International Journal of Engineering Research and Development
e-ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 11, Issue 09 (September 2015), PP.41-52

Mitigation of Voltage Sag/Swell with Fuzzy Control Reduced Rating DVR

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Abstract: - Power quality has been an issue that is becoming increasingly pivotal in industrial electricity consumers point of view in recent times. Modern industries employ Sensitive power electronic equipments, control devices and non-linear loads as part of automated processes to increase energy efficiency and productivity. Voltage disturbances are the most common power quality problem due to this the use of a large numbers of sophisticated and sensitive electronic equipment in industrial systems is increased. This paper discusses the design and simulation of dynamic voltage restorer for improvement of power quality and reduce the harmonics distortion of sensitive loads. Power quality problem is occurring at non-standard voltage, current and frequency. Electronic devices are very sensitive loads. In power system voltage sag, swell, flicker and harmonics are some of the problem to the sensitive load. The compensation capability of a DVR depends primarily on the maximum voltage injection ability and the amount of stored energy available within the restorer. This device is connected in series with the distribution feeder at medium voltage. A fuzzy logic control is used to produce the gate pulses for control circuit of DVR and the circuit is simulated by using MATLAB/SIMULINK software.

Index Terms: - *Dynamic voltage restorer (DVR), power quality, unit vector, voltage harmonics, voltage sag, voltage swell, Hysteresis Voltage Controller.*

I. INTRODUCTION

Power quality and reliability in distribution systems have been tracking 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. These disturbances are responsible for problems ranging from malfunctions or errors to plant shut down and loss of manufacturing capability. Voltage sags/swells can occur more frequently than any other power quality phenomenon. These sags/swells are the most important power quality problems in the power distribution system [1].

The main problem of this simple controller is the correct choice of the PI gains and the fact that by using fixed gains, the controller may not provide the required control performance, when there are variations in the system parameters and operating conditions. Various control strategies have been developed to mitigate the voltage sag and swell have been proposed for three phase voltage source PWM converters. They can be divided into two main groups: linear and nonlinear, linear controllers include the ramp-comparison current regulator, Synchronous PI regulator, state feedback regulator and predictive and dead-beat regulator. The neural network and Fuzzy Logic (FL) based regulators belong to the non-linear controllers. It appears that the non-linear controller is more suitable than the linear type since the DVR is truly a nonlinear system. The DVR is a non-linear device due to the presence of power semiconductor switches in the inverter bridge.

This paper introduces Dynamic Voltage Restorer (DVR) and its operating principle, also presents the proposed controllers of PI and fuzzy controllers. Then, simulation results using MATLAB/SIMULINK provide a comparison between the proposed and the conventional PI controllers in terms of performance in voltage sag/swell compensation at the end, discussions of the results and conclusion are given.

II. DYNAMIC VOLTAGE RESTORER (DVR)

DVR is a Custom Power Device used to eliminate supply side voltage disturbances. DVR also known as Static Series Compensator maintains the load voltage at a desired magnitude and phase by compensating the voltage sags/swells and voltage unbalances presented at the point of common coupling.
The power circuit of the DVR is shown in Fig. 1.The DVR consists of 6 major parts:-

a) Voltage Source Inverter (VSI): These inverters have low voltage ratings and high current ratings as step up transformers are used to boost up the injected voltage.
b) Injection Transformers: Three single phase injection transformers are connected in delta/open winding to the distribution line.

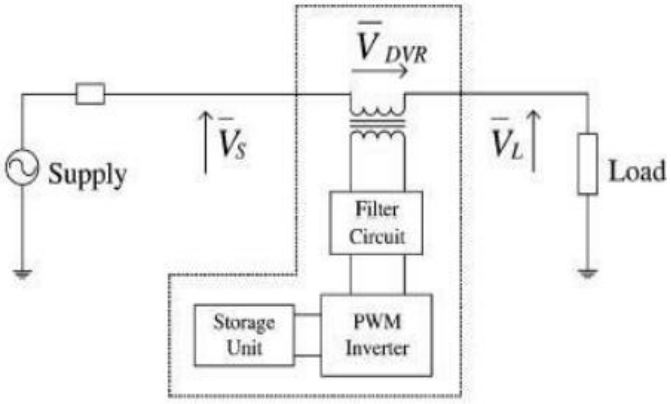


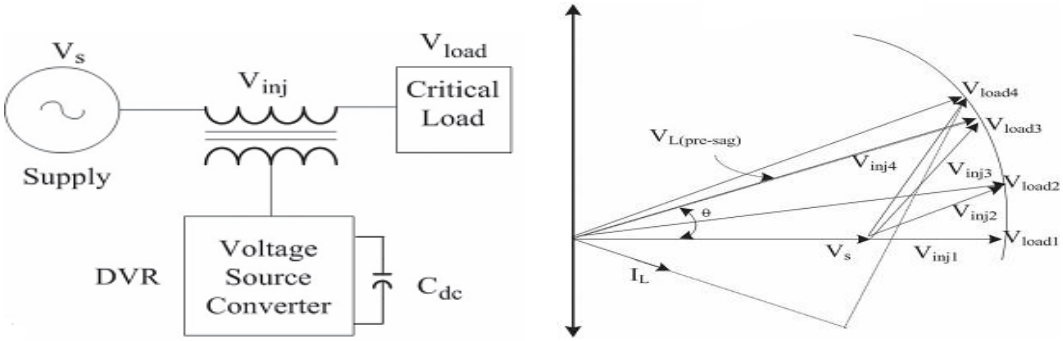
Fig.1: DVR series connected topology

These transformers can be also connected in star/open winding. The star/open winding allows injection of positive, negative and zero sequence voltages whereas delta/open winding only allows positive and negative sequence voltage injection.
c) Passive Filters: Passive filters are placed at the high voltage side of the DVR to filter the harmonics. These filters are placed at the high voltage side as placing the filters at the inverter side introduces phase angle shift which can disrupt the control algorithm.
d) Energy storage: Batteries, flywheels or SMEs can be used to provide real power for compensation. Compensation using real power is essential when large voltage sag occurs.
e) Capacitor: DVR has a large DC capacitor to ensure stiff DC voltage input to inverter.
f) By-Pass Switch: If the over current on the load side exceeds a permissible limit due to short circuit on the load or large inrush current, the DVR will be isolated from the system by using the bypass switches and supplying another path for current.

