

**COMPARATIVE ANALYSIS OF THE PI, FUZZY AND HYBRID PI-FUZZY
CONTROLLERS BASED DVR**

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IN

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CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled "COMPARATIVE ANALYSIS OF THE PI, FUZZY AND HYBRID PI-FUZZY CONTROLLERS BASED DVR" in partial fulfillment of requirement for the award of the M.E. in POWER SYSTEM AND ELECTRIC DRIVES submitted in the ELECTRICAL AND INSTRUMENTATION ENGINEERING department, Thapar University, Patiala is an authentic record of my own work carried out under the guidance of Mr. PARAG NIJHAWAN, (Assistant Professor EIED, Thapar University).

The matter presented in this thesis has not been submitted for the award of any degree of this or any other university.

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ABSTRACT

Due to complexity of power system combined with other factors such as increasing susceptibility of equipment, power quality is apt to waver. With electricity demand growing, low power quality is on the rise & becoming notoriously difficult to remedy [1]. Distribution system needs to be protected against voltage sags, dips & swells that adversely affect the reliability & quality of power supply at the utility end. The Dynamic voltage restorer (DVR), which has been utilized in optimized way so as to improve performance, has been put under new technique of sag detection. Various control strategies have been developed to mitigate the voltage sag/swell and the mitigation of unbalanced voltage dips. The applications of Fuzzy logic controller have taken new dimension in various fields. In this thesis, full panorama of power quality disturbances, with background theory and guidelines on measurement procedures & problem solving techniques are presented. The essentials of control scheme with immediate voltage generation to regulate the unbalance voltage phase in three phase system and a tested method to improve the reliability within the distribution system is presented. The 11kV system is controlled by linear & non-linear techniques and their performance levels are compared. The simulation results of the recommended system states the better reliability & compatibility of non-linear techniques with non-linear loads than the system with linear techniques with non-linear loads. The capability of DVR is demonstrated using MATLAB/SIMULINK simulation models. From the obtained results, we have considered the feasibility & practicability of the approach for the linear and non-linear load under voltage sag condition.

LIST OF ABBREVIATIONS

CPD	-	Custom Power Device
DVR	-	Dynamic Voltage Restorer
PI	-	Proportional Integral
FACTS	-	Flexible AC Transmission System
SVC	-	Static VAR Compensator
STATCOM	-	Static Synchronous Compensator
TCSC	-	Thyristor Controlled Series Compensator
SSSC	-	Static Synchronous Series Compensator
UPFC	-	Unified Power Flow Conditioner
IPFC	-	Interline Power Flow Conditioner
HVDVR	-	High Voltage Dynamic Voltage Restorer
IPM	-	Intelligent Power Module
SVPWM	-	Space Vector Pulse Width Modulation
VSC	-	Voltage Source Converter
PSCAD	-	Power System Computer Aided System
EMTDC	-	Electromagnetic Transients Including DC
SPLL	-	Software Phase Locked Loop
VSVPWM	-	Voltage Space Vector Pulse Width Modulation
MOSFET	-	Metal-Oxide Semi-conductor Field effect
ESS	-	Energy Storage System
FLC	-	Fuzzy Logic Controller
THD	-	Total Harmonic Distortion
FFT	-	Fast Fourier Transform
IEEE	-	Institute of Electrical and Electronics Engineer
EPQ	-	Electric Power Quality
BESS	-	Battery Energy Storage System
SA	-	Surge Arrester
SMES	-	Super Magnetic Energy Storage System
GTO	-	Gate Turn-Off Thyristor
IGBT	-	Insulated Gate Bipolar Transistor
IGCT	-	Insulated Gate Commutated Thyristor

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INTRODUCTION

1.1 OVERVIEW

The economy invested in the distribution system is large enough to take into account the concept of equipment protection against various disturbances that affects the reliability of not only the distribution system but the entire power system incorporating generation & transmission too. The wide acceptance of sophisticated electronic devices at the utility end deteriorates the quality of supply & utility is suffering from its bad effects on large scale. The various power quality problems[1] encompass the voltage sags, voltage dips & voltage swells, flickers, harmonics & transients accompanied by unbalanced power, which are results of various faults with three phase fault being the most severe among all, starting of induction motor which is most often used due to its rugged construction, switching off large loads and energizing of capacitor banks. The higher index of reliability & power quality [2] to satisfy the customer has reflected the need for the development & application of compensation systems. Compensating systems [3] also known as the custom power devices (CPD) offer a handful of protection & security to the system under observation. They tend to absorb the various disturbances by injecting appropriate voltage, current or both into the system; thereby relieving the main source from meeting the reactive power demand of the load. This dissertation attempts to explain the various control strategies providing a reliable solution to the faulted system with the help of DVR (Dynamic voltage restorer). This series conditioner device is capable of generating or absorbing real and reactive power with the help of its essential components, namely power circuit & control circuit. Various control techniques are available to obtain a controlled output voltage, to be injected into the system. They are known as Linear & Non-linear techniques. A PI controller with a linear structure offers satisfactory performance over a wide range of operation [5]. The problem encountered by the controller is the setting of PI parameters i.e. the gains (K_p , K_i). In the influence of varying parameters and operating conditions, the fixed gains of linear controller don't adapt accordingly to give good dynamic response. To overcome the problems faced by a linear technique, non-linear technique is an effective solution [10]. The recommended system uses the PI, Fuzzy [20] [21] [22] and Hybrid PI-Fuzzy [28] controllers to investigate the performance level of various controllers in a regard to increase the capability of the existing system by creating immunity

