

# Voltage Quality Improvement using Dynamic Voltage Restorer

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**Abstract:** Power quality is one of major problems in the presence era. It has become importance especially, with the introduction of sophisticated devices, whose performance is very sensitive to quality of power supply. power quality problem is an occurrence manifested as a nonstandard voltage,current,or frequency that results in a failure of end use euipement.One of the major problem deal here is the voltage sag. To solve this problem, custom power devices are used. One of those devices is the Dynamic Voltage Restorer (DVR),which is the most effective modern custom power device used in power distribution networks.Its appeal includes lower cost, smaller size, and its fast dynamic response to the disturbances.

**Keywords—** DVR, Power Quality, Voltage Sag, Voltage Swell, Fuzzy Logic Controller, PI controller MATLAB/SIMULINK.

## I. INTRODUCTION

Power distribution systems, ideally, should provide their customers with an uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency [1] however, in practice, power systems, especially the distribution systems, have numerous nonlinear loads, which significantly affect the quality of power supplies. As a result of the nonlinear loads, the purity of the waveform of supplies is lost. This ends up producing many power quality problems. Apart from nonlinear loads, some system events, both usual (e.g. capacitor switching, motor starting) and unusual (e.g. faults) could also inflict power quality problems [2]. Power quality phenomenon or power quality disturbance can be defined as the deviation of the voltage and the current from its ideal waveform. Faults at either the transmission or distribution level may cause voltage sag or swell in the entire system or a large part of it. Also, under heavy load conditions, a significant voltage drop may occur in the system. Voltage sag and swell can cause sensitive equipment to fail, shutdown and create a large current unbalance. These effects can incur a lot of expensive from the customer and cause equipment damage [1]. The voltage dip magnitude is ranged from 10% to 90% of nominal voltage and with duration from half a cycle to 1 min and *swell* is defined as an increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min. Typical magnitudes are between 1.1 and 1.8 p.u[2-5].

There are many different methods to mitigate voltage sags and swells, but the use of a custom power device is considered to be the most efficient method, There are different types of Custom Power devices used in electrical network to improve power quality problems. Each of the devices has its own benefits and limitations. A few of these reasons are as follows. The SVC pre-dates the DVR, but the DVR is still preferred because the SVC has no ability to control active power flow [3]. Another reason include that the DVR has a higher energy capacity compared to the SMES and UPS devices. Furthermore, the DVR is smaller in size and cost is less compared to the DSTATCOM and other custom power devices. Based on these reasons, it is no surprise that the DVR is widely considered as an effective custom power device in mitigating voltage sags. In addition to voltage sags and swells compensation, DVR can also add other features such as harmonics and Power Factor correction. Compared to the other devices, the DVR is clearly considered to be one of the best economic solutions for its size and capabilities [4-5].

## II. DYNAMIC VOLTAGE RESTORER

Dynamic Voltage Restorer (DVR) is a series connected device capable of regulating the load side voltage in a distribution network. The DVR provides a three phase independently controlled voltage source utilizing power electronic components, whose voltage vector (magnitude and angle) is added to the source voltage to restore the load voltage to a prescribed level [7]. The main function of DVR is the protection of sensitive loads from voltage sags/swells arising from the distribution network. Thus it is generally installed in a distribution system between the supply and the sensitive load feeders [8]. In addition to voltage sags and swells compensation, DVR can also be used for line voltage harmonics compensation, voltage transients reductions and fault current limitations. Various circuit topologies and control schemes are available that can be used to implement a DVR[6]

## III. CONFIGURATION OF DYNAMIC VOLTAGE RESTORER

The general configuration of the DVR consists of an Injection transformer, a Harmonic filter, a Voltage Source Converter (VSC), Energy Storage Unit and a Control and Protection unit as shown in Fig 1. Energy Storage Unit in DVR can be external batteries or capacitors charged from the supply line feeder through a rectifier. Generally the energy storage unit of a DVR can be divided into two parts (i.e. Storage devices and DC Charging Circuit). The purpose of energy storage devices is to supply the necessary energy to the VSC via a dc link for the generation of injected voltages.

