

# Comparative Analysis of Feed-Forward and Synchronous Reference Frame Control-Based Dynamic Voltage Restorer

A. Rini Ann Jerin, K. Palanisamy, S. Umashankar  
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**Abstract** The protection of nonlinear and sensitive loads can be achieved economically through series compensation-based dynamic voltage restorer. The effective voltage compensation by dynamic voltage restorer depends on the controller used for voltage sag detection. In this paper, the sag detection of dynamic voltage restorer employing feed-forward control and synchronous reference frame control are compared. The efficiency of sag detection of these controls in dynamic voltage restorer for in-phase compensation of balanced sags with PWM-based injection of compensation voltage is analyzed. Comparisons on the performance of the controllers are shown clearly using Matlab/Simulink-based simulated results.

**Keywords** Dynamic voltage restorer · Series compensation · Balanced sags  
Voltage sag · Feed-forward control · SRF control

## 1 Introduction

Voltage sags are the most frequent power quality issues among power quality disturbances during any fault conditions. This calls for compensation and protection of sensitive loads to maintain a constant voltage and current. Voltage sags can be defined as reduction in the supply voltage by 10% or even up to 90% from the nominal voltage for a duration of 10 ms to 1 min [1]. The steady increase in the power electronic equipment usage has also raised the harmonic levels in the system thereby requiring mandatory power quality improvement to maintain the system

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stability. The efficiency of voltage profile improvement using dynamic voltage restorer (DVR) with new control strategy is a very important study in the current scenario. Studies of power quality issues in grid-connected wind turbines have been carried out in the recent past and have even suggested the implementation of DVR for improving the LVRT capability [2]. Therefore, comparative analysis of the control strategies utilized for DVR operation will help in analyzing the operation and functionality of the device [3].

DVR is connected through a series injection transformer between the grid and the sensitive or nonlinear loads, and a voltage source converter (VSC) injects voltage in series [4]. The compensation voltages are injected across the distribution line according to the controlled switching sequence of the VSC, by drawing real power from the energy source connected [5]. Filters based on inductors and capacitors are connected to mitigate the ripples and harmonics in the injected voltage. A DVR is capable of restoring voltage sags, swells, harmonics, and even transients [5]. The DVR using conventional feed-forward control and synchronous reference frame (SRF) theory controller for voltage sag detection is compared in this paper. Based on the compensation the load voltage is restored back to the nominal voltage amplitude during fault conditions [6].

Generally, the controller efficiency determines the performance of a DVR. Therefore, design of high-performance control algorithms which are robust and have effective steady-state and transient performance becomes crucial. Hence, the voltage injection control using conventional feed-forward control and the SRF theory control of DVR system as shown in Fig. 1 is compared in this paper.

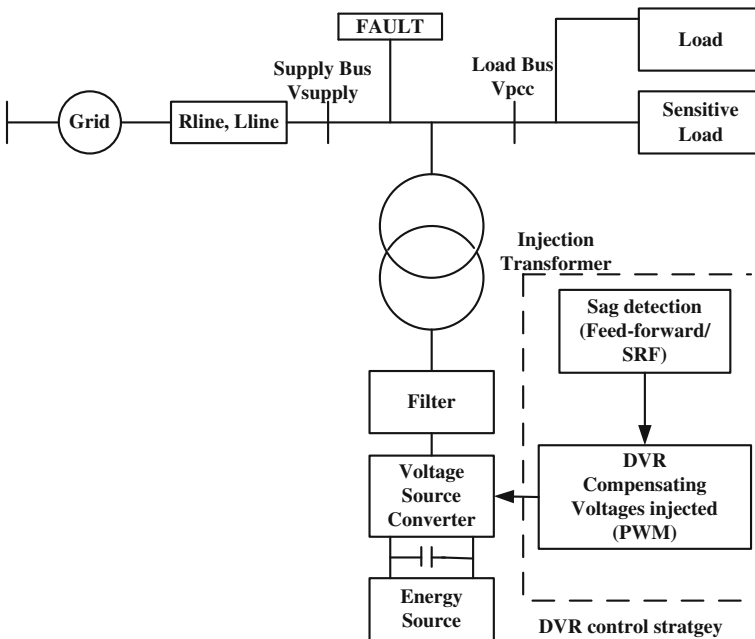


Fig. 1 Dynamic voltage restorer-based power quality improvement

The comparison is made for the total harmonic distortion (THD) values using both the control strategies. The Matlab/Simulink-based simulation results for comparison of the control strategies using in-phase compensation technique are shown to validate the results.