from disturbances. Simulation results of voltage sag condition for a linear & non-linear load are presented.

1.2 LITERATURE SURVEY

According to the recent power disturbance studies, Voltage sags are considered to be the most frequent type with severe impact on sensitive loads. Their worst consequence leads to disruptions & substantial economic losses. There are many different methods to mitigate voltage sags, but a Custom Power (CPD) device is considered to be the most efficient method. There are many types of CPD. This dissertation studied various methods and concluded that the Dynamic Voltage Restorer (DVR) is the most efficient and effective device to protect sensitive equipment against voltage sags. Its appeal among power quality devices is due to its lower cost, smaller size, and its good dynamic response to the disturbance.

Several research papers and publications have addressed the improvement of power quality using DVR. A brief review of the work undertaken so far is as follows:

C. Sankaran [1] introduced the clear description of power quality & its associated problems in power system. He presented the examples & steps to solve power quality problems in terms of illustrations, figures & their worst effects on power system performance leading to disruptions & substantial economic losses. He also explained the various power quality issues using graphs.

N.G.Hingorani *et al.* [2] introduced a technology popularly known as FACTS (flexible Ac transmission system) based on power electronics to enhance the controllability, stability & power transfer capability of ac transmission system. He revolutionized the area of power electronics by discussing in-depth the FACTS controllers including SVC, STATCOM, TCSC, SSSC, UPFC, IPFC plus voltage regulators, phase shifters, and special Controllers with a detailed comparison of their performance attributes. He presented a practical approach to FACTS & their major applications in power industry.

Satyaveer Gupta *et al.* [5] presented a comprehensive survey on custom power devices in distribution network. He gave a brief review of compensating devices to mitigate the power quality problems at distribution level to enhance power quality.

N.H. Woodley *et al.* [13] described the Installation of the world's first Dynamic Voltage Restorer (DVR) on a system to protect a critical customer load from voltage disturbances. The proposed DVR was installed on 12.47-kV system at an automated yarn manufacturing and weaving factory where it protected the plant from disturbances from the distribution system. The test load consists of combination of reactive, resistive and non-linear rectifier load elements to provide a range of kW loads with varying power factors and harmonic current. Voltage sags were imposed on the line voltage waveform by connecting various impedance elements in series with the incoming line.

H.P. Tiwari *et al.* [14] analyzed the performance of the system to compensate voltage sag with different DC storage capacity so as to achieve rated voltage at a given load. Various cases with different load condition are considered to study the effect of DC storage on sag compensation. The effectiveness of a DVR system mainly depends upon the rating of DC storage rating and the percentage of voltage sag.

Poh Chiang Loh *et al.* [15] implemented and controlled a high voltage dynamic voltage restorer in power distribution network to compensate for sags in utility voltages. The HVDVR consists of a multilevel inverter topology with isolated dc energy storages that directly connects the HVDVR to the distribution network relieving from a bulky and costly series injection transformer.

John Godsk Nielsen *et al.* [16] tested and controlled DVR with advanced technique at medium voltage level of 10kV. The DVR is tested for different methods to initiate voltage dips. From simulation results at 10 kV level, the DVR's capability to maintain fixed voltage to a sensitive load in the case of voltage dips is demonstrated. Furthermore, even in the case of a transformer failure the system also works very fine.

Brito *et al.* [17] implemented a low cost topology for compensation of voltage sags and swells. The dynamic voltage restorer neither uses rectifier stage nor a dc capacitor with only thyristors being used as switching devices. The control system is simple, eliminating the use of powerful computational platforms, causing a cost reduction and reliability increase.

Bipin Singh *et al.* [18] introduced a study of 5-level inverter controlled with DVR technique. His work deals with modeling and simulation of five- level inverter based Dynamic Voltage

Restorer (DVR). The proposed converter is suitable for high voltage and high power applications and has ability to synthesize waveforms with better harmonics spectrum. Further, the heating is reduced since the harmonics in the output of cascaded inverter are less.

