International Journal of Advanced Technology and Innovative Research

www.ijatir.org

ISSN 2348–2370
Vol.08,Issue.01,
January-2016,
Pages:0195-0201

Comparison of Different Control Strategies for Voltage Sag/Swell Compensation using Z-Source Inverter DVR

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Abstract: The power system especially the distribution system, have numerous non linear loads which significantly affects the quality of power supply. Voltage sags, swells, harmonics can cause equipment to fail, mis-operate or shut down, as well as create huge current imbalances which could blow fuses or trip breakers. These effects can be very expensive for the customer, ranging from minor quality variations to production downtime and equipment damage. The Dynamic Voltage Restorer (DVR) is fast, flexible and efficient solution to voltage sag/swell problem. In this work Z-source inverter (ZSI) based DVR will be proposed. The ZSI uses an LC impedance grid to couple power source to inverter circuit and prepares the possibility of voltage buck and boost by short circuiting the inverter legs. ZSI based DVR can controlled by using different controllers. This paper presents the performance comparison of PI controller, Fuzzy controller and Fuzzy-PI controller. The PI control scheme suffers from fixed gains i.e. it cannot adapt itself to the varying parameter and conditions of system. To overcome this drawback this work proposes a fuzzy controller. This is a non linear controller and it can provide a better performance under changing system parameters and operating conditions based on knowledge base and rule base. This work proposes another control method of Hybrid fuzzy-PI which is combination of PI and fuzzy controllers. The control schemes of ZSI based DVR are modelled and simulated in MATLAB/SIMULINK under voltage sags and swells.

Keywords: Power Quality, Z-Source Inverter, Fuzzy, Hybrid Fuzyy-PI.

I. INTRODUCTION

Power Quality is the delivery of sufficiently high grade electric service to the customer. A power quality problem is the non standard voltage, current or frequency. The Distribution system have numerous non-linear loads which affect power quality, 90% of average customer interruptions are due to Distribution network failure. Apart from non-linear loads, some system events, both usual (capacitor switching, motor starting) and unusual (faults) could also inflict power quality problems. The consequence of power quality problems could range from a simple nuisance flicker in electric lamps to a loss of thousand of rupees due to power shutdown. Voltage sag/swell, flicker, harmonic distortion, impulse transients, frequency variations, transients and interruptions are the various power quality problems occurred in distribution system. These result in failure or miss operation of customer equipment. The voltage sag / swell is the most common and serious power quality related problem among the industries. Such voltage sag / swell have a major impact on the performance of the microprocessor based loads as well as the sensitive power electronic loads. In a power line voltage sags / swells can occur as a result of load switching, motor starting, faults, lightning, non-linear loads, intermittent loads etc., Voltage sag is defined by the IEEE1159 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. These are shown in Table 1[1].

Table I. Definitions for Voltage Sag and Swell

Type of disturbance	Voltage	Duration
Voltage Sag	0.1-0.9pu	0.5-30 cycles
Voltage Swell	1.1-1.8pu	0.5-30 cycles

To compensate Voltage sag/swell STATCOM, SSSC, DSTATCOM, IPFC, APF, DVR and UPQC are the various devices used. But among the devices DVR is considered to be the best and cost effective device to compensate Voltage sag/swell [8]. It is connected in series to the distribution system and it injects or suppresses the voltage of suitable magnitude and phase in series with the line. Dynamic Voltage Restorer is consists of a series voltage source (VSI) or current source (CSI) [13]. The main disadvantage of these inverters is either buck or boost type voltage characteristics. In this paper Z- Source Inverter based DVR is used to obtain both type of voltage characteristics i.e. boost and buck [2]. The controlling employed in ZSI based DVR is PI controller which has high response ratio. PI controller has simple structure and it can offer relatively satisfactory performance over a wide range of operation. But by using fixed gains, the controller may not provide the required control performance, when there are variations in the system parameters and operating conditions. It appears that the non linear controllers are more suitable than the linear type since the DVR is truly a non linear system. The proposed fuzzy controller will provide the desired injecting voltage. Fuzzy controller is employed to achieve better performance over PI controller under varying system and operating conditions. But it is also suffers from low response time over PI controller. So in this paper another controller is proposed named Hybrid Fuzzy-PI controller, which is advantageous over PI and Fuzzy controller. This controller responds quickly as it has PI controller and gives better performance under changing system conditions. The main objective of this paper is to improve the voltage quality in distribution system. The Z-source Inverter based DVR is used to mitigate the voltage sag/swell and the compensation is further improved by using Hybrid Fuzzy-PI controller.

