Z-SOURCE INVERTER BASED DVR FOR VOLTAGE SAG/SWELL MITIGATION

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Abstract*— Power quality is one of the major concerns in the era of power system. Failures due to disturbances like voltage sag, swell and interruption create high impact on production cost. Inorder to overcome this problem Dynamic Voltage Restorer is used, which eliminates voltage sag and swell in the distribution line. The DVR is a dynamic solution for protection of critical loads from voltage sags/swells. The DVR helps to restore constant load voltage and voltage wave form by injecting an appropriate voltage. A new topology based on Z-source inverter is presented in order to enhance the voltage restoration property of dynamic voltage restorer. Z-source inverter ensures a constant DC voltage across the DC-link during the process of voltage compensation. The modeling of Z-source based dynamic voltage restorer is carried out component wise and their performances are analyzed using MATLAB software.

***Index Terms*— Z-Source Inverter, Dynamic Voltage Restorer, Pulse Width Modulation, Total Harmonic Distortion**

I. INTRODUCTION

Modern power system has complex networks comprising of several generating stations and load centers which are interconnected through transmission lines. Power systems have numerous non linear loads that significantly affect the quality of the power supply. Deviation of voltage, current or frequency can be described as a power quality problem which may further result in incorrect operation or even collapse of equipments. Voltage sag, flicker, harmonic distortion, impulse transients and interruptions are various power quality problems we interface. Among those the most prominent ones are voltage sag and swell as it possesses a serious threat to industries since it can occur more frequently. Reactive power can be utilized to help voltage restoration by injecting voltage with a phase advance with respect to the sustained source-side voltage. As there was growing interest in mitigating power quality disturbance, the idea of custom power devices was introduced.

Voltage sag/sell which is a challenging problem to the utility industry can be compensated by injecting power into the distribution system. Dynamic Voltage Restorer (DVR) is one among the most significant custom power devices which is connected in series to the distribution system. It is usually installed in the distribution system between the supply and the critical load feeder at the point of common coupling (PCC). Other than voltage sag and swell compensation, DVR can also add other features like: line voltage harmonics compensation, reduction of transients in voltage and fault current limitations.

Dynamic Voltage Restorer comprises of a set of series and shunt converters connected back-to-back, three series transformers, and a dc capacitor and is normally installed on common dc link. The Pulse-width modulation of Z-source inverter has recently been proposed as an alternative power conversion concept as they have both voltage buck and boost property.

Generally, the DVRs consists of voltage source inverter based DVR (VSI-DVR), current source inverter based DVR (CSI-DVR) and impedance source inverter based DVR (ZSI-DVR). The main disadvantage of VSI-DVR is their buck (step-down) type output voltage characteristics thereby the maximum output voltage is limited by DC link voltage. The upper and lower devices of each leg cannot be gated on simultaneously, so a shoot-through would occur and destroy the devices. The shoot-through is a forbidden switching state for the VSI. The CSI-DVR is a boost type so its output voltage has to be greater than the DC voltage. For the application where a wide voltage range is desirable an additional DC-AC boost converter is needed. The additional power conversion stages increase system cost and lowers efficiency. At least one of the upper devices and one of the lower devices have to be gated on and maintain on at any time. Otherwise, an open circuit of the DC inductor would occur and destroys the devices. ZSI is a new type of converter in power conversion which has unique features that can overcome the limitations of VSI and CSI. The unique feature of the ZSI is that the output AC voltage can be any value between zero and infinity regardless of the DC voltage. That is, the ZSI is a buck-boost inverter that has a wide range of obtainable voltage. Unlike a VSI and CSI, the shoot-through state is not harmful and actually has been utilized in ZSI.