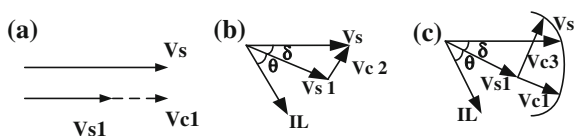
## 2 DVR Operation and Control

DVR operation is very simple and consists of a voltage source converter controlled through voltage sag detection and reference generation. The sag detection method discussed in this paper consists of the conventional feed-forward control and the SRF theory control. The control method measures and analyzes the voltage sag in the grid voltage based on the specific control strategy. The efficiency of the DVR operation during different disturbance conditions is determined by the control technique employed for the sag detection [7]. The reference signal for injecting the series injection voltage is obtained through any one of the three compensation strategies which are available. The three compensation strategies for reference generation are in-phase compensation, pre-sag compensation, and minimal energy compensation methods [1].

During in-phase compensation, the PLL will not be locked and the voltage rating in the dc-link is minimal. Therefore, reduced rating of voltage source converter is possible by utilizing this in-phase compensation method. But since this method leads the load voltage magnitude, it is unable to correct the voltage sags with phase jumps [1]. Therefore, this compensation method is not suitable for loads which are sensitive for phase jumps. In Fig. 2  $V_s$  denotes supply voltage,  $V_{s1}$  denotes the supply voltage with reduced amplitude due to sag, and  $I_L$  is the load current.  $V_{c1}$  is compensation voltage with same magnitude and in-phase to the supply voltage but not in-phase to load voltage, therefore not suitable for loads sensitive to phase jump.  $V_{c2}$  is the compensation voltage where it is compensated to pre-sag values with same amplitude and phase angle in pre-sag compensation but requires higher rating of the voltage source converter.  $V_{c3}$  is the compensation voltage in quadrature to load current in minimized energy compensation with only reactive power supply from DVR and this method is utilized for self-supported DVR [3]. In this paper the in-phase compensation is utilized.

The compensation voltage is injected by the voltage source converter based on the signals generated using PWM control strategy. A series injection transformer is connected between the point of common coupling (PCC) of the distribution side of

**Fig. 2** DVR compensation techniques, **a** In-phase. **b** Pre-sag. **c** Minimum energy compensation



the grid and load. The control strategy and the compensation technique are chosen to determine the efficiency of the DVR.

### 2.1 Feed-Forward Control

Feed-forward is a conventional open-loop type control technique which compares the supply voltage with the reference values and measures the error to give the required value of injected voltage. In this control, the three-phase supply voltage is transformed into d-q components using a PLL [3]. Using in-phase compensation technique, the PLL is synchronized and therefore will not be locked during the compensation. The supply of d-q components is compared and subtracted from the reference voltage d-q components ( $v_{dref}, v_{qref}$ ) to obtain the necessary injected voltage d-q components. The transformed three-phase injection voltage is supplied from the voltage source converter through the series injection transformer. This control strategy is shown in Fig. 3 where the supply voltage components are  $v_{sa}, v_{sb}, v_{sc}$ , and  $v_s$  is the supply voltage for determining  $\theta$  value for calculating phase angle using PLL. ( $v_{ca}, v_{cb}, v_{cc}$ ) are the compensation voltage components injected through the voltage source converter.

### 2.2 Synchronous Reference Frame (SRF) Control Technique

The synchronous reference frame (SRF) theory is used for detecting the sag and generating the appropriate reference for deriving the IGBT gating signals [8]. This control includes the feedback control of the reference load voltage  $v_L^*$  which is derived and converted to rotating reference frame using abc-dq0 by Park's transformation [9]. This is done using the  $\sin \theta, \cos \theta$  unit vectors from a phase-locked loop (PLL) [10].

