A NOVEL LOAD SIDE COMPENSATION FOR VOLTAGE SAG / SWELL USING DYNAMIC VOLTAGE RESTORER

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Abstract: Power quality is one of major concern in modern era and has become important with the introduction of very advanced devices, whose performance is very sensitive to the quality of power supply. Power quality problem such as non-standard voltage, current or frequency leads to equipment failures of end user. The major power quality problems are voltage sag, swell and harmonics. To solve this problem, custom power device called Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern device used in the power distribution networks.

The objective of the proposed DVR is to compensate the voltage sag, swell and harmonics by load side compensation. To compensate the voltage distortions for long duration, DVR without energy storage and load side connected shunt converter topology is proposed. Based on this topology, the DVR consists of uncontrolled rectifier for giving DC supply to Z- Source converter through DC link. Z- Source Converter based topology is used in order to enhance the voltage restoration property of the device.

The control of shoot through capability of Z- Source Inverter using IGBTs provides ride-through capability during voltage sag and swell, which increases its reliability. A control scheme called Hysteresis Voltage loop controller is proposed to synthesis the desired injecting voltage. Simulation and experimental results are provided to demonstrate the validity and the features of the proposed novel method.

Key words: Dynamic Voltage restorer (DVR), Sag, Swell, Harmonics, Hysteresis Voltage Controller, Z-Source Inverter.

1. Introduction

A situations in which the waveform of the supply voltage or load current deviating from the sinusoidal waveform at rated frequency with amplitude corresponding to the rated rms value for a three-phase system is called Power Quality (PQ). Power quality disturbances are impulsive and oscillatory transients, voltage sag, voltage swell, harmonics and flicker [1]. Quality of electric power is one of the major concerns for electrical end user. If the electric power is not up to the needs then it is called as quality lagging [2].

The Dynamic Voltage Restorer (DVR) is a series compensator intended to protect sensitive loads from the effects of voltage sag and swell at the point of common coupling (PCC). DVR consists of a series-connected injecting transformer, impedance source inverter, filter, load side shunt converter, uncontrolled rectifier and dc-link capacitor [3]. The basic operation of DVR is injecting a voltage of the required magnitude, frequency and phase angle in series with distribution feeder to maintain the desired amplitude and waveform for load voltage, even during times when the voltage is unbalanced or distorted. Many topologies and control methods have been presented for DVRs, two topologies take energy from the grid and the other two topologies take energy from the energy storage devices during the voltage sag [5]. Among the various topologies, DVR with no storage and load side connected shunt converter has highest rank in compensating both balanced and unbalanced voltage distortions.

The DVR is to transfer the voltage sag and swell compensation value from DC side of the inverter to the injected transformer after the filter. The compensation capacity of a particular DVR depends on the maximum voltage injection capability, and maximum amount drawn from the distribution line and the active power that can be supplied by the DVR Sunil Kumar Gupta [6]. When voltage disturbance occurs, active power or energy should be injected from DVR to the distribution system [7] As standard information tracking (or) detection methods such as the Fourier transform (or) phase locked loop (PLL) are required for fast evaluation of parameters [8]. This DVR or a voltage-sag compensator consisting of a set of series and shunt converters connected back-to-back, three phase series transformers, a dc capacitor installed on the common dc link [9][10]. The DVR is based on forced-commutated Impedance source converter (ZSC) has been proved suitable for the task of compensating voltage sags/swells. Z-Source converters control method for implementation of dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion. It employs a unique impedance network (or circuit) to couple the converter main circuit to the power source, load or another converter which is used for providing unique features that cannot be observed in the traditional voltage and current source converters, where an inductor and a capacitor are used respectively. By controlling the shoot-through duty cycle, the z-source inverter system using IGBTs provide ride-through capability during voltage sags, voltage swells and extends output voltage rang[14],[15]. The buck and boost modes of operation is achieved by adjusting the shoot through periods.

