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SRF THEORY BASED REDUCED RATING DYNAMIC VOLTAGE RESTORER FOR VOLTAGE SAG MITIGATION

S.Sunandha[1], M.Lincy Luciana[2] and K.Sarasvathi[3]

[1]*M.E., EEE, M.Kumarasamy College of Engineering, Karur, India.*
[2]*M.E., EEE, M.Kumarasamy College of Engineering, Karur, India.*
[3]*M.E., EEE, M.Kumarasamy College of Engineering, Karur, India.*

***Abstract*-- With the restructuring of power systems and with shifting trend towards distributed and dispersed generation, the issue of power quality is going to take newer dimensions. The present research is to identify the prominent concerns in this area and hence the measures that can enhance the quality of power are recommended. Voltage sag is a common and undesirable power quality phenomenon in the distribution systems which puts sensitive loads under the risk. An effective solution to mitigate this phenomenon is to use dynamic voltage restorers and consequently, protect sensitive loads. In addition, different voltage injection schemes for DVRs are explored to inject minimum energy for a given apparent power of DVR. The performance of this proposed DVR is examined with different control strategies like conventional Proportional and Integral (PI) control and Synchronous Reference Frame (SRF) Theory based PI control. TheproposedReduced Rating DVR with SRF theory based PI Controller offers economic solution for voltage sag mitigation. Simulation results are carried out by MATLAB with its Simulink to analyze the proposed method.**

***Index Terms* – Dynamic Voltage Restorer, Voltage Sag, PI Controller, SRF theory based PI Controller.**

I.INTRODUCTION

Power Quality and reliability in distribution system have been attracting an increasing interest in modern times and have become an area of concern for modern industrial and commercial applications. Introduction of sophisticated manufacturing systems, industrial drives, precision electronic equipments in modern times demand greater quality and reliability of power supply in distribution networks than ever before. Power Quality problems encompass a wide range of phenomena. Voltage sag/swell, flicker, harmonics distortion, impulse transients and interruptions are a prominent few [1]. These disturbances are responsible for problems ranging from malfunctions or errors to plant shut down and loss of manufacturing capability. Among the power quality problems voltage sag is the most frequently occurring one. Therefore this sag is the most important power quality problem in the power distribution system.

Voltage Sag or Voltage Dip is defined by the IEEE 1159 as the decrease in the RMS voltage level to 10%-90% of nominal, at the power frequency for durations of ½ cycles to one minute. The IEC (International Electro-technical Commission) terminology for voltage sag is dip. The IEC defines voltage dip as a sudden reduction of the voltage at a point in the electrical system, followed by voltage recovery after a short period, from ½ a cycle to a few seconds. Voltage sags are usually associated with system faults but they can also be generated by energisation of heavy loads or starting of large motors which can draw 6 to 10 times its full load current during starting. There are two types of voltage sag which can occur on any transmission lines; balanced and unbalanced voltage sag which are also known as symmetrical and asymmetrical voltage sag respectively. Most of these faults that occur on power systems are not the balanced three-phase faults, but the unbalanced faults. In the analysis of power system under fault conditions, it is necessary to make a distinction between the types of fault to ensure the best results possible in the analysis.

- Unsymmetrical voltage sag
    - Single phase voltage sag
    - Two phase voltage sag
- Symmetrical voltage sag
    - Three phase voltage sag

As the quality of power is strictly related to the economic consequences associated with the equipment and should therefore be evaluated considering the customers point of view. So the need for solutions dedicated to single customers with highly sensitive loads is great since a fast response of voltage regulation is required. Further it needs to synthesize the characteristics of voltage sags both in domestic and industrial distributions.

In order to meet these challenges, it needs a device capable of injecting minimum energy so as to regulate load voltage at its predetermined value. The traditional mitigating methods include tap-changing transformers and uninterrupted power supplies. These methods are costly and not fast enough to mitigate voltage sag but the use of custom power devices is considered to be the most proficient method. The term custom power pertains to the use of power electronics controller in a distribution system. There are three custom power devices such as distribution-STATCOM (D-STATCOM), Dynamic Voltage Restorer (DVR), and Unified Power Quality Conditioner (UPQC). Dynamic

Voltage Restorer (DVR) is one of the prominent devices for compensating the power quality problems associated with voltage sags/swells [2-5]. Dynamic voltage restorer (DVR) can provide an effective solution to mitigate voltage sag by establishing the appropriate predetermined voltage level required by the loads [6It is recently being used as the active solution for voltage sag mitigation in modern industrial applications [7].DVR could maintain load voltage unchanged during any kind of faults, if the capability of energy storage of DVR was infinite. Because of the energy limitations of energy storage of DVR, it is necessary to minimize energy injection from DVR [8]-[10].