The Z-source converter employs a unique X-shaped impedance network on its dc side for achieving both voltage buck and boost capabilities this unique features that cannot be obtained in the traditional voltage-source and current source converters. The proposed system enables the compensation of long and significantly large voltage sags. Passivity-based dynamical feedback controllers can be derived for the indirect stabilization of average output voltage. The derived controllers are based on a suitable stabilizing “damping injection” scheme. Installation of the world's first Dynamic Voltage Restorer (DVR) was on major US utility system to protect a critical customer plant load from power system voltage disturbances. The proposed model of Z-Source inverter based dynamic voltage restorer for voltage sag/swell compensation is simulated using MATLAB software in this paper.

II. DYNAMIC VOLTAGE RESTORER

Dynamic voltage restorer was originally proposed to compensate for voltage disturbances on distribution systems. A typical DVR scheme is shown in Fig. 1. The restoration is based on injecting AC voltages in series with the incoming three-phase network, the purpose of which is to improve voltage quality by adjustment in voltage magnitude, waveshape and phase shift. These are significant voltage attributes as they can affect the performance of the load equipment. Voltage restoration involves energy injection into the distribution systems and this determines the capacity of the energy storage device required in the restoration scheme.

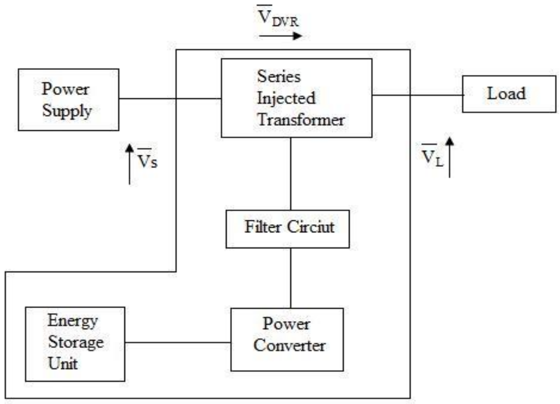

Fig.1. Block Diagram of DVR Circuit

The basic functions of the DVR are the detection of voltage sag/swell occurred in the power line and injection of balance voltage through injection transformer so as to maintain the desired load voltage. This can be achieved either by receiving or rejecting the active and reactive power. It basically consists of, Battery energy storage, Voltage Source Inverter, Passive Filter and Injection/ Booster Transformer.

A. Injection /Booster Transformer

The primary of the injection transformer is connected in series with the distribution line whereas the secondary of the injection transformer is connected to the DVR power circuit. The main functions of Injection /Booster Transformer are the increasing the voltage supplied by the filtered Voltage Source Inverter (VSI) to a desired level and isolation of the DVR circuit from distribution network.

B. Passive filter

It consists of an inductor and a capacitor. It can be placed on either high voltage side or low voltage side of the injection transformer. By placing it on inverter side higher order harmonic current do penetrate to the secondary side of the transformer. The main objective of the filter is to keep the harmonic voltage content generated by the inverter within the permissible level.

C. Power Converter

Its basic function is to convert the DC Voltage supplied by the energy storage device to a sinusoidal voltage at any required frequency, magnitude and phase angle. There are four types of switching devices: Metal Oxide Semiconductor Field Effect Transistor (MOSFET), Gate Turn off thyristor (GTO), Insulated Gate Bipolar Transistor (IGBT) and Integrated Gate Commutated Thyristor (IGCT). Each type has its own benefits and drawbacks.

D. DC energy Storage device

It is used to supply the real power requirement for the compensation during the period of voltage sag. Lead-acid batteries, Super Conducting Magnetic Energy Storage (SMES), Flywheels and Super capacitors can be used as the storage devices. For DC drives such as capacitors, batteries and SMES, DC to AC conversion (inverters) is needed to deliver power, whereas for flywheel, AC to AC conversion is required.

Today in phase voltage injection technique is widely used in DVR control where the load voltage V2 is assumed to be in-phase with the pre-sag voltage. As the DVR is required to inject active power into the distribution line during the period of compensation, the capacity of the energy storage unit can become a limiting factor in the disturbance compensation process. If capacitors are used as energy storage, the DC-link voltage will decrease with the dwindling storage energy during compensation.