Further, the shoot-through state caused by the electromagnetic interference will not destroy the circuit [16][17]. Therefore a more reliable single stage power converter for both buck and boost operation is obtained. The hysteresis current control technique has proven to be the most suitable solution for applications such as active filters, machine drives, and high-performance converters. The harmonic performance of a hysteresis controller can be improved by varying the hysteresis band to achieve a constant switching frequency[18],[19]. The Hysteresis loop control method adopted for DVR injection voltage control can have similar characteristic as the PI controller, with high gains at both the positive and negative line frequencies (±50 Hz) and give almost zero steady-state error for the positive and negative sequence components control for unbalanced voltage regulation by proper selection of the weighting functions along with explicitly specified degree of robustness in the face of parameter variations. An inner current feedback loop is also employed for transient and stability improvement. The multi-loop DVR controller would guarantee both good transient performance and steady-state error tracking [20],[21]. The design of the DVR voltage control is consists of two loops, namely i) Hysteresis outer voltage loop and ii) Hysteresis inner current loop. Similar to a typical multi-loop control design approach, the DVR controller design is an iterative process. A Hysteresis loop controller is first designed with specified robustness and error tracking performance based on a given plant including inner current loop. The inner current regulator is then fine-tuned with consideration of its influence on the synthesized Hysteresis loop controller and the generated new plant and its relations to load current disturbance rejection capability. After the inner current loop regulator gain is determined, a Hysteresis voltage controller is finally obtained based on the best-tuned inner current loop. Based on the reference voltage and distorted voltage, the error voltage generated as pulse signals. This pulse signals given to switches of the Z source inverter, it gets injected compensated voltage.

2. Basic Operation of DVR

Dynamic voltage restorer (DVR) is a series connected custom power device used to compensate voltage sags and swells in the distribution systems. DVR is one of the most effective solutions for "restoring" the quality of voltage at its load-side terminals when the voltage at its source-side terminals is disturbed. In this paper, load side compensation is employed. The load voltage is taken to uncontrolled rectifier in order to convert the ac voltage into dc voltage. This dc voltage is given as supply to the ZSI through the DC link capacitors John Godsk Nielsen and Frede Blaabjerg (2005). DVR consist of Voltage source inverter, series injection transformer and energy source unit. Voltage source inverter has low harmonics in the output voltage but it has a disadvantage that it can perform buck operation. The Z-source inverter has been an alternative to existing inverter topologies with many inherent features and it facilitates both voltage-buck and boost capabilities. Reliability is high because it is less affected to EMI
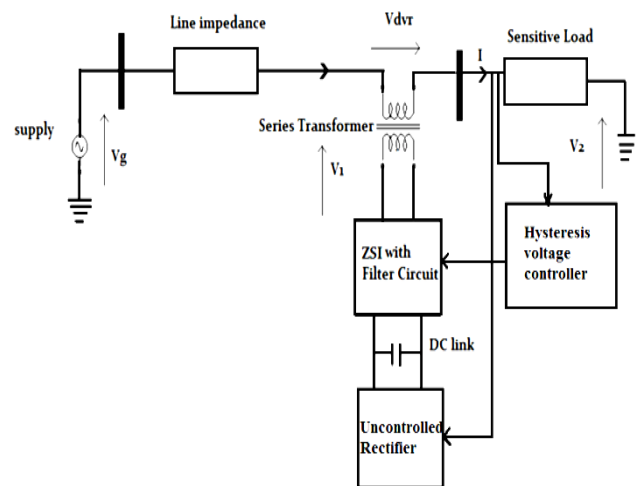

Fig 1 Schematic diagram of a DVR System

If the injected voltage (VC) is in quadrature with the load current then power requirement of DVR is zero if we neglect losses. To raise the voltage at the load bus, the injected voltage by the DVR is capacitive and VL leads VS1. In figure it shows the in-phase compensation for comparison and it is noted that the current phasor is determined by the load bus voltage phasor and the power factor of the load..
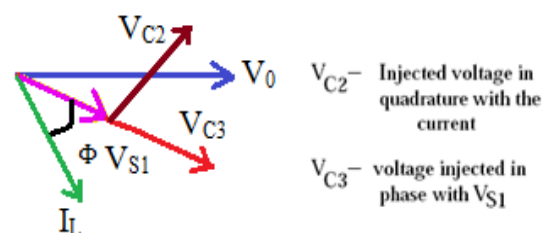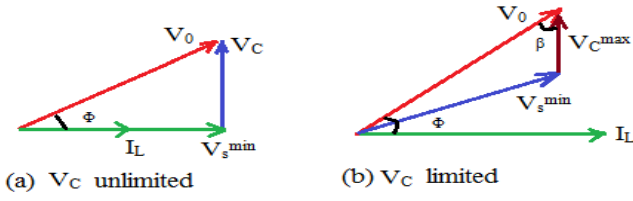
Fig.2 DVR control strategy

