International Journal of Electrical Engineering.
ISSN 0974-2158 Volume 8, Number 1 (2015), pp. 17-28

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A Cost Effective Topology of DVR for a 3 Phase 4 Wire Distribution System

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Abstract

Power quality problems are of great concern due to the excess use of power electronic devices in power system. Voltage related power quality problems and its solution are discussed in this paper. Dynamic voltage restorer (DVR) is one of the custom power devices used to mitigate voltage related power quality issues such as voltage sag/ swell, voltage distortions due to harmonics etc. Of these voltages sag is found to be the most common disturbance in the distribution systems.In this paper a cost effective design of DVR for a three phase four wire distribution system is proposed. Hysteresis controller is used to generate switching pulse for DVR. The cost effective design is accomplished by the use of hysteresis controller and also with a low voltage rated dc link capacitor. Compensation techniques and control strategy is well explained in this paper.In this paper DVR for low voltage level (LV) is proposed.A simulation study of the proposed system has been carried out using MATLAB/Simulink, and the results are presented. A comparative analysis of results using DVR and without using DVR is discussed. By analyzing the results it is clear that the proposed topology maintains the power quality at desired standards and specifications as required.

Keyword: Custom power device, voltage source inverter (VSI), Dynamic voltage restorer (DVR), Hysteresis controller, Insulated gate bipolar transistor (IGBT)

I. INTRODUCTION

As more sensitive loads have come into wide use, power quality is a big issue of customers and utilities. The term power quality generally refers to voltage quality.

That is maintaining nearly rated voltage at rated frequency at the load terminals.Major power quality problems in the distribution systems are voltage sag/swell, harmonics, inter harmonics, drop in reactive power and low power factor.This is due to the advent of a large numbers of sophisticated electrical and electronic equipment, such as computers, programmable logic controllers, variable speed drives, and so forth. The use of these equipments very often requires power supplies with very high quality. Various custom power devices are used to mitigate these power quality problems. Dynamic voltage restorer (DVR) is one of the most advanced and economical [1] custom power devices used to mitigate voltage related power quality problems such as voltage sag / swell, voltage distortions and harmonics in the voltage waveform.

Dynamic voltage restorers are mainly used to protect sensitive loads from the electrical network voltage disturbances such as sags or swells, used to reduce harmonic distortion of ac voltages and also it can tightly regulate the voltage at the load bus.The DVR consists of essentially a series-connected injection transformer, a voltage source inverter, an inverter output filter circuit, and an energy storage device connected to the dc link [2].Voltage sag, which is a momentary decrease in rms voltage magnitude in the range of 0.1 to 0.9 per unit (p.u.) [3], is considered as the most serious problem of power quality. It is often caused by faults in power systems or by starting of large induction motors. It can interrupt or lead to malfunction of any electric equipment which is sensitive to voltage variations[4].

DVR functions by injecting ac voltages in series with the incoming three-phase network, the purpose of which is toimprove voltage quality by adjustment in voltage magnitude, wave shape, and phase shift. These attributes of the load voltage are very important as they can affect the performance of the protected load. The voltage-sag compensation involves injection of real and reactive power to the distribution system, and this determines the capacity of the energy storage device required in the restoration scheme. The reactive power requirement can be generated within the voltage source inverter of the DVR. The voltage source inverter is supplied from dc link capacitor. Therefore for the successful operation of DVR, the dc capacitor voltage is to be maintained at all periods of time. For that external energy storage is necessary to meet the real-power requirement[1]. Usually a battery or superconducting magnetic energy storage (SMES) is used as energy storage. Single line diagram of DVR connected to an electrical system is shown in fig.1.