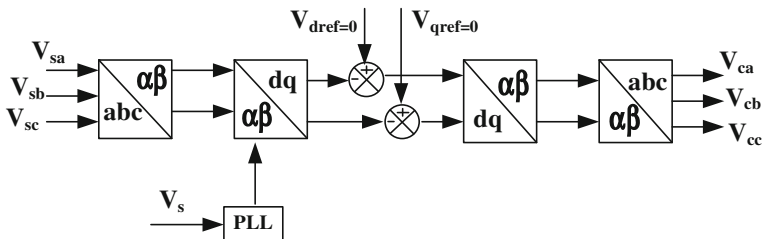


Fig. 3 Feed-forward control strategy for DVR

$$\begin{bmatrix} v_{Lq} \\ v_{Ld} \\ v_{L0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin \theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_{La}^* \\ v_{Lb}^* \\ v_{Lc}^* \end{bmatrix} \quad (1)$$

$$v_{Dd} = v_{Sd} - v_{Ld} \quad (2)$$

$$v_{Dq} = v_{Sq} - v_{Lq} \quad (3)$$

$$v_{Dd}^* = v_{Sd}^* - v_{Ld} \quad (4)$$

$$v_{Dq}^* = v_{Sq}^* - v_{Lq}. \quad (5)$$

The reference calculated by subtracting the reference from the actual is used to regulate using two PI controllers [11].

where load voltages in abc frame are as follows:

Load voltages:  $(v_{La}, v_{Lb}, v_{Lc})$ ; Reference load voltages:  $(v_{La}^*, v_{Lb}^*, v_{Lc}^*)$ .

Load voltages in d-q frame are as follows:

Load voltages:  $(v_{Ld}, v_{Lq}, v_{L0})$ ; Reference load voltages:  $(v_{Ld}^*, v_{Lq}^*)$ .

PCC voltages in rotating reference frame in d-q frame are as follows:

Supply voltage:  $(v_{sd}, v_{sq})$ ; Reference supply voltage:  $(v_{sd}^*, v_{sq}^*)$

$$\begin{bmatrix} v_{dvra}^* \\ v_{dvrb}^* \\ v_{dvrc}^* \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} v_{Dq}^* \\ v_{Dd}^* \\ v_{D0}^* \end{bmatrix}. \quad (6)$$

DVR voltages in rotating reference frame in d-q frame are as follows:

DVR voltages:  $(v_{Dd}, v_{Dq})$ ; DVR reference voltages:  $(v_{Dd}^*, v_{Dq}^*, v_{D0}^*)$ .

DVR voltage in abc frame are as follows: Actual DVR voltages:  $(v_{dvra}, v_{dvrb}, v_{dvrc})$ ; Reference DVR voltages:  $(v_{dvra}^*, v_{dvrb}^*, v_{dvrc}^*)$ . These are used to generate the PWM pulses to a voltage source converter of the DVR which is operated at 10 kHz. The control strategy operates as shown in Fig. 4.

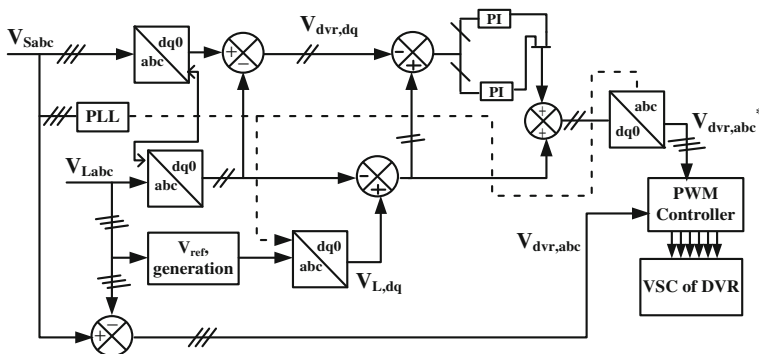


Fig. 4 Synchronous reference frame theory (SRF) control for DVR

Table 1 Parameters used for simulation

System parameters	Values
Supply voltage and frequency	415 V, 50 Hz
Line impedance	( $L_s$ ) 1 mH ( $R_s$ ) 0.1 $\Omega$
Turns ratio series injection transformer	1:1
Filter inductance	0.9 mH
Filter capacitance	10 $\mu$ F
Load-active power	1 kW
DC voltage of DVR	300 V

### 3 Simulation Results

The simulation of the DVR using feed-forward control and SRF control for RL load during 0.3 pu balanced sag for 0.8 ms time interval is observed. The sag compensation and harmonic mitigation are observed and the THD values are compared. Table 1 gives the parameters used in the simulation done with MATLAB/Simulink tool.