The corresponding phasor diagram describing the electrical conditions during voltage sag is depicted in Fig. 2, where only the affected phase is shown for clarity. Let the parameters I1, 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. 2, only in-phase compensation is considered. Here the injected voltage is in phase with the supply voltage ($\alpha = \delta$).

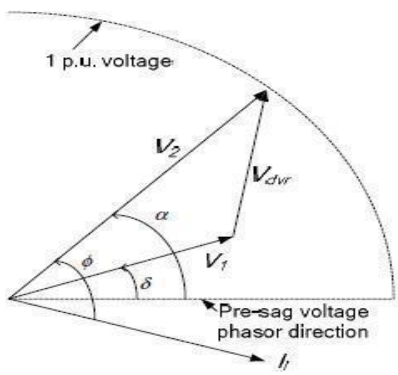

Fig.2. Vector Diagram of Voltage Injection Method

III. Z-SOURCE INVERTER

Z-source Inverter has X-shaped impedance network on its DC side, which interfaces the source and inverter H-bridge. It facilitates both voltage- buck and voltage - boost capabilities. It also has an impedance network composed of split inductors and two capacitors. The supply can be either DC voltage source or DC current source. Z-Source inverter can be of current source type or voltage source type. Fig. 3 depicts the general block diagram of Z-Source inverter. The impedance network consists of two inductors and capacitors. This combination network circuit provides the energy storage and filtering element for impedance source inverter. The second order filter property is provided by impedance source inverter. This is more efficient to suppress voltage and current ripples. Another peculiarity is that inductor and capacitor requirement should be smaller as compared to the traditional inverter.

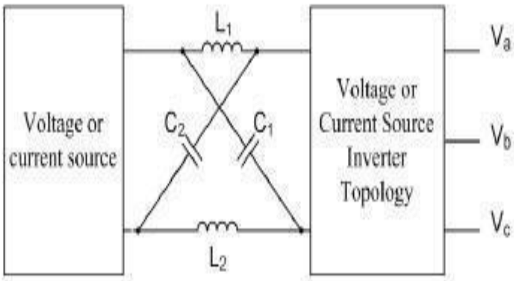

Fig.3. General Block Diagram of Z-Source Inverter

The Z-Source Inverter has been an alternative to the existing inverter topologies with many inherent advantages. The Z-Source Inverter has an additional zero vector called as shoot-through switching state, which is forbidden in the traditional voltage and current source inverter. Compared to VSI and CSI, Z-Source Inverter is less affected by the EMI noise.

In Table I it is shown that the single-phase Z -Source Inverter has five switching modes of which two active modes in which the dc source voltage is applied to load, two zero modes in which the inverter's output terminals are short circuited by *S1* and *S3* or *S2* and *S4* switches and a shoot-through mode which occurs as two switches on a single leg are turned on are present.

Table 1. Switching Modes

S_4	S_3	S_2	S_1	Switching mode
1	0	0	1	Active mode
0	1	1	0	
0	1	0	1	Zero mode
1	0	1	0	
0 or 1	0 or 1	1	1	Shoot-through mode

The shoot through period which is the time period when two switches of the same leg are gated allows the voltage to be boosted to the required value when the input dc voltage is not upto the required level. Otherwise the shoot through state is not used thus enabling the ZSI to operate as both a buck-boost inverter unlike the traditional voltage source and current source inverters. The merits of the new topology are:

- Same voltage boost capability is retained by providing same polarity of capacitors but with a reduced value of voltage stress across them.
- The inrush current at startup is effectively reduced since there is no path for current at start-up.
- The current and the voltage ripples in both the topologies are same, but the current across the inductor in the existing topology decreases in the non shoot through state. In the existing topology, the voltage across the capacitors is given by

$$Vc = (1- D)Vs/(1-2D) \qquad (1)$$

And in the new topology it is given as,

$$Vc = [D/(1-2D)] /Vs \qquad (2)$$

Where Vc = capacitor voltage, D = duty ratio of the shoot through state and Vs = supply voltage.

