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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. To overcome this problem, Dynamic Voltage Restorer (DVR) is used, which eliminate voltage sag and swell in the distribution line, it is efficient and effective power electronic device. The DVR is a dynamic solution for protection of critical loads from voltage sags/swells. The DVR restores constant load voltage and voltage wave form by injecting an appropriate voltage. A new topology based on Z-source inverter (ZSI) is presented in order to enhance the voltage restoration property of dynamic voltage restorer. Z-source inverter would ensure 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.**

Keywords—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 system 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.By injecting voltage with a phase advance with respect to the sustained source-side voltage, reactive power can be utilized to help voltage restoration. As there was growing interest in mitigating power quality disturbance, the idea of custom power devices was introduced.

Voltage sag/sell is most important power quality problems challenging the utility industry can be compensated and power is injected into the distribution system. Dynamic Voltage Restorer (DVR) is one among the most significant custom power device which is connected in series to the distribution system. It is normally 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, which consists of a set of series and shunt converters connected back-to-back, three series transformers, and a dc capacitor installed on the 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.

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.

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The Z-source converter employs a unique X-shapedimpedance network on its dc side for achieving both voltagebuck and boost capabilities this unique features that cannotbe obtained in the traditional voltage-source and currentsourceconverters. The proposed system is able tocompensate long and significantly large voltage sags. Passivity-based dynamical feedback controllers canbe derived for the indirect stabilization of the average outputvoltage. The derived controllers are based on a suitablestabilizing "damping injection" scheme.Installation of theworld's first Dynamic Voltage Restorer (DVR) on a majorUS. Utility system to protect a critical customer plant loadfrom power system voltage disturbances. The installedsystem at an automated yarn manufacturing and weavingfactory provides protection from disturbances. In thispaper the modeling and control of voltage sag/swellcompensation using Z-Source inverter based dynamicvoltage restorer are simulated using MATLAB software.

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 important 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.

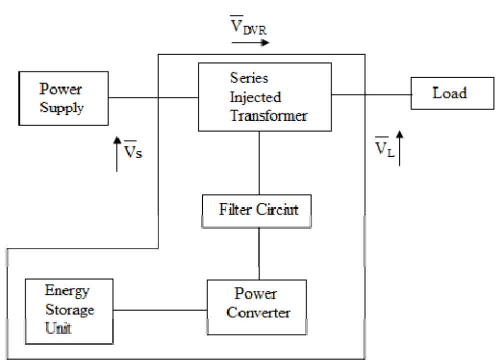

Fig.1Block Diagram of DVR Circuit

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 absorbing or injecting the active and reactive power. It basically consists of, Battery energy storage, Voltage Source Inverter, Passive Filter, Injection/ Booster Transformer.

A. Injection /Booster Transformer

The primary of the injection transformer is connected in series with the distribution line and 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 either high voltage side or low voltage side of the injection transformer. By placing it inverter side higher order harmonics are prevented from passing through the voltage transformer. And it will reduce stress on the injection transformer. When the filter is placed on the high voltage side, the higher order harmonic current do penetrate to the secondary side of the transformer, a higher rating of the transformer is required.The main task of the filter is to keep the harmonic voltagecontent generated by the inverter within the permissible level.

C. Power Converter

It converters 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 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) are needed to deliver power, whereas for flywheel, AC to AC conversion is required

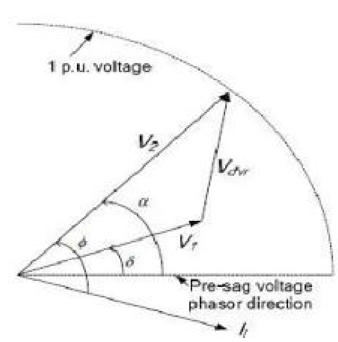

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Fig.2 Vector Diagram of Voltage Injection Method

Widely used in present DVR control is the so-called inphase voltage injection technique where the load voltage V2 isassumed to be in-phase with the pre-sag voltage. As the DVRis required to inject active power into the distribution lineduring the period of compensation, the capacity of the energystorage unit can become a limiting factor in the disturbancecompensation process. In particular, if capacitors are used asenergy storage, the DC-link voltage will decrease with thedwindling storage energy during compensation.

The corresponding phasor diagram describing the electricalconditions during voltage sag is depicted, where only theaffected phase is shown for clarity. Let the voltage quantitiesIl, φ, δ and α represent the load current, load power factorangle, supply voltage phase angle and load voltage advanceangle respectively. Although there is a phase advancement of αin the load voltage with respect to the pre-sag voltage in Fig. 2,only in-phase compensation where the injected voltage is inphase with the supply voltage (α = δ) is considered.

