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Research Article

Dynamic Voltage Restoration using DC-DC Converter

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Abstract

This paper presents the application of dynamic voltage restorer (DVR) for the mitigation of voltage sags/ swells on power distribution systems connected to critical loads. DVR is a type of compensating custom power devices. The impedance source inverter employs a unique impedance network coupled with inverter main circuit and rectifier. By dynamically controlling the shoot-through duty cycle, the Z-source inverter system has the capacity to inject the boost or buck voltage required to compensate sags or surges. The proposed DVR topology is simulated using Matlab/Simulink and the experimental results are presented.

Keywords Power quality; Voltage sags; Dynamic Voltage Restorer; Impedance Source Inverter; Z-Source Inverter.

Introduction

Modern power systems are complex networks consisting of more number of generating stations and load centers which are interconnected through the power transmission lines. Industrial processes containing voltage sensitive devices, vulnerable to degradation in the quality of power supply. Such sensitive or critical loads are found in are modern electronic and food processing industries for example, and require a high quality robust power supply, however the power distribution system on which they are networked have numerous nonlinear loads which significantly affects the quality of power supply [1]. The power quality problems occur either on source side or load side. If load side problems are associated with change in current, shunt compensation is required, but if load exceeds the capacity of the source fluctuations of load result. Similarly if source side problems are associated with change in voltage, series compensation is required. The deviation in voltage, current and frequency which can be described as power quality problems [2]. Voltage sag/swell, flicker, harmonics distortion, impulse transients and interruptions are the various

power quality problems addressed in the distribution system. Of the above power quality problems, a voltage sag/swell disturbance poses a series threat to the industries, particularly modern electronic process control industries. It can occur more frequently than any other power quality phenomenon.

Voltage sag is defined by the IEEE 1159 as the decrease in the RMS voltage level to 10%-90% of nominal, at the power frequency for duration of half to one minute. Voltage swell is defined by IEEE 1159 as the increase in the RMS voltage level to 110%-180% of nominal, at the power frequency for duration of half cycles to one minute. Voltage fluctuations, often in the form of voltage sags/swells, can cause severe process disruptions and result in substantial economic loss. So, cost effective solutions which can help such sensitive loads ride through momentary power supply disturbances have attracted much research attention [3]. Among various types of custom power devices which are developed recently, the dynamic voltage restorer (DVR) is being used in distribution systems and performing more effectively.

The basic principle of the dynamic voltage restorer is to inject a voltage of required magnitude and frequency, so that it can restore the load side voltage to the desired amplitude and waveform even when the source voltage is

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unbalanced or distorted. Generally, it employs a gate turn off thyristor (GTO) solid state power electronic switches in a pulse width modulated (PWM) inverter structure. The DVR can generate or absorb independently controllable real and reactive power at the load side. In other words, the DVR is made of a solid state DC to AC switching power converter that injects a set of three phase AC output voltages in series and synchronicity with the distribution and transmission line voltages [4].

The source of the injected voltage is the commutation process for reactive power demand and an energy source for the real power demand. The energy source may vary according to the design and manufacturer of the DVR. Some examples of energy sources applied are DC capacitors, batteries and that drawn from the line through a rectifier. In normal conditions, the dynamic voltage restorer operates in stand-by mode. However, during disturbances, nominal system voltage will be compared to the voltage variation [5]. This is to get the differential voltage that should be injected by the DVR in order to maintain supply voltage to the load within limits.

The amplitude and phase angle of the injected voltages are variable, thereby allowing control of the real and reactive power exchange between the dynamic voltage restorer and the distribution system. The DC input terminal of a DVR is connected to an energy storage device of appropriate capacity. As mentioned, the reactive power exchange between the DVR and the distribution system is internally generated by the DVR without AC passive reactive components. The real power exchanged at the DVR output AC terminals is provided by the DVR input DC terminal by an external energy source or energy storage system. Also, there is a resemblance in the technical approach to DVRs to that of providing low voltage ride-through (LVRT) capability in wind turbine generators. The dynamic response characteristics, particularly for line supplied DVRs are similar to LVRT-mitigated turbines. Moreover, since the device is connected in series, there are conduction losses, which can be minimized by using integrated gate-commutated thyristor (IGCT) technology in the inverters [1-5].