The Z-Source Inverter can be operated in both boost and buck operations depending on values of modulation index (M) of Pulse Width Modulation. If M is greater than 0.5 it acts as boost inverter, if M is less than 0.5 then it acts as buck inverter.

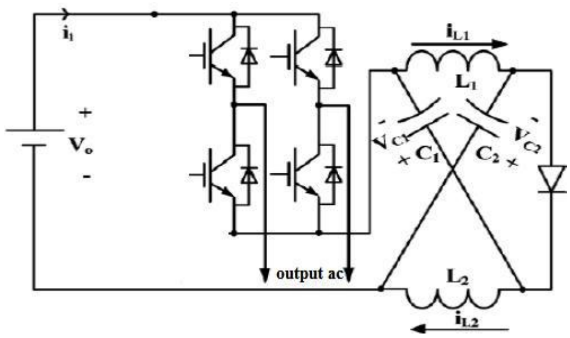

Fig.4. Proposed Z-Source Inverter topology

IV. SYSTEM CONTROL SCHEME

ZSI integrated DVR is having a closed loop control technique in which a PI controller is used to regulate the error signal and the output of which is obtained as the control signal. The output voltage from the load side after the occurrence of fault is sent to a summer block where it is compared along with a reference voltage signal. The error signal generated is then sent to a PI controller .Through the controller, the incoming error signal is tuned and thus the control signal is obtained. This control signal is utilized for the generation of firing signals of the switching devices in the voltage source inverter section of a Z- source inverter.

Pulse Width Modulation technique is used for controlling the output pulses. Simple boost control technique is used for the purpose of pulse width modulation. The modulation index also called as amplitude modulation ratio (M) which is the main control factor is defined as the ratio of amplitude of reference wave to the amplitude of carrier wave. The linearity between the modulation index and the output voltage is achieved by under modulation index ($M < 1$). Actually, this control strategy inserts shoot through in all the PWM traditional zero states during one switching period. This maintains the six active states unchanged as in the traditional carrier based PWM.

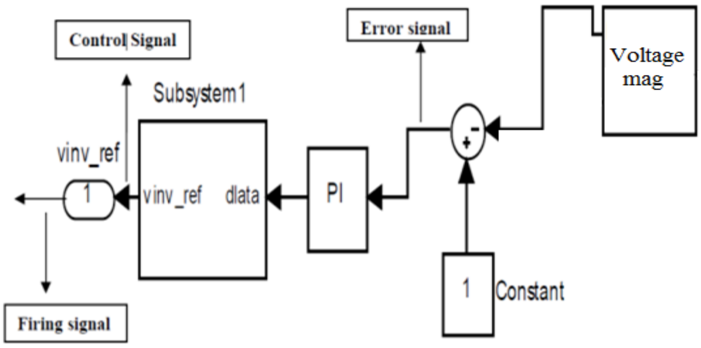

Fig.5. Block diagram of control scheme

V. SAGAND SWELLCOMPENSATION OFPROPOSED SYSTEM

A. Voltage Sag Compensation in DVR system

Closed loop control operation is performed for the required value of the voltage as per need. The simulink model of closed loop control of voltage sag compensation in a DVR system is shown in the Fig.6. During the occurrence of a fault, the DVR system starts functioning so as to neutralize the error in the system. Initially the system was subjected to 25% voltage sag. The voltage during the period of sag is sent to subsystem 1 which is the rectifier part. The subsystem1 converts ac voltage to dc.