II. DYNAMIC VOLTAGE RESTORER

A power electronic converter based series compensator that can protect the critical loads from all the supply side disturbances other than outages is called Dynamic voltage restorer. 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 unbalanced or distorted. The DVR is a solid-state dc to ac switching power converter that injects a set of three-phase ac output voltage in series and synchronism with the distribution feeder voltages. The amplitude and phase angle of the injected voltages are variable thereby allowing control of the real and reactive power exchange between the DVR and the distribution system within predetermined positive (power supply) and negative (power absorption) limits. The reactive power exchanged between the DVR and the distribution system is internally generated by the DVR without any ac passive reactive components, e.g. reactors or capacitors. Real power exchanged at the DVR ac terminals must be provided at the DVR dc terminal by an external energy source or energy storage system[4-5]. In Custom Power applications, the DVR is connected in series with the distribution feeder. By inserting voltages of controllable amplitude, phase angle and frequency (fundamental and harmonic) into the distribution feeder via a series insertion transformer, the DVR can "restore" the quality of voltage at its load-side terminals when the quality of the source-side terminal voltage is significantly out of specification for sensitive load equipment.

A typical DVR scheme is shown in Fig1. In the Fig. 1, Vs is the source voltage, V1 is the incoming supply voltage before compensation, V2 is the load voltage after compensation, Vdvr is the series injected voltage of the DVR and I is the line current. The restorer typically consists of an injection transformer, the secondary winding of which is connected in series with the distribution line, a pulse-width modulated (PWM) voltage source inverter (VSI) bridge connected to the primary of the injection transformer and an energy storage device connected at the dc-link of the inverter bridge. The series injected voltage of the DVR, Vdvr, is synthesized by modulating pulse widths of the inverter-bridge switches. The injection of an appropriate Vdvr in the face of an up-stream voltage disturbance requires a certain amount of real and reactive power supply from the DVR. The reactive power requirement is generated by the inverter. The widely used voltage compensation technique in present DVR control is the In phase voltage injection technique where the load voltage V2 is assumed to be in-phase with the pre-sag voltage.

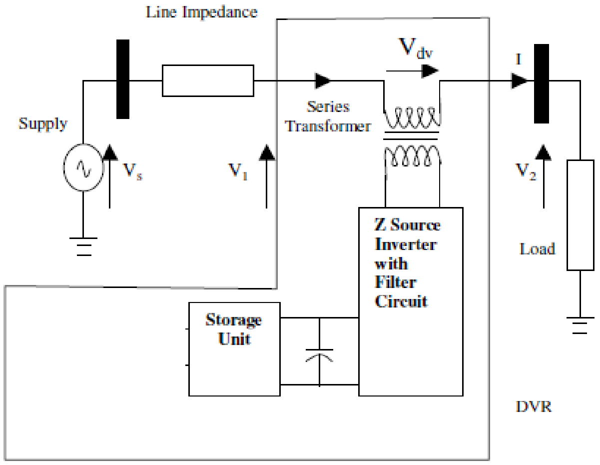

Fig.1. Schematic representation of the DVR.

The corresponding phasor diagram describing the electrical conditions during voltage sag is depicted, where only the affected phase is shown for clarity. Let the voltage quantities I, 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 Fig2, only in-phase compensation where the injected voltage is in phase with the supply voltage (α = δ) is considered [4].