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/swells both in domestic and industrial distributions. Alongside the variation in magnitudes, voltage sags/swells can also be accompanied by a change in phase angle. This phenomenon is known as phase angle jump (i.e. the variation of phase angle before the onset and during the voltage sag/swell events and is calculated as an argument of the complex voltage). 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. DVR is one the prominent methods for compensating the power quality problems associated with voltage sags/swells. DVR can provide an effective solution to mitigate voltage sag/swell by establishing the appropriate predetermined voltage level required by the loads [6].

Voltage sag/swell is most important power quality problems challenging the utility industry can be compensated and power is injected into the distribution system. By injecting voltage with a phase advance with respect to the sustained source-side voltage, reactive power can be utilized to help voltage restoration DVR is one of such power quality device used in power distribution networks. It has lower cost, smaller size and fast dynamic response to the disturbance [7]. The output voltage of the inverter is varied by using different PWM schemes available. Given to the nonlinear nature of the semiconductor devices voltage waveform distortion associated with the high frequency harmonics at the output of the inverter circuit is a common phenomenon. A harmonic filter unit is generally used at the output of the inverter circuit to keep the harmonic distortions at a permissible level. Although the filter unit keeps the harmonic distortion minimum and improves the quality of the generated voltage, it can also introduce voltage drop and phase shift in the fundamental component of the inverter output and needs to be accounted for in the generated compensation voltage [8].

In the conventional VSI and CSI based DVR, ac output voltage is limited below dc voltage and additional converters are required to meet desired ac output above dc input. The upper and lower devices of each phase leg cannot be gated simultaneously otherwise shoot through will occur and destroy the device [7-8]. In Z-source based topology, output voltage amplitude is not limited to DC sources voltage summation similar to traditional cascaded multilevel inverters and can be boosted with Z network shoot-through state control, therefore in the renewable sources supported DVR, other DC/DC converters are not needed and DVR is more reliable against short circuit. Recently proposed quasi-Z-source inverters (qZSIs) have some new attractive advantages more suitable for application in PV systems [9-10].

In this paper, a new topology of quasi Z-source inverter (qZSI) based DVR is proposed. In the proposed system, the size of energy storage element is decreased in comparison with the conventional systems, lower component rating and harmonic factor. The simulation results of conventional VSI based DVR and quasi-Z-source based DVR are compared.

Dynamic voltage restorer

We deal with the Dynamic Voltage Restorer (DVR) using Z-Source Inverter. Voltage sag is a crucial power quality problem faced by the utility industry which has resulted in increased attention. The DVR is a series power quality conditioning device used to eliminate the voltage disturbance. The DVR compensates the voltage disturbances by injecting the voltage of suitable magnitude and phase in series with the line. The compensation capability of a dynamic voltage restorer primarily depends on the maximum voltage injection ability and the amount of stored energy available within the restorer. The topology is proposed in this project in order to enhance the voltage restoration property of the device. A constant dc-link is ensured during sag compensation by having an X-shaped impedance network with inherent shoot-through capability.

The function of the DVR is to ensure that any load voltage disturbance can be compensated for effectively and the disturbance is therefore transparent to the load. The corresponding phasor diagram describing the electrical conditions during voltage sag is depicted in Fig. 1, where only the affected phase is shown for clarity. Let Il, φ, δ and α represent the load current, load power factor angle, supply voltage phase angle and load voltage advance angle respectively. Although there is a phase advancement of α in the load voltage with respect to the pre-sag voltage in Fig.1, only in-phase compensation where the injected voltage is in phase with the supply voltage (α = δ) is considered in this project.

