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ADVANCED INTELLIGENT CONTROL FOR POWER QUALITY WITH REDUCED RATING DVR

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ABSTRACT

Now-a-days most of the people are using the sophisticated electrical equipment based on Power semiconductor device, this equipment pollutes the power quality. The sag and swell problem not only occur by the disturbed power quality but also due to high system tapping at the point of common coupling in the system. The non linear load is also creating the same problem at the load end. The Dynamic Voltage Restorer is recognized as the best solution for mitigation of voltage sag and swell associated problems in the highly taped distribution system. This device is connected in series with the distribution feeder at medium voltage. The size of DVR is small, cost is low and fast dynamic response to the disturbance. By injecting an appropriate voltage, the DVR restores a voltage waveform and ensures constant load voltage. The compensation of the voltage sag, swell, and harmonics is demonstrated using a reduced-rating DVR. A fuzzy logic control is proposed. Simulation result carried out by Matlab/Simulink verifies the performance of the proposed method.

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

I. INTRODUCTION

Power quality problems such as transients, sags, swells, affect the performance of these equipment pieces. Technologies such as custom power devices are emerged to provide protection against power quality problems. Custom power devices are mainly of three categories such as series-connected compensators known as dynamic volt-age restorers (DVRs), shunt connected compensators such as distribution static compensators, and a combination of series-and shunt-connected compensators known as unified power quality conditioner. The DVR can regulate the load [1, 2]. Two of the main problems in the field of power quality are voltage sag and instantaneous power loss. In addition, voltage sag has two main parameters including magnitude and time duration [3]. Typically, DVR voltage injection method is used to compensate the difference between voltage when sag occurs and before sag occurs, using AC voltage in series [4, 5].

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 [7, 8]. They can be divided into

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two main groups linear and nonlinear, linear controllers include the ramp-comparison controller, Synchronous PI regulator, state feedback regulator and predictive and dead-beat regulator. The PI 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 [9, 10].

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.

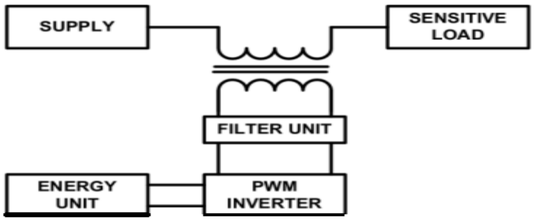

Fig.1.DVR series connected topology.

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. 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.

d) Energy storage: Batteries, flywheels or SMEs can be used to provide real power for 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.

International Journal of Electrical and Electronics Engineers
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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 V_s 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_s with 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 .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 V_s by a small angle. InV_{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 [10] .Vinj4 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. 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).

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. The equivalent voltage of the supply of phase A V_{ma}connected to the point of common coupling (PCC) V_{Sa} through short-circuit impedance Z_{sa}. 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 T_r, L_r and C_r 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.

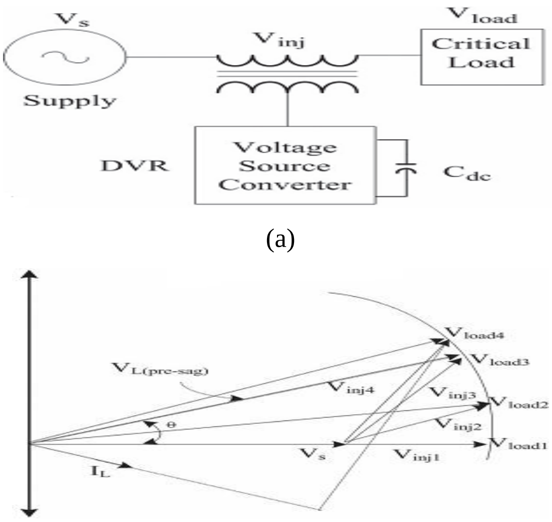

Fig.2. (a) Basic circuit of DVR. (b) Phasor diagram of the DVR voltage injection schemes.