In this paper, Dynamic Voltage Restorer (DVR) is designed and implemented with the proposed compensation strategy, which is capable of compensating power quality problems associated with voltage sags/swells with minimum energy and maintaining a prescribed level of supply voltage. The simulation of the proposed DVR is accomplished using MATLAB/ SIMULINK. The performance of the proposed DVR for different supply disturbances is tested under various operating conditions.

II. DYNAMIC VOLTAGE RESTORER

The schematic diagram of Dynamic Voltage Restorer (DVR) connected distribution system is shown in Fig. 1. DVR is a solid state inverter which injects the series voltage with a controlled magnitude and phase angle to restore the quality of voltage to the pre-specified value and avoid load tripping. The function of the DVR will inject the missing voltage in order to regulate the load voltage from any disturbance due to immediate distort of source voltage. The DC side of DVR is connected to an energy source or an energy storage device, while its ac side is connected to the distribution feeder by a three-phase inter facing injection transformer. Since DVR is a series connected device, the source current, is same as load current. DVR injected voltage in series with line such that the load voltage is maintained at sinusoidal nominal value [11]. It is normally installed in a distribution system between the supply and the critical load feeder at the point of common coupling (PCC).

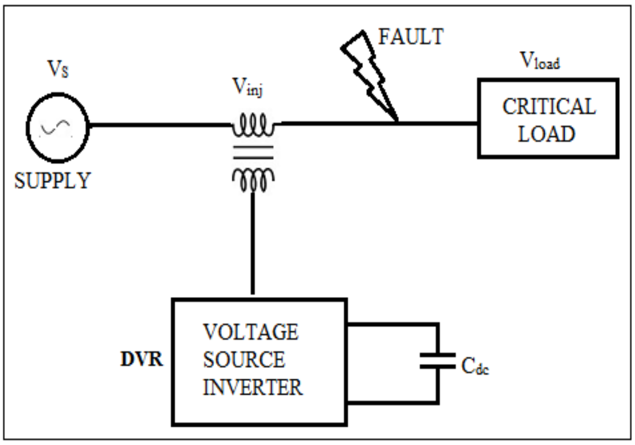

Fig. 1. Basic Circuit of DVR Connected System

A.*OPERATING PRINCIPLE of DVR*

The schematic diagram of a self-supported DVR is shown in Fig.2. Three phase source voltages (Vsa, Vsb, and Vsc) are connected to the 3-phase critical load throughseries impedance (Za, Zb, Zc) and an injection transformer in each phase. The terminal voltages (Vta, Vtb, Vtc) have power quality problems and the DVR injects compensating voltages (VCa, VCb, VCc) through an injection transformer to get undistorted and balanced load voltages (VLa, VLb, VLc). The DVR is implemented using a three leg voltage source inverter with IGBTs along with a dc capacitor (Cdc). A ripple filter (Lr, Cr) is used to filter the switching ripple in the injected voltage. The considered load, sensitive to power quality problems is a three-phase balanced lagging power factor load. A self-supported DVR does not need any active power during steady state because the voltage injected is in quadrature with the feeder current.

