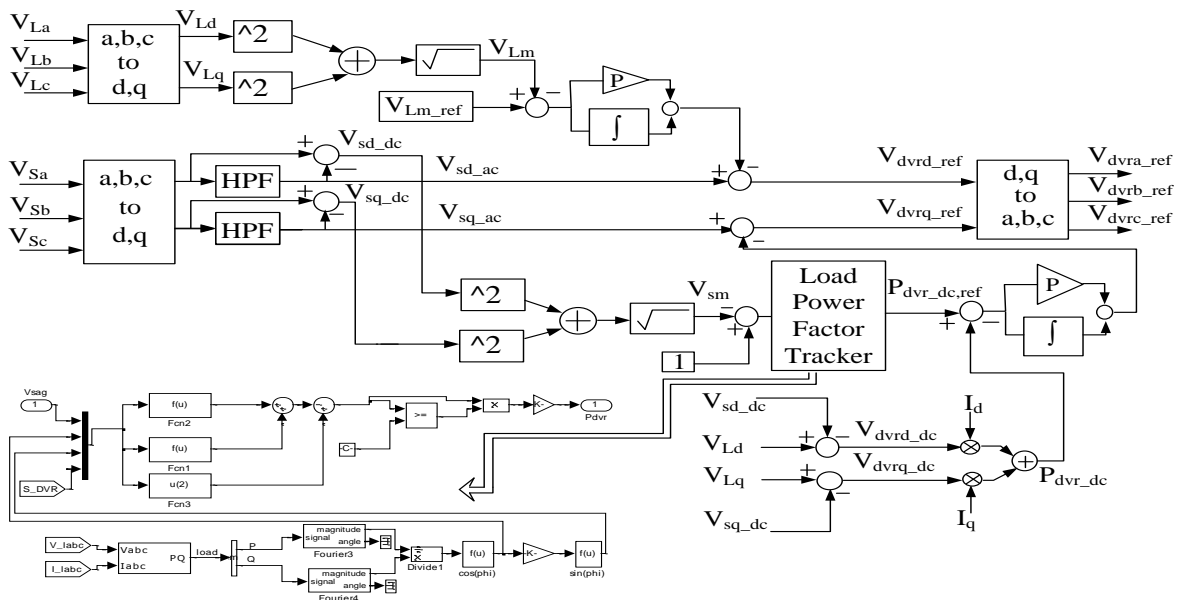Note that, all of the above mentioned quantities are based on per unit values.

Fig. 8. Suggested system control based on minimum active power injection strategy

5. SIMULATION RESULTS
What should be done during the sag, retrieve the load voltage into previous status (before sag) i.e. 1.0^{pu}. In this simulation, sag is occurred at t=0.1 ^{sec} and will remain for 0.2^{sec}. In the interim, the parameters of network and DVR are presented in Table1.

Table 1. The System and DVR Parameters

C_S	R_S	L_S	Storage Voltage	Load Power	Load Voltage
500µF	1Ω	100mH	270volt	100KVA	400volt

5.1. Balance Voltage Sag

In this part of the study, the performance of suggested controller has been tested by considering balanced voltage sag 0.25^{pu}. It is assumed that when the sag happened, the load power factor has changed from 0.9 to 0.8. Since the controller [11] cannot track this variation, the value of $P_{dvr\_dc,\ ref}$ has increased and accordingly the reference values of V_{aref}, V_{bref} and V_{cref} have reduced, and consequently the injected voltage by DVR (as shown in Fig. 9) will be decreased.
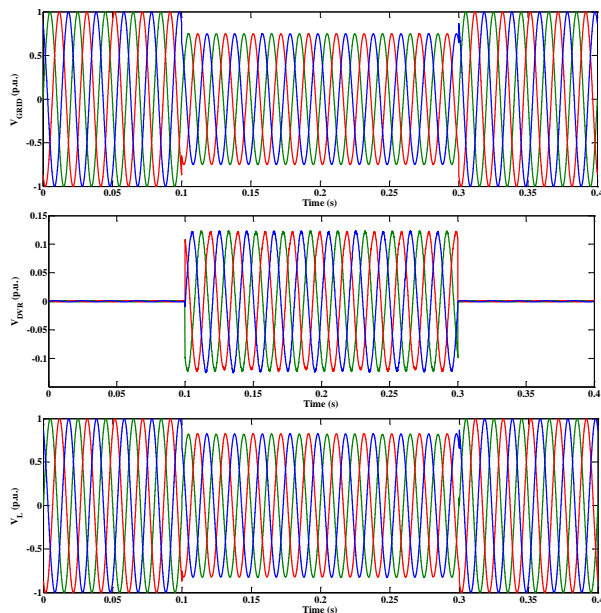