International Journal of Electrical and Electronics Engineers
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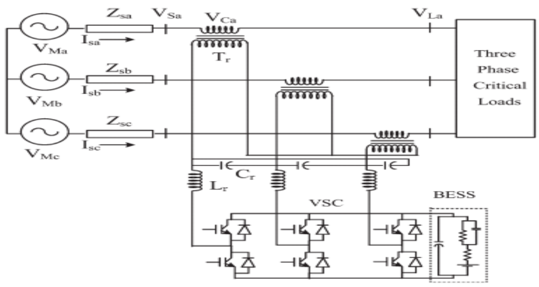

Fig.3. Schematic of the DVR-connected system

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. 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.

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. 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

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

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

$$v_{Dd} = v_{Sd} - v_{Ld} \tag{2}$$

$$v_{Dq} = v_{Sq} - v_{Lq}. \tag{3}$$

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

$$v^*_{Dd} = v^*_{Sd} - v_{Ld} \tag{4}$$

$$v^*_{Dq} = v^*_{Sq} - v_{Lq}. \tag{5}$$

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

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

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Reference DVR voltages $(v^*_{\text{dvra}}, v^*_{\text{dvrb}}, v^*_{\text{dvrc}})$ and actual DVR voltages $(v_{\text{dvra}}, v_{\text{dvrb}}, v_{\text{dvrc}})$ 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.

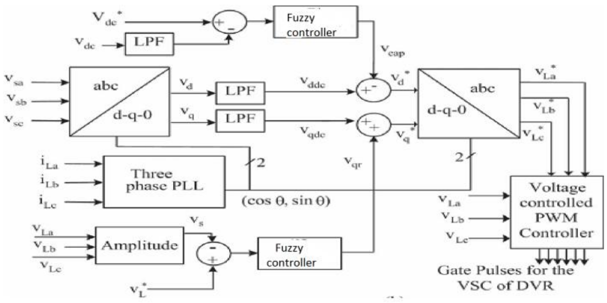

Fig. 4.Control block of the DVR that uses the SRF method of control.

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

Fig.5.shows a schematic of a capacitor-supported DVR connected to three-phase critical loads, and control block of the DVR in which the SRF theory is used for the control of self-supported DVR. Voltages at the PCC are converted to the rotating reference frame using abc−dqo conversion using Park's transformation. 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

$$v_d = v_{d\text{dc}} + v_{dac} \tag{7}$$

$$v_q = v_{q\text{dc}} + v_{qac}. \tag{8}$$

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:

$$v^*_d = v_{d\text{dc}} - v_{\text{cap}}. \tag{9}$$

The amplitude of load terminal voltage V_L is controlled to its reference voltage V^*_a 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

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

The reference load quadrature axis voltage is expressed as follows:

$$v^*_q = v_{q\text{dc}} + v_{qr} \tag{11}$$

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}) 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

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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.6). 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.

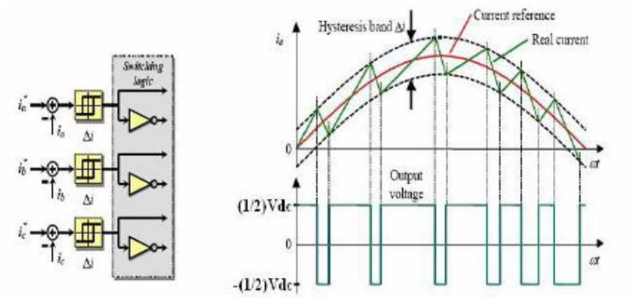

Fig.5.Hysteresis PWM Current Control and Switching Logic.

V. FUZZY LOGIC CONTROLLER

Fuzzy logic theory is considered as a mathematical approach combining multi-valued logic, probability theory, and artificial intelligence to replicate the human approach in reaching the solution of a specific problem by using approximate reasoning to relate different data sets and to make decisions. The performance of Fuzzy Logic Controllers is well documented in the field of control theory since it provides robustness to dynamic system parameter variations as well as improved transient and steady state performances. In this study, a fuzzy logic based feedback controller is employed for controlling the voltage injection of the proposed Dynamic Voltage Restorer (DVR). Fuzzy logic controller is preferred over the conventional PI and PID controller because of its robustness to system parameter variations during operation and its simplicity of implementation. Since the proposed DVR uses energy storage system consisting of capacitors charged directly from the supply lines through rectifier and the output of the inverter depends upon the energy stored in the dc link capacitors. The proposed FLC scheme exploits the simplicity of the Mamdani type fuzzy systems that are used in the design of the controller and adaptation mechanism

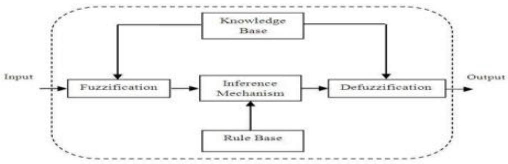

Fig.7.Basic Diagram of Fuzzy Logic Control.