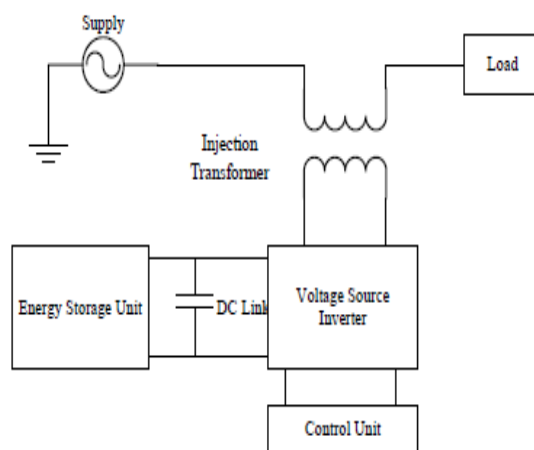


Fig.1 schematic diagram of DVR configuration

The different kinds of energy storage devices are superconductive magnetic energy storage (SMES) [9], batteries, and capacitors [10, 11]. In fact, the capacity of the stored energy directly determines the duration of the sag which can be mitigating by the DVR. Batteries are the common choice and can be highly effective if a high voltage battery configuration is used [12]. However, batteries in general have a short lifetime and often require some type of battery management system, which can be quite costly [13]. An interesting alternative to batteries is the use of super capacitors, which have a wider voltage range than batteries and can be directly paralleled across the input bus. Super capacitors have a specific energy density less than that of a battery, but a specific power greater than a battery, making them ideal for short (up to several seconds) pulses of power. Certain super capacitors can hold charge over extended periods of time, so as to act like a battery. However, unlike batteries, these super capacitors have a short charging time and much longer lifetime [10, 11]. The purpose of the DC Charging Circuit is to charge the energy storage devices after the compensation of a voltage sag/swell event as well as maintain a nominal dc link voltage. The charging circuit can be an external power supply or a rectifier fed from the supply mains of the distribution network. A Voltage Source Converter is a power electronic system capable of generating a sinusoidal voltage at any required frequency, magnitude, and phase angle. DVR configurations use the VSC to generate the voltage required to compensate for the voltage sag/swell events [14, 15]. Since the majority of the voltage sags/swells observed on distribution systems are unbalanced, the VSC will often be required to operate with unbalanced switching functions for the three phases and must therefore be able to treat each phase independently. Moreover, sag on one phase may result in swell on another phase, so the VSC must be capable of handling both sags and swells simultaneously. The output voltage of the inverter is varied by using different PWM schemes available. Given to the nonlinear nature of the semiconductor devices Voltage waveform distortion associated with the high frequency harmonics at the output of the inverter circuit is a common phenomenon. A harmonic filter unit is generally used at the output of the inverter circuit to keep the harmonic distortions at a permissible level. Although the filter unit keeps the harmonic

distortion minimum and improves the quality of the generated voltage, it can also introduce voltage drop and phase shift in the fundamental component of the inverter output and needs to be accounted for in the generated compensation voltage [16]. Injection transformers are responsible for connecting the DVR to the sensitive loads in the distribution network via the high tension windings and transforming and coupling of the injected compensating voltages generated by the voltage source converters to the incoming supply voltage. In addition, the

Injection transformer also serves the purpose of isolating the load from the system (VSC and control mechanism). Generally three single-phase transformers are used as injection transformers for injecting the compensating voltages to the system at the load bus. Proper integration of the injection transformer into the DVR, the MVA rating, the primary winding voltage and current ratings, the turn-ratio and the short-circuit impedance values of transformers are required. The existence of the transformers allow for the design of the DVR in a lower voltage level, depending upon the stepping up ratio. In such case, the limiting factor will be the ability of the inverter switches to withstand higher currents [17].

The control unit of DVR is solely responsible for controlling the compensating voltage generation by controlling the PWM pulses to the gates of semiconductor switches of the VSC. To maximize dynamic performance of DVR, efficient control architecture capable of achieving fast compensation is necessary [18, 19]. The protection unit of DVR generally consists of Bypass switches, breakers, measuring and protection relays etc. Depending upon the operating conditions, the control and protection unit maximizes the system performance and minimizes the losses associated with the operation of DVR.