III. Z-SOURCE INVERTER

Z-source Inverter has X-shaped impedance network on itsDC side, which interfaces the source and inverter H-bridge. Itfacilitates both voltage-buck and boost capabilities. Theimpedance network composed of split inductors and twocapacitors. The supply can be DC voltage source or DCcurrent source or AC source. Z-Source inverter can be ofcurrent source type or voltage source type. Fig. 3 shows thegeneral block diagram of Z-Source inverter. The impedance network is the combination of twoinductors and capacitors. This combination network circuit isthe energy storage are filtering element for the impedancesource inverter. The impedance source inverter provides thesecond order filter. This is more effective to suppress voltageand current ripples. The inductor and capacitor requirementshould be smaller compared to the traditional inverter.

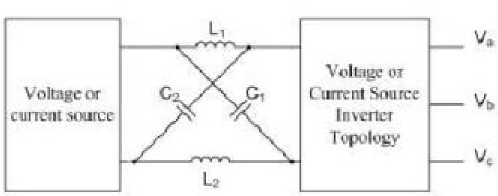

Fig.3General Block Diagram of Z-Source Inverter

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, the 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.

As shown in Table I, the single-phase Z -Source Inverterhas five switching modes. Two active modes in which the dcsource, 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. Christo Ananth et al.[5] presented a brief outline on Electronic Devices and Circuits which forms the basis of the Clampers and Diodes.

The shoot through period i.e., 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. Else 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 the current source inverters.

TABLE I. 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 merits of the new topology are:

- The voltage polarity of the capacitors remain the same providing similar voltage boost capability, but with reduced 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 remain the same, whereas the current across the inductor in the existing topology decreases in the non shoot through state. In the

$$V_c = (1-D)V_s \,/\, (1-2D) \quad (1)$$

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existing topology, the voltage across the capacitors is given by
And in the new topology it is given as,

$$V_c = \{D/(1-2D)\}/V_s \qquad (2)$$

Where V_c= capacitor voltage; D = duty ratio of the shoot through state; and V_s = supply voltage.

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

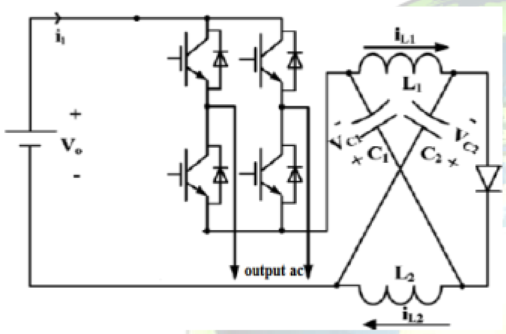

Fig.4 Proposed Z-Source Inverter topology

IV. Sag and Swell Compensation of Proposed System

A. *Voltage Sag Compensation in DVR System*

In order to meet the requirement of constant voltage control, closed loop operation is performed for the desired value of the voltage according to the need. The simulink model of closed loop control of voltage sag compensation in a DVR system is shown in the Fig.5. Initially the system was subjected to 25% voltage sag.

Q_{in}

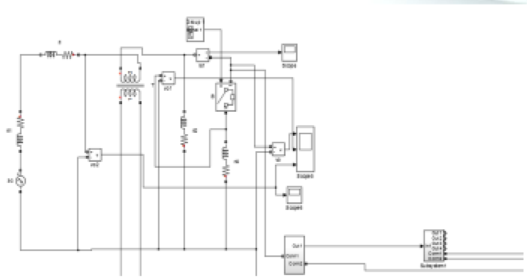

Fig.5 Closed Loop Control of Voltage Sag Compensation in a DVR System

In the fig.5 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 as pulses for controlling the Z-Source inverter.

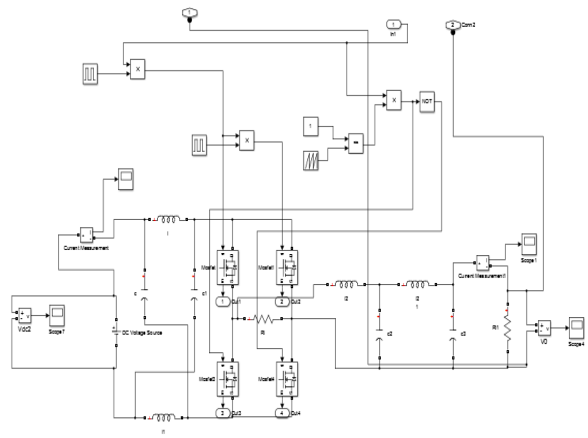

Fig.5 Z-Source Inverter section of Closed Loop Control of Voltage Sag CompensationDVR system