International Journal of Electrical and Electronics Engineers
Vol. No.8 Issue 02, July-December 2016
ISSN (O) 2321-2055
ISSN (P) 2321 -2045

That can be identified by level of memberships in the fuzzy sets. The inference mechanism uses the collection of linguistic rules to convert the input conditions to fuzzified output. Finally, the defuzzification converts the fuzzified outputs to crisp control signals using the output membership function, which in the system acts as the changes in the control input (u).

The typical input membership functions for error and change in error are respectively, whereas the output membership function for change in control input. The output generated by fuzzy logic controller must be crisp which is used to control the PWM generation unit and thus accomplished by the defuzzification block. Many defuzzification strategies are available, such as, the weighted average criterion, the mean-max membership, and center-of-area (centroid) method. The defuzzification technique used here is the set of fuzzy control linguistic rules. The inference mechanism of fuzzy logic controller utilizes these rules to generate the required output based upon centroid method.DVR is generally connected in feeders having sensitive loads whose terminal voltage has to be regulated

VI. MATLAB/SIMULINK RESULTS

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

Case 1: Voltage Sag/Swell Compensation by using Proposed DVR using PI Controller

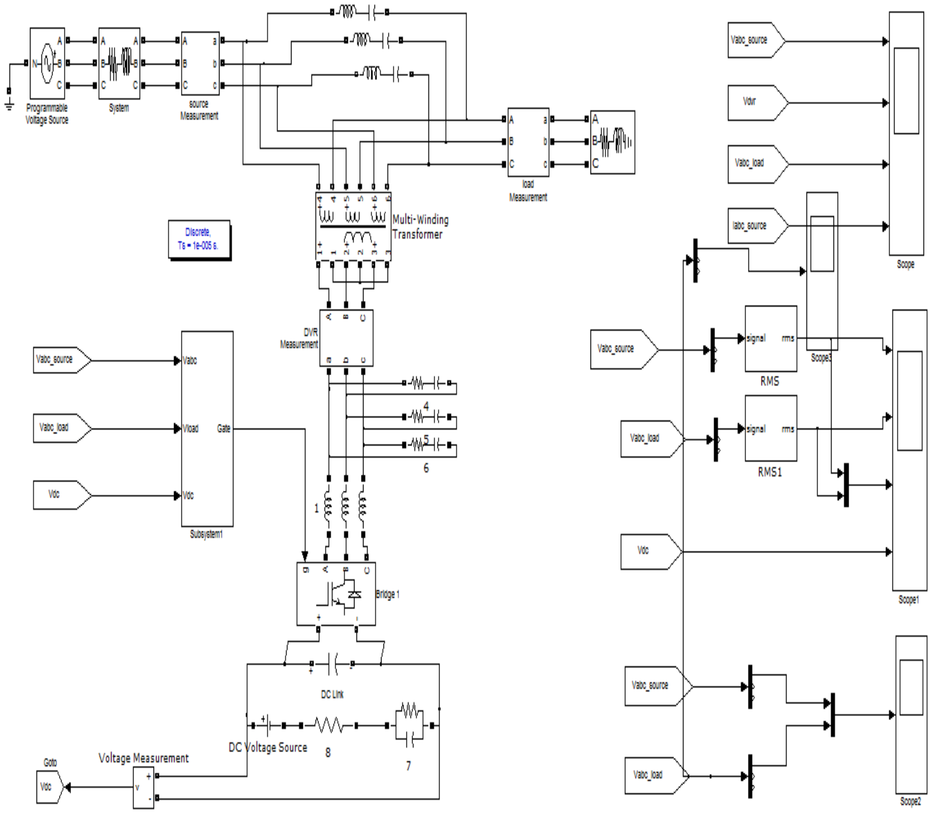

Fig.8. Matlab/Simulink Modelling of Proposed DVR under Voltage Sag/Swell Issues.