(a) V$_C$ unlimited   (b) V$_C$ limited

Fig.3 Phasor diagrams determining V_s^{min} with quadrature injection

Implementation of the minimum energy compensation requires the measurement of the load current phasor in addition to the supply voltage. The DVR supplies only reactive power when VC is in quadrature with the load current. However, full load voltage compensation is not possible unless the supply voltage is above a minimum value that depends on the load power factor..

$$V_s^{min} = V_0 \cos . V_s^{min} \qquad (1)$$

When the magnitude of V$_C$ is not constrained, the minimum value of V$_S$ that still allows full compensation is Where Á is the power factor angle and V$_o$ is the required magnitude of the load bus voltage. If the magnitude of the injected voltage is limited, the minimum supply voltage that allows full compensation is given by

$$V_s^{min} = V_0 \cos . V_s^{min} = \left[V_0^2 . V_c^{max} . \sin + \left(V_c^{max} \right)^2 \right] \qquad (2)$$

Note that at the minimum source voltage, the current is in phase with VS for the case (a). If the source voltage magnitude is less than Vsmin, the DVR has to supply non-zero energy to provide full compensation. But it is possible to devise a strategy that results in minimum energy requirement for full compensation. The system impedance depends on the fault level of the load bus. When the system voltage drops, the DVR injects a series voltage with the help of injection transformer, and the desired load voltage magnitude can be maintained. The DVR series injected voltage can be written as

$$V_{DVR} = V_L - Z_{TH} . I_L - V_{TH} \qquad (3)$$

Where

V$_L$:   The desired load voltage magnitude

Z$_{TH}$:   The load impedance.

I$_L$:   The load current

V$_{TH}$:   The system voltage during fault condition

The load current IL is given by,

$$I_L = \frac{[P_L + jQ_L]}{V} \qquad (4)$$

The DVR complex power injection can be written as,

$$S_{DVR} = V_{DVR} * I_L^* \qquad (5)$$

3.   Novel Proposed DVR

The DVR consists of mainly a Z- source converter, passive filter and a control system to regulate the output voltage of ZSC. The DVR injects ac voltage in synchronism with the supply voltage. These voltages have control over amplitude, phase angle and frequency which enable the DVR to restore the quality of the voltage at the load side when the supply voltage is distorted..
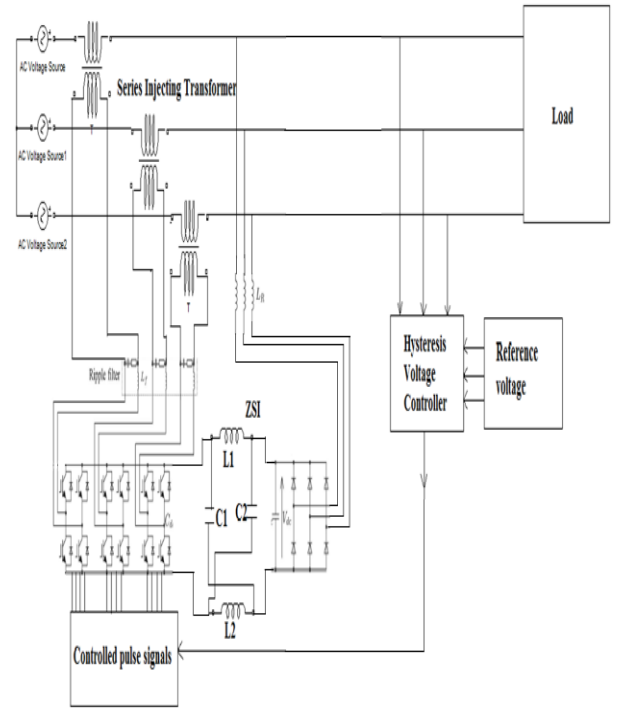

Fig.4. Block Diagram of the Novel proposed DVR

A shunt converter is connected to the load side is uncontrolled charged rectifier. The load may be linear or non-linear. The output of rectifier feeds DC-DC Step up converter (dc voltage). These boost output voltage can feed the Z-source inverter, which is connected in series to the power supply through series transformer. The impedance network is used to boost or buck the input voltage depends on the boosting factor. Three phase supply voltage is taken to the hysteresis controller where, they get compared with the reference voltage for the detection of voltage distortion. Based on the error signal it generates digital pulses. Hysteresis controller produced controlled switching pulses to Z-source inverter. The

hysteresis controller can control the voltage sag, swell & harmonic by producing PWM signal based on the error with their reference voltage. The injection transformer serves the purpose of isolating the load from the system.