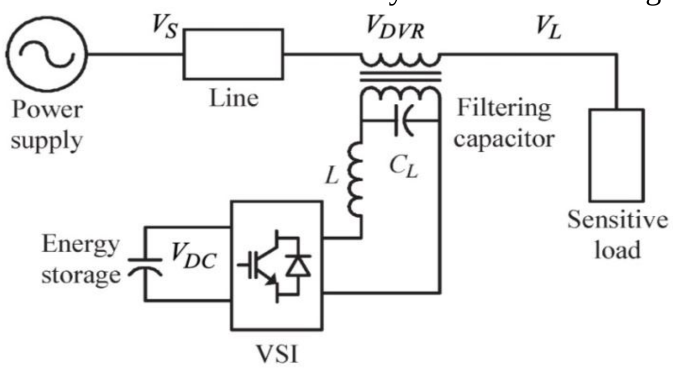

Fig.1 Block schematic representation of single line diagram of DVR connected between source and load

DVR for medium voltage level is discussed and implemented with a new controller in [2]. For compensating voltage sags and damping of high frequency oscillations simultaneously using possible control schemes and its effect on oscillation damping using DVR for medium voltage level is discussed in [5] and it is tested on a 10 kV prototype DVR system.ArindamGhoshand Gerard Ledwich [14] suggested compensation of distribution system voltages using DVR, also it is demonstrated that this device can tightly regulate the voltage at the load terminal against imbalance or harmonic in the source side. In [15] Implementation of the DVR have been proposed at both a low voltage (LV) level, as well as a medium voltage (MV) level and various methods are illustrated for protecting sensitive loads from voltage sags using DVR. It also reports practical test results obtained on a medium voltage level using a DVR at a Distribution test facility in Kyndby, Denmark to protect a 400KVA load from 0.5 P.U. maximum voltage sag.

In this paper DVR for a three phase four wire distribution system is proposed. The proposed topology has the capability to mitigate voltage sag/ swell and voltage distortions at low voltage levels with a reduced dc link voltage rater capacitor. Since the dc link voltage is reduced, switching losses is reduced further as said in [13]. Also the negative and zero sequence components are eliminated since the negative terminal of dc link capacitor is connected to system neutral point. The simple control strategy enables the system to be a cost effective design.In this paper hysteresis controller is used in order turn on IGBT switches at appropriate instants. Various compensation methods of DVR for voltage sag are also discussed.In this topology batteries are used as an external energy storage device. The design can be extended further by using a renewable energy system to keep the voltage steady in the batteries. The proposed design of DVR is verified and analyzed using MATLAB/Simulink.

II. DESCRIPTION OF THE TOPOLOGY

The proposed topology uses a 3 phase, 4 wire, two level voltage source inverter topology as shown in fig 2. In this topology DVR is connected between a stiff source and load composed of both linear and nonlinear loads. Here Vs represents the 3 phase source voltage, Rs and Ls represents the source resistance and inductance, Vdvra, Vdvrb, Vdvrc represents the voltage injected by the DVR for all the 3 phases, Lse, Cse and Rsw represents series inductance, series capacitance and series resistance respectively connected as in fig 2 in order to protect the active power filter from high currents and switching surges. The capacitor (Cse) and Inductor (Lse) acts as filter, which minimizes ripples. Here R_L and L_L represents load resistance and inductance. Here the system neutral is connected to the negative terminal of dc link capacitor [13], which eliminates the fault current in the neutral terminal.

In this topology IGBT switches are used. It is mostly preferred under the conditions of low duty cycle, low frequency and small load variations. It found applications that employ high voltages, high temperatures and high output powers. T_a, T_b and T_c are the switches used for upper legs of VSI and T_{aa}, $T_{bb}$and T_{cc} are the switches used in the lower legs of VSI. Hysteresis voltage controller is used to control the switching of the IGBT switches when a sag/swell occurs in the system. The control strategy of DVR is explained in detail in section IV. The performance of DVR depends on the proper selection of VSI parameters of series active filter. The design of the VSI parameters are explained in detail in [6] [13].