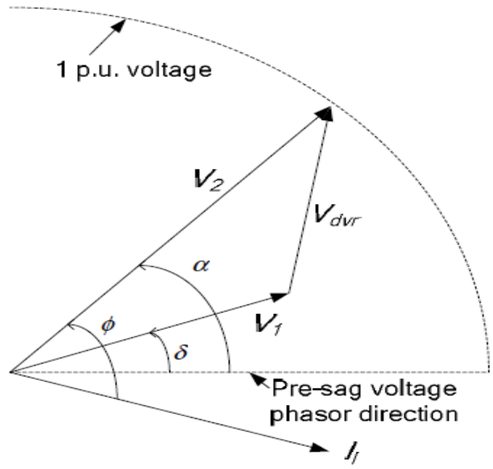

Fig. 1. Phasor Diagram of power distribution system during a sag

Z-Source Inverter based DVR

For describing the operation principles of Z-source inverter, consider Fig.2, which shows voltage type three phase Z-source inverter. Traditional VSI has eight switching states, out of that six are active states and the other two are null states. Whereas voltage type Z-source inverter has nine switching states, due to the presence of additional shoot-through state. In this state the H bridge arm is shorted. This additional state facilitates the boost actions in the impedance network. However with conventional inverters the shoot through state has been avoided to protect the inverter switches [11].

Although Z-source inverter has three different states null, active and shoot-through, null and active states can be represented in the same equivalent circuit for steady state analysis and it was named as non-shoot-through state.Fig.1 shows that V2 is regulated by the DVR through the injection voltage V dvr Assume that the load has an inductance Ll, a resistance Rl and the DVR harmonic filter has an inductance of Lf, a resistance of Rf and a capacitance of C_f. The DVR injection transformer has a combined winding resistance of r_t and a leakage inductance of L_t

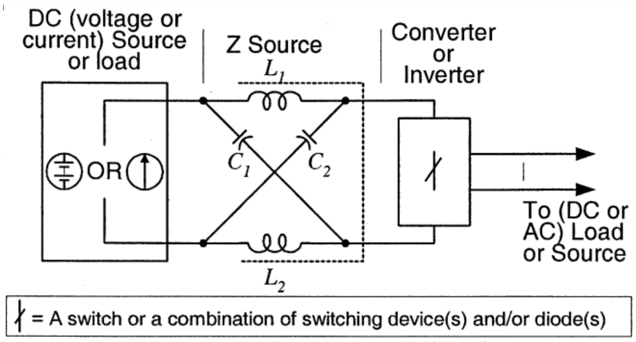

Fig. 2. A Z-Source Inverter (ZSI)

For simplicity of steady state analysis, inductors and capacitors are assumed to be ideal and are considered to have equal values. The inverter's action is replaced with a current source plus a single switch.

Then network becomes symmetrical therefore;

VC1=VC2=VC and vL1=vL2=vL

State equation can be obtained as in (1).

$$v_L = V_{DC} - V_C$$
$$v_d = V_{DC}$$
(1)
$$v_S = V_C - v_L$$

Where Z-source is in shoot-through state the following equations can be obtained.

$$v_L = V_C$$
$$v_d = 2V_C$$
(2)
$$v_S = 0$$

The total duration of non-shoot-through time and total shoot-through time are denoted by T1 and T0. Then consider the average voltage across the inductor which should sum up to zero and from (1) and (2);

$$V_C = \frac{T_1}{T_1 - T_0} V_{DC}$$

Control algorithm

The basic functions of a controller in a DVR are the detection of voltage sag/swell events in the system; computation of the correcting voltage, generation of trigger pulses to the sinusoidal PWM based DC-AC inverter, correction of any anomalies in the series voltage injection and termination of the trigger pulses when the event has passed. The controller may also be used to shift the DC-AC inverter into rectifier mode to charge the capacitors in the DC energy link in the absence of voltage sags/swells [12].

The dqo transformation or Park's transformation is used to control of DVR. The dqo method gives the sag depth and phase shift information with start and end times. The quantities are expressed as the instantaneous space vectors. Firstly convert the voltage from a-b-c reference frame to d-q-o reference. For simplicity zero phase sequence components is ignored. Fig. 3 illustrates a flow chart of the feed forward dqo transformation for voltage sags/swells detection. The detection is carried out in each of the three phases. The control scheme for the proposed system is based on the comparison of a voltage reference and the measured terminal voltage (Va,Vb,Vc).The voltage sags is detected when the supply drops below 90% of the reference value whereas voltage swells is detected when supply voltage increases up to 25% of the reference value. The error signal is used as a modulation signal that allows generating a commutation pattern for the power switches (IGBT's) constituting the voltage source converter. The commutation pattern is generated by means of the sinusoidal pulse width modulation technique (SPWM); voltages are controlled through the modulation. The block diagram of the phase locked loop (PLL) is illustrated in Figure. The PLL circuit is used to generate a unit sinusoidal wave in phase with mains voltage.