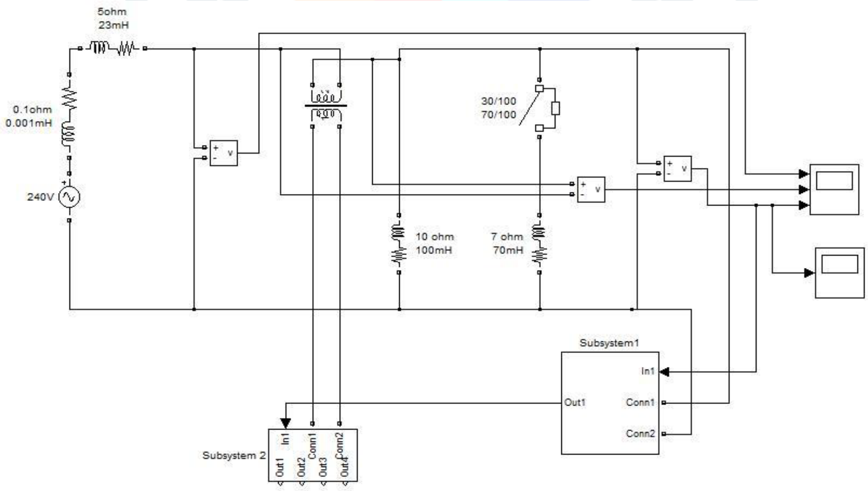

Fig.6. Closed loop control of Voltage Sag Compensation in a DVR system

In the Fig.7 subsystem 1 consists of resistor section and the AC output voltage is rectified to DC supply and then a reference voltage is given for the error. This error is sent to the PI controller. The saturator value is given out as pulses which are the input for controlling the Z-Source inverter. Pulse Width Modulation technique is used for controlling the firing pulses to the Z-Source Inverter.

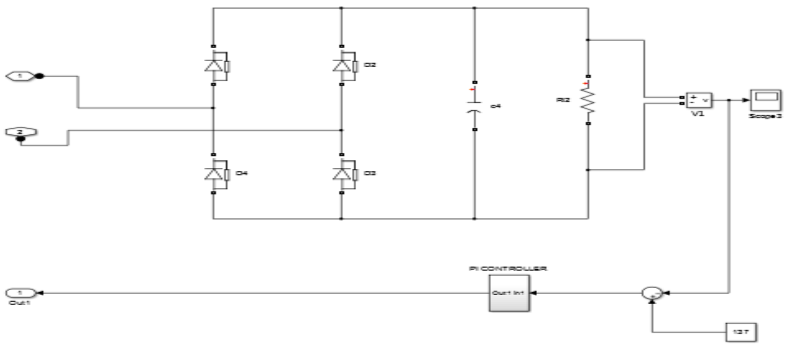

Fig.7. Subsystem 1of the Closed loop control of Voltage Sag Compensation in a DVR System

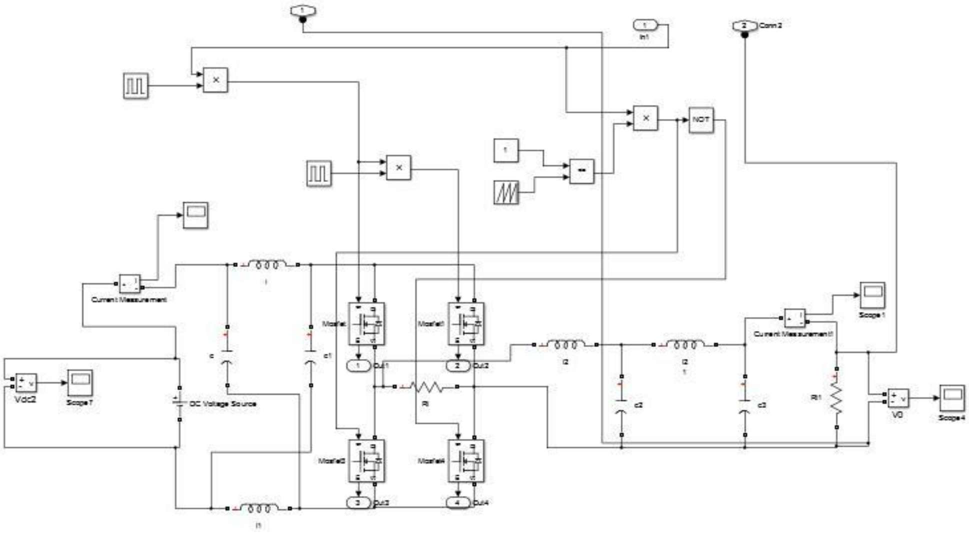

Fig.8. Z-Source Inverter section of Closed Loop Control of Voltage Sag Compensation DVR system