#### IV. OPERATING PRINCIPLE OF DVR

The basic function of the DVR is to inject a dynamically controlled voltage VDVR generated by a forced commutated converter in series to the bus voltage by means of a booster transformer. The momentary amplitudes of the three injected phase voltages are controlled such as to eliminate any detrimental effects of a bus fault to the load voltage  $V_L$ . This means that any differential voltages caused by transient

Disturbances in the ac feeder will be compensated by an equivalent voltage generated by the converter and injected on the medium voltage level through the booster transformer. The DVR works independently of the type of fault or any event that happens in the system, provided that the whole system remains connected to the supply grid, i.e. the line breaker does not trip. For most practical cases, a more economical design can be achieved by only compensating the positive and negative sequence

components of the voltage disturbance seen at the input of the DVR. This option is Reasonable because for a typical distribution bus configuration, the zero sequence part of a disturbance will not pass through the step down transformer because of infinite impedance for this component.

The DVR has two modes of operation which are: standby mode and boost mode. In standby mode ( $V_{DVR}=0$ ), the booster transformer's low voltage winding is shorted through the converter. No switching of semiconductors occurs in this mode of operation, because the individual converter legs are triggered such as to establish a short-circuit path for the transformer connection. Therefore, only the comparatively low conduction losses of the semiconductors in this current loop contribute to the losses. The DVR will be most of the time in this mode. In boost mode ( $V_{DVR}>0$ ), the DVR is injecting a compensation voltage through the booster transformer due to a detection of a supply voltage disturbance.

## V. COMPENSATION METHODS

Compensation of voltage sags/swells is dependent upon a number of factors including DVR power rating, different load conditions and different types of voltage sags/swells. Some loads are very sensitive to phase angle jump while others are tolerant to it. Therefore, the \*compensation strategy depends upon the type and characteristics of the load connected to DVR. There are three different methods for DVR voltage injection which are presented below.

### A. PRE-DIP COMPENSATION (PDC)

The PDC method tracks the supply voltage continuously and compensates load voltage during fault to pre-fault condition. In this method, the load voltage can be restored ideally, but the injected active power cannot be controlled and it is determined by external conditions such as the type of faults and load conditions. This method is achieved by using a fault detector to freeze the output from the Phase Locked Loop (PLL) circuit, when the fault occurs. Then, the frozen angle is used to restore the previous balanced load voltages by using the Park transform [17, 18, 19]. The lack of the negative sequence detection in this method leads to the phase-oscillation in the case of single-line faults. Figure 2 shows the single-phase vector diagram of this method. According to Figure 2, the apparent power of DVR is:

$$S_{1DVR} = I_L V_{1DVR}$$

$$= I_L \sqrt{V_L^2 + V_S^2 - 2V_L V_S \cos(\theta_L - \theta_S)}$$

And the active power of DVR is:

$$P_{1DVR} = I_L (V_L \cos \theta_L - V_S \cos \theta_S)$$

The magnitude and the angle of DVR voltage are:

$$V_{1DVR} = \sqrt{V_L^2 + V_S^2 - 2V_L V_S \cos(\theta_L - \theta_S)}$$

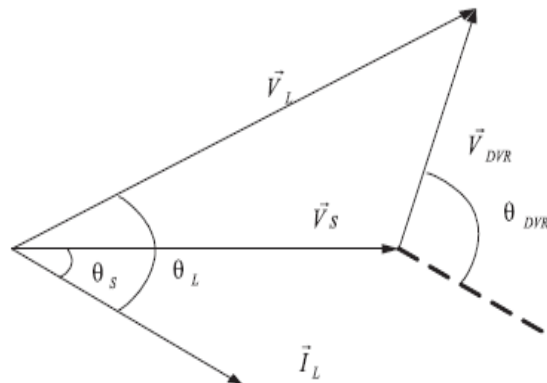


Fig.2 single –phase vector diagram of the PDC method

### B. IN-PHASE COMPENSATION (IPC)

This is the most straight forward and used method in which the injected DVR voltage is in phase with the supply side voltage regardless of the load current and the pre-fault voltage as shown in Figure 3. This method is achieved by two different ways. The first is by using a synchronized PLL with the post-fault voltage [20] and the second is the symmetrical components method [21]. Although the post fault PLL is a fast control algorithm, it cannot avoid phase jumps on the load voltage at the fault occurrence which can disturb the phase-angle controlled rectifier loads. On the other hand, the symmetrical components method has a delay time introduced by the Fortecue transform calculation [22], and parameter dependence of the filter sequence [23]. Moreover, the symmetrical components method can tolerate the effect of a phase jump by using the pre-fault phase angle [24].