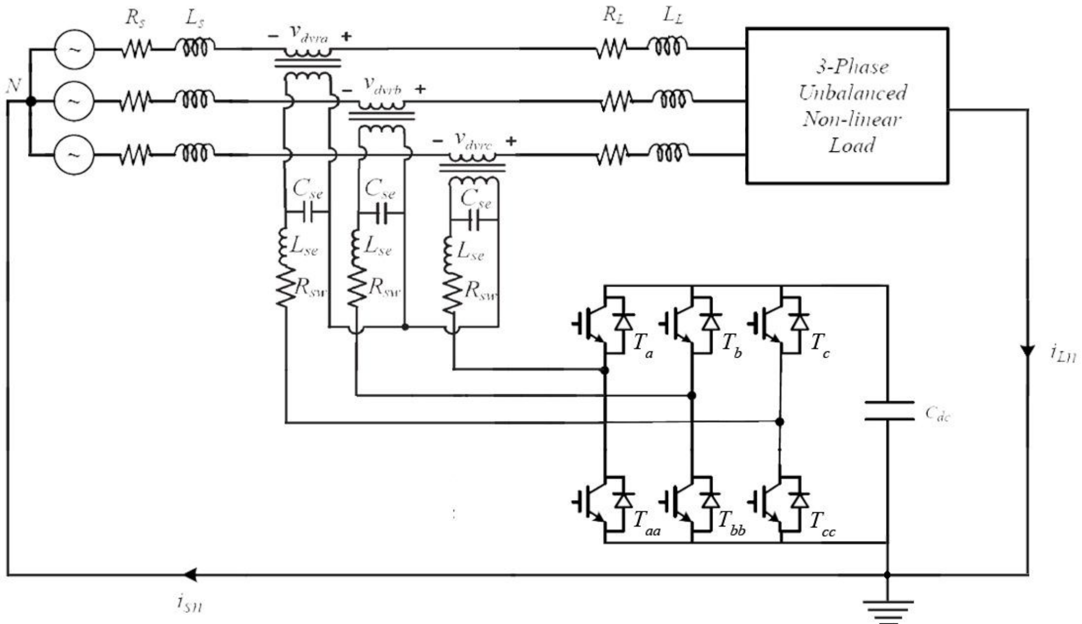

Fig.2 Equivalent circuit of a DVR connected electrical system including its control circuitry

Whenever the supply voltage undergoes sag then DVR injects suitable voltage with supply. The DVR injects a voltage represented by the equation.

$V_{DVR} = V_L^* + Z_L I_L - V_S$ (1)

Where V_{DVR}, V^*_L, V_S, Z_L and I_L represents the voltage injected by DVR, reference load voltage, actual source voltage, line impedance and load current respectively.

The load current is given by $I_L = \frac{[P_L + Q_L]}{V}$ (2)

When V_L is considered as reference, equation can be written as

$V_{DVR}\angle 0 = V_L\angle 0 + Z_L\angle\beta - \theta - V_S\angle\delta$ (3)

where α, β and δ are the angles of V_{DVR}, Z_L and V_S respectively. θ is the load power angle.

$\theta = \tan^{-1}\theta\frac{Q_L}{P_L}$ (4)

Complex power injection of DVR can be written as,

$S_{DVR} = V_{DVR} I^*_L$ (5)

It requires the injection of only reactive power and the DVR itself is capable of generating the reactive power.

III. COMPENSATION TECHNIQUES OF DVR

For the mitigation of voltage sag three methods are normally employed. They are pre-sag compensation, in-phase compensation and optimized energy compensation [7]-[11].

A. PRE-SAG COMPENSATION

This method is most suitable for the systems where both magnitude as well as phase angles are to be regulated. The DVR injects the voltage difference between sag and pre-sag voltages. DVR thus maintains voltage magnitude and phase angle. It is one of the best solution method for maintaining the load voltage as that of pre-fault voltage. This method is most suited for the systems having sensitive loads.The phasor diagram for pre-sag compensation method is shown in fig.3.

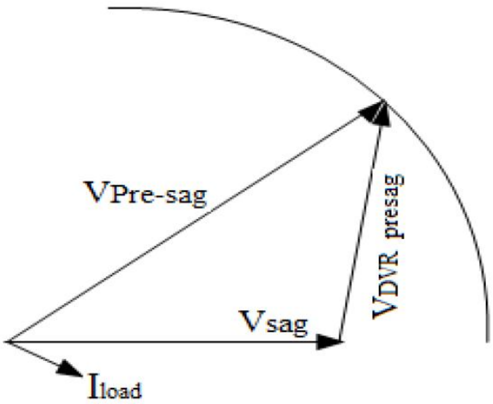

Fig 3 Pre-Sag Compensation technique

B. IN-PHASE COMPENSATION

In this method the injected voltage is in phase with supply voltage (Vsag). Here only voltage magnitude is compensated. This method is suitable for loads that can withstand phase angle errors (linear loads). In this method the voltage to be injected is minimum. The phasor diagram for in-phase compensation is shown in fig 4.