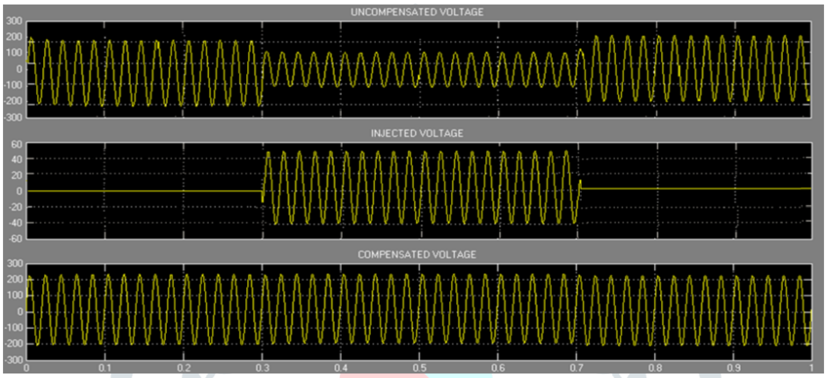

Fig.9. Simulation results of Closed Loop Control DVR under 25% sag (A. Uncompensated Voltage, B. Injected DVR Voltage, C. Compensated Voltage)

In the Fig 8, the Z-Source inverter is controlled by the PI Controller. The Z-Source starts conducting when it obtains the pulse from the saturator. Fig. 9 shows the output waveform of closed loop control of voltage sag compensation. Fig. 9.A shows the uncompensated AC voltage with 25% sag. Fig. 9.B shows the injected DVR voltage. Fig. 9.C gives the compensated output voltage.

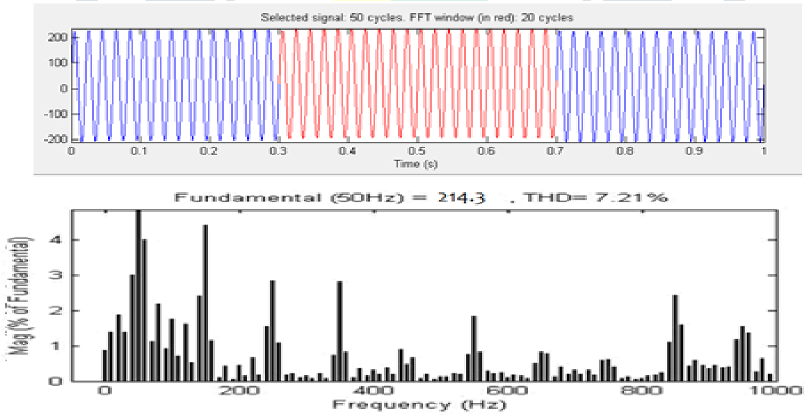

Fig.10. FFT Analysis of Closed Loop Control of Voltage Sag Compensation in a DVR System

In Fig.10, the Fast Fourier Transform (FFT) analysis is performed for the compensated output voltage. Here the Total Harmonic Distortion (THD) value is 7.21%. The simulation was done under transient performance at the sag appearance and recovery was observed. The load voltage is maintained at the same value throughout the simulation. Thus voltage sag compensation using closed loop control is simulated more precisely.

A. Voltage Swell Compensation in DVR system

The simulink model of voltage swell compensation using closed loop control in a DVR system is shown in Fig.11. Initially the system was subjected to 30% voltage swell. Subsystem 1 of the closed loop DVR system contains resistor section and the PI controller. The AC output voltage is rectified to DC voltage and then a reference voltage is given for the error signal. This error is sent to the PI controller. Sufficient value is set in the saturator for giving the pulses for controlling the Z-Source inverter.