III. OPERATION OF DVR

The schematic of a DVR-connected system is shown in Fig. 2(a). The voltage V_{inj} is inserted such that the load voltage V_{load} is constant in magnitude and is undistorted, although the supply voltage Vs is not constant in magnitude or is distorted. Fig. 2(b) shows the phasor diagram of different voltage injection schemes of the DVR. $V_{L\ (pre-sag)}$ is a voltage across the critical load prior to the voltage sag condition. During the voltage sag, the voltage is reduced toV_{swith} a phase lag angle of θ. Now, the DVR injects a voltage such that the load voltage magnitude is maintained at the pre-sag condition. According to the phase angle of the load voltage, the injection of voltages can be realized in four ways [7]. V_{inj1} represents the voltage injected in-phase with the supply voltage. With the injection ofV_{inj2}, the load voltage magnitude remains same but it leads Vs by a small angle. In V_{inj3}, the load voltage retains the same phase as that of the pre-sag condition, which may be an optimum angle considering the energy source. V_{inj4} is the condition where the injected voltage is in quadrature with the current, and this case, is suitable for a capacitor-supported DVR as this injection involves no active power [8]. However, a minimum possible rating of the converter is achieved byV_{inj1}.

The DVR is operated in this scheme with a battery energy storage system (BESS) [4]. Fig. 3 shows a schematic of a three-phase DVR connected to restore the voltage of a three-phase critical load. A three-phase supply is connected to a critical and sensitive load through a three-phase series injection transformer [5]. The equivalent voltage of the supply of phase A v_{Ma} is connected to the point of common coupling (PCC) v_{Sa} through short-circuits impedance Zsa. The voltage injected by the DVR in phase A v_{Ca} is such that the load voltage v_{La} is of rated magnitude and undistorted. A three-phase DVR is connected to the line to inject a voltage in series using three single-phase transformers Tr, Lr and Cr represent the filter components used to filter the ripples in the injected voltage. A three-leg VSC with insulated-gate bipolar transistors (IGBTs) is used as a DVR, and a BESS is connected to its dc bus.



(a) **(b)**

Fig.2. (a) Basic circuit of DVR. (b) Phasor diagram of the DVR voltage injection schemes.

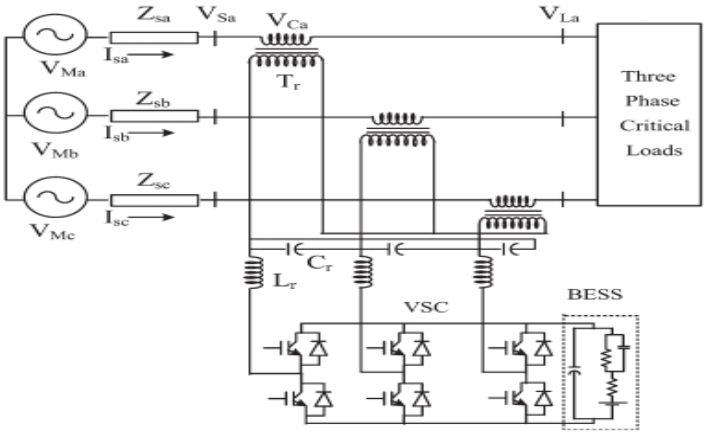


Fig.3. Schematic of the DVR-connected system

IV. CONTROL OF DVR

The compensation for voltage sags using a DVR can be performed by injecting or absorbing the reactive power or the real power [8]. When the injected voltage is in quadrature with the current at the fundamental frequency, the compensation is made by injecting reactive power and the DVR is with a self-supported dc bus. However, if the injected voltage is in phase with the current, DVR injects real power, and hence, a battery is required at the dc bus of the VSC. The control technique adopted should consider the limitations such as the voltage injection capability (converter and transformer rating) and optimization of the size of energy storage.

A. Control of DVR with BESS for Voltage Sag, Swell, and Harmonics Compensation

Fig. 4 shows a control block of the DVR in which the SRF theory is used for reference signal estimation. The voltages at the PCC v_S and at the load terminal v_L are sensed for deriving the IGBTs' gate signals. The reference load voltage V_L^* is extracted using the derived unit vector [9]. Load voltages (V_{La},V_{Lb},V_{Lc}) are converted to the rotating reference frame using abc−dqo conversion using Park's transformation with unit vectors(sin,θ,cos,θ) derived using a phase-locked loop as

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

Similarly, reference load voltages $(V_{La}^*, V_{Lb}^*, V_{Lc}^*)$ and voltages at the PCC v_S are also converted to the rotating reference frame. Then, the DVR voltages are obtained in the rotating reference frame as

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

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

The reference DVR voltages are obtained in the rotating reference frame as

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

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

The error between the reference and actual DVR voltages in the rotating reference frame is regulated using two proportional–integral (PI) controllers. Reference DVR voltages in the abc frame are obtained from a reverse Park's transformation taking V^*_{Dd} from (4),V^*_{Dq} from(5),V^*_{D0} as zero as

$$\begin{bmatrix} v^*_{\mathrm{dvr}a} \\ v^*_{\mathrm{dvr}b} \\ v^*_{\mathrm{dvr}c} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} v^*_{Dq} \\ v^*_{Dd} \\ v^*_{D0} \end{bmatrix} \tag{6}$$

Reference DVR voltages $\left(v^*_{\mathrm{dvr}a}, v^*_{\mathrm{dvr}b}, v^*_{\mathrm{dvr}c}\right)$ and actual DVR voltages $\left(v_{\mathrm{dvr}a}, v_{\mathrm{dvr}b}, v_{\mathrm{dvr}c}\right)$ are used in a pulse width modulated (PWM) controller to generate gating pulses to a VSC of the DVR. The PWM controller is operated with a switching frequency of 10 kHz.