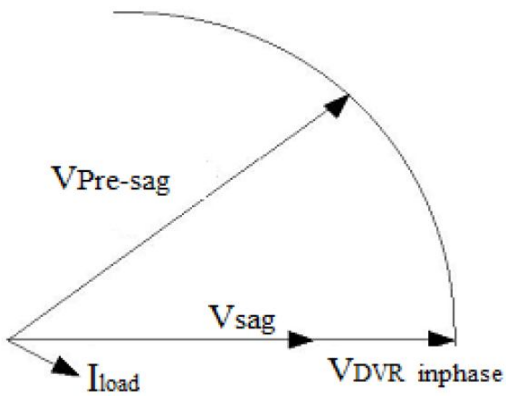

Fig.4 In-Phase Compensation Technique

C. OPTIMIZED ENERGY INJECTION METHOD

In this method the use of real power is minimized by injecting voltage at 90^0phase angle to the load current in order to improve the active power supply of the network. It is done by increasing the reactive power supplied by the compensator [11]. The phasor diagram for optimized energy injection technique is shown in fig.5.

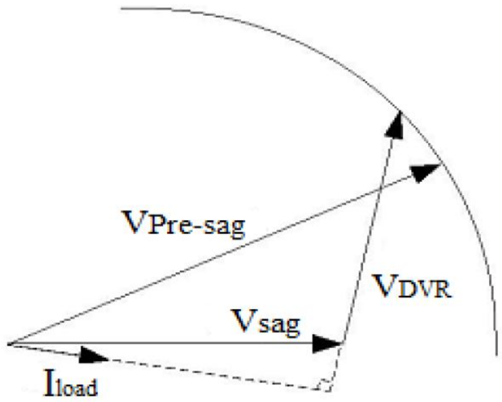

Fig.5 Optimized Energy Injection Technique

IV. CONTROL STRATEGY AND OPERATION OF DVR

The basic function of the DVR is to detect any voltage sag/swell occurred in the power line and injects the balance voltage from the DVR. This is achieved either by absorbing or injecting active or reactive power [12].The compensation performance of a DVR is determined by its controller [2].That is proper switching of semiconductor switches at appropriate interval enhances the compensation of voltage sag/swell and voltage distortions. Hysteresis voltage controller is used to turn on IGBT switches.

Hysteresis controller is based on a feedback loop. Whenever the voltage exceeds a predetermined positive values, upper switches are turned on and whenever the voltage exceeds a predetermined negative values, lower switches are turned on [13].Thus it controls the switching devices in VSI. Hysteresis controllers are widely used for power quality enhancement applications due to its advantages such as simple and cost effective design, positive peak and negative peak depends on ac waveforms etc. the control scheme of DVR is explained as in fig 6.

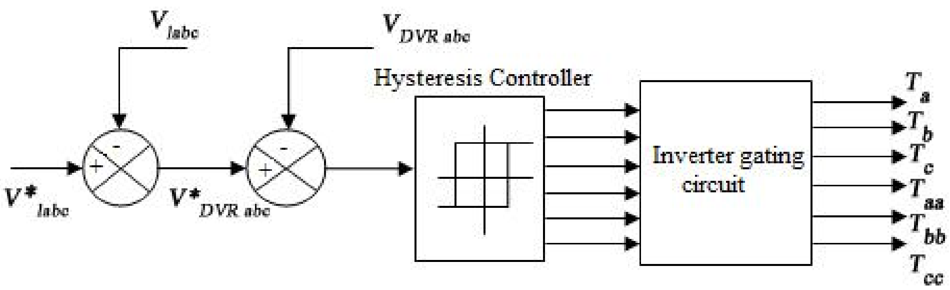

Fig 6: Control circuit of DVR

Control strategy involves maintaining the voltage at load balanced and sinusoidal, thereby making the source side balanced and sinusoidal. The working of DVR is as per equation 1. In closed loop control scheme of the series inverter, the three phase load voltage (V_{La}, V_{Lb} and V_{Lc}) are subtracted from the three phase supply voltage (V_{Sa}, V_{Sb} and V_{Sc}), and are also compared with reference supply voltage which results in three phase voltages (V_{DVRa}, V_{DVRb} and V_{DVRc}). These voltages are to be injected in series with the load which cancels out the distortions present in supply voltages. In order to inject this voltage across the load, gate pulses are to be generated to turn on appropriate switches of series active filters. For that the reference voltage is fed to hysteresis controller.