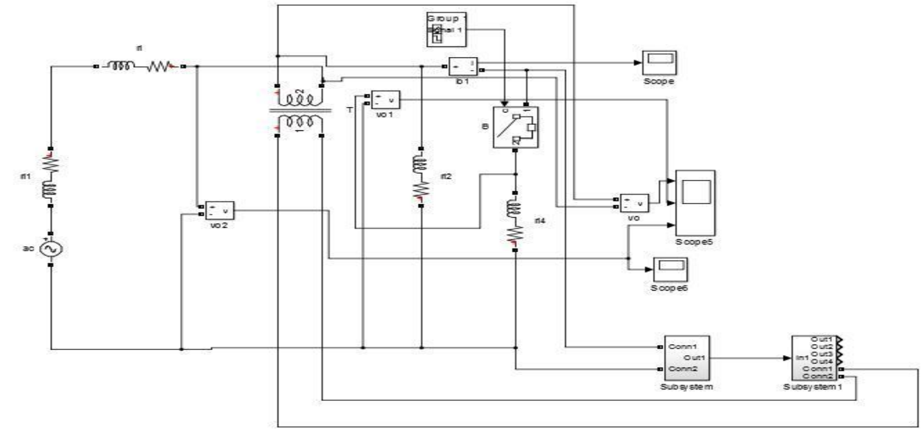

Fig.11. Closed loop control of Voltage Swell Compensation in a DVR system

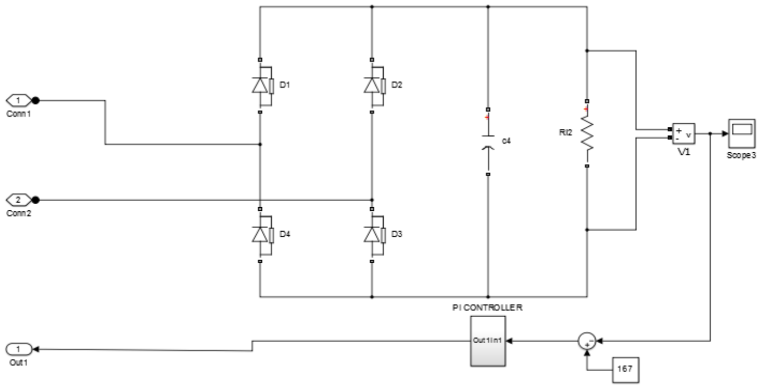

Fig.12. Subsystem 1of the Closed loop control of Voltage Swell Compensation in a DVR System

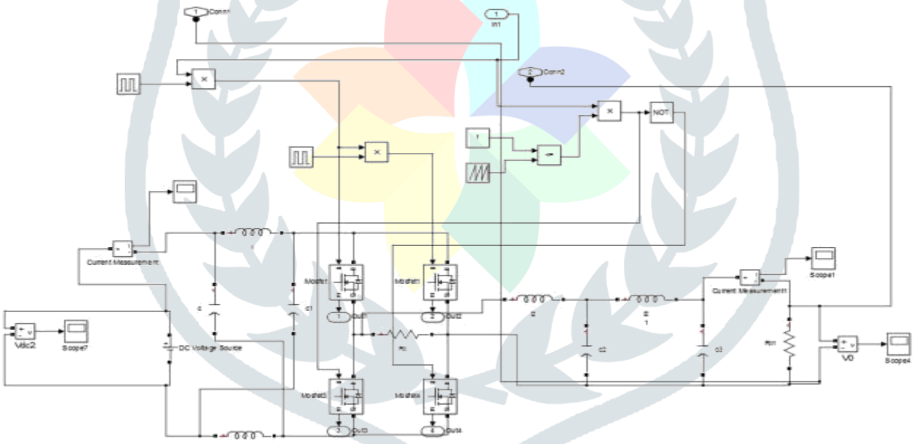

Fig.13. Z-Source inverter section of Closed Loop Control of Voltage Swell Compensation in a DVR System

Fig.14 shows the output waveform of closed loop control of voltage swell compensation. Fig. 14.A shows the uncompensated AC voltage with 30% swell. Fig. 14.B is the injected DVR voltage. Fig. 14.C shows the compensated output voltage.