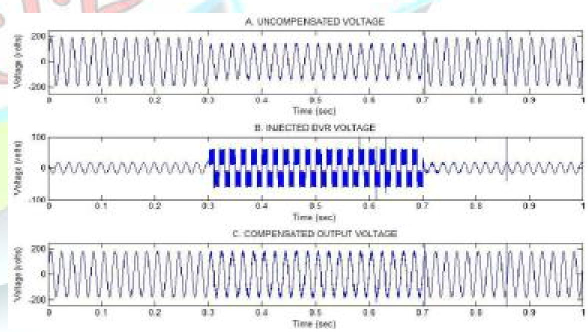

Fig. 6 Simulation results of Closed Loop Control DVR under 25% sag (A.Uncompensated Voltage, B. Injected DVR Voltage, C. Compensated Voltage)

The Z-Source starts conducting when it obtains the pulse from the saturator.Fig. 6 shows the output waveform of closed loop control of voltage sag compensation. Fig. 6.A shows the uncompensated AC voltage with 25% sag. Fig. 6.B shows the injected DVR voltage. Fig. 6.C gives the compensated output voltage.

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B. VOLTAGE SWELL COMPENSATION IN DVR SYSTEM

The simulink model of closed loop control of voltage swell compensation in a DVR system is shown in the Fig.7.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 supply and then a reference voltage is given for the error. This error is sent to the PI controller. Value is set in the saturator for giving the pulses for controlling the Z-Source inverter.

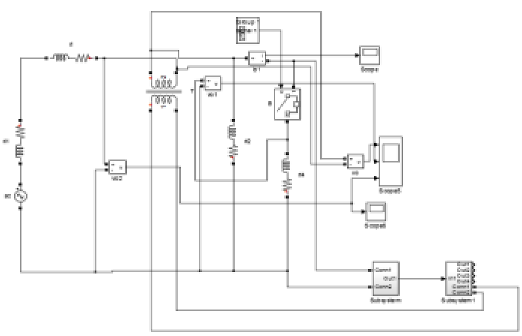

Fig.7 Subsystem 2 of Closed Loop Control of VoltageSwell Compensation in a DVR System

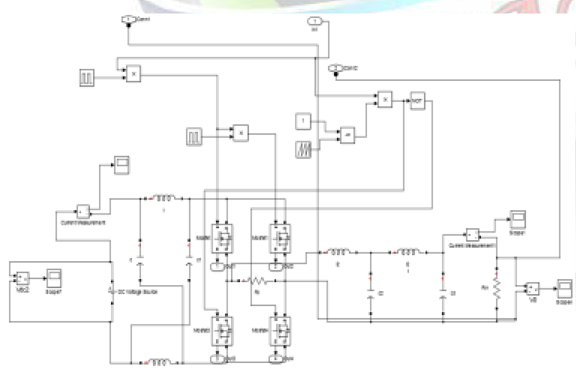

Fig.8 Z-Source inverter section of Closed Loop Control of Voltage Swell Compensation in a DVR System

Fig.9 shows the output waveform of closed loop control of voltage swell compensation. Fig. 9.A shows the uncompensated AC voltage with 30% swell. Fig. 9.B is the injected DVR voltage. Fig. 9.C shows the compensated output voltage.

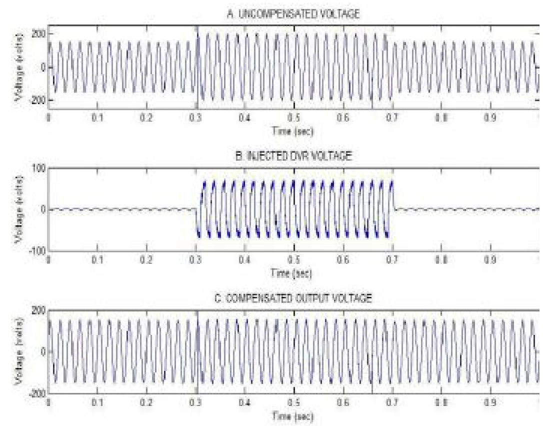

Fig. 15 Simulation results of Closed Loop Control DVR with 30% swell (A.Uncompensated Voltage, B. Injected DVR Voltage, C. Compensated Voltage)

V. CONCLUSION

DVR serves as 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. Thecontrol technique is designed using in-phase compensation andused a closed loop control system to detect the magnitude errorbetween voltages during pre-sag and sag periods. The modelingand simulation of closed loop control of voltage sag/swellmitigation were carried out using MATLAB software.The simulation results show that the developed controltechnique with proposed single phase DVR is simple andefficient.

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