Operation of DVR for injecting balance voltage is explained [16] as follows:

An unbalance or distortion in a 3 phase system is due to positive, negative and zero-sequence fundamental and harmonic components. The terminal voltage V_t can be expressed as

$$V_t(t) = V_{t+}(t) + V_{t-}(t) + V_{t0}(t) + \sum V_{th}(t) \quad (6)$$

Where subscripts +, - and 0 refers to the positive, negative and zero sequence fundamental components respectively. The positive, negative and zero-sequence fundamental frequency components of the system voltages are given by

$$V_{t+}(t) = V_{t+}\sin(\omega t + \emptyset_+) \quad (7)$$

$$V_{t-}(t) = V_{t-}\sin(\omega t + \emptyset_-) \quad (8)$$

$$V_{t0}(t) = V_{t0}\sin(\omega t + \emptyset_0) \quad (9)$$

Also

$$\sum V_{th}(t) = \sum V_{th}\sin(h\omega t + \emptyset_h) \quad (10)$$

Equation no. 10 represents the harmonics in the voltage waveform, h is the harmonic order; and$\emptyset_+$,$\emptyset_-$,$\emptyset_0$ and $\emptyset_h$ are the corresponding voltage phase angles.

Usually, the voltage at the load terminal is expected to be sinusoidal with a fixed amplitude V_L;

$$V_L(t) = V_L\sin(\omega t + \emptyset_+) \quad (11)$$

Hence the series converter will need to compensate for the following components of voltage:

$$V_{dvr}(t) = V_L(t) - V_t(t)$$

$$= (V_L - V_{t+})\sin(\omega t + \emptyset_+) - V_{t-}(t) - V_{t0}(t) - \sum V_{th}(t) \quad (12)$$

The control system should automatically control the series active filter so that its generated voltage at its output terminals is $V_{dvr}(t)$ in fig.1 and matched with equation no 12.

V. RESULTS AND ANALYSIS

In this topology a balanced 3 phase voltage is generated and fed to a load comprised of both linear and nonlinear unbalanced loads. The main aim of DVR is to make the load voltage free from distortion and to maintain balanced and sinusoidal voltage at the load terminal.Here the source voltage is taken as 230 V. The voltage across the dc bus is taken 1.5 times that of full load line voltage. Here the dc bus voltage is maintained at 560 V for a line voltage of 400V. Inverter output voltage varies only between zero and + Vdc. Negative values of Vdc is restricted since the negative terminal of dc link capacitor is grounded [13]. Whenever a distortion occurs in the voltage waveform, DVR injects the required voltage so as to maintain the load voltage balanced and sinusoidal. The values of the various design parameters are noted in appendix.

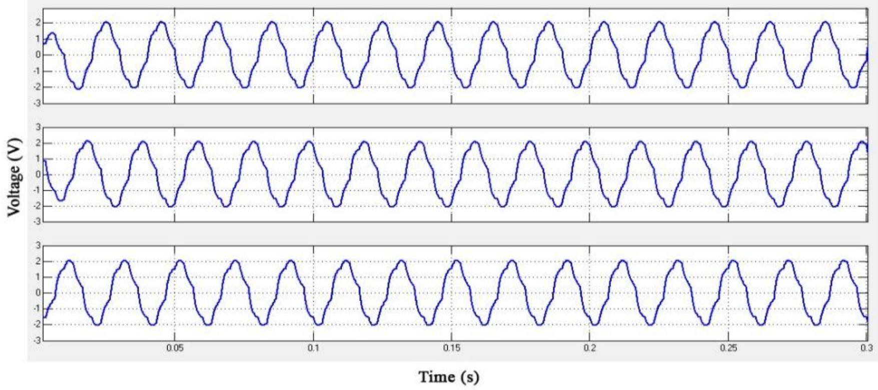

Fig.7Voltage injected by DVR

Fig.7 shows the voltage injected by DVR in order to mitigate the voltage related power quality problems in the source side and load side respectively. Since the load is composed of both linear and nonlinear loads, the some distortions such as flicker, voltage sag/swell may occur. Series active filter effectively mitigates the voltage related problems. Fig 8 shows the load voltage in all the 3 phases at the point of common coupling. By analyzing the load voltage waveforms for all the 3 phases, it is found that the load voltage waveform is balanced, sinusoidal and distortion free. Fig 9 shows the load current at the load terminal. Nearly sinusoidal current waveform is obtained in using the proposed topology.