3.1 Detection of Sags/Swell in Supply Voltage

In this paper, monitoring of V_d and V_q is used to return the magnitude and phase load voltage to the magnitude and phase reference load voltage. 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.

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = P \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (6)$$

$$P = \begin{bmatrix} \cos\theta & \cos\left(\theta - \dfrac{2\pi}{3}\right) & \cos\left(\theta - \dfrac{4\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \dfrac{2\pi}{3}\right) & \sin\left(\theta - \dfrac{4\pi}{3}\right) \\ \dfrac{1}{\sqrt{2}} & \dfrac{1}{\sqrt{2}} & \dfrac{1}{\sqrt{2}} \end{bmatrix} \quad (7)$$

$$\theta = \theta_0 - \int_0^t wt.dt \quad (8)$$

The detection block detects the voltage sag/swell. this block generates the reference load voltage if voltage sag/swell occurs . The sag detection strategy is based on root means square (rms) of the error vector. The addition of Closed loop load voltage feedback and implementation in the frame 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 ZSI to produce the preferred voltage with the use of the Hysteresis voltage control.

3.2 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 (V_{inj}) and a reference voltage of DVR (V_{ref}) which produces proper control signals K.Ravi Chandrudu and P.Sangameswara Raju (2011), Huifeng Mao et.al. (2012), H.Ezoji et.al (2009), Walid Emar et.al.(2011). 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).
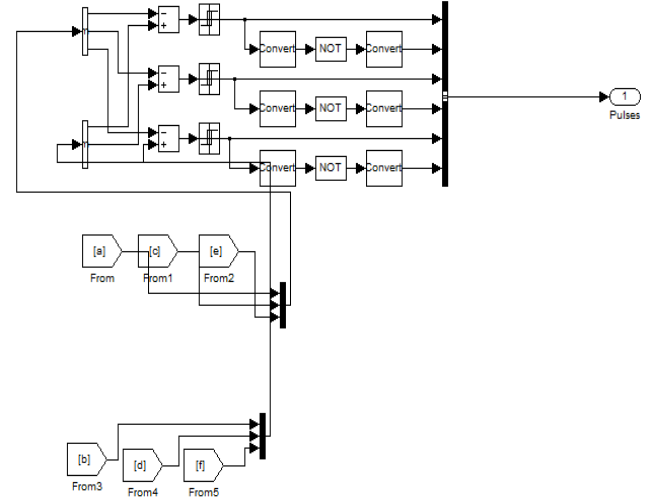

Fig. 5 Hysteresis Controller

A maximum obtainable load current can be created up to *R/Vdc* (R is the load resistance) and for increasing the load current, it is needed to apply the shoot through states in modulation scheme in order to boost the output voltage. For this purpose, the shoot through duty cycle can be estimated from below equation

$$D_0 = \frac{T_0}{T} = \frac{V_i - V_{dc}}{2V_i - V_{dc}} \quad (9)$$

3.3 Harmonic Filter

A Low pass filter consists of a capacitor and an inductor. It can be placed either at the high voltage side or the inverter side of the injection transformer. The working of injection transformer is it filters out the switching harmonic components from the injected voltage. The higher order harmonics are prevented from penetrating into transformer by placing the filter at the inverter side, thereby it reduces the voltage stress on the injection transformer. When the filter is placed on the high voltage side, because harmonics can penetrate into the high voltage side of the transformer, a higher rating transformer is necessary.

3.4 DC Link

The energy storage unit consists of capacitor. The rectifier unit acts a source for ZSI. The rectified output voltage is fed to the Impedance network of the ZSI. The purpose is to supply the necessary energy to

the ZSI through a DC link for the generation of injected voltages. Ultra capacitors and Batteries are the common types of energy storage devices. The capacity of the stored energy directly determines the duration of the sag which can be mitigating by the DVR C. Gopinath and R.Ramesh (2011), Wei Qian et.al (2011), T. Meenakshi and K. Rajambal (2010), K.Ravi Chandrudu and P.Sangameswara Raju (2011).