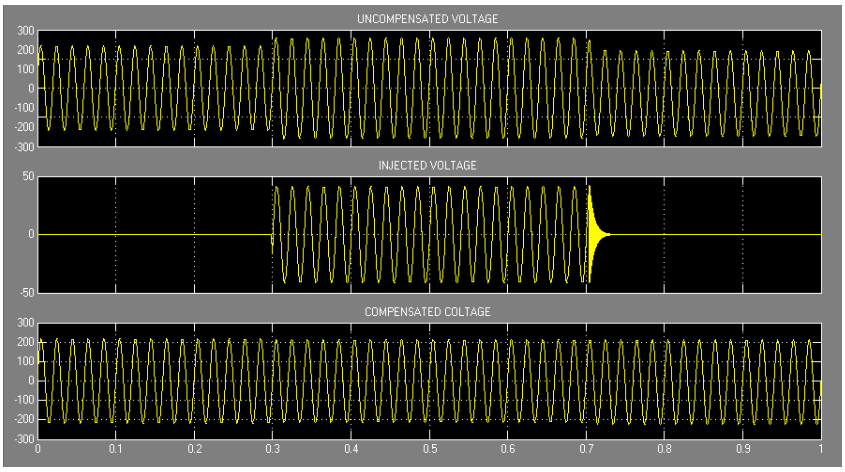

Fig.14. Simulation results of Closed Loop Control of DVR with 30% swell (A. Uncompensated Voltage, B. Injected DVR Voltage, C. Compensated Voltage)

In Fig.15, FFT analysis is performed for the compensated output voltage. Here the THD value is 6.92%. The simulation was done under transient performance at the swell front and recovery was observed. The load voltage is maintained at the same value throughout the simulation. Thus voltage swell compensation using closed loop control is simulated.

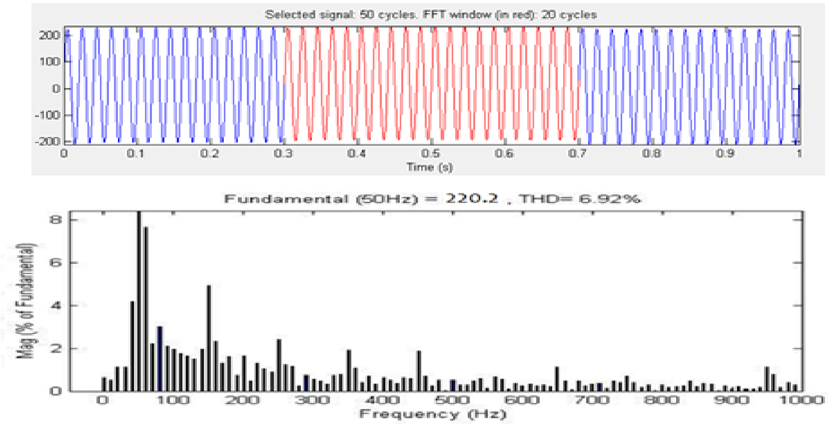

Fig.15. FFT Analysis of the Closed Loop Control of Voltage Swell Compensation in a DVR System

VI. CONCLUSION

DVR is an effective custom power device for mitigating voltage sag/swell in the distribution system. In case of external disturbances the proposed DVR injects appropriate voltage component to dynamically correct any deviation in supply voltage in order to maintain balanced and constant load voltage at nominal value.. In this paper Z-Source inverter based DVR is modeled and the same is installed in the distribution system to provide required load side compensation. The control technique is designed using in-phase compensation and used a closed loop control system to detect the magnitude error between voltages during pre-sag and sag periods. The modeling and simulation of closed loop control of voltage sag/swell mitigation were done using MATLAB software. The simulation results show that the developed control technique with proposed single phase DVR is simple and efficient.

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