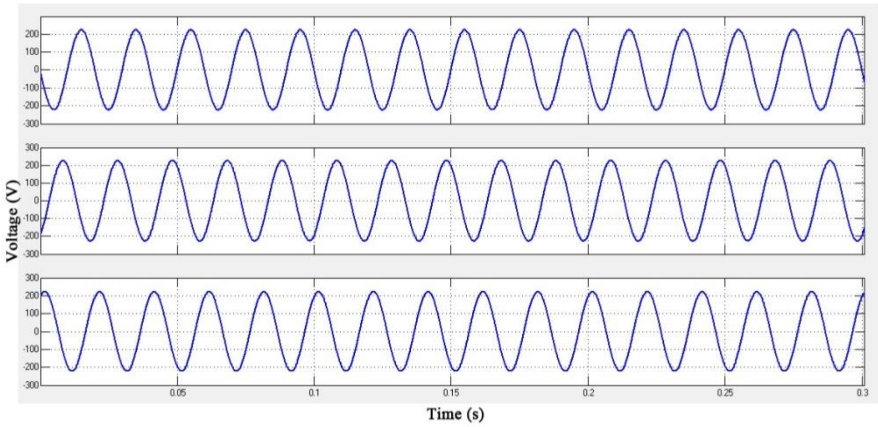

Fig.8 The load voltage for all the 3 phases after compensation

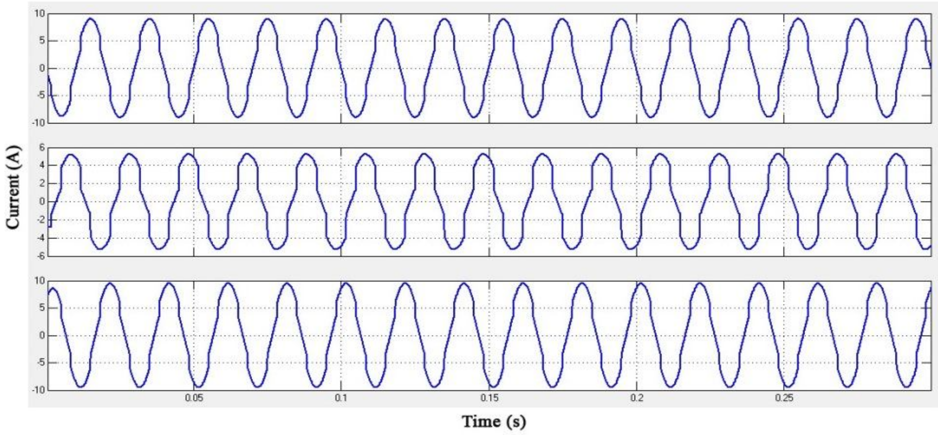

Fig.9 The load current for all the 3 phases

A comparative analysis of topologies without using DVR and with using DVR is shown in figs 10 and 11. Since unbalanced loads are connected in an uncompensated system (without DVR), the load voltage comprised of unbalanced voltage waveforms for 2 phases. From fig 11 it is clear that balanced and sinusoidal load voltages are obtained from the proposed system. It shows the effectiveness of the proposed design.