3.5   Z Source Inverter (ZSI)

This ZSI employs a unique impedance network coupled with the inverter main circuit to the power source. The impedance network not only is used to buck or boost the input voltage depends upon the boosting factor but also acts as a second order filter. This should require less inductance, less capacitances and their sizes are in small. This impedance network, constant impedance output voltage fed to the three phase inverter main circuit [14]-[17]. The inverter main circuit consists of six switches. Gating signals are generated by the Hysteresis voltage controller. The Z-source network makes the shoot-through zero state possible and shoot-through zero state provides the unique buck-boost feature to the inverter.

4.   Simulation Results

A 3Φ, 415V, 50 Hz supply side can feed the two or more loads through distribution line, sudden increase in load which results dip in voltage. In distribution line, due to fault occurrence, voltage distortion takes place. This can be avoided by using load side compensation of DVR with ZSC instead of VSC. Fault is occurred at time 0.5s; the DVR gets activated and can inject the required voltage. This range of distortion can be detected by taking voltage for sag detection or swell detection with the help of HVL controller. The fault is cleared at 0.8s, DVR deactivated. DC supply for energy storage of DVR system is taken from load side. Hence this compensation called load side compensation. From load side, three phase voltage is taken and fed to uncontrolled rectifier, which converts three phase ac voltage into uncontrolled DC voltage. The uncontrolled DC voltage converted into controlled DC voltage with help of DC link capacitor of ZSC. The DC link replenishes the DVR for long duration voltage sags.
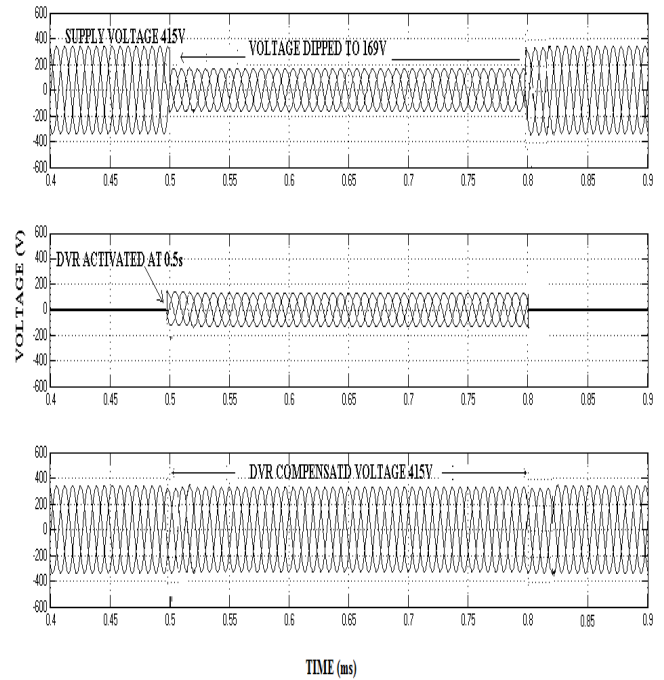

Fig. 6. Simulation results of three phase voltage sag compensation using DVR

Three phase fault occurred in distribution line at 0.5s. At this time, the supply voltage (415V) gets dipped to 60% (169V). Simultaneously, DVR activated at 0.5s and injects the distorted voltage 60%, voltage gets protected by DVR.
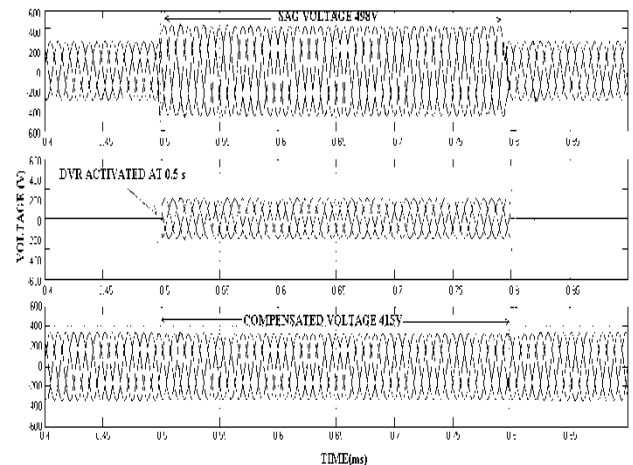

Fig.7. Simulation results of three phase voltage swell compensation using DVR

Sudden removal of large loads in the distribution line at 0.5s, the voltage swell occurred, the supply voltage (415V) gets swelled to 20% above the normal (498V). Simultaneously, DVR activated at 0.5s and injects the compensating voltage by 20%, voltage gets protected by DVR.