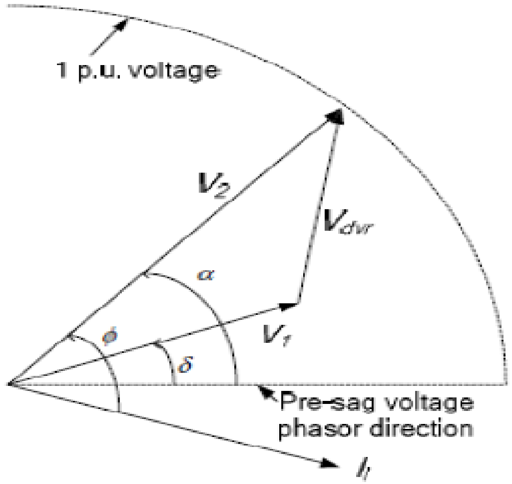

Fig.2. Vector Diagram of Voltage Injection Method

III. Z-SOURCE INVERTER

The traditional converters are voltage source inverter and current source inverter. Voltage Source converter is widely used but it has conceptual and theoretical barriers and limitations. The output of VSI has limited voltage and it can't boost voltage. Two devices in one leg can't be gated simultaneously either by purpose or by EMI noise which results in shoot –through and destroy the device. To improve sinusoidal waveform LC filter is needed which causes additional power loss and control complexity. Current Source Inverter (CSI) has also limitations such as it is only a boost converter for dc-ac converter and shoot-through problems etc,.To overcome these problems of VSI and CSI this paper presents an impedance source power converter called as Z-source inverter. It has X-shaped impedance network on its DC side, which interfaces the source and inverter H-bridge. It facilitates both voltage-buck and boost capabilities. The impedance network composed of split inductors and two capacitors. The supply can be DC voltage source or DC current source or AC source. Z-source inverter can be of current source type or voltage source type. Fig. 3 shows the general block diagram of Z-Source inverter voltage.

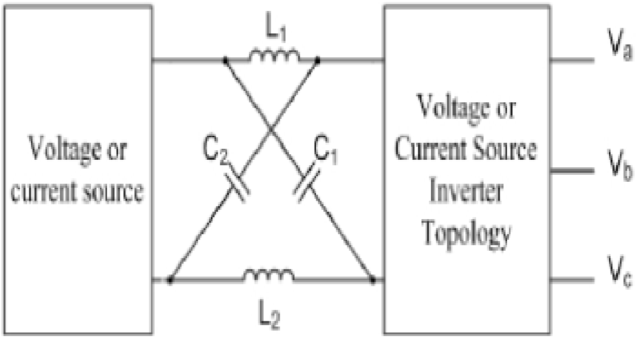

Fig.3. General Block Diagram of Z-Source Inverter.

As shown in Table II, the single-phase Z-Source inverter has five switching modes. 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.

Table II. 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

Three phase Z-source inverter bridge has nine permissible switching states unlike traditional VSI or CSI that has eight. The extra zero state or shoot-through state is ON condition of two devices in any one phase leg or any two phase legs or all three phase legs. Applying a distinctive PWM method is necessary for ZSI considering the defined operational modes. Z-Source Inverter can be operated in Active mode, Zero mode and shoot-through mode.

A. Active mode

In this mode Z-Source Inverter is operated as traditional inverter. The ac output voltage is less than the dc input voltage. This mode is shown in fig 4.

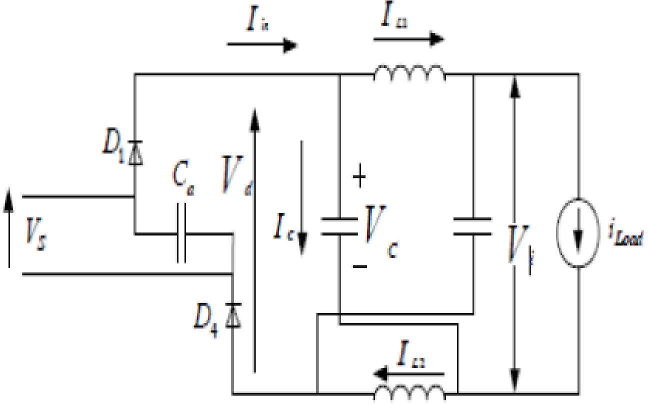

Fig.4. Active mode.