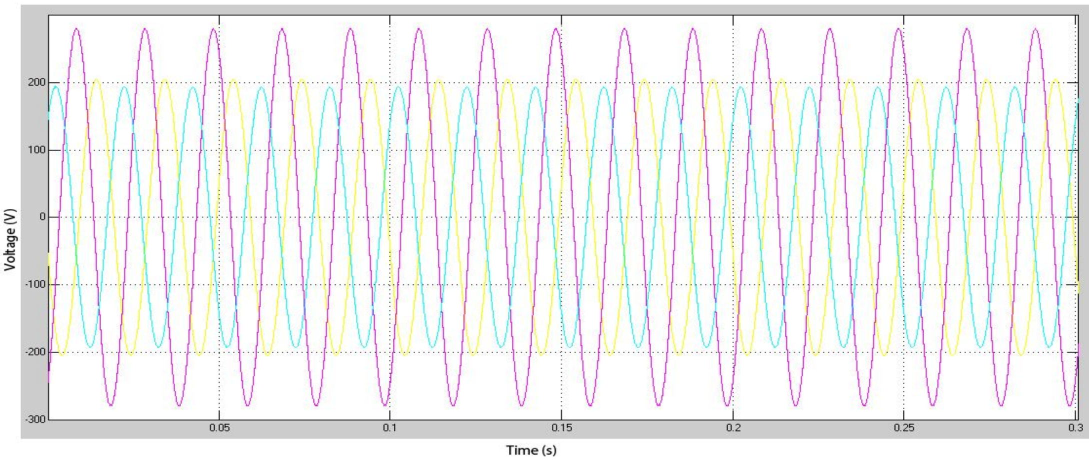

Fig 10: Load voltages for all the 3 phases without using DVR

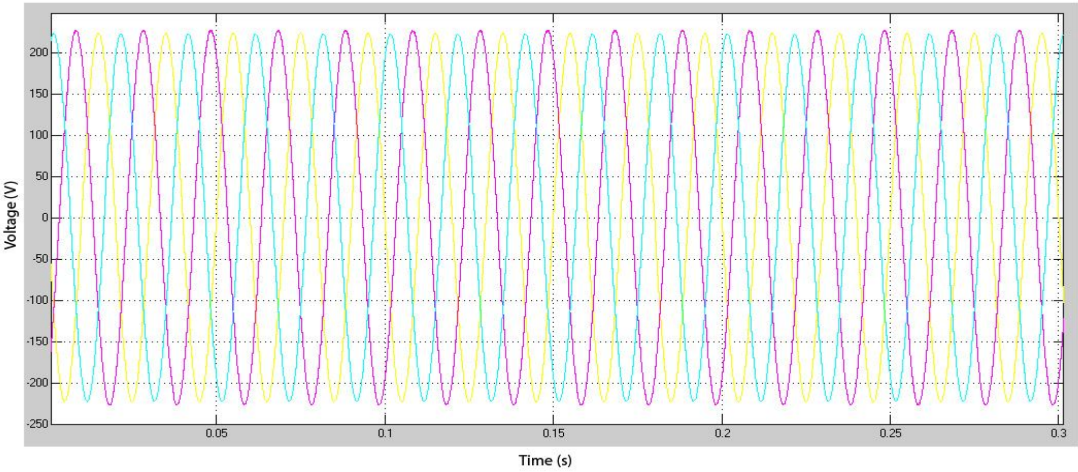

Fig 11: Load voltages for all the 3 phases with a DVR compensated system

Since a reduced dc link voltage rated capacitor is used in this topology, less voltage rated switching devices are used, which reduces the cost of the design.Switching losses were also reduced. By analyzing the results it is clear that the proposed DVR topology satisfies the designed conditions. Hysteresis controller turns on/off appropriate switches at appropriate periods so as to maintain the load voltage balanced and sinusoidal.

VI. CONCLUSION

In this paper, a fast and cost effective DVR topology is presented, which has the capability to mitigate voltage sag/sell and other voltage distortions.Hysteresis controller is used control the IGBT switches used in this topology. An ideal design with one of the simplest controller enables the DVR to perform in a cost effective manner. Matlab/Simulink results show the effectiveness of the proposed design. From the results, it is clear that the proposed DVR system can compensate for voltage sag/swell, voltage distortions and harmonics in voltage waveform thereby making the load voltage balanced and sinusoidal.A comparative analysis of results using DVR and without using DVR is discussed. By analyzing the results it is clear that the proposed topology maintains the load voltage balance and sinusoidal even if it is connected to an unbalanced load comprised of both linear and nonlinear loads.

Appendix

Source Voltage : 230 V (Phase voltage)
System Frequency: 50 Hz
Feeder Impedance: Z= 1+j3.141 ohms
Linear Load Impedance: Z_{La}= 34 +j47.5 ohm, Z_{Lb}= 81+j39.6 ohm, Z_{Lc}=31.5+j70.9 ohm

Non-Linear Load: 3 phase full bridge rectifier load feeding a R-L load of 150 ohm, 300 mH
DC Link bus Voltage: V_{DC}= 560 V.

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