The growth in the use of power electronics has caused a greater awareness of power quality. 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 is controlled by PI controller. 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, Dynamic Voltage Restorer (DVR), Voltage sag/swell, Z-Source Inverter (ZSI), Pulse Width Modulation (PWM), Fuzzy, Hybrid fuzzy

INTRODUCTION

The voltage sag/swell is the most common 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 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, Voltage sags/swells as shown in Table 1 and within which
controlling equipment should be connected together with the critical loads as corrective measures [1]. DVR is a commercially available cost effective device, which is capable of addressing the above voltage sag problem effectively.

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. A power quality problem is defined as any manifested problem in voltage or current of leading to frequency deviations that result in failure or miss operation of customer equipment.

Power quality problems associated with an extensive number of electromagnetic phenomena in power systems with broad ranges of time frames such as long duration variations, short duration variations and other disturbances. Short duration variations are mainly caused by either fault conditions or energisation distance related to impedance type of grounding and connection of transformer between the faulted location and node, there can be temporary load of voltage reduction (sag) or voltage rise (swell) at different nodes of the system.

Here the control scheme used employed in Z-source inverter based DVR is fuzzy controller. The most common choice controller of the DVR is the PI controller since it 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.

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 is able to compensate long and significantly large voltage sags [2], [5] and [9].

### DYNAMIC VOLTAGE RESTORER

The DVR employs IGBT solid-state power-electronic switching devices in a Pulse-Width Modulated (PWM) inverter structure and is capable of generating or absorbing independently-controllable real and reactive power at its ac power-frequency transformer. So, the transformer size, weight and stress factor is reduced considerably [3]. Output terminal. Its dc input terminal is connected to an energy source or an energy storage device of appropriate capacity.

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

<table>
<thead>
<tr>
<th>Type of disturbance</th>
<th>Voltage</th>
<th>Duration</th>
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<tbody>
<tr>
<td>Voltage Sag</td>
<td>0.1 - 0.9 pu</td>
<td>0.5 - 30 cycles</td>
</tr>
<tr>
<td>Voltage Swell</td>
<td>1.1 - 1.8 pu</td>
<td>0.5 - 30 cycles</td>
</tr>
</tbody>
</table>

Table 1: Definitions for Voltage Sag and Swell
power exchange between the DVR and the distribution system within predetermined positive (power supply) and negative (power absorption) limits. The PWM main inverter structure within the prototype portable trailer enclosure. 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.

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. Dynamic voltage restorer was originally proposed to compensate for voltage disturbances on distribution systems. A typical DVR scheme is shown in Figure 1.

In the Figure 1, Vg is the source voltage, V1 is the incoming supply voltage before compensation, V2 is the load voltage after compensation, 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. Widely used in present DVR control is the so-called in phase voltage injection technique where the load voltage V2 is assumed to be in-phase with the pre-sag voltage.

The corresponding phasor diagram describing the electrical conditions during voltage sag is

![Figure 1: Schematic Representation of the DVR](image1)

![Figure 2: Vector Diagram of Voltage Injection Method](image2)
depicted, where only the affected phase is shown for clarity. Let the voltage quantities $I_l$, $\varphi$, $\delta$ and $\alpha$ 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 $\alpha$ in the load voltage with respect to the pre-sag voltage in Figure 2, only in-phase compensation where the injected voltage is in phase with the supply voltage ($\alpha = \delta$) is considered.

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 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. Figure 3 shows the general block diagram of Z-Source inverter voltage.

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. A stream of pulse width modulation is produced to control the switch as shown in the Figure 4.

As shown in Table 2, 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.

Applying a distinctive PWM method is necessary for ZSI considering the defined operational modes. In a symmetric impedance network, the following equations are valid:

<table>
<thead>
<tr>
<th>Table 2: Switching Modes</th>
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<tr>
<td>$S_4$</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>0</td>
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<tr>
<td>0</td>
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The equivalent circuits of rectifier fed ZSI in shoot-through and active modes are presented in Figures 5 and 6 respectively. Figure 7 shows the equivalent circuit of inverter in shoot-through mode. The following is obtained according to that equivalent circuit:

\[ V_d = V_{L1} + V_{C2} \]  
\[ \ldots (8) \]

\[ V_{L1} = V_{C1} \]  
\[ \ldots (9) \]

where \( V_d \) is the impedance network input voltage.