The IPC method is suitable for minimum voltage or minimum energy operation strategies [18]. In other word, this approach requires large amounts of real power to mitigate the voltage sag, which means a large energy storage device. According to Figure 3, the apparent power of DVR is:

$$S_{2DVR} = I_L V_{DVR} = I_L (V_L - V_S)$$

And the active power of DVR is:

$$P_{2DVR} = I_L V_{DVR} \cos \theta_S = I_L (V_L - V_S) \cos \theta_S$$

The magnitude angle and the angle of the DVR voltage are:

$$\begin{aligned} V_{2DVR} &= V_L - V_S \\ \theta_{2DVR} &= \theta_S \end{aligned}$$

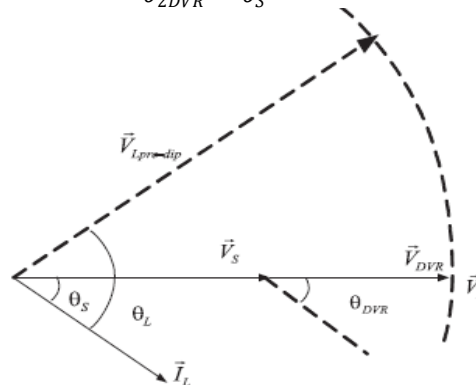


Fig. 3 phasors diagram of the IPC method

### C. IN PHASE ADVANCE COMPENSATION (IPAC)

Pre-Dip and in-phase compensation method must inject active power to loads to correct voltage disturbance. However, the amount of possible injection active power is confined to the stored energy in DC link, which is one of the most expensive components in DVR. Due to the limit of energy storage capacity of DC link, the DVR restoration time and performance are confined in these methods. For the sake of controlling injection energy, in phase advance compensation method was proposed. The injection active power is made zero by means of having the injection voltage phasor perpendicular to the load current phasor. This method can reduce the consumption of energy stored in DC link by injecting reactive power instead of active power. Reducing energy consumption means that ride-through ability is increased when the energy storage capacity is fixed. On the other hand, the injection voltage magnitude of in-phase advance compensation method is larger than those of pre-dip or in-phase compensation methods and the voltage phase shift can cause voltage waveform discontinuity, inaccurate zero crossing and load power swing. Therefore, in phase advance compensation method should be adjusted to the load that is tolerant to phase angle jump, or transition period should be taken while phase angle is moved from pre-fault angle to advance angle. In short, IPAC method uses only reactive power and unfortunately, not all the sags can be mitigated without real power, as a consequence, this method is only suitable for a limited range of sags.

## VI. PROPOSED DVR CONTROL IMPLEMENTATION

A DC to AC inverter regulates this voltage by sinusoidal PWM technique. All through normal operating condition, the DVR injects only a small voltage to compensate for the voltage drop of the injection transformer and device losses. However, when voltage sag occurs in the distribution system, the DVR control system calculates and synthesizes the voltage required to preserve output voltage to the load by injecting a controlled voltage with a certain magnitude and phase angle into the distribution system to the critical load.[25]

### A. PROPORTIONAL-INTEGRAL (PI) CONTROLLER

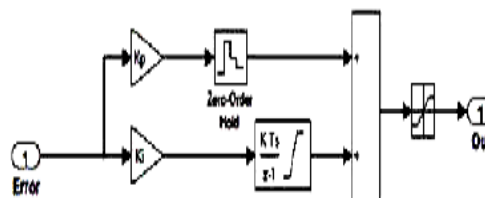


Fig. 4 Discrete PI Controller

Fig. 4: Discrete PI Controller Discrete PI Controller shown in Fig.4 is a feedback controller which drives the plant to be controlled with a weighted sum of the error and the integral of that value. 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. The error is first multiplied by the integral gain,  $K_I$  and then was integrated to give an accumulated offset that have been corrected previously.[27]