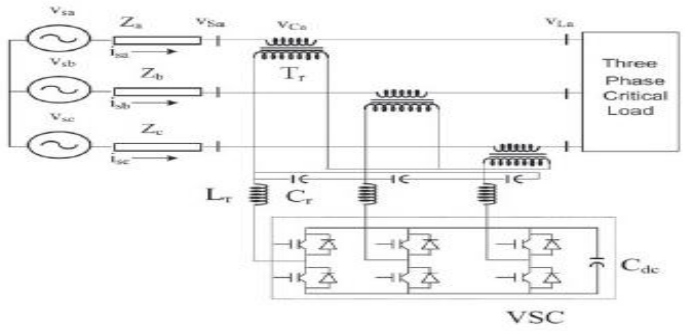


Fig. 4(a).capacitor-supported DVR connected to three-phase critical loads

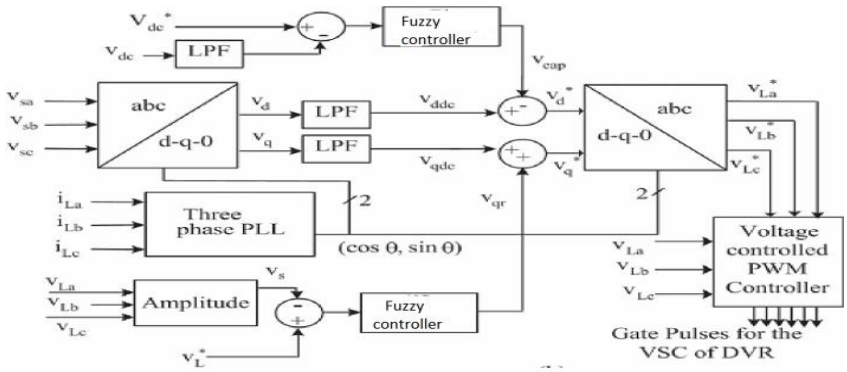


Fig. 4(b).Control block of the DVR that uses the SRF method of control

B. Control of Self-Supported DVR for Voltage Sag, Swell, and Harmonics Compensation

Fig4 (a).shows a schematic of a capacitor-supported DVR connected to three-phase critical loads, and Fig 4(b) shows a control block of the DVR in which the SRF theory is use for the control of self-supported DVR. Voltages at the PCC v_s are converted to the rotating reference frame using abc−dqo conversion using Park's transformation [6]. The harmonics and the oscillatory components of the voltage are eliminated using low pass filters (LPFs). The components of voltages in the d- and q-axes are

$$v_d = v_{\mathrm{ddc}} + v_{\mathrm{dac}} \tag{7}$$

$$v_q = v_{\mathrm{qdc}} + v_{\mathrm{qac}}. \tag{8}$$

The compensating strategy for compensation of voltage quality problems considers that the load terminal voltage should be of rated magnitude and undistorted. In order to maintain the dc bus voltage of the self-supported capacitor, a PI controller is used at the dc bus voltage of the DVR and the output is considered as a voltage v_{cap} for meeting its losses

The referenced-axis load voltage is therefore expressed as follows:

$$v^*_d = v_{\mathrm{ddc}} - v_{\mathrm{cap}}. \tag{9}$$

The amplitude of load terminal voltage V_L is controlled to its reference voltage V^*_L using another PI controller. The output of the PI controller is considered as the reactive component of voltage v_{qr} for voltage regulation of

the load terminal voltage. The amplitude of load voltage V_L at the PCC is calculated from the ac voltages (v_{La},v_{Lb},v_{Lc}) as

$$V_L = (2/3)^{1/2} \left(v_{La}^2 + v_{Lb}^2 + v_{Lc}^2\right)^{1/2}. \tag{10}$$

The reference load quadrature axis voltage is expressed as follows:

$$v_q^* = v_{q\mathrm{dc}} + v_{qr} \tag{11}$$

Reference load voltages (V_{La}^*,V_{Lb}^*, V_{Lc}^*) in the abc frame are obtained from a reverse Park's transformation as in (6).

The error between sensed load voltages (v_{La}, v_{Lb},v_{Lc}) and reference load voltages is used over a controller to generate gating pulses to the VSC of the DVR.

C. About Hysteresis Current Controller

Hysteresis band PWM control is basically an instantaneous feedback current control method of PWM, where the actual current continuously tracks the command current within a hysteresis band. A reference sine wave, current wave is compared with the actual phase current wave. When the current exceeds a prescribed hysteresis band, the upper switch in the inverter bridge is turned off and the lower switch is turned on, and the current starts to decay. As the current crosses the lower band limit, the lower switch is turned off and the upper switch is turned on. The actual current is forced to track the sine reference within the hysteresis band by back and forth (or bang-bang) switching of the upper and lower switches. The inverter then essentially becomes a current source with peak-to-peak current ripple, which is controlled within the hysteresis band, which makes the source current to be sinusoidal.

The switching logic is realized by three hysteresis controllers, one for each phase (Fig.5). The hysteresis PWM current control, also known as "bang-bang "control, is done in the three phases separately. Each controller determines the switching -state of one inverter half-bridge in such a way that the corresponding current is maintained within a hysteresis band.

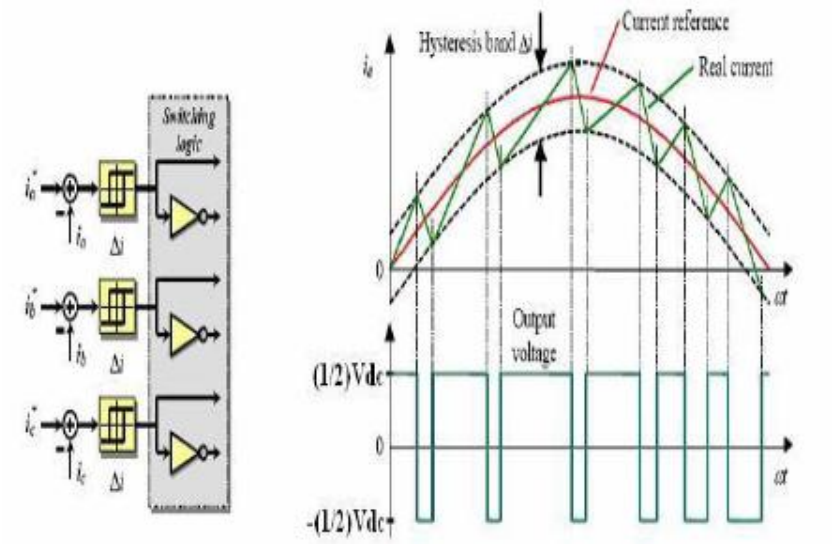


Fig.5 Hysteresis PWM Current Control and Switching Logic

To increase a phase current, the affiliated phase to neutral voltage is equal to the half dc bus voltage until the upper band-range is reached. More complicated hysteresis PWM current control techniques also exist in practice, e.g. adaptive hysteresis current vector control is based on controlling the current phasor in a α/β - reference frame. These modified techniques take care especially for the interaction of the three phases. Obviously, the dynamic performance of such an approach is excellent since the maximum voltage is applied until the current error is within predetermined boundaries (bang-bang control). Hysteresis current control is used for operation at higher switching frequency, as this compensates for their inferior quality of modulation. The switching losses restrict its application to lower power levels. Due to the independence of system parameters, hysteresis current control is often preferred.