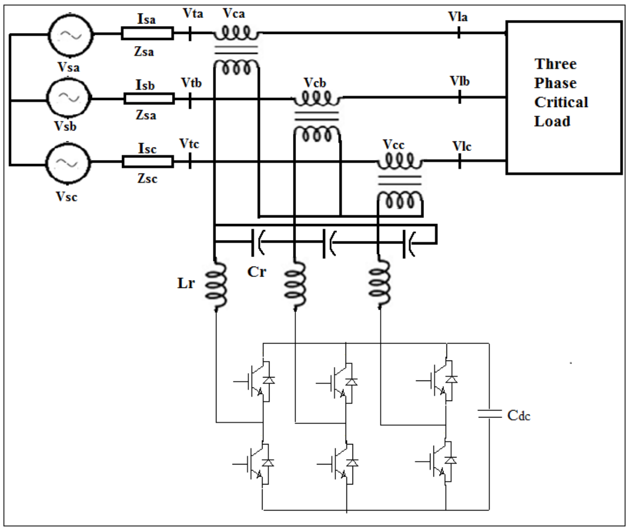

Fig.2. Schematic Diagram of Capacitor Supported DVR

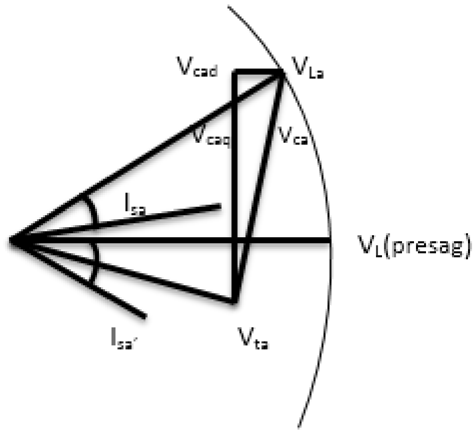

Fig.3. Phasor Diagram for Voltage Sag

The DVR operation for the compensation of sag in supply voltage is shown in Fig.3. Before sag the load voltages and currents are represented as VL (presag) and Isa' as shown in Fig.3. After the sag event, the terminal voltage (Vta) is gets lower in magnitude and lags the presag voltage by some angle. The DVR injects a compensating voltage (VCa) to maintain the load voltage (VL) at the rated magnitude. VCa has two components, VCad and VCaq. The voltage in-phase with the current (VCad) is required to regulate the dc bus voltage and also to meet the power loss in the VSI of DVR and an injection transformer [5]. The voltage in quadrature with the current (VCaq) is required to regulate the load voltage (VL) at constant magnitude.

III. CONTROL OF DVR

The efficiency of DVR depends on the performance of the control technique involved in switching of inverters. Hence different control techniques such as PI controller, and SRF theory based PI controller were used here. Based on the comparison between the performances of these controllers in controlling the switching of PWM inverter switches, the optimum controller that improves the performance of DVR is suggested.

A. PI CONTROLLER

A PI controller output signal is directly proportional to the linear combination of measured actuating error signal and its time.

A proportional-integral (PI) controller shown in fig.4.drives the plant to be controlled with a weighted sum of the error (difference between the actual sensed output and desired set-point) and the integral of that value. An advantage of a proportional plus integral controller is that its integral term causes the steady-state error to be zero for a step input. PI controller input is an actuating signal which is the difference between the Vref and Vin. Output of the controller block is of the form of an angle δ, which introduces additional phase-lag/lead in the three-phase voltages.
The output of error detector is Vref - Vin.
Vref equal to 1 p.u. voltage
Vin voltage in p.u. at the load terminals.