Figure 5 shows compensation of the balanced sag using feed-forward control. But this control is not suitable for unbalanced voltage sags due to the negative sequence components. Using abc to d-q transformation in SRF control, simple PI structures are used for the power and current controllers. Since they operate on DC converter variables in the synchronous frame and they can achieve zero steady-state error because of the infinite DC gain of a PI regulator, and also, when the voltage is unbalanced, negative sequence component appears. Therefore, proper current reference calculation and regulation is required to fully control the system. The compensation of balanced sag using SRF control is shown in Fig. 6.

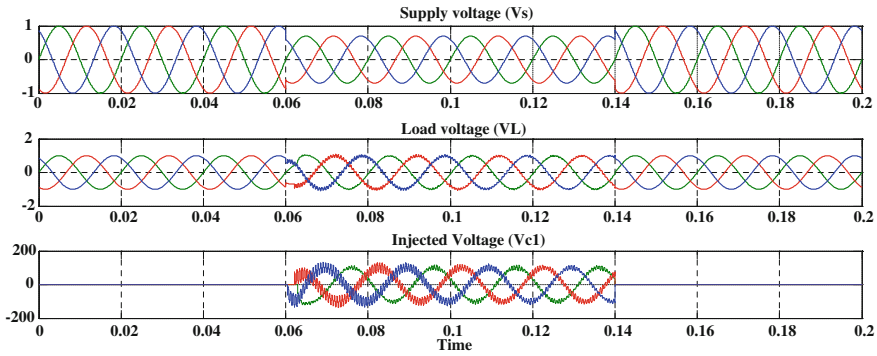


Fig. 5 DVR with feed-forward control for 0.3 pu balanced sag between 0.06 and 0.14 s

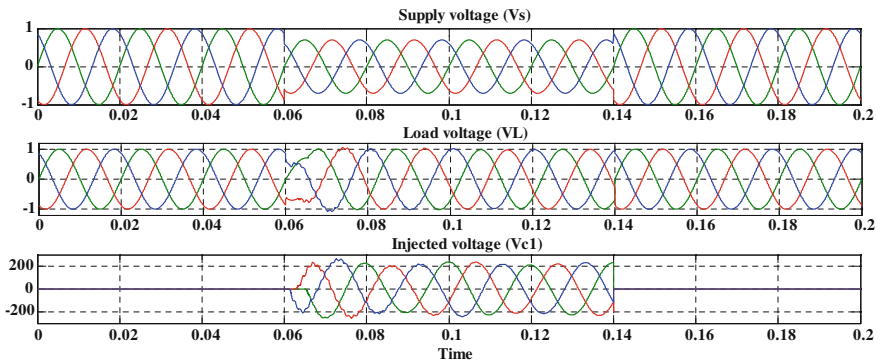


Fig. 6 DVR with SRF control for 0.3 pu balanced sag between 0.06 and 0.14 s

Table 2 Comparison of THD values for the feed-forward and SRF control

THD values	Feed-forward control (%)	SRF control (%)
Supply voltage	30	30
Supply current	5.18	1.34
Load voltage	5.24	1.35
Load current	5.18	1.34

### 4 Comparison and Discussion

The comparison of the performance of feed-forward control and SRF control of DVR based on the total harmonic distortion (THD) values with RL load for 30% harmonics in supply voltage is done and shown in Table 2.

The harmonic compensation using feed-forward control is shown in Fig. 7 and using SRF control is shown in Fig. 8. Figure 9 shows that the THD value of DVR