Fig. 9. Grid voltage, injected voltage by DVR, Load voltage under 0.25^{pu} voltage sag with controller [11]

Similarly, if the controller has been designed for load power factor 0.7 and afterward to be changed into 0.8 in the time of sag event, the value of $P_{dvr\_dc,\ ref}$ has reduced and the reference values of V_{aref}, V_{bref} and V_{cref} will be increased and subsequently accordingly the reference values of V_{aref}, V_{bref} and V_{cref} have increased. Since DVR has no ability to generate a sine wave voltage for these inputs, it has generated 3-phase non-sinusoidal voltages with magnitude more than 0.37^{pu} (as shown in Fig. 10). As a result, the load voltage will be encountered with a quasi-sinusoidal waveform with magnetite of more than 1.0^{pu}.
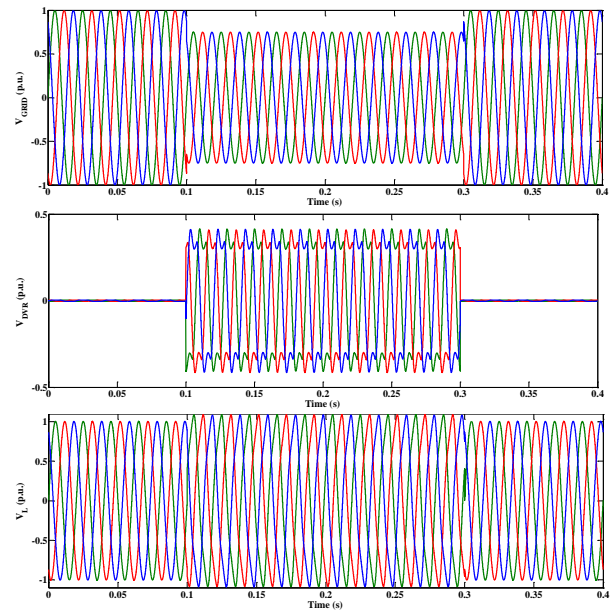

Fig. 10. Grid voltage, injected voltage by DVR, Load voltage under 0.25^{pu} voltage sag with controller [11]

It is worth mentioning that the presence of DVR has not satisfactory for both variations in load power factor in order to improvement of load voltage. But then, as soon as the load power factor to be changed, the suggested controller has tracked this variation and accordingly accurate reference signals i.e. V_{aref}, V_{bref} and V_{cref} are generated in order to injection of appropriate voltage by DVR (Fig. 11).
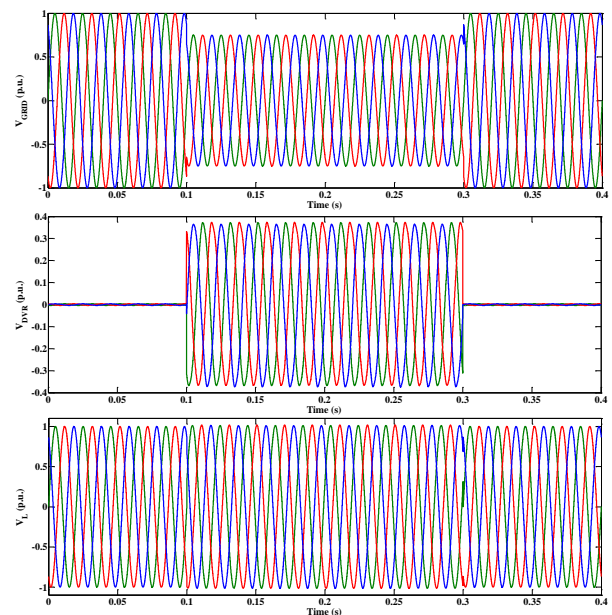

Fig. 11. Grid voltage, injected voltage by DVR, Load voltage under 0.25^{pu} voltage sag with suggested controller