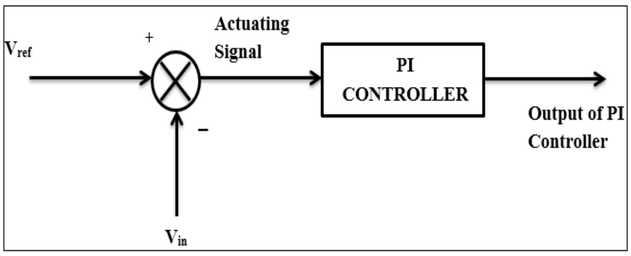

Fig.4. PI Controller

B. *SRF THEORY BASED PI CONTROLLER*

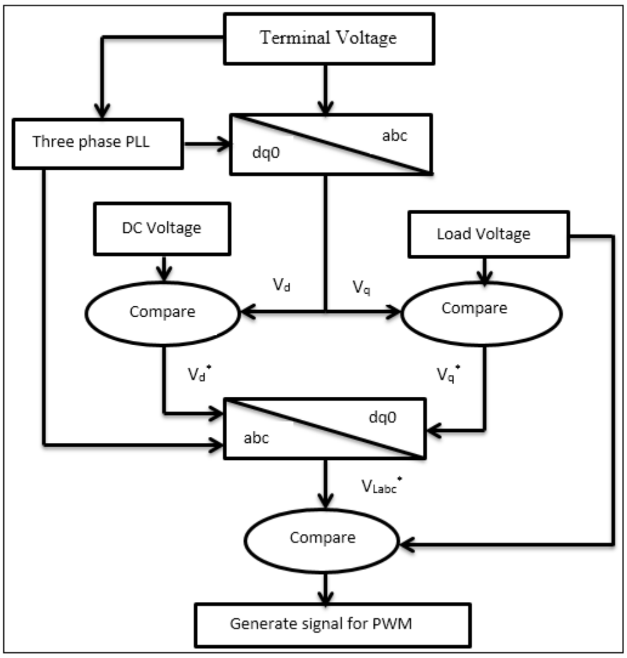

Fig.5. SRF Control Algorithm for DVR

Fig. 5. shows the SRF control algorithm which is able to detect different types of power quality problems without an error and introduces the appropriate voltage component to correct instantly any deformity in the terminal voltage to keep the load voltage balanced and constant at the nominal value [12], [13]. This is a closed loop system which needs DC link voltage of DVR and amplitude of load voltage to produce direct axis and quadrature axis voltages. When the load voltage descents 10% of its reference load voltage then the error signal is generated by the DVR controller to generate the PWM waveform for 6-pulse IGBT device.

SRF Theory is used for the control of DVR. The voltages at the PCC are transformed to the reference frame using abc-dq0 conversion as,

$$\begin{bmatrix} V_{Tq} \\ V_{Td} \\ V_{T0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} V_{Ta} \\ V_{Tb} \\ V_{Tc} \end{bmatrix}$$

The harmonics and the oscillatory components are excluded using low pass filters. The components of voltages in d-axis and q-axis are,

$$V_d = V_{d\ dc} + V_{d\ ac}$$
$$V_q = V_{q\ dc} + V_{q\ ac}$$

The SRF based method is also used to acquire the direct axis and quadrature axis components of load voltage. The load voltages in three phases are changed to d-q-0 frame using Park's transformation. A three phase PLL is used to synchronize these signals with the terminal voltages. The d-q components are passed through low pass filters to extract the dc components V_d' and V_q'. In order to maintain the dc bus voltage of DVR, the error between the reference dc bus voltage and the sensed dc bus voltage of DVR is given to a

PI controller of which output is considered as the loss component of voltage and is added to the dc component of V_d' to generate V_d*. The reference d-axis load voltage is therefore as

$$V_{Ld}^{*} = V_{Td\ dc} - V_{loss}$$

Similarly, a second PI controller is used to standardize the amplitude of the load voltage. The amplitude of load voltage at point of common coupling is calculated from the ac voltages (V_{La}, V_{Lb}, V_{Lc}) as,

$$V_L = \sqrt{\left(\frac{2}{3}\right)(V_{La}^2 + V_{Lb}^2 + V_{Lc}^2)}$$

The amplitude of the load voltage (V_L) is employed over the reference amplitude (V_L^*) and the output of PI controller is considered as the reactive component of voltage (V_{qr}) for regulation of load voltage added with the dc component of V_q' to generate V_q^*. The reference q-axis load voltage is therefore as,

$$V_{Lq}^{*} = V_{Tq\ dc} + V_{qr}$$

The resultant voltages (V_d^*, V_q^*, V_0) are again altered into a-b-c frame using reverse Park's transformation as,

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

Reference load voltages and the sensed load voltages are used in PWM generator to generate gate pulses for the switches.

IV. PROPOSED COMPENSATION STRATEGY

In a three phase distribution system, when the voltage sag occurs, the fuel cell based DVR needs to provide essential voltage to compensate it. The voltage $V_{inj}$is inserted such that the load voltage V_{load} is constant in magnitude and undistorted even though the supply voltage V_s is not constant in magnitude or is distorted.

Fig. 6. shows the phasor diagram for different voltage injection schemes of the DVR. $V_{L(presag)}$ is a voltage across the critical load prior to the voltage sag. During the voltage sag, the load voltage is reduced to $V_{L(sag)}$ with a phase lag angle of θ. Now the DVR needs to provide some voltage such that the load voltage magnitude is maintained at the pre-sag condition. Based on the phase angle of load voltage, the voltage injected by DVR can be comprehended in four ways. V_{inj1} represents the voltage injected by DVR that is in-phase with the $V_{L(sag)}$. With the injection of V_{inj2}, the load voltage magnitude retains the same but it leads $V_{L(sag)}$ by a small angle. In V_{inj3}, the load voltage holds the same phase as that of the pre-sag condition.