V. MATLAB/SIMULINK RESULTS

Here simulation is carried out by several cases, in that 1) Voltage Sag/Swell Compensation by using Conventional DVR, 2) Voltage Sag/Swell Compensation by using Proposed DVR using PI Controller, 3) Voltage Sag/Swell Compensation by using Proposed DVR using fuzzy logic control.

Case 1: Voltage Sag/Swell Compensation by using Conventional DVR

The DVR-connected system consisting of a three phase critical loads, and the series injection transformer is modeled in MATLAB/SIMULINK environment along with a simpower system toolbox. An equivalent load considered is a 10-KVA 0.8-pf lag linear load. The performance of the DVR is demonstrated for different supply voltage disturbance such as voltage sag and swell. At 0.2 s a sag in supply voltage is created and at 0.2 s a swell in supply voltage is created. The phase voltage is 440 volts and phase current is 16.4amp for this circuit.

Fig.6 shows the MATLAB/SIMULINK Modeling of Conventional DVR under Voltage Sag/Swell Issues using computer simulation tool. Waveforms are shown in Fig.7.

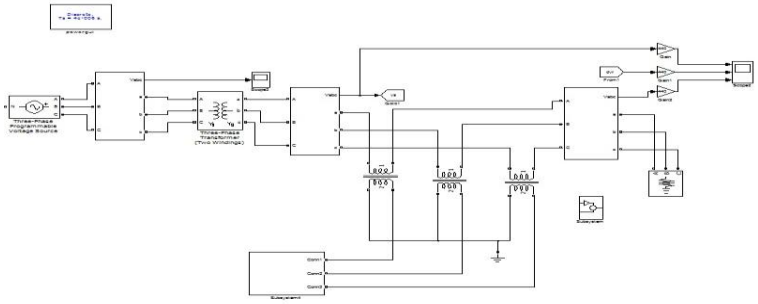


Fig.6 Matlab/Simulink Modelling of Conventional DVR under Voltage Sag/Swell Issues.

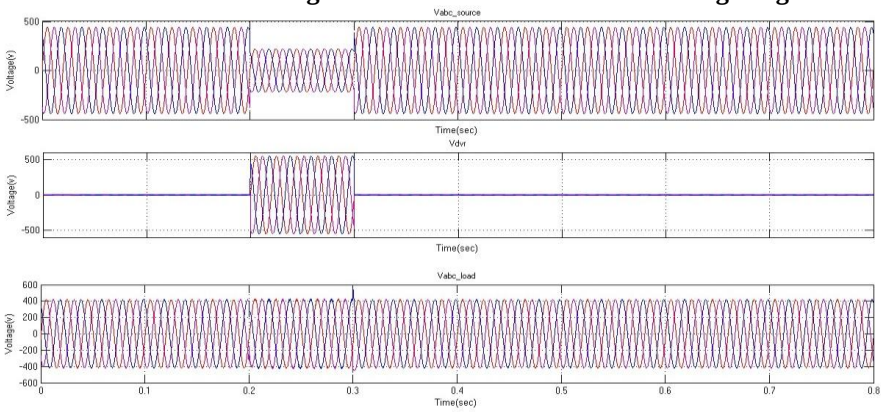


Fig.7.Source Voltage, DVR Injected Voltage, Load Voltage

In Fig.7 first waveform shows the Source Voltage, second waveform shows DVR Injected Voltage and third waveform shows Load Voltage of the conventional DVR under Voltage Sag Compensation Scheme.

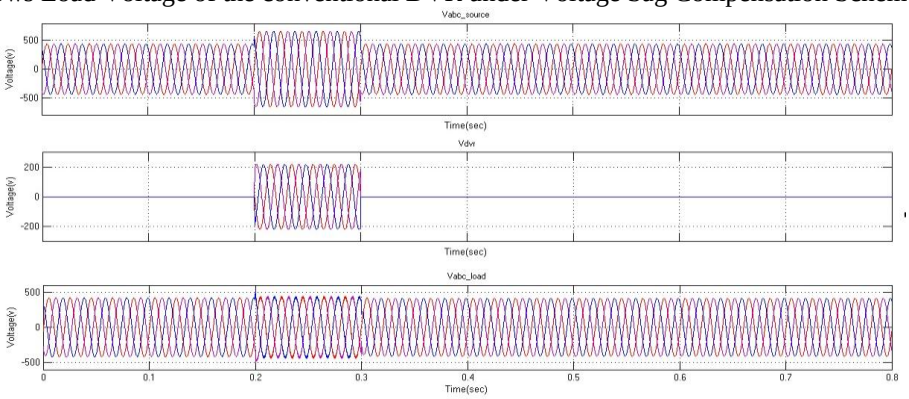


Fig.8.Source Voltage, DVR Injected Voltage, Load Voltage

In Fig.8 first waveform shows the Source Voltage, second waveform shows DVR Injected Voltage and third waveform shows Load Voltage of the conventional DVR under Voltage Sag Compensation Scheme.

Case 2: Voltage Sag/Swell Compensation by using Proposed DVR using PI Controller

The DVR-connected system consisting of a three phase critical loads, and the series injection transformer is modeled in MATLAB/SIMULINK environment along with a simpower system toolbox. An equivalent load considered is a 10-KVA 0.8-pf lag linear load. The performance of the DVR is demonstrated for different supply voltage disturbance such as voltage sag and swell. At 0.2 s a sag in supply voltage is created and at 0.2 s a swell in supply voltage is created.