5. Hardware Results

The hardware implementation of the experimental prototype of the proposed load side compensation Dynamic Voltage Restorer is presented. The general experimental set-up is presented for single phase DVR system. The overall control system is implementing by using operational amplifier because of cost effective.

5.1 Hardware Setup and Results

Supply Transformer (230/50V) is step down transformer feeding 50V nonlinear RL load through bridge rectifier. There are many step down transformer for different circuit like control circuit and isolation circuit. In isolation circuit, the transistor requires 12V DC so there is (0-12V) step down transformer which feeds diode rectifier hence it converts the 12V Ac into 12V DC. Next one is center tapped transformer (18-0-18) V, which is taken as supply voltage for control circuits where op-amp (LM324) used. For control circuit input reference voltage and output feedback voltage required for voltage distortion detection hence step down transformer (230/6V), 300 mA. A series injecting transformer (20/10V) is used for injecting the voltage when any voltage distortion occurs. The output voltage is taken across series injecting transformer and non-linear load, load voltage will appear. Then vary the rheostat to maximum the supply voltage gets dipped, when change the toggle switch position DVR compensation takes place. For swell creation add special type inductor load with RL load keep the load for some moment, when suddenly remove the Inductor swell get created.
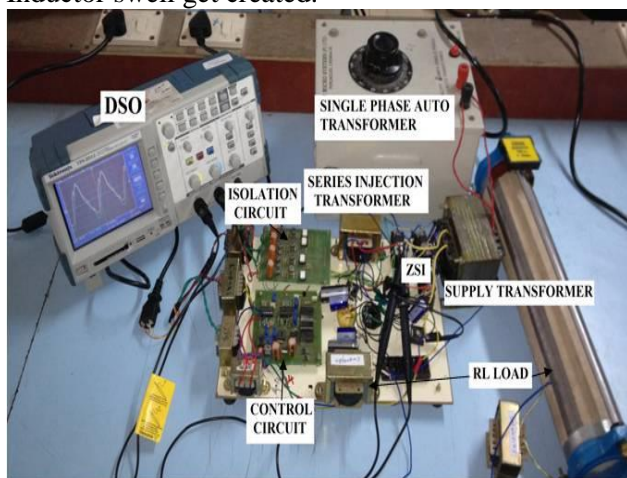

Fig. 8. Overview of the Hardware Setup

5.2 Results

The following graphs show the experimental results of implementation of DVR system with Load side compensation along with Z-source inverter topology to enhance the performance. Various voltage waveforms during sag as well as normal conditions are shown below. For the cost constraint, the hardware implemented with the supply voltage of 50V in single phase DVR system. Sag distortion is created by increasing the load requiring voltage (i.e) adding another load and swell is created by sudden removal of load. DVR is functioned by switch connected is series with the distribution line, so that we can create distortions and get compensation.

In this system non-linear load is used, so load draws current with harmonics. So load voltage gets distorted due to harmonics.
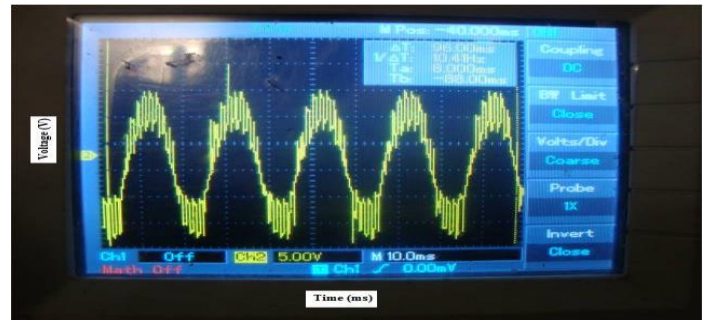