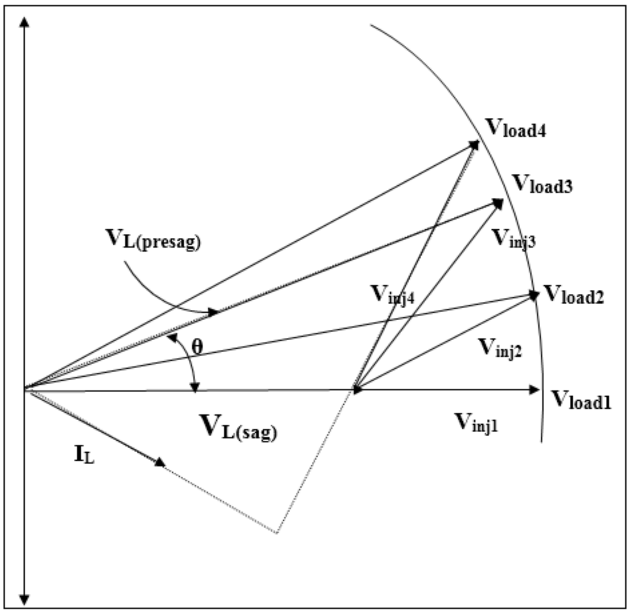

Fig. 6. Phasor diagram for voltage injection schemes

V_{inj4} is the condition where the injected voltage is in quadrature with the current and this injection comprises no active power. On assessment of these four voltage injection schemes, with the injection of V_{inj1}, a minimum possible rating of the converter is achieved. The sinusoidal signal is phase modulated by means of the angle δ and the modulated three phase voltages are given by,

$$V_a = \sin(\omega t + \delta)$$

$$V_b = \sin(\omega t + \delta + \frac{2\pi}{3})$$

$$V_c = \sin(\omega t + \delta + \frac{4\pi}{3})$$

V. MODELING AND SIMULATION

The voltage sag is created in a 415V, three phase distribution system with the help of a three phase to ground fault and a DVR is modeled to mitigate sag event and is simulated using MATLAB is shown in Fig. 7. The control algorithm used is SRF theory along with PI controller. The proposed compensation technique is also implemented to reduce the rating of DVR. An equivalent load considered is a 10kVA 0.8-pf lagging linear load. The parameters of the considered system for the simulation study are given in the Appendix.

VI. PERFORMANCE OF THE PROPOSED SYSTEM

The performance of DVR is validated for supply voltage disturbance such as balanced and unbalanced voltage sag. Unbalanced voltage sag is created in supply voltage for duration of 0.2s to 0.4s by using single line to ground fault and double line to ground fault are shown in fig.8. (a),(b) respectively. Balanced voltage sag is created in supply voltage for duration of 0.2s to 0.4s by using three phase fault is shown in fig.8 (c). Voltage sag which is a condition of a temporary reduction in supply voltage, the DVR injects an equal positive voltage component in all three phases which are in phase with the supply voltage to correct it, is shown in fig.9. (a),(b),(c) respectively. The load voltage is sustained sinusoidal by injecting proper compensation voltage by the DVR is shown in fig.10.

To implement the reduced rating DVR, it is necessary to find the optimal voltage injection angle. The magnitude of the voltage injected by the DVR for mitigating the same kinds of sag event in the load with different angles of injection is observed. The volt-ampere ratings of the DVR for the four voltage injection schemes are given in Table. I. In Scheme-1, the DVR voltage is injected in-phase with sag voltage. In Scheme-2, the DVR voltage is injected at a small angle of 30o and in Scheme-3, the DVR voltage is injected at an angle of 45o. The injection of voltage in quadrature with the line current comes under Scheme-4.

On comparison of four voltage injection schemes, when the DVR injects voltage in-phase with the sag voltage (scheme-1), the output power supplied by DVR is minimized is shown pictorially in fig. 11 (a), (b) for both the PI and SRF theory based PI controller respectively.