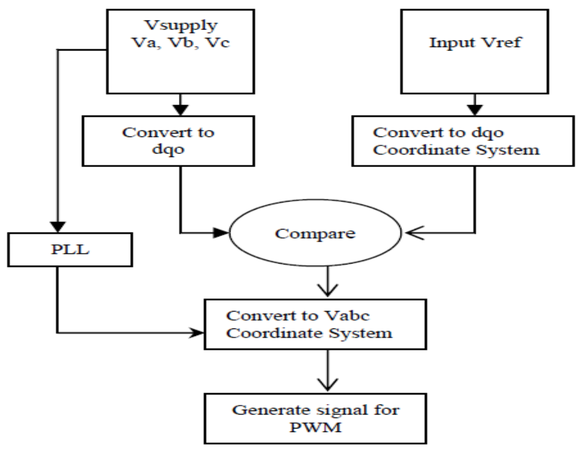

Fig. 3. Flow chart of feed forward control technique for DVR based on dqo transformation

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & 1 \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix}$$
---(1)

Equation (1) defines the transformation from three phase system a, b, c to dqo stationary frame. In this transformation, phase A is aligned to the d axis. That is in quadrature with the q-axis. The theta (θ) is defined by the angle between phase A to the d-axis. *dq*0 or *dqo* transformations.

Direct–quadrature–zero (or dq0 or dqo) transformation or zero–direct–quadrature (or 0dq or odq) transformation is a mathematical transformation used to simplify the analysis of three-phase circuits. In the case of balanced three-phase circuits, application of the dqo transform reduces the three AC quantities to two DC quantities. Simplified calculations can then be carried out on these imaginary DC quantities before performing the inverse transform to recover the actual three-phase AC results. It is often used in order to simplify the analysis of three-phase synchronous machines or to simplify calculations for the control of three-phase inverters [13].

The dqo transform applied to three-phase currents is shown below in matrix form:

$$I_{dqo} = T I_{abc} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

The inverse transform is:

$$I_{abc} = T^{-1} I_{dqo} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \sin(\theta) & \frac{\sqrt{2}}{2} \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_o \end{bmatrix}$$

abc_to_dq0 Transformation-Perform Park transformation from three-phase (abc) reference frame to dq0 reference frame. The abc_to_dq0 Transformation block computes the direct axis, quadratic axis, and zero sequence quantities in a two-axis rotating reference frame for a three-phase sinusoidal signal. The following transformation is used:

$$V_d = \frac{2}{3}(V_a \sin(\omega t) + V_b \sin(\omega t - 2\pi/3) + V_c \sin(\omega t + 2\pi/3))$$

$$V_q = \frac{2}{3}(V_a \cos(\omega t) + V_b \cos(\omega t - 2\pi/3) + V_c \cos(\omega t + 2\pi/3))$$

$$V_0 = \frac{1}{3}(V_a + V_b + V_c),$$

Phase locked loop

A phase-locked loop or phase lock loop (PLL) is a control system that generates an output signal whose phase is related to the phase of an input "reference" signal. It is an electronic circuit consisting of a variable frequency oscillator and a phase detector. This circuit compares the phase of the input signal with the phase of the signal derived from its output oscillator and adjusts the frequency of its oscillator to keep the phases matched. The signal from the phase detector is used to control the oscillator in a feedback loop.

Frequency is the derivative of phase. Keeping the input and output phase in lock step implies keeping the input and output frequencies in lock step. Consequently, a phase-locked loop can track an input frequency, or it can generate a frequency that is a multiple of the input frequency. The former property is used for demodulation, and the latter property is used for indirect frequency synthesis. An integrated circuit can provide a complete phase-locked-loop building block with output frequencies from a fraction of a hertz up to many Giga hertz [14].

Proposed control method

The main stages of the control system of a DVR include: detection of the start and finish of the sag, voltage reference generation, injection voltage generation, and protection of sensitive load.