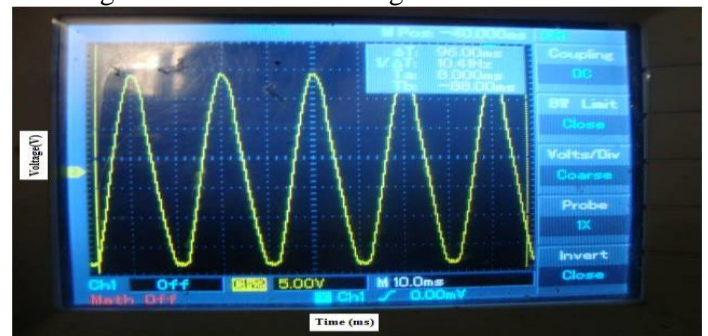Fig.9 Distorted Load Voltage due to harmonics

Fig.10 Compensated Load Voltage when DVR activated

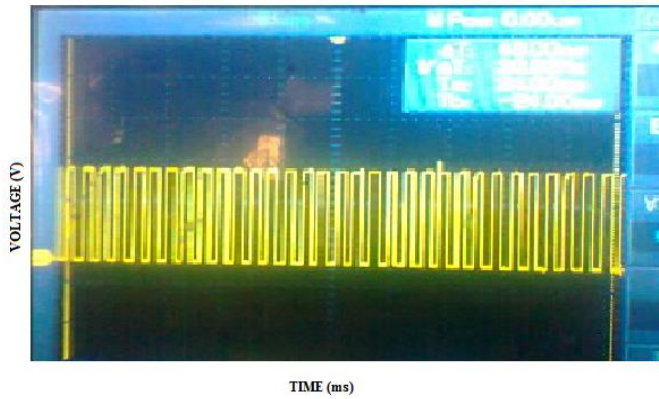Fig.11 Control pulses from Control Circuit

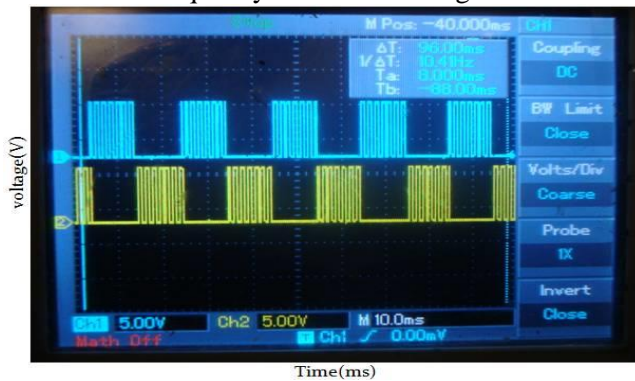Fig.12 555 Timer generating High Frequency control Pulse signal

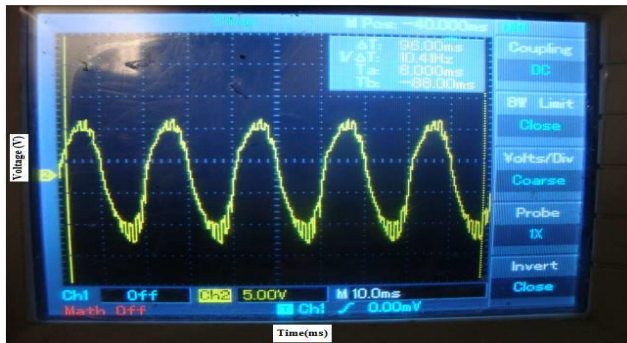Fig.13 Generating high frequency gate pulses for IGBT Switches

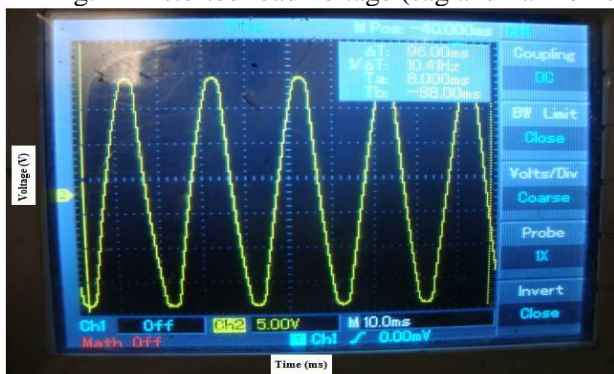Fig.14 Distorted load voltage (sag and harmonics)