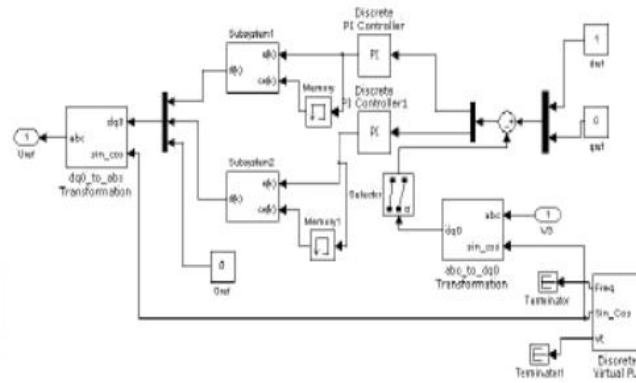


Fig. 5 Control circuit using PI with fuzzy logic controller

Fig.5 shows the control circuit designed in Matlab/Simulink software. The input of the controller come from the output voltage,  $V_3$  measured by three-phase V-I measurement at Load in pu.  $V_3$  is then transformed in dq term (expressed as instantaneous The voltage sag is detected by measuring the error between the dq-voltage and the reference values. The d-reference is set to rated voltage whilst q reference is set to zero. The dq components of load voltage are compared with the reference values and the error signal is then entering to PI controller. Two PI controller block are used for error signal-d and error signal-q separately. For error signal-d,  $K_P$  is set to 40 and  $K_i$  is set to 100 whilst for error signal-q,  $K_P$  is set to 30 and  $K_i$  is set to 150 respectively. All the gains selected use to tune up the error signal d and q so that the signal is stable and well responses to system disturbances. The outputs of the PI controller then are transformed back into  $V_{abc}$  before forwarded to PWM generator.space vector).

### B.FUZZY LOGIC CONTROLLER(FLC)

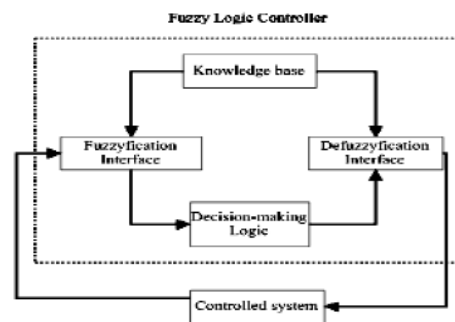


Fig. 6 Basic configuration of FL controller

Unlike Boolean logic, fuzzy logic allows states (membership values) between 0 or 1. Its major features are the use of linguistic variables rather than numerical variables. Linguistic variables, defined as variables whose values are sentences in a natural language (such as small and big), may be represented by fuzzy sets [26]. The general structure of an FLC is represented in Fig.6 and comprises four principal components:

- a fuzzyfication interface which converts input data into suitable linguistic values;
- a knowledge base which consists of a data base with the necessary linguistic definitions and control rule set;
- a decision making logic which, simulating a human decision process, infers the fuzzy control action from the knowledge of the control rules and the linguistic variable definitions; and
- a defuzzification interface which yields a nonfuzzy control action from an inferred fuzzy control action.

In this paper, two FL controller block are used for error signal-d and error signal-q as shown in Fig.7. The process also same as before except the controller now is Fuzzy Logic. For both blocks (error signal-d and q) the FL controller consists of three linguistic variables from input which is; Negative (N), Zero (Z) and Positive (P). Each parameter from linguistic variables for error signal is shown in Fig.8. For delta error, there are three linguistic variables, Negative (N), Zero (Z) and Positive (P). Both variables can be depicted as in Fig.9.