B. Shoot-through mode

This shoot-through zero state provides the unique buck-boost feature to the inverter. If two devices in a phase leg are in ON condition the load is short-circuited. In this condition the inductors and capacitors are charged through energy source at full rated capacity. When load is connected this charged devices are discharged through load hence increase in voltage more than storage device. It has highest boost factor. The boost factor can be derived as

$$\beta = 1/ [1 - 2(T0/T)] \qquad (1)$$

Where, T_0 and T show the shoot-through mode application period and switching period, respectively [2].

The equivalent circuits of rectifier fed ZSI in shoot-through modes are presented in Fig5

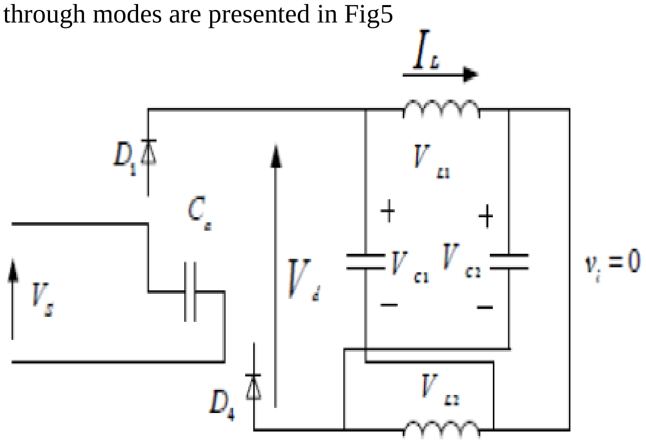

Fig.5. Shoot through mode.

Z-Source inverter operation is controlled by multiple pulse width modulation. The output of the Z-Source inverter is controlled by using pulse width modulation, generated by comparing a triangular wave signal with an adjustable DC reference and hence the duty cycle of the switching pulse could be varied to synthesize the required conversion [6]. A stream of pulse width modulation is produced to control the switch as shown in the Fig 6. The performance of ZSI DVR is depends upon the reference signal given to pulse width modulation since the compensation voltage is generated from DVR is based on reference signal. Hence output voltage controlled by changing reference signal and it is generated by different controlling techniques such as PI controller, Fuzzy controller and Hybrid-Fuzzy controller [9].

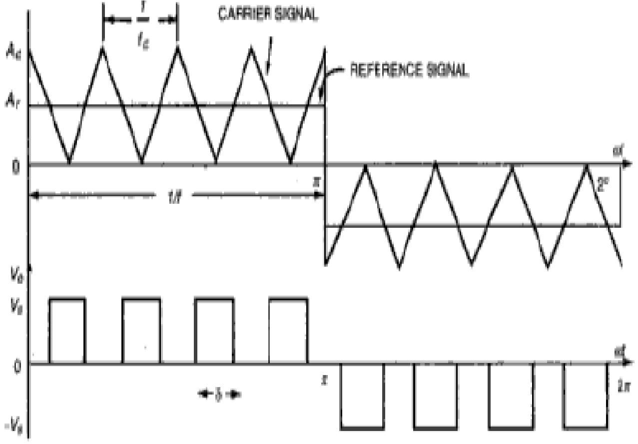

Fig.6. Multiple Pulse Width Modulation.

IV. CONTROLLERS

A. PI-Controller

PI is a feedback controller that uses the weighted sum of error and its integral value to perform the control operation. The proportional response can be adjusted by multiplying the error by constant $K_{p,}$ called proportional gain. The contribution from integral term is proportional to both the magnitude of error and duration of error.