International Journal of Electrical and Electronics Engineers
Vol. No.8 Issue 02, July-December 2016
ISSN (O) 2321-2055
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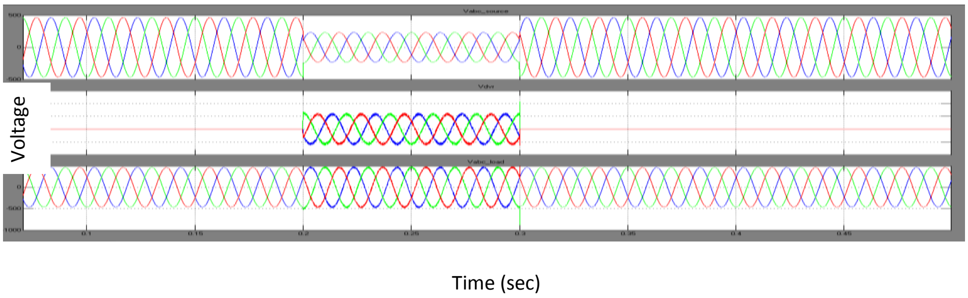
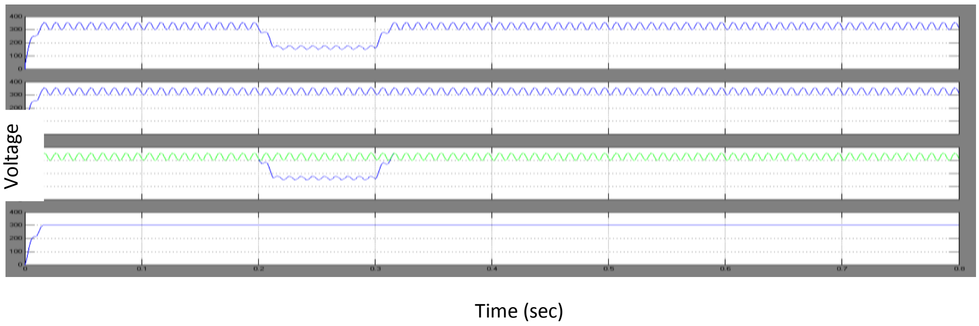
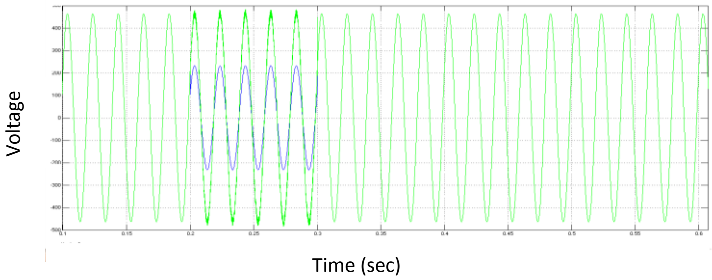


(a) Source Voltage, DVR Injected Voltage, Load Voltage.

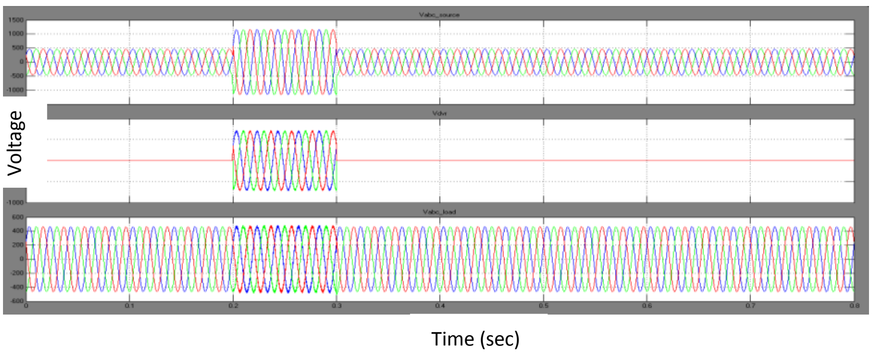


(b) .RMS value of source voltage, load voltage, Its comparison, DC Link Voltage



(c) Source Voltage & Load Voltage.