The phase voltage is 338.84 v and phase current is 16.4amp for this circuit

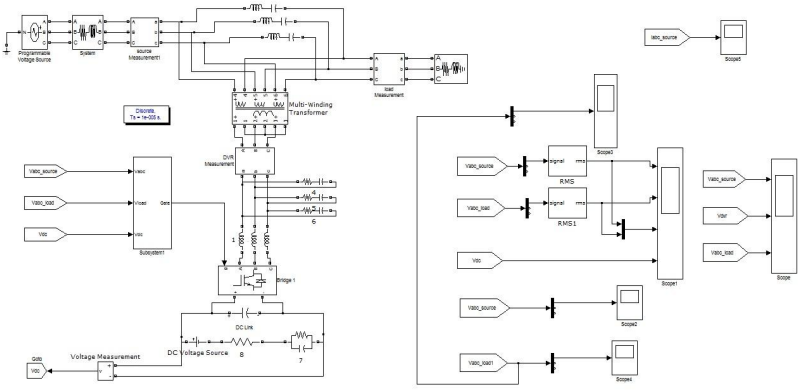
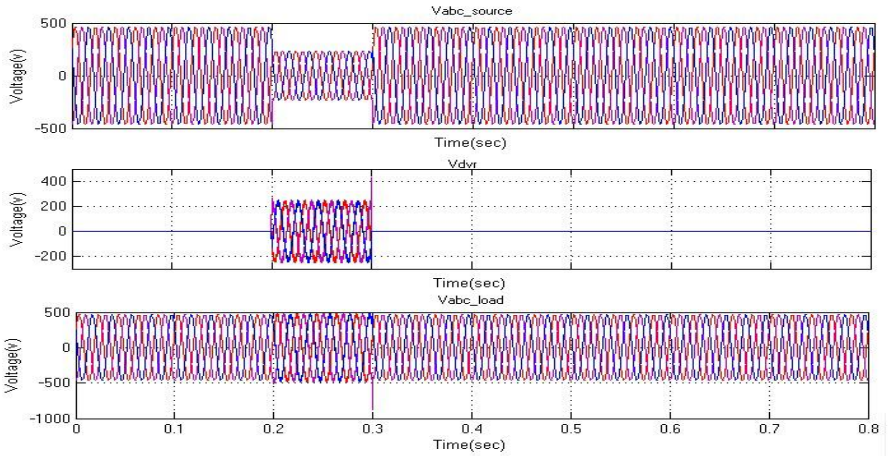
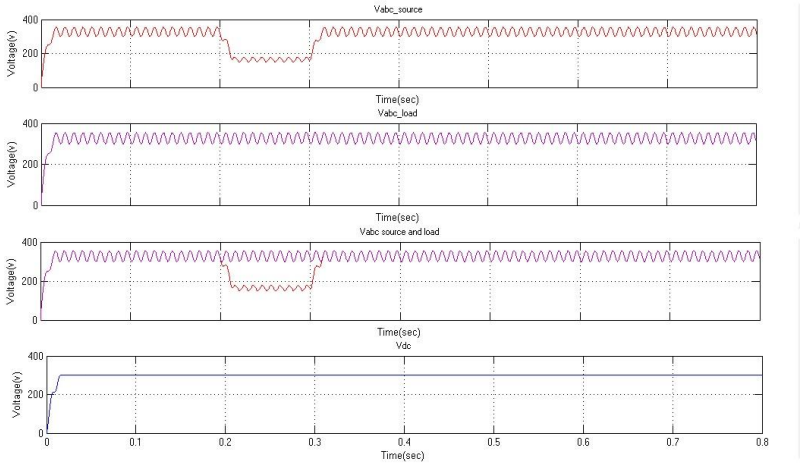


Fig.9 Matlab/Simulink Modelling of Proposed DVR under Voltage Sag/Swell Issues

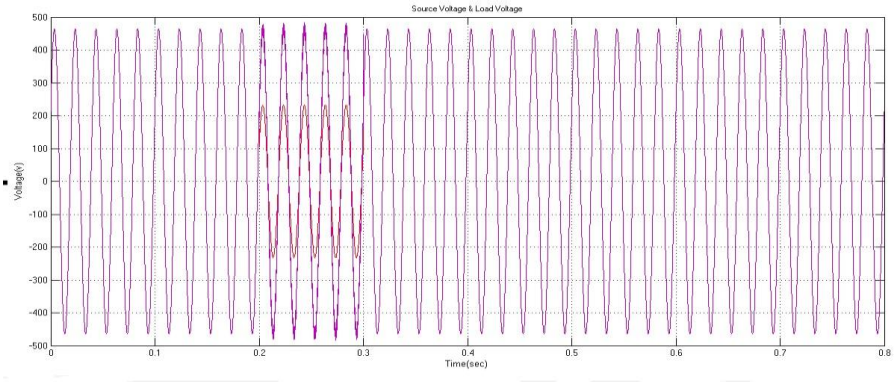
Fig.9 shows the MATLAB/SIMULINK Modeling of Proposed DVR under Voltage Sag/Swell Issues using computer simulation tool. Waveforms are shown below.



(a) Source Voltage, DVR Injected Voltage, Load Voltage.



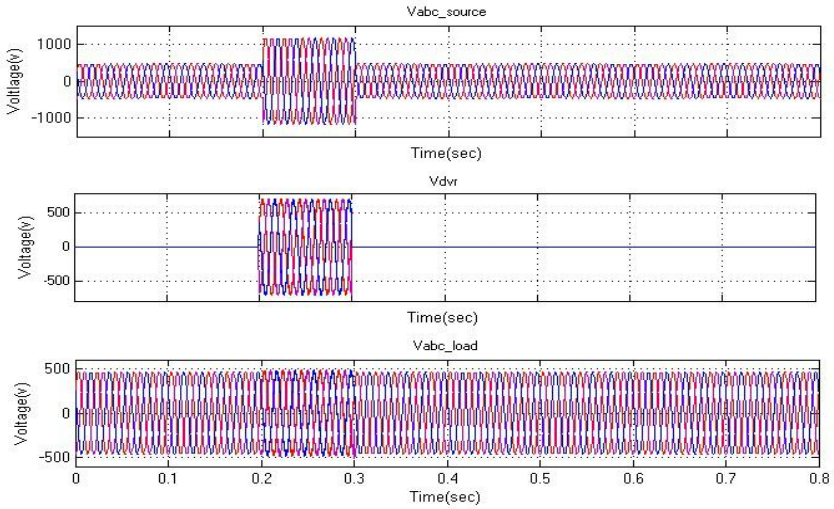
(b) RMS value of source voltage, load voltage, Its comparison, DC Link Voltage