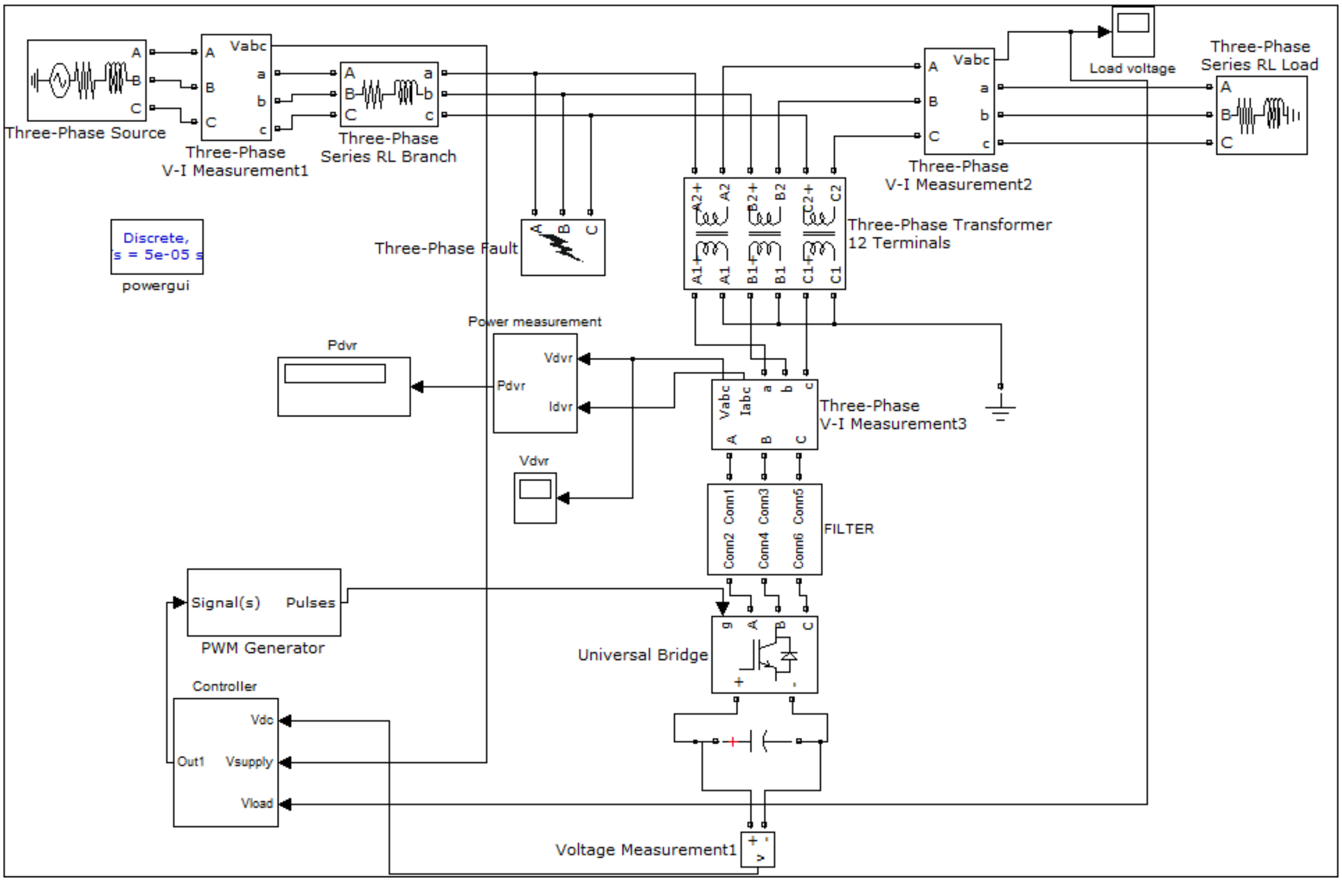

Fig. 7. Simulink Model of DVR Connected System

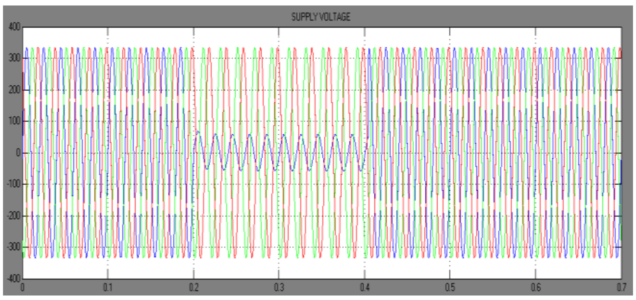

Fig. 8 (a). Simulation of Single Phase Voltage Sag

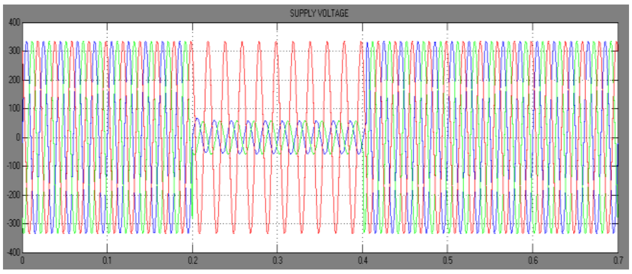

Fig. 8 (b). Simulation of Two Phase Voltage Sag

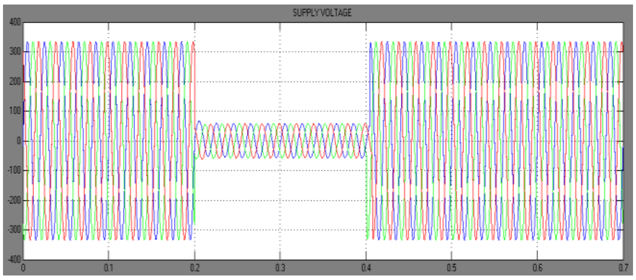

Fig. 8 (c). Simulation of Three Phase Voltage Sag

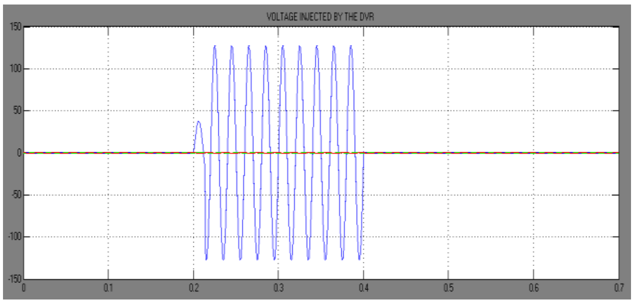

Fig. 9 (a). DVR Output for Compensating Single Phase Sag

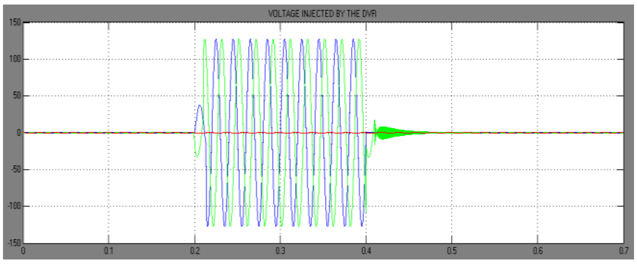

Fig. 9 (b). DVR Output for Compensating Two Phase Sag

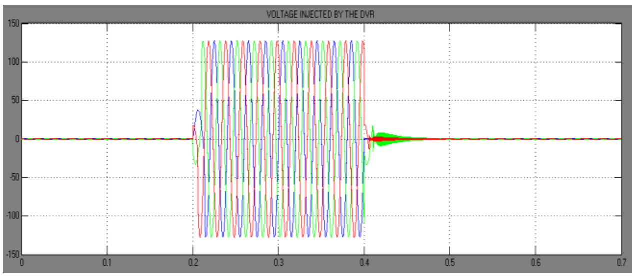