Fig.9. Source Voltage, DVR Injected Voltage, Load Voltage, Source Current, (b) RMS value of source voltage, load voltage, its comparison, DC Link Voltage, (c) Source Voltage & Load Voltage of the Proposed DVR under Voltage Sag Compensation Scheme.



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

International Journal of Electrical and Electronics Engineers
Vol. No.8 Issue 02, July-December 2016
ISSN (O) 2321-2055
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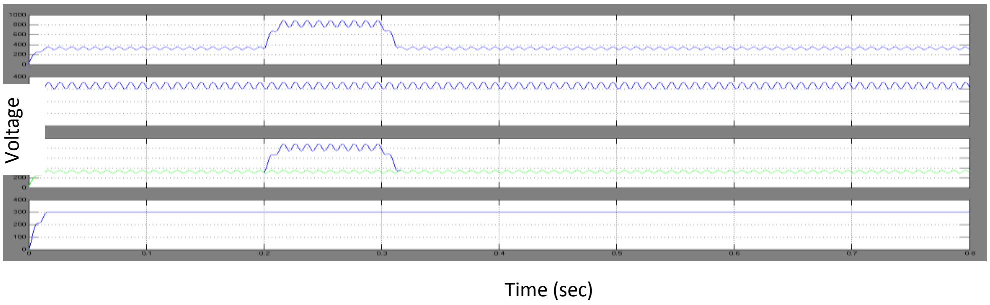
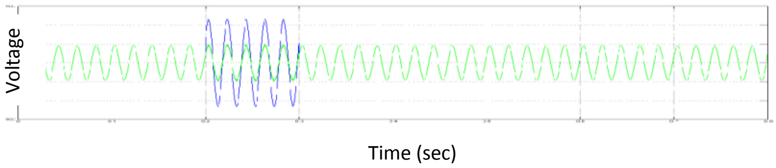
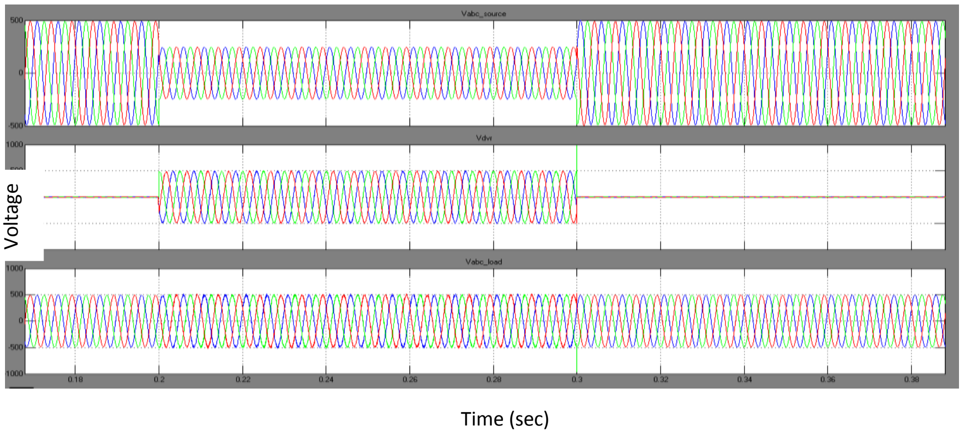


(b) RMS value of source voltage, load voltage, Its comparison, DC Link Voltage.