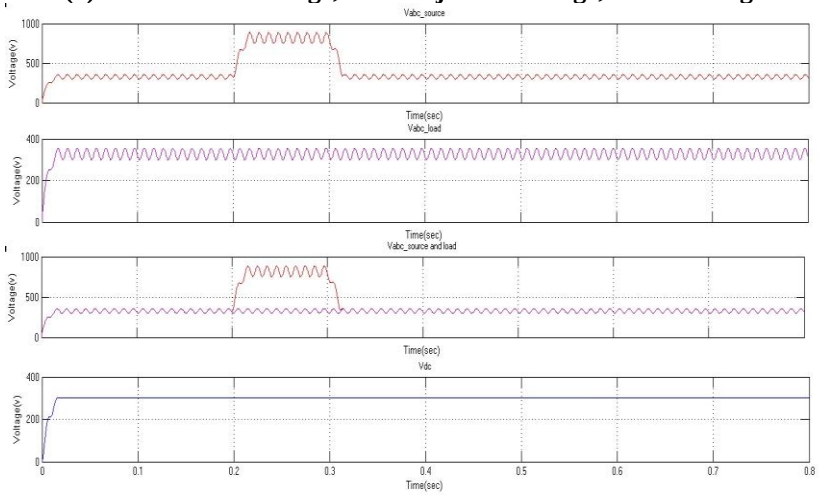
(c) Source Voltage & Load Voltage

Fig 10(a) source voltage, injected voltage, load voltage, (b) RMS value of source voltage, load voltage, its comparison, DC link voltage, (c) source voltage & load voltage

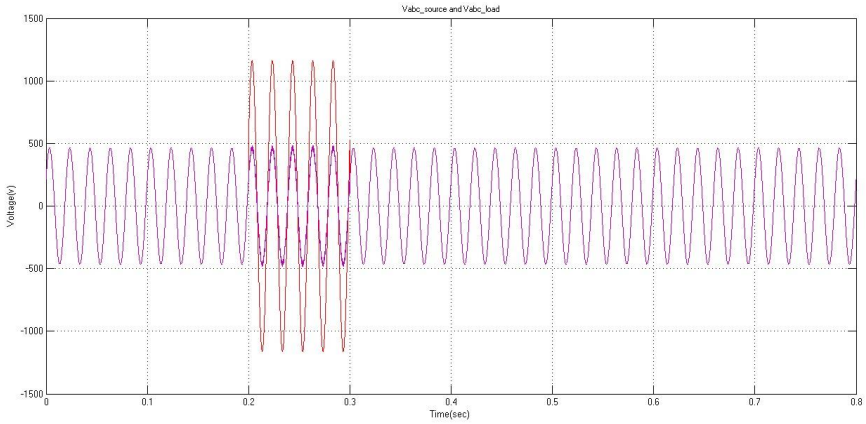
In Fig.10 (a) first waveform shows Source Voltage, second waveform shows DVR Injected Voltage and third waveform shows Load Voltage. In fig.10 (b) first waveform shows the RMS voltage value of source voltage, second waveform shows the value load voltage, third waveform its comparison, fourth waveform is DC Link Voltage. In fig 10(c) shows Source Voltage & Load Voltage of the Proposed DVR under Voltage Sag Compensation Scheme.



(a) Source Voltage, DVR Injected Voltage, Load Voltage.



(b) RMS value of source voltage, load voltage, Its comparison, DC Link Voltage

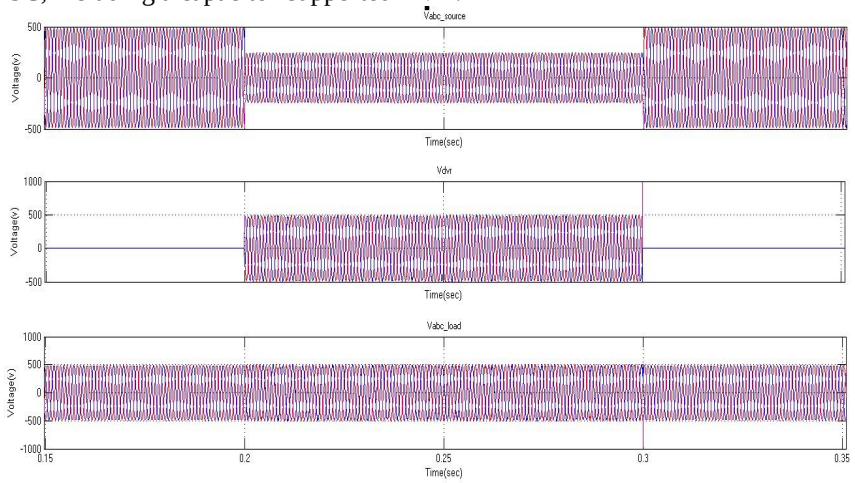


(c) Source Voltage & Load Voltage

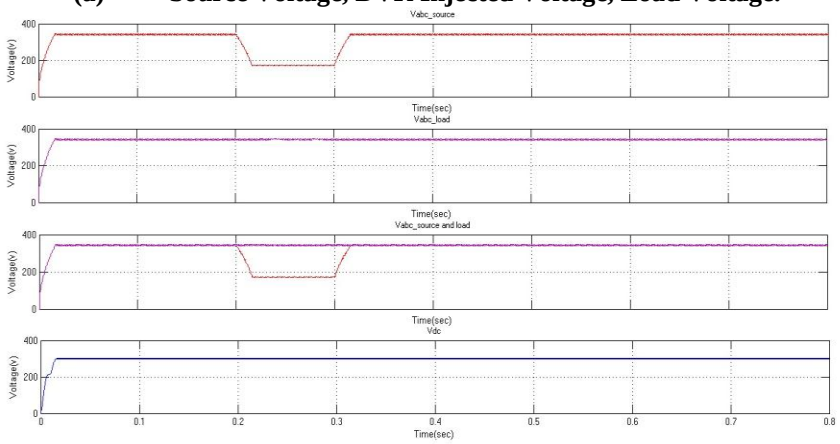
Fig 11(a) source voltage, injected voltage, load voltage,
(b) RMS value of source voltage, load voltage, its comparison, DC link voltage,
(c) Source voltage & load voltage

In Fig.11 (a).first waveform shows Source Voltage, second waveform shows DVR Injected Voltage, third waveform shows Load Voltage, In fig.11 (b) first waveform shows RMS voltage value of source voltage, second waveform shows load voltage, third waveform shows its comparison, fourth waveform shows DC Link Voltage and In fig.11(c) shows Source Voltage & Load Voltage of the Proposed DVR under Voltage Swell Compensation Scheme.