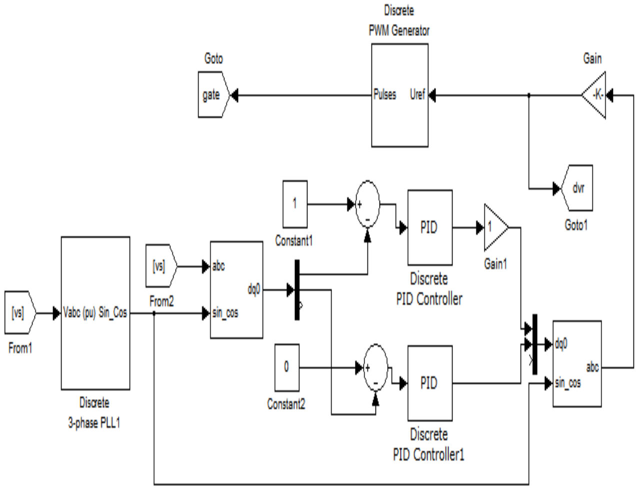

Fig.7. The input to the PI controller is the difference between reference value and error value of voltage.

The output from PI controller is used as the reference value in PWM pulse generator which is given to devices in DVR. The advantage of PI controller is its simple structure and linear which avoids harmonics. But disadvantage is fixed gains cannot adapt itself to varying system conditions and parameters.

B. Fuzzy controller

Fuzzy controller is a non-linear controller that gives satisfactory performance under the influence of changing system parameters and operating conditions. Fuzzy controller overcomes the drawback in PI controller. A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by expert experience or knowledge database. The basic Fuzzy controller is shown in fig.8. It consists mainly four Functional blocks. These are knowledge base, Fuzzification, Inference mechanism and defuzzification [7].

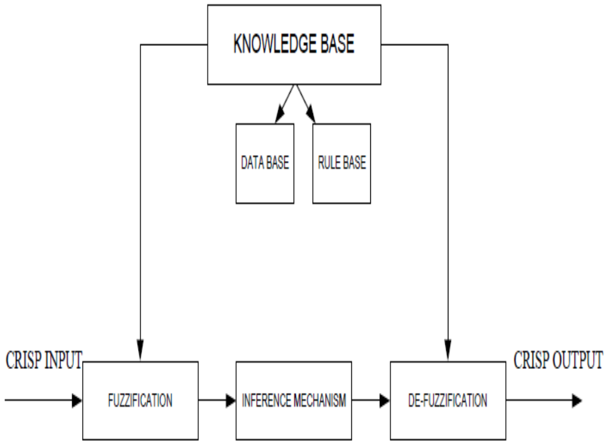

Fig.8. Schematic diagram of Fuzzy controller.

Fuzzification is the process of converting a numerical variable (real number) convert to a linguistic variable (fuzzy number) is called fuzzification. De-fuzzification is the rules of FLC generate required output in a linguistic variable (Fuzzy Number), according to real world requirements; linguistic variables have to be transformed to crisp output (Real number). Database stores the definition of the membership Function required by fuzzifier and defuzzifier [9]. The inference mechanism uses the collection of linguistic rules to convert the input conditions of fuzzified outputs to crisp control conditions using output membership function, which in the system acts as the changes in the control input(u). The inputs to the Fuzzy controller are error 'e' and change in error 'ce'. The error is the difference between the load voltage and the reference voltage. The change in error is obtained by differentiating the error. To convert these variables into linguistic variables, the following seven fuzzy levels or sets are chosen as: NL (negative large), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive large). Based on knowledge base rule base is constructed as shown in Table III [7] [1].

TABLE III. Rule Base For Fuzzy Logic Controller

e ce	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	Z
NM	NL	NL	NL	NM	NS	Z	PS
NS	NL	NL	NM	NS	Z	PS	PM
Z	NL	NM	NS	Z	PS	PL	PM
PS	NM	NS	Z	PS	PM	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PL	Z	PS	PM	PL	PL	PL	PL

C. Hybrid Fuzzy-PI Controller

The advantages of both fuzzy and PI controller can be implemented as a hybrid Fuzzy-PI controller in order to obtain improved speed control. The FLC is one of the popular controllers in the artificial intelligence techniques. The drawback of conventional PI controller can be overcome by using FLC. The hybrid PI-Fuzzy control scheme uses fuzzy as adjustor to adjust the parameters of proportional gain Kp and integral gain Ki based on the error e and the change of error Δe. PI-Fuzzy based Controller has been designed by taking inputs as error which is difference between measured voltage and reference voltage of DVR for voltage regulator and its derivative while ΔKp and ΔKi as output for voltage regulator where Kp and Ki are proportional gain and integral gain respectively[10]. The schematic block diagram of Hybrid Fuzzy-PI is shown in Fig.9.