Detection of Sags / Swell in the Supply voltage

Fitzer, Barnes and Green (2004), analyzed and compared several detection techniques. In this study, monitoring of Vd and Vq is used to return the magnitude and phase load voltage to the magnitude and phase reference load voltage. The control system is presented in Fig. 5. The three-phase supply voltage is connected to a transformation block that convert to rotating frame (d q) with using a software based Phase – Lock Loop (PLL). Three-phase voltage is transformed by using Park transform, from a-b-c to o-d-q frame:

$$\begin{bmatrix} v_d \\ v_q \\ v_o \end{bmatrix} = p \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$p = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{4\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

$$\theta = \theta_0 - \int_0^t \omega t \, dt$$

The detection block detects the voltage sag/swell. If voltage sag/swell occurs, this block generates the reference load voltage. The sag detection strategy is based on root means square (rms) of the error vector. Closed loop load voltage feedback is added, and is implemented in the frame in order to minimize any steady state error in the fundamental component. The injection voltage is also generated according to the difference between the reference load voltage and the supply voltage and is applied to the VSC to produce the preferred voltage, with the using the Hysteresis Voltage Control [15].

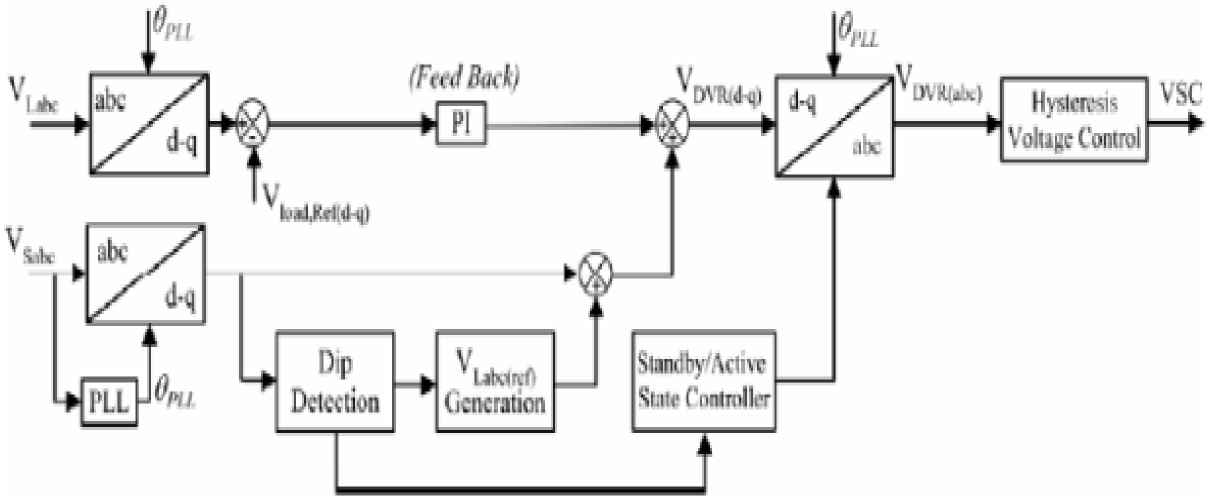

Fig. 5. Control Structure of DVR

Hysteresis Voltage Control

In this paper, hysteresis voltage control is used to improve the load voltage and determine switching signals for inverters gates. A basic of the hysteresis voltage control is based on an error signal between an injection voltage (Vinj) and a reference voltage of DVR (Vref) which produces proper control signals [16]. There is Hysteresis Band (HB) above and under the reference voltage and when the difference between the reference and inverter voltage reaches to the upper (lower) limit, the voltage is forced to decrease (increase) as shown in Fig. 4.

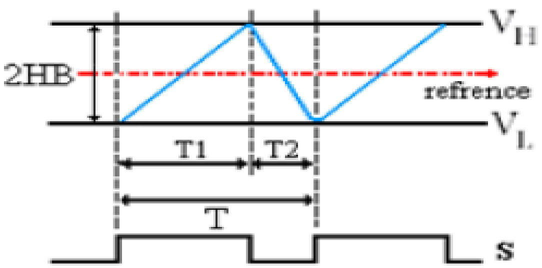

Fig. 4. Hysterisis Band Voltage Control

$$T_1 + T_2 = T_c = 1/f_c$$

Where HB and fc are Hysteresis Band and switching frequency respectively. The HB that has inversely proportional relation to switching frequency is defined as the difference between VH and VL (HB=VH-VL). In comparison with the other PWM methods, the hysteresis voltage control has a very fast response, a simple operation and a variable switching frequency.