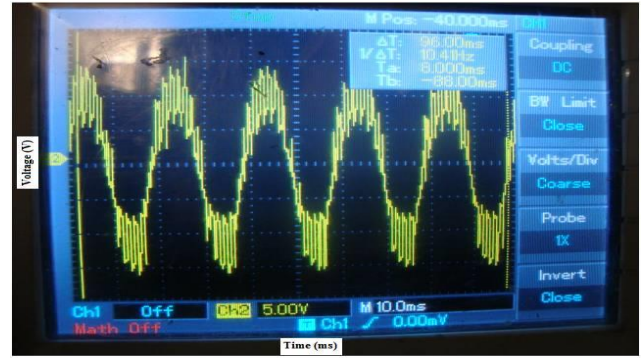Fig.15 Load voltage get normalized when DVR activated

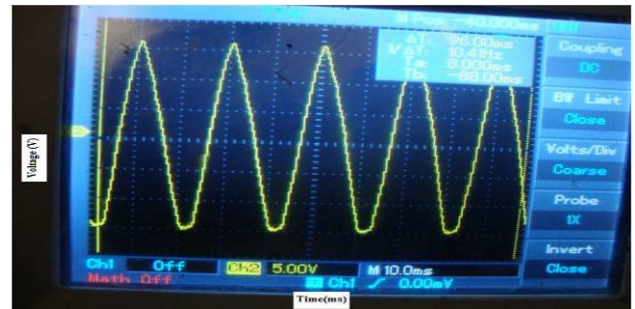Fig.16 Distorted Load Voltage waveform due to Swell and Harmonics

Fig.17 Load voltage get normalized when DVR activated

Harmonics presented in Load Voltage will be eliminated by the control circuit of DVR system. The control circuit performed its function and produce control digital pulse for generating the gate pulses to Z-source inverter switches. But this control pulse has switching frequency only about 20Hz.. While transmitting control pulse some of the gain gets dropped, so the performance of Z- Source Inverter gets lowered. In order to avoid that situation, 555 timer is used to generate high frequency gate pulse signals. At a time two switches can be connected to make closed circuit. Above gate pulses are the respective gate pulse signals to the inverter switches. When increasing load, voltage get distorted. Hence voltage dipped to 10% of normal voltage. When any distortions occur, manually DVR switch get closed to inject the compensating voltage to normalize the voltage to load. While sudden removal of load, the voltage gets distorted. Hence voltage increased to 10% of normal voltage When swell voltage occurs, manually DVR switch get closed to inject the negative voltage to suppress the extra 10% of normal voltage.

6. Conclusion

This proposed DVR compensates deep and long duration voltage sag, voltage swell by load side compensation of DVR. The DVR is based on a shunt rectifier fed series Z source inverter through dc-to-dc

step up converter. A method of incorporating voltage compensation capability to the DVR has been proposed using hysteresis voltage control.

A Hysteresis voltage controller was designed for DVR voltage regulation with explicit robustness in the face of system parameter variations. A proper selection of weighting functions would specify the robustness and error tracking performance, and the synthesized Hysteresis controller can be tuned with significant gains at positive and negative line frequencies so that it would effectively regulate the positive- and negative-sequence components. An inner current loop is also designed and embedded within the Hysteresis voltage loop. The design of the components of the DVR has been presented. Based on the design procedure, band controlled DVR is designed and further validated by simulation and experimental results.

In simulation, 3 phase fault created at 0.5s and clear at 0.8s. During this fault time voltage distortion takes place, which recovered by DVR. This DVR get activated at 0.5s and inject the distorted voltage up to 0.8s. During sag distortion, the supply voltage 415V dipped to 169V at 0.5s. With the help of DVR compensator, the dipped voltage gets increase to supply voltage at 0.8s. Similarly, in swell distortion the supply voltage increased to 498V at 0.5s. With the help of DVR compensator, the voltage swells decrease to its supply voltage at 0.8s. Hence, with the help of load side compensating DVR we can achieve voltage regulation during fault time. Similarly in experimental type, load is increased and removed suddenly to create distortion (10% of normal voltage) for short time period. Those distortions are recovered by this proposed DVR system. The simulation results and hardware experimental results were verified.

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