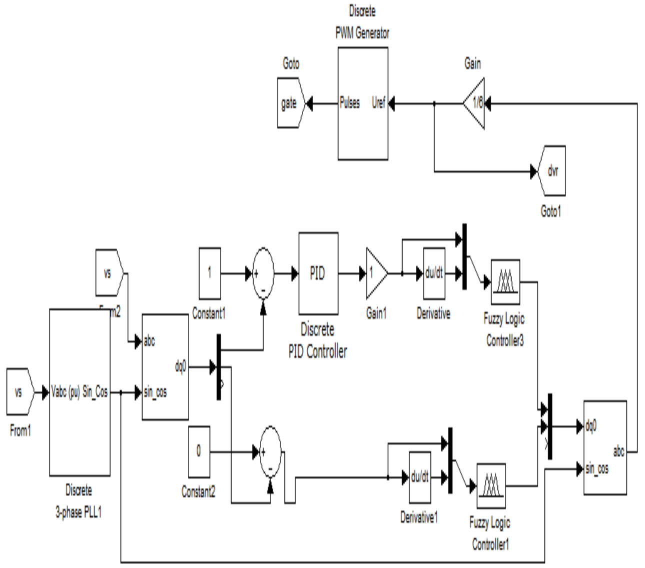

Fig.9. Simulation diagram of Hybrid Fuzzy-PI controller.

V. MATLAB MODELEING AND SIMULATION RESULTS

Voltage sag/swell is created by subjecting source to a three phase fault. The disturbance in source voltage is shown in fig11. The simulation diagram for voltage sag/swell compensation is shown in fig10. The compensated voltage is injected by DVR in series to the line voltage.

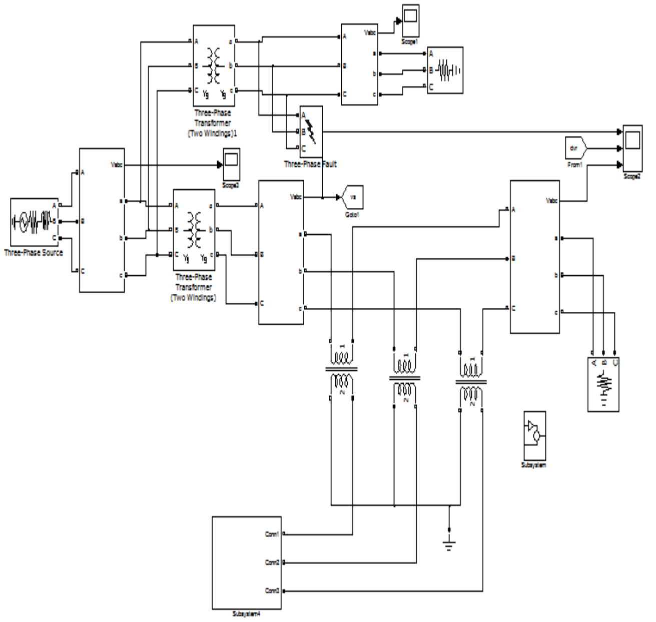

Fig.10. Simulation diagram of three phase DVR.

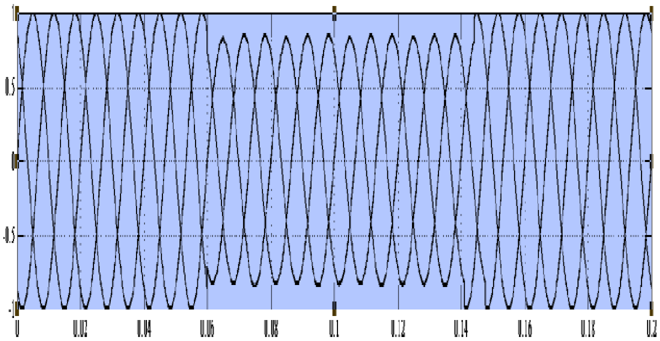

Fig.11. Source voltage before compensation.