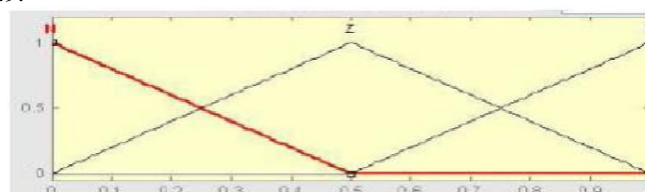


Fig. 7 Linguistic variables from error

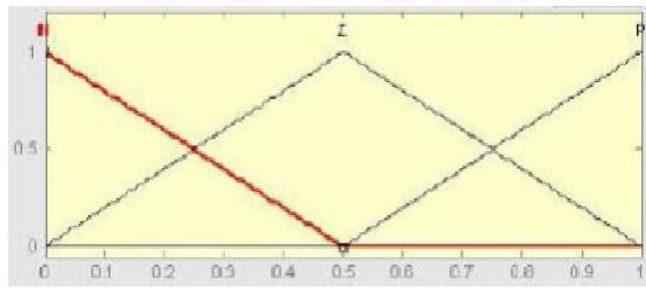
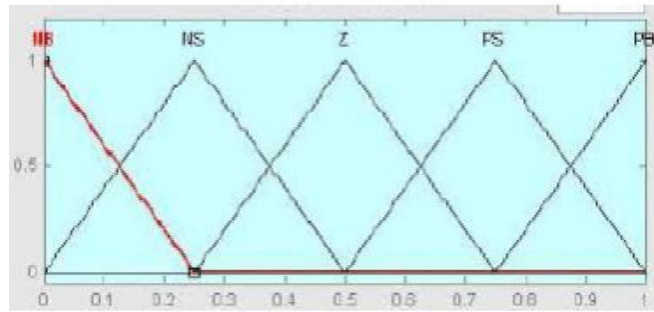


Fig. 8 Linguistic variables from delta error



positive Small (PS), Fig.9. Shows each parameter for output signal.

Table 1: Rule Base

| E\DE | N  | P  |
|------|----|----|
| N    | NB | Z  |
| Z    | NS | PS |
| P    | Z  | PB |

In the decision-making process, there is rule base that linking between input (error signal) and output signal. Table 1 show the rule base used in this FL controller.

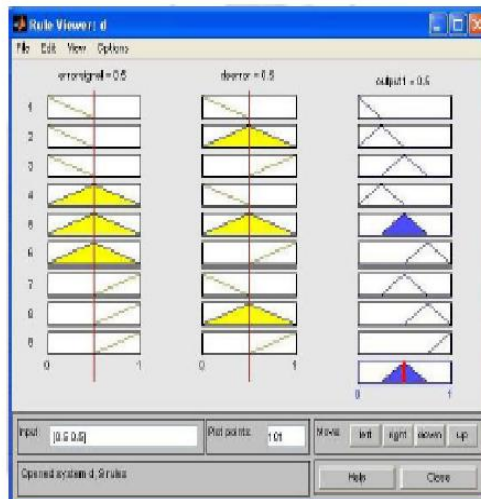


Fig. 10 Rule viewer of d reference

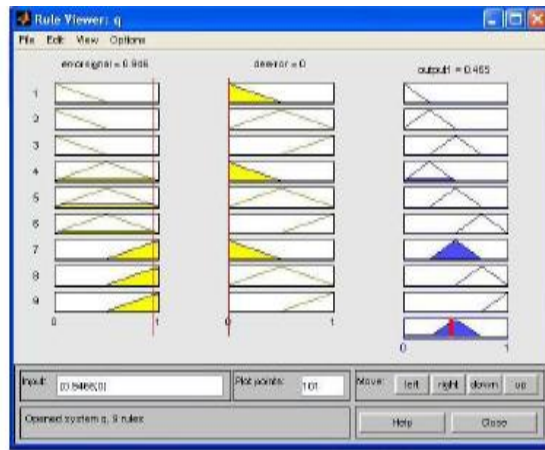


Fig. 11 Rule viewer of q reference

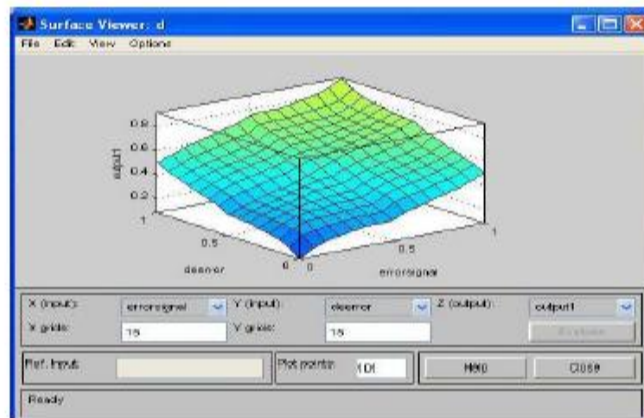


Fig. 12 Surface viewer

**VII. SIMULATION RESULTS AND DISCUSSION**

In order to understand the performance of the DVR along with control, a simple distribution network as shown in Fig.13 is implemented. There are different fault conditions like normal system, single line to ground fault, double line to ground fault, three phase fault and voltage sag simulated using MATLAB/SIMULINK software. PI with fuzzy logic controller is used for the control purpose. The DVR system connected to the distribution system using a booster transformer.