M.Sharanya *et al.* [19] solved various power quality problems using DVR. She gave an overview of the compensating device, its strategies & control methods in detail. While comparing various compensating strategies, she concluded that the linear controllers provide simpler operation & less computational efforts as compared to other methods but nonlinear controller is more suitable than the linear type since the DVR is truly a non-linear system due to the presence of power semiconductor switches in the inverter bridge.

U. Vidhu Krishnan *et al.* [20] presented a control system based on dqo technique which is a scaled error between source side of the DVR and its reference for sags/swell correction. His work confirmed the effectiveness of the device in compensating voltage sags and swells with very fast response (relative to voltage sag/swell time) by MATLAB using simulation.

Amardeep Shitole *et al.* [21] has presented the implementation of control algorithm for DVR and detection of a power quality problem such as voltage sag/swell by the use of dSPACE (DS1104) real time simulator by using the Real Time Workshop toolbox. His work with highly satisfactory simulation results have validated use of dSPACE which resulted in reduction of complexity of hardware and simplified the generation of pulses required for the Intelligent Power Module (IPM). The working of DVR has become more reliable.

P.N.K.Sreelatha *et al.* [22] studied the restoration of supply voltages using a DVR with Space vector control technique. SVPWM method is an advanced, computation intensive PWM method and possibly the best among all the PWM techniques. He studied the effect of X/R ratio on the voltage sag after a fault and its restoration, so that any distribution line can be compensated with a DVR with different X/R ratios. The ratio is kept low so that the regulation of the line is within 5%.

P. Ananthababu *et al.* [23] presented two pulse width modulation-based control techniques, viz. sinusoidal PWM and space vector PWM, for controlling the electronic valves in two levels Voltage Source Converter (VSC) used in the DVR system. His work presented the performance of Dynamic Voltage Restorer (DVR) against voltage sags and voltage swells

using space vector PWM technique through PSCAD/EMTDC software and results were compared with sinusoidal PWM. He concluded that space vector PWM can utilize the better dc voltage and generates the fewer harmonic in inverter output voltage.

Rosli Omar *et al.* [24] discussed a new control algorithm based on Space Vector Pulse Width Modulation (SVPWM) technique to generate the pulses & investigated it through computer simulation by using PSCAD/EMTDC software. From simulation the results show a very good compensation for compensating voltage sags.

Changjiang Zhan *et al.* [25] proposed a compensation strategy based on an SPLL algorithm for the DVR, which is applied for the dynamic compensation of voltage sags with a phase jump. The PWM inverter control of the DVR adopts a conventional VSVPWM method for the maximum utilization of the dc-link voltage supported by lead-acid batteries. An SCC (self-charging control) technique was presented to replenish energy into the lead-acid batteries. Further, a 3-dimensional voltage space vector PWM algorithm has been used for the control of a DVR using the 3-phase 4-wire split-capacitor inverter that can inject three independent voltages into the main circuit to maintain the voltage waveform at the sensitive load. Its validity has been demonstrated thorough EMTDC simulation.

Ming Fang *et al.* [26] have demonstrated the voltage restoring capability of a novel series Dynamic Voltage Restorer, based on the use of cryogenic power electronics technology, and validated the reference voltage tracking control strategy. It indicated a potential use of the Cryo-MOSFET as a competitive high-speed large-current switching device in the future.

D.N.Katole *et al.* [27] presented the Dynamic Voltage Restorer (DVR) with ESS based PI Controller method to compensate balanced voltage sag. A controller based on feed forward technique is used which utilizes the error signal (difference between the reference voltage and actual measured voltage) to trigger the switches of an inverter using a Pulse Width Modulation (PWM) scheme. The advantages of a d-q based sag detector over rms voltage have been shown.

S.Deepa *et al.* [28] have presented a new DVR system based on the Z-source inverter. The impedance source inverter employs a unique impedance network couple with inverter main circuit and rectifier. By controlling the shoot through duty cycle, the Z source inverter system

using MOSFET provide ride through capability during voltage sags, reduces line harmonics and improves power factor. Simulation results verified the operational and demonstrated the promising Features of DVR with 8-bus system in supporting load voltages under voltage sags conditions.

B.Panda *et al.* [29] have modeled & simulated a fast PWM-based DVR with Fuzzy Logic controller (FLC) under voltage sag/swell phenomena. The capability of DVR to mitigate the voltage sag is demonstrated by digital simulation.

Md. Riyasat Azim *et al.* [30] for both, detection of sag/swell and for quantification have used the classical Fourier Transform (FT) and a Fuzzy Logic controller that makes use of the error signal (difference between the reference voltage and actual measured load voltage) to control the firing sequence of the switches of an inverter using a Sinusoidal Pulse Width Modulation (SPWM) scheme.