Fig. 9 (c). DVR Output for Compensating Three Phase Sag

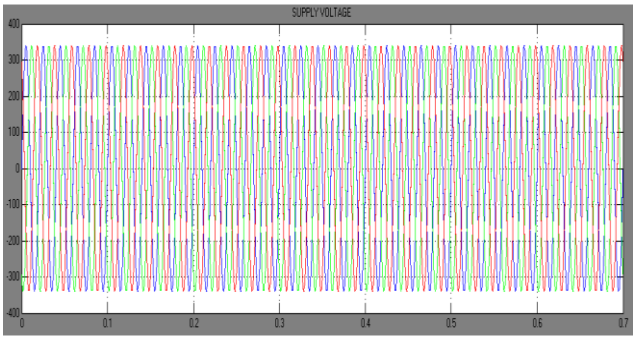

Fig. 10. Simulation of Compensated Load Voltage

TABLE. I. Comparison of Power Output of DVR

S.No.	**Angle of Injection (degrees)**	**Power Injected by DVR with PI Controller (VAR)**			**Power Injected by DVR with SRF-PI Controller (VAR)**		
		Unbalanced Sag		Balanced Sag	Unbalanced Sag		Balanced Sag
		Single Phase	Two Phase		Single Phase	Two Phase	
1.	**0**	**1038**	**1083**	**1133**	**790.2**	**831.6**	**870.3**
2.	30	1077	1127	1178	902.1	955.5	1001
3.	45	1126	1181	1234	1046	1093	1145
4.	60	1321	1376	1415	1218	1265	1325