Considering (4), (8) and (9), the following relation is obtained:

\[ V_d = 2V_C \]  
\[ \ldots (10) \]

In shoot-through mode operation, the rectifier is not able to inject current and energy to impedance network. Figure 6 shows the equivalent circuits of rectifier fed ZSI in shoot-through and active modes are presented in Figures 5 and 6 respectively. Figure 7 shows the equivalent circuit of inverter in shoot-through mode. The following is obtained according to that equivalent circuit:

\[ V_d = V_{L1} + V_{C2} \]  
\[ \ldots (8) \]

\[ V_{L1} = V_{C1} \]  
\[ \ldots (9) \]

where \( V_d \) is the impedance network input voltage. Considering (4), (8) and (9), the following relation is obtained:

\[ V_d = 2V_C \]  
\[ \ldots (10) \]

In shoot-through mode operation, the rectifier is not able to inject current and energy to impedance network. Figure 6 shows the
equivalent circuit of ZSI in active mode. Considering Figure 6, the following relation is obtained,

\[ V_d = V_s(t) - 2V_g \]  ...(11)

**CONSTRUCTION OF FUZZY CONTROLLER**

Figure 7 shows the internal structure of the control circuit. The control scheme consists of Fuzzy controller, limiter, and three phase sine wave generator for reference current generation and generation of switching signals. The peak value of reference currents is estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a set reference value. The error signal is then processed through a Fuzzy controller, which contributes to zero steady error in tracking the reference current signal.

A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by expert experience or knowledge database. Firstly, input voltage Vdc and the input reference voltage Vdc-ref have been placed of the angular velocity to be the input variables of the fuzzy logic controller. Then the output variable of the fuzzy logic controller is presented by the control Current Imax. To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen as: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big) as shown in Figure 8.

The fuzzy controller is characterized as follows:

- Seven fuzzy sets for each input and output;
- Fuzzification using continuous universe of discourse;
- Implication using Mamdani’s ‘min’ operator;
- De-fuzzification using the ‘centroid’ method.

**Fuzzification:** The process of converting a numerical variable (real number) to a linguistic variable (fuzzy number) is called fuzzification.

**De-fuzzification:** 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:** The Database stores the definition of the membership Function required by fuzzifier and defuzzifier.

**Rule Base:** The elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse in-put/output variables; in the steady state, small errors need fine control, which requires fine input/output variables. Based
on this the elements of the rule table are obtained as shown in Table 1, with \( V_{dc} \) and \( V_{dc-ref} \) as inputs.

**Hybrid Fuzzy**

This paper investigates two fuzzy logic controllers that use simplified design schemes. Fuzzy logic PD and PI controllers are effective for many control problems but lack the advantages of the fuzzy controller. Design methodologies are in their infancy and still somewhat intuitive. Fuzzy controllers use a rule base to describe relationships between the input variables. Implementation of a detailed rule base increases in complexity as the number of input variables grow and the ranges of operation for the variables become more defined. We propose a hybrid fuzzy controller which takes advantage of the properties of the fuzzy PI and PD controllers and a second method which adds the fuzzy PD control action to the integral control action.

The effectiveness of the two PID fuzzy controller implementations, PD and PI fuzzy controllers have the same design disadvantages as their classical counterparts. Therefore, in some cases a fuzzy PID controller maybe required. The fuzzy PID controller entails a large rule base which presents design and implementation problems. First, a reduced rule fuzzy PID scheme was implemented to take advantage of both PD and PI control actions. Some further research is required for the process of switching between the control actions. The second fuzzy PID control scheme used only the PD portion with an integral term added to eliminate steady-state error. Results from
Figure 10: Shows the z-Source Inverter for the Proposed Three Phase DVR Model

Figure 11: Supply Voltage and Output Voltage
simulations of both control schemes demonstrate the effectiveness of the PID controllers.

MATLAB MODELEING AND SIMULATION RESULTS

Compensation of Three Phase Voltage Sag and Voltage Swell Using DVR

Figure 12: Matlab/Simulink Model of Proposed Three Phase DVR using Matlab/Simulink Platform.

Figure shows the Supply and Output Voltages without DVR, both voltage sag and swell problem in output voltage.
Figure 14: Simulated Output Voltage of PI Controlled DVR

Figure 15: Matlab/Simulink Model of Fuzzy Controller for DVR

Figure 16: Simulated Output Wave Forms of Output Voltage and Supply Voltage with Fuzzy Controlled DVR
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 will be 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 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 PI and fuzzy controller.

REFERENCES


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