5.2. Unbalance Voltage Sag

In this part of the study, the performance of suggested controller has been tested by considering unbalance voltage sag which voltage 'phase_a' dropped to 0.21^{pu} and voltage 'phase_b' and 'phase_c' fell down to as 0.11^{pu}. Similar to previous section, it is presumed that when the sag happened, the load power factor has changed from 0.9 to 0.8. Since the controller [11] cannot track this variation, the value of $P_{dvr\_dc,\ ref}$ has increased and accordingly the reference values of V_{aref}, V_{bref} and V_{cref} have reduced, and consequently the injected voltage by DVR (as shown in Fig. 12) will be decreased.
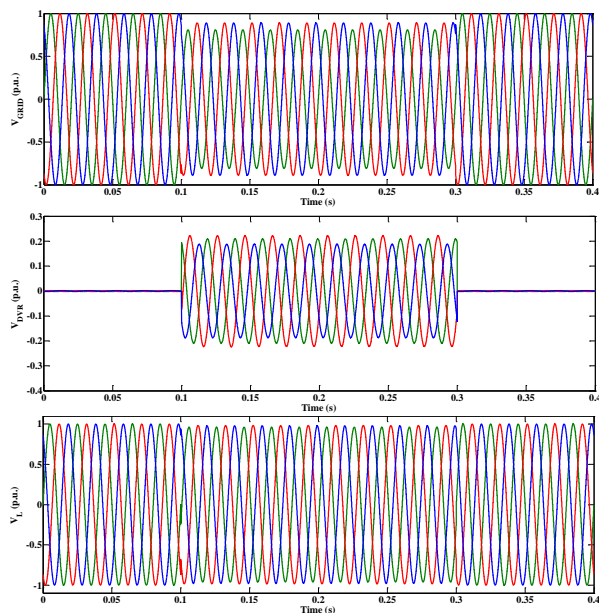

Fig. 12. Grid voltage, injected voltage by DVR, Load voltage under unbalanced 0.21^{pu} and 0.11^{pu} voltage sag with controller [11]

In the time of unbalance voltage event, the suggested controller will have appropriately done the compensating operation as the balanced state (as shown in Fig. 13).
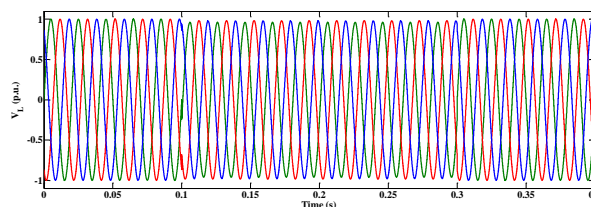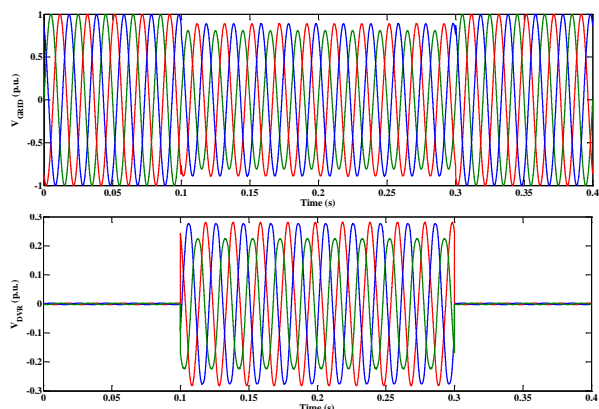

Fig. 13. Grid voltage, injected voltage by DVR, Load voltage under unbalanced 0.21^{pu} and 0.11^{pu} voltage sag with suggested controller

6. CONCLUSION

Application of DVR in distribution system could be regarded as important solution to protect sensitive loads during the sudden voltage sag. Minimum injected active power strategy has been executed in order to partly unravel the restriction issue of energy storage in DVR's capacitors. Even so, this device is highly sensitive against the variation in load power factor so that the compensating operation will not be absolutely performed. The suggested controller based on minimum active power strategy has solved the problem of variation in load power factor. To sum up, the simulation results have transparently revealed the high performance of suggested controller in order to retrieve the load voltage to previous status of sag event (balance and unbalance) in spite of variation in load power factor.

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