Results and Discussion

Simulation Model of DVR in MATLAB

To verify the adopted control system, the total system of DVR was developed using the MATLAB/SIMULINK. As show in the below figs.7 to 9 the simulation results during voltage sag/ swell with the proposed control scheme. Voltage sag and swell are simulated by temporary connection of different impedances at the supply side bus.

Voltage Swell

The three phase voltage swell is simulated for 0.5 m sec from t=0msec to t=0.5 m sec as shown in Fig.10.The DVR regulate the load voltage to the reference voltage by injecting appropriate voltage component (negative voltage magnitude).

Voltage Sag

The three phase voltage sag is simulated for 0.5 m sec from t= 1.5 m sec to t=2 m sec as shown in Fig.8. As in the case of voltage swell, the DVR injects appropriate voltage to regulate the load voltage to reference voltage. The simulation results illustrates that the proposed Z-Source inverter control scheme restoring the DC voltage across the DC-link during the voltage is very effectively. The voltage swell and sag mitigation is performed with a smooth, stable and rapid DVR response.

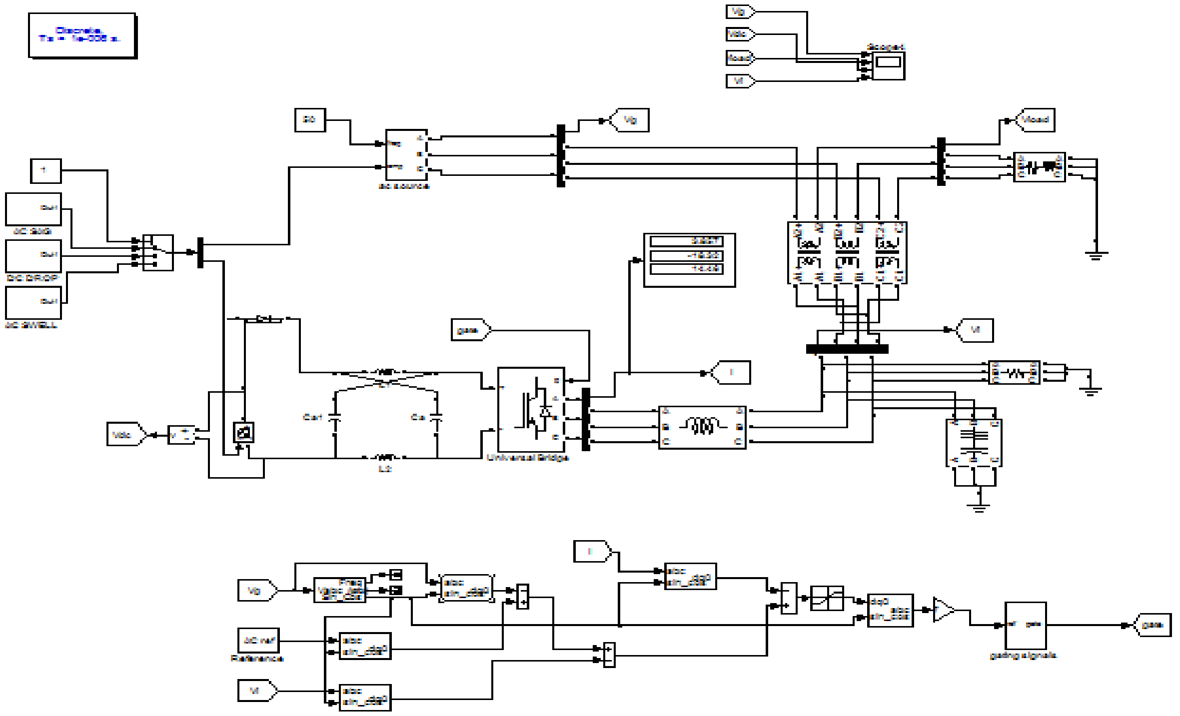