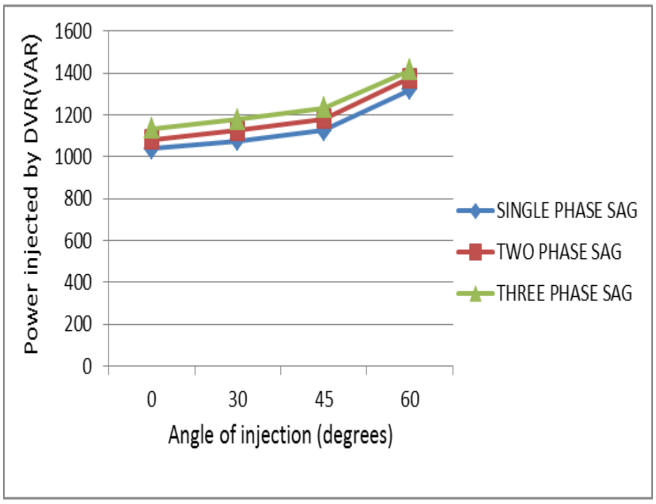

Fig. 11 (a). Comparison of voltage injection schemes for PI controller

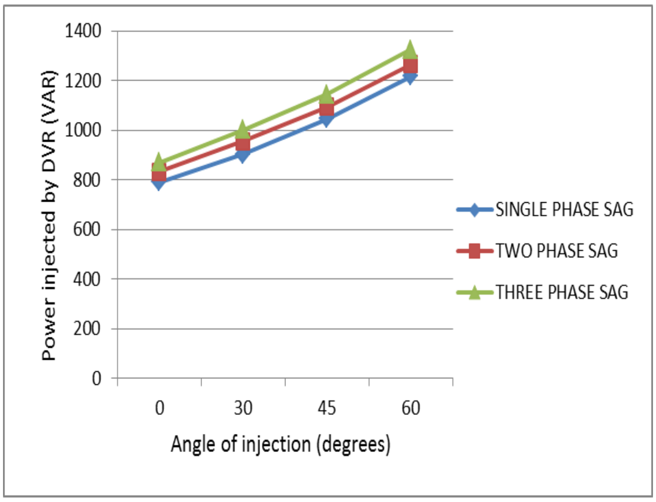

Fig.11 (b). Comparison of voltage injection schemes for SRF theory based PI controller

VII. CONCLUTION

The operation of DVR has been demonstrated with conventional PI controller and SRF theory based PI controller using various voltage injection schemes for both balanced and unbalanced voltage sag compensation in MATLAB/Simulink. From the simulation analysis, the DVR based on Synchronous Reference Frame theory is able to detect different types of power quality problems without an error and injects the appropriate voltage component to correct immediately any abnormality in the terminal voltage to keep it balanced and constant at the nominal value. Simulation and experimental results shows that the DVR with the proposed compensation strategy successfully protects the sensitive load against symmetrical and unsymmetrical voltage sag. A comparison of the performance of the DVR with different voltage injection schemes has been performed. Based on the performance analysis it is concluded that the voltage injection in-phase with the sag voltage reduces the power injected by DVR. This results in minimum rating of DVR which makes the DVR more economical with optimum size. This work can also be extended to other power quality problems.

APPENDIX

AC Line Voltage	: 415V, 50Hz
Line Impedance	: Ls = 3.0mH, Rs = 0.01Ω
Linear Loads	: 10-kVA, 0.80-pf lag
Ripple Filter	: Cf = 10μF, Rf = 4.8Ω
DC Voltage of DVR	: 300V
DC Bus Voltage PI Controller	: Kp1 = 0.5, Ki1 = 0.35
AC Load Voltage PI Controller	: Kp2 = 0.5, Ki2 = 0.35
PWM Switching Frequency	: 10kHz
Series Transformer	: 10kVA, 200V/300V

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