Kamil. C. Bayindir *et al.* [10] proposed a control scheme combining the excellent voltage regulation capabilities of FLC with carrier modulated PWM inverter. Effectiveness of the control scheme was shown by comparison with conventional method on the basis of THD & per unit values for several cases.

Francisco Jurado *et al.* [9] has compared the output response of DVR with PI and FLC demonstrating that the transient response of DVR with FLC is better than with PI. The voltage error and its derivative are the Fuzzy Logic controller input crisp values. When a Fuzzy Logic controller is used, the tracking error and transient overshoots of PWM can be considerably reduced. The simulations carried out show that the Dynamic voltage restorer provides excellent voltage regulation capabilities.

M. Ashari *et al.* [31] used a Fuzzy Logic controller with 3 inputs to maintain the load voltage through d-q transformation. He applied 3 inputs of error d, error q and error Δd with membership functions to maintain the injection voltage.

R. H. Salimin *et al.* [8] has assessed the performance of DVR with two controllers namely, PI & FLC. In his study, the dq0 transformation or Park's transformation is used in voltage calculation in both controllers and further, output is controlled by PI and FLC respectively.

M A Hannan *et al.* [32] presents the multi-level; 24-pulse DVR with SPWM based control system using the PSCAD/EMTDC Software package. Various issues have been addressed in the simulation studies such as, the effectiveness of DVR in mitigating voltage sags, impact of phase shift during voltage sag on sizing of DVR, harmonic reduction in the DVR and influence of induction motor loads on the voltage sag compensation capability. From the simulation results, the designed DVR responded well in compensating voltage sags. Simulation results also prove that the DVR is equally capable of restoring the load voltage for both static and induction motor loads.

Fawzi AL Jowder *et al.* [33] developed models for different system topologies of the dynamic voltage restorer (DVR) using Simulink SimPowerSystem Toolbox. The control of the DVR system topologies is based on hysteresis voltage control. Simulation tests on radial distribution system, equipped with the DVR under three-phase and single-phase voltage sags with phase jump, are used to verify the operation of different DVR topologies. Time domain simulations have been used to verify the operation of these models. He also presented the easy modifications that can be carried out with these models.

S.Ezhilarasan *et al.* [34] dealt with various power quality problems & optimized the performance of DVR by considering its efficiency & effectiveness in compensating voltage sag, which is further dependent on the control technique. His work confirmed the control of DVR based PI using Fuzzy logic software which worked well both in balance & unbalance conditions.

1.3 SCOPE OF WORK

Power quality gains its importance with the introduction of sophisticated electrical gadgets. Nowadays, non-linear loads cause the distortion of sinusoidal waveform which adversely affect the power quality performance. Switching of heavy loads, capacitors, and transformers and unbalanced load on a three phase system are some of the sources that contribute to voltage sag. Due to these voltage sags, the performance and the life of the equipments deteriorate considerably. This calls for the introduction & usage of Custom Power devices (CPD) with philosophy of improvement of the power quality. As per the

literature review, the DVR provides excellent voltage regulation capabilities in the influence of various power quality problems.

The objective of the proposed dissertation is to promise power quality & reliability in the distribution network with the simulation of various control strategies of DVR .The three control schemes namely PI,Fuzzy,PI-Fuzzy have been compared on account of the amount of compensation being injected into the system under voltage sag condition for linear & non-linear loads. The three controllers provide almost equivalent compensation for linear loads but the difference in compensation occurs during non-linear loads. The capability of DVR control schemes is demonstrated using MATLAB/SIMULINK simulations. The Simulink models have been developed for the distribution networks with linear and non-linear loads. The effectiveness of PI controller based DVR, Fuzzy controller based DVR and hybrid PI-Fuzzy controller based DVR in these distribution network is investigated.

1.4ORGANISATION OF THESIS

The content of the thesis is arranged as follows.

Chapter-1 includes the brief introduction, different approaches in the field of power quality improvement by several researchers & the proposed work.

Chapter-2 defines the various concepts of power quality and the terms related to power quality issue. The causes and characteristics properties of the voltage sags are analyzed & their mitigation techniques are discussed.

Chapter 3- explains the various custom power devices available to improve the performance & the reliability of power system. The custom power devices are at a fence solution to the distribution network.

Chapter 4 – discusses the basic concept of DVR. Moreover, various control strategies employed to the tested system are also included.

Chapter 5- presents the SIMULINK test models & their results.

Chapter 6-explains the conclusion of the work presented & future scope of work.

POWER QUALITY

2.1 INTRODUCTION

Most of the more important international standards define power quality as the electric supply protected from any deviation in voltage, current or frequency under normal conditions & don't disrupt or disturb the customer's processes. Quality of power supply is basically defined by its two pivotal factors, voltage quality & supply reliability. These pivotal factors lead to power quality problems when they suffer change in their characteristics due to equipment failure or sudden system disturbances. The increasing trend of non