Fig. 6. Simulation Model of DVR

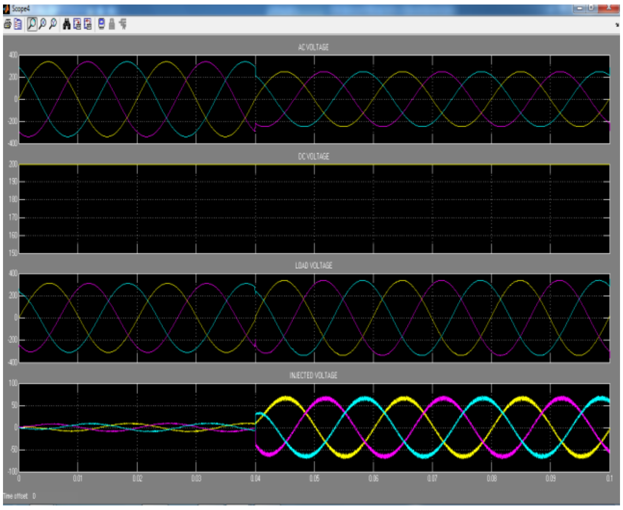

Fig. 7. Simulation Result for Voltage Sag and DVR Compensation

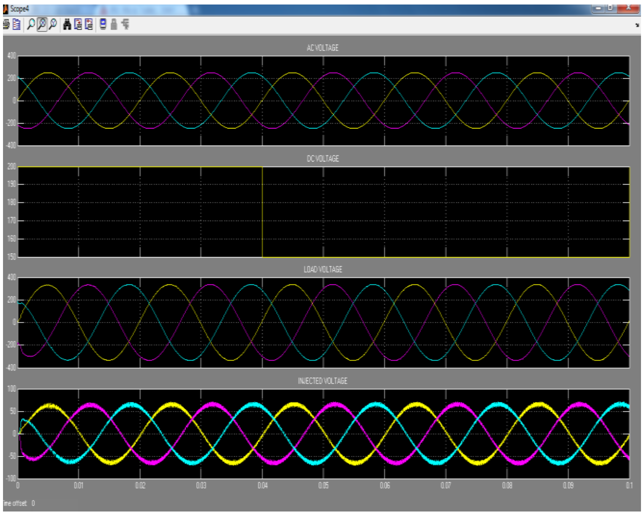

Fig. 8. Simulation result for DC Voltage Drop and the effect of DVR

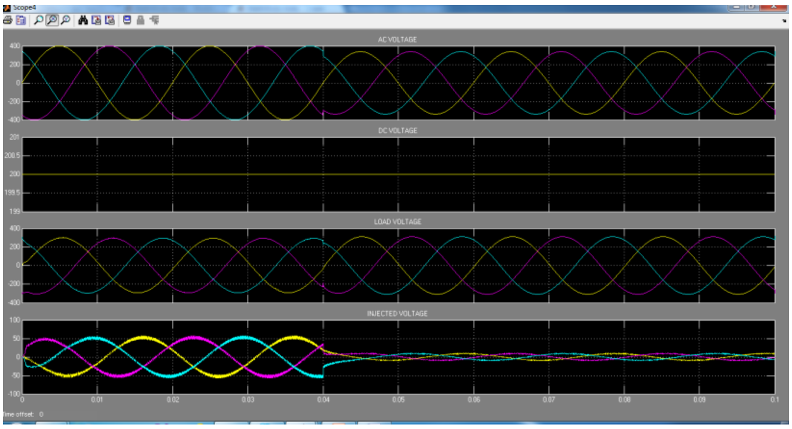

Fig. 9. Simulation Result for Voltage Swell and DVR Compensation

Conclusions

This project presented a new DVR topology derived from Z-source inverter, which enhances the capability of the DVR through better utilization of the stored energy. The Z-source based DVR design is well suited to this application, as sags and swells are intermittent or temporary occurrences lasting only tens of seconds in duration; and the Z-source makes full use of its storage for intermittent compensations. Moreover the Z-source has inherent EMI filtering characteristics vital for high quality power. The scope of this treatment and simulation is limited to balanced three phase load, although they can be applied to unbalanced and poly phase situations also.

Conflict of interest

Authors declare there are no conflicts of interest.

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