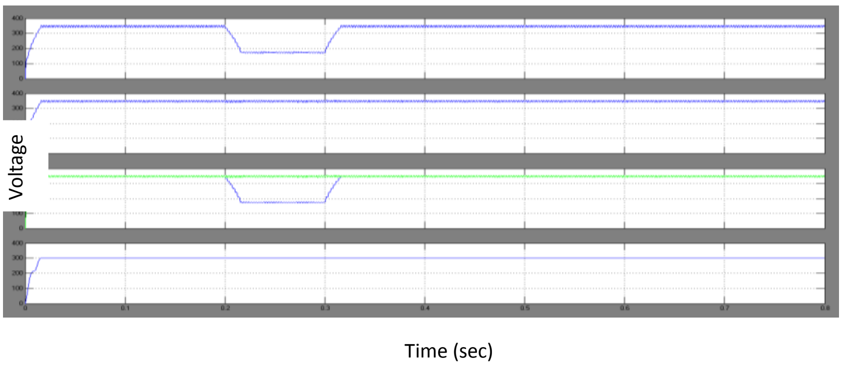


(a) Source Voltage & Load Voltage.

Fig.10.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 of the Proposed DVR under Voltage Swell Compensation Scheme.

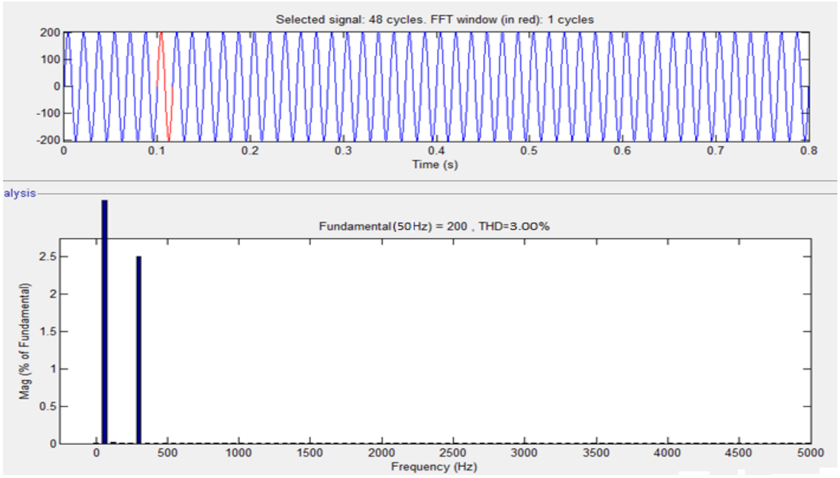


(a).Source Voltage, DVR Injected Voltage, Load Voltage.



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

International Journal of Electrical and Electronics Engineers
Vol. No.8 Issue 02, July-December 2016
ISSN (O) 2321-2055
ISSN (P) 2321 -2045



(C) THD Analysis of load voltage.

Fig.11 Source Voltage, DVR Injected Voltage, Load Voltage, Source Current, (b) RMS value of source voltage, load voltage, its comparison, DC Link Voltage, (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.

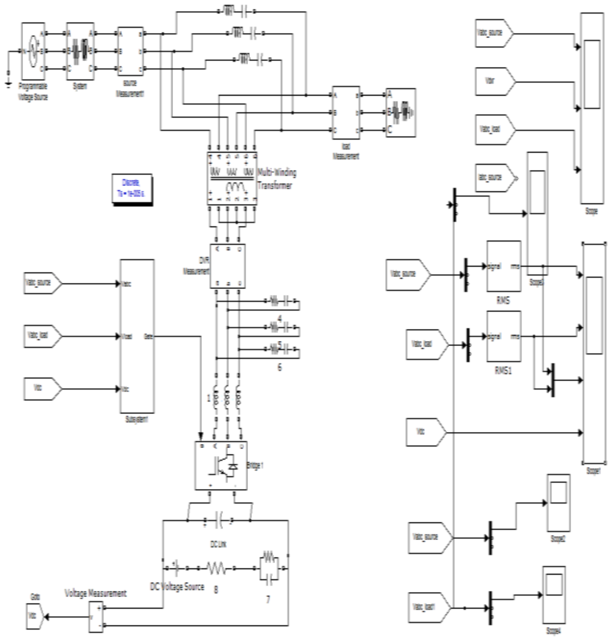
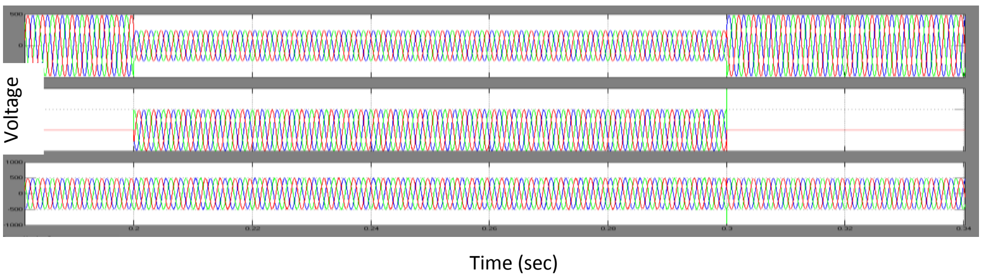