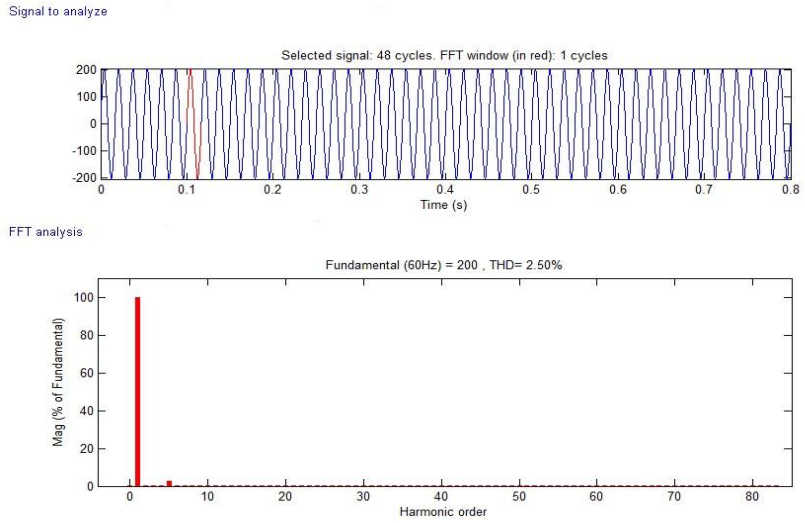
A comparison of the performance of the DVR with different schemes has been performed with a reduced-rating VSC, including a capacitor-supported DVR.



(a) Source Voltage, DVR Injected Voltage, Load Voltage.



(b) RMS value of source voltage, load voltage, its comparison, DC Link Voltage.



(c) THD Analysis of Supply voltage.

Fig 12(a) source voltage, injected voltage, load voltage, (b) RMS value of source voltage, load voltage, its comparison, DC link voltage, (c) THD analysis of supply voltage

In Fig.12 (a) first waveform shows Source Voltage, second waveform shows DVR Injected Voltage, third waveform shows Load Voltage. In fig.12 (b) first waveform shows RMS voltage value of source voltage, second waveform shows load voltage, third waveform shows its comparison, fourth waveform shows DC Link Voltage. In fig12(c) THD Analysis of Source Voltage of the Proposed DVR under Harmonics Compensation Scheme. These harmonics are in the range of IEEE-519 standards.

Case 3: Voltage Sag/Swell Compensation by using Proposed DVR using fuzzy logic control.

The DVR-connected system consisting of a three phase critical loads, and the series injection transformer is modeled in MATLAB/SIMULINK environment along with a simpower system toolbox. An equivalent load considered is a 10-KVA 0.8-pf lag linear load. The performance of the DVR is demonstrated for different supply voltages. At 0.2 s a harmonics in supply voltage is created.

Fig.13 shows the MATLAB/SIMULINK Modeling of Proposed DVR under Voltage Sag/Swell Issues by using fuzzy logic control with the help of computer simulation tool. Waveforms are shown below.