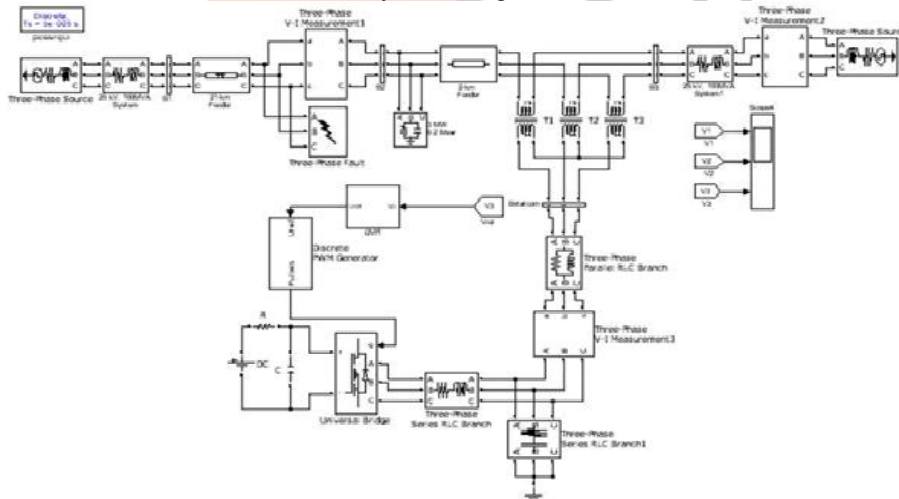


Fig. 13 Simulink Model of DVR Test System

In this system different fault conditions like normal system, single line to ground fault, double line to ground fault, three phase fault and voltage sag with feeder for the duration of 0.25s to 0.35s with fault resistance is 20 ohms and the ground resistance is 0.001 ohms. The output results for the above system are shown below.

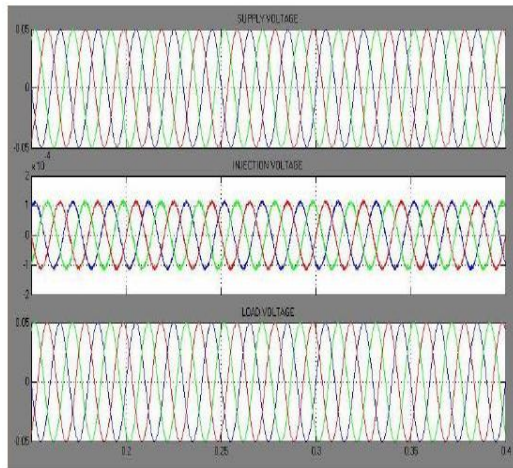


Fig. 14 Normal system (a) Supply voltage, (b) Injection voltage, and (c) Load voltage

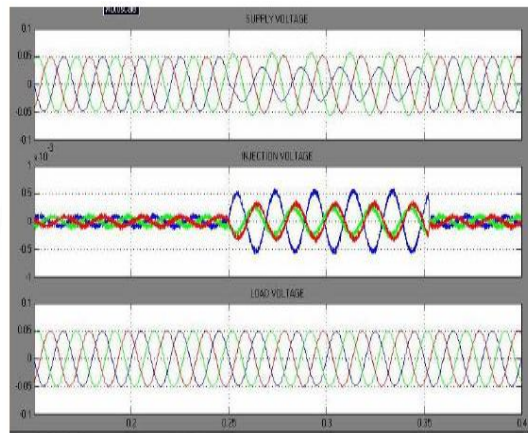


Fig. 15 Single line to ground fault; (a) Supply voltage, (b) Injection voltage, and (c) Load voltage

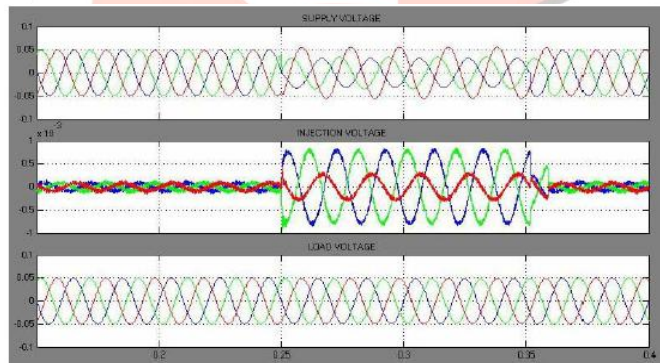


Fig. 16 Double line to ground fault; (a) Supply voltage, (b) Injection voltage, and (c) Load voltage