Fig.12 Matlab/Simulink Modeling of Proposed DVR under Voltage Sag/Swell Issues using fuzzy logic control.



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

International Journal of Electrical and Electronics Engineers
Vol. No.8 Issue 02, July-December 2016
ISSN (O) 2321-2055
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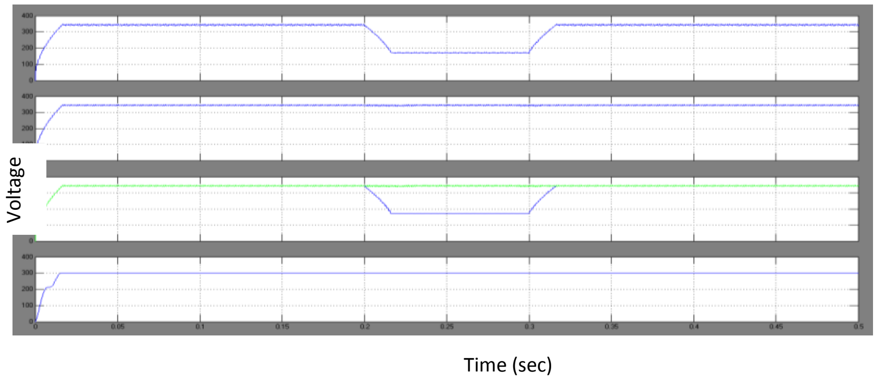
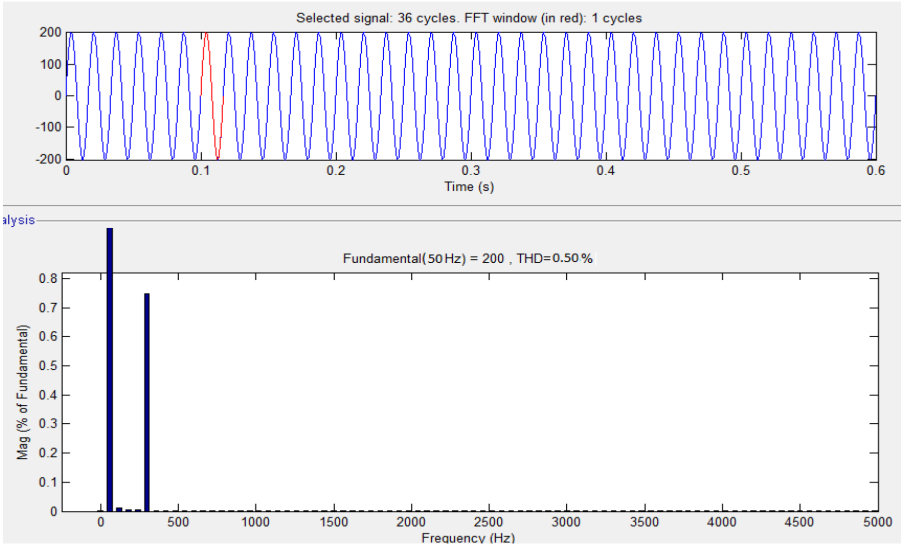


(b). RMS value of source voltage, load voltage, its comparison, DC Link Voltage.



(c). THD Analysis of load voltage

Fig.13.(a) Source Voltage, DVR Injected Voltage, Load Voltage, Source Current, (b) RMS value of source voltage, load voltage, its comparison, DC Link Voltage, (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.

VII. CONCLUSION

The performance of the proposed fuzzy logic based DVR is evaluated by using MATLAB/SIMULINK program as a simulation platform. 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

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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