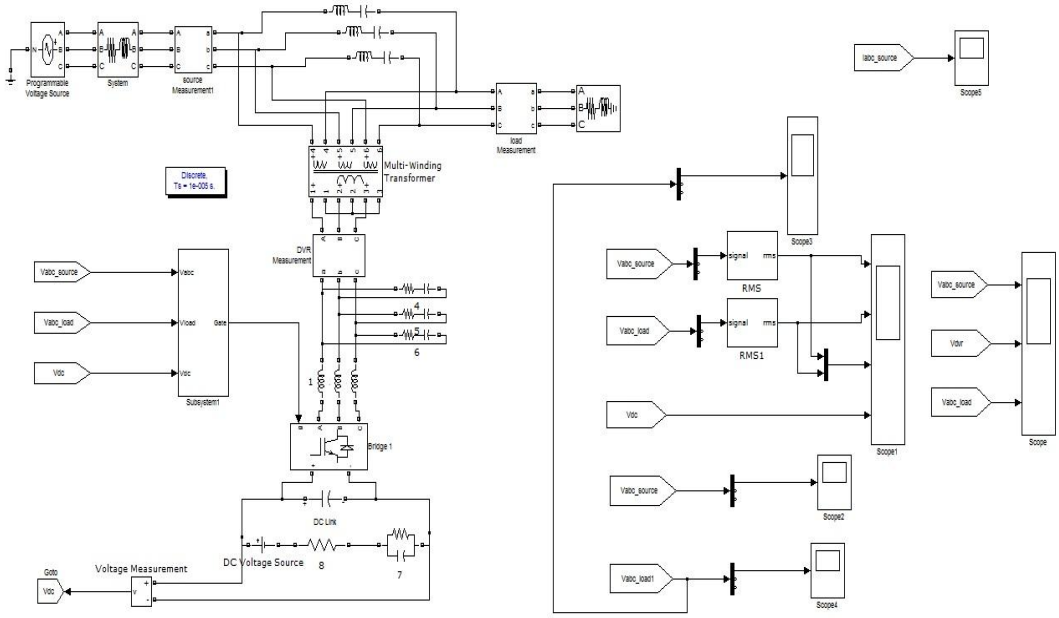
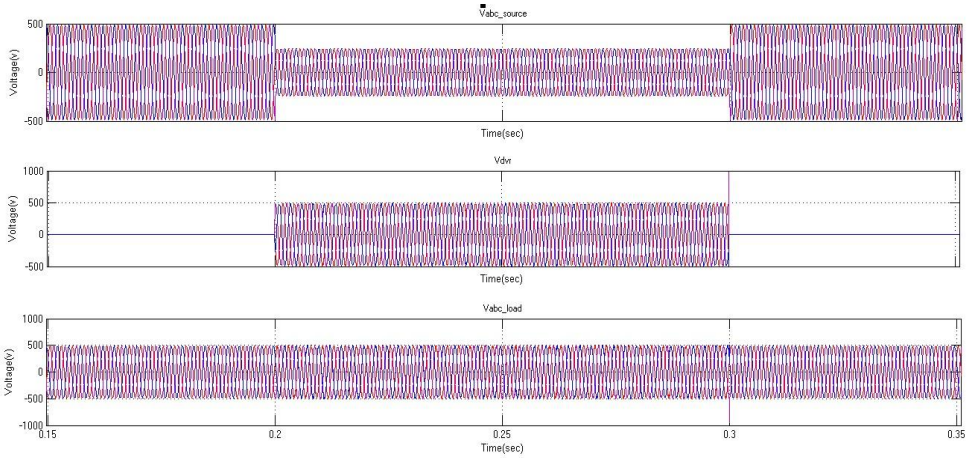
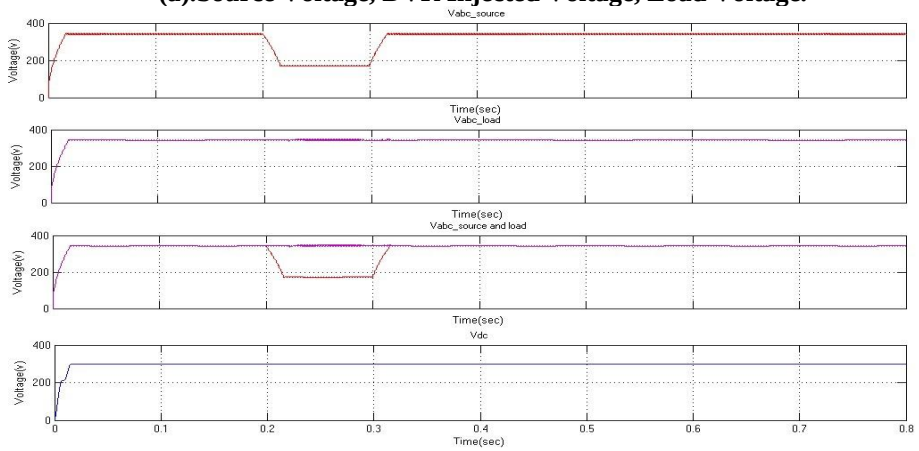


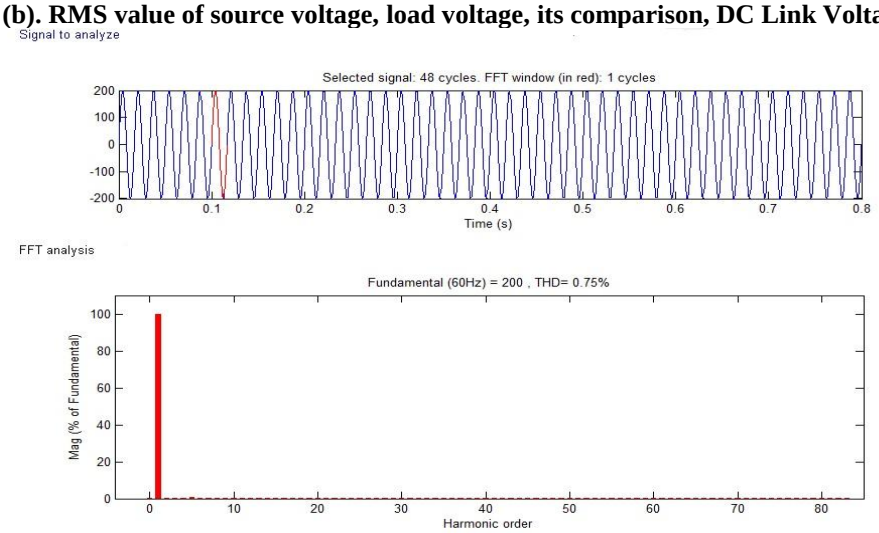
Fig.13 Matlab/Simulink Modeling of Proposed DVR under Voltage Sag/Swell Issues using fuzzy logic control.



(a).Source Voltage, DVR Injected Voltage, Load Voltage.



(b). RMS value of source voltage, load voltage, its comparison, DC Link Voltage.



(c). THD Analysis of Supply voltage

Fig 14(a) source voltage, injected voltage, load voltage, (b) RMS value of source voltage, load voltage, its comparison, DC link voltage, (c) THD analysis of supply voltage

In Fig.14 (a) first waveform shows Source Voltage, second waveform shows DVR Injected Voltage, third waveform shows Load Voltage, Source. In fig. (b) first waveform shows RMS voltage value of source voltage, second waveform shows load voltage, third waveform shows its comparison, DC Link Voltage. In fig.14(c) THD Analysis of Source Voltage of the Proposed DVR under Harmonics Compensation Scheme with fuzzy logic controller. These harmonics are in the range of IEEE-519 standards.

VI. CONCLUSION

The operation of a DVR has been demonstrated with a new control technique using various voltage injection schemes. A comparison of the performance of the DVR with different schemes has been performed with a reduced-rating VSC, including a capacitor-supported DVR. The reference load voltage has been estimated using the method of unit vectors, and the control of DVR has been achieved, which minimizes the error of voltage injection. The SRF theory has been used for estimating the reference DVR voltages. It is concluded that the voltage injection in-phase with the PCC voltage results in minimum rating of DVR but at the cost of an energy source at its dc bus. The analysis of mitigating harmonics, DVR under fuzzy controller is carried out using MATLAB Power System Block set. The results of simulation are presented and discussed. The total harmonic distortion (THD) of voltage at the PCC, supply current, and load voltage. It is observed that the load voltage THD is reduced to the level of 0.75% from the PCC voltage of 2.50%. The THD and the amount of unbalance in load voltage are decreased with the application of DVR. The proposed system performs better than the traditional methods in mitigating harmonics and voltage sags.

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