A. PI output

The output voltage waveform after compensation by using PI controller is shown in Fig. 12. It can be observed that magnitude of voltage is decreased during compensation. The THD percentage in this waveform is 0.58%.

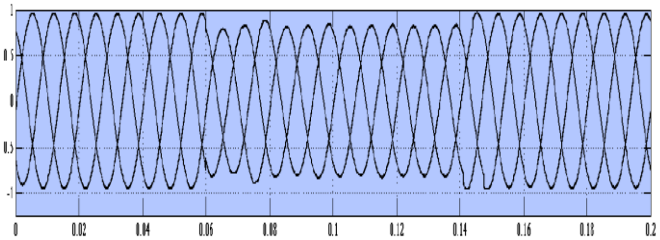

Fig.12. Output voltage with PI controller.

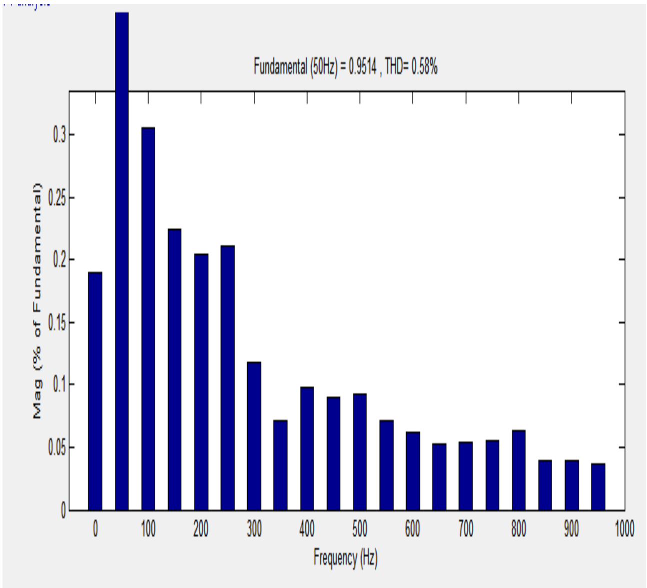

Fig.13. THD in output with PI controller.

B. Fuzzy output

The output voltage waveform after compensation by using Fuzzy controller is shown in Fig. 14. It can be observed that magnitude of voltage is increased during compensation. But the THD percentage in this waveform is increased to 1.87%.

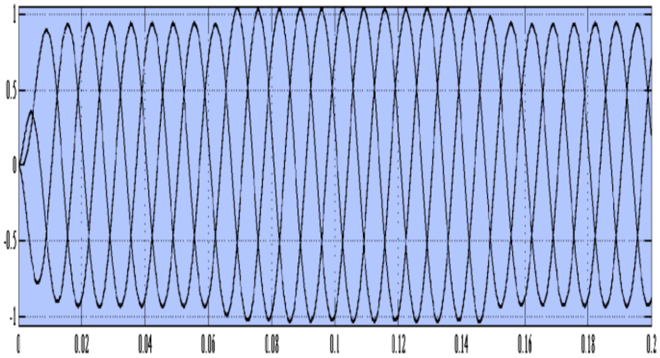

Fig.14. Output voltage with Fuzzy controller.