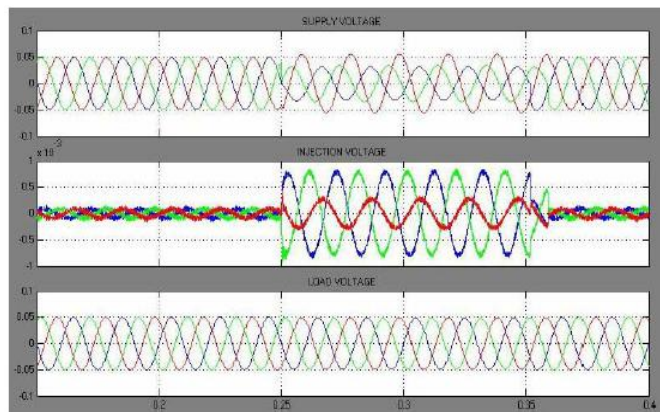


Fig. 17 Three phase fault; (a) Supply voltage, (b) Injection voltage, and (c) Load voltage



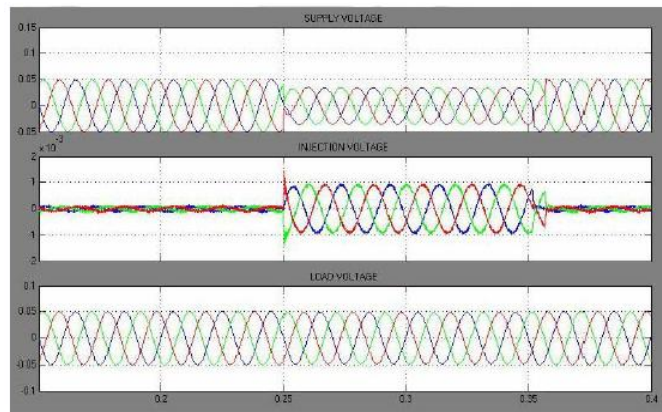


Fig. 18 Voltage sag; (a) Supply voltage, (b) Injection voltage, and (c) Load voltage

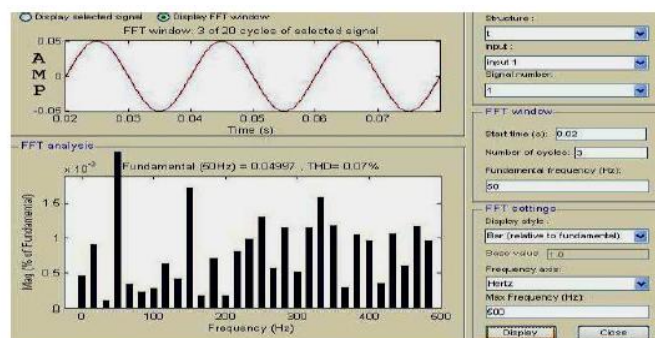


Fig. 19 THD for load voltage using PI with Fuzzy Logic controller

Table 2: THD for Vdc

| Sr.No. | Vdc(V) | THD(%) |
|--------|--------|--------|
| 1      | 250    | 0.37   |
| 2      | 200    | 0.30   |
| 3      | 150    | 0.22   |
| 4      | 100    | 0.15   |
| 5      | 50     | 0.07   |

## VIII. CONCLUSION

In this paper, the modeling and simulation of DVR controlled by PI with Fuzzy Logic Controller has been developed using Matlab/Simulink. For the controller, the simulation result shows that the DVR compensates the sag quickly (50 $\mu$ s) and provides excellent voltage regulation. DVR handles different fault condition like normal system, single line to ground fault, double line to ground fault, three phase fault, voltage sag, balanced and unbalanced fault without any difficulties and injects the appropriate voltage component to correct any fault situation occurred in the supply voltage to keep the load voltage balanced and constant at the nominal value. In this paper, the DVR has shown the ability to compensate for voltage sags at the grid side, this can be proved through simulation. The efficiency and the effectiveness in voltage sags compensation showed by the DVR makes it an interesting power quality device compared to other custom power devices. Therefore, when it comes to implementation, it is crucial to consider these factors, so that the performance of DVR is optimized.

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