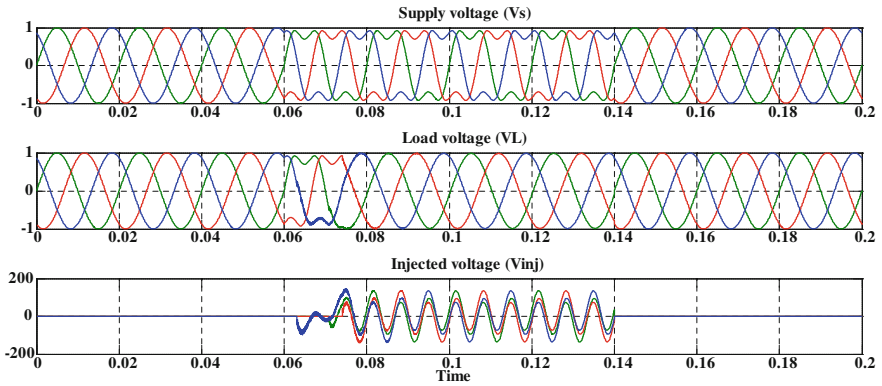


Fig. 7 Harmonic mitigation of DVR with feed-forward control for 30% harmonics in the supply voltage sag between 0.06 and 0.14 s

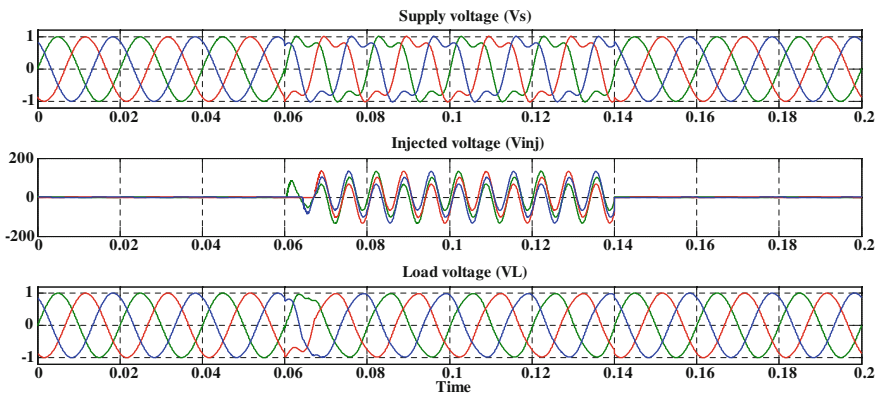
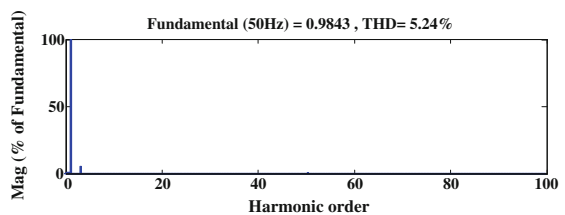


Fig. 8 Harmonic mitigation of DVR with SRF control for 30% harmonics in the supply voltage sag between 0.06 and 0.14 s

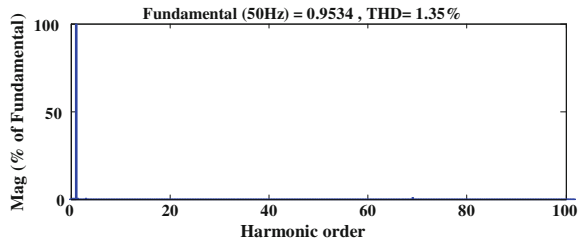
Fig. 9 THD of DVR Load voltage with feed-forward control



load voltage after sag mitigation using feed-forward control is 5.24%, and Fig. 10 shows THD value of DVR load voltage using SRF control with 1.35%. It is quite obvious that the THD values are improved using SRF control. Also, it is observed



**Fig. 10** THD of DVR load voltage with SRF control



that feed-forward control causes phase jump, whereas the SRF control avoids phase jump. Therefore, SRF control is comparatively better and more suitable for phase-sensitive critical loads.

## 5 Conclusion

The power quality improvement using DVR through series voltage compensation is considered. The performance of DVR with feed-forward control and SRF control are compared in this paper. The comparison of THD values shows the effectiveness of the control strategies. The comparison of the THD values indicates that the SRF control could be more suitable for power quality improvement during unbalanced sag and transient conditions. The reduced rating of the DVR voltage source converter could be possible with in-phase compensation. But this may require external source and at the cost of phase jumps, which may not be desirable for loads which are sensitive to phase jumps. In comparison the SRF control has lower THD and within the IEEE 519 standard compared to the feed-forward control. Therefore, SRF control seems to be more suitable for critical loads which are sensitive to phase jumps.

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