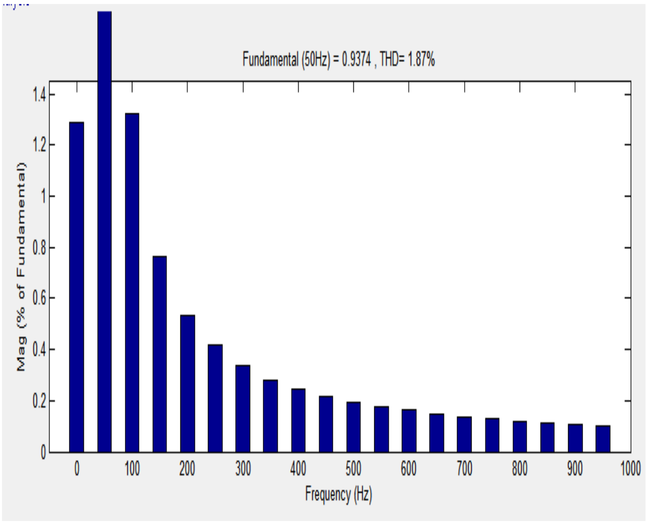

Fig.15. THD in output with Fuzzy controller.

C. Hybrid Fuzzy-Pi Controller

The output voltage waveform after compensation by using Hybrid Fuzzy-PI controller is shown in Fig. 16. It can be observed that magnitude of voltage is increased during compensation. The THD percentage in this waveform is reduced to 0.41%.

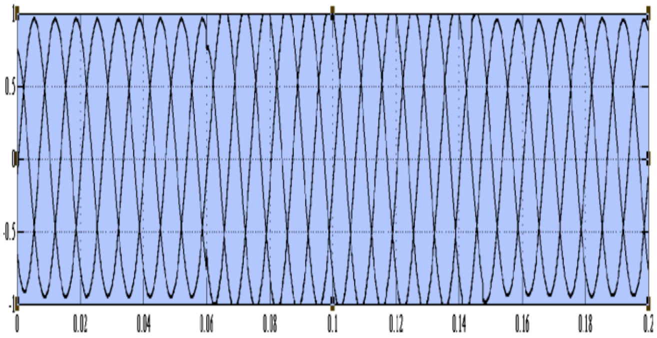

Fig.16. Output with Hybrid Fuzzy-PI controller.

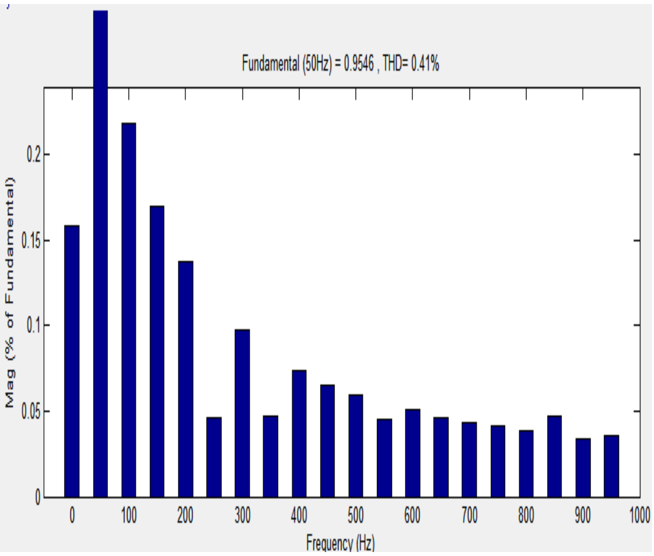

Fig.17. THD in Output with Hybrid Fuzzy-PI controller.

V. CONCLUSION

The Dynamic Voltage Restorer (DVR) is fast, flexible and efficient solution to voltage sag/swell problem. In this work Z-source inverter (ZSI) based DVR was proposed. DVR serves as an effective custom power device for mitigating voltage sag/swell in the distribution system. In this paper Z–source inverter based DVR along with hybrid fuzzy controller is modeled and the same is installed in the distribution system to provide required load side compensation. The simulation of the DVR along with the proposed controller is carried out using MATLAB/ SIMULINK software. The simulation results shows that the performance of Z – source inverter based DVR along with Hybrid fuzzy controller is better compared to fuzzy controller. From the Table 4 it is observed that Hybrid fuzzy-PI controller is better than PI and Fuzzy which increases magnitude and reduces harmonics.

Table IV. Comparison between Controllers

	PI	**Fuzzy**	**Hybrid Fuzzy-PI**
Magnitude	**Decreased**	**Increased**	**Increased**
THD	0.58%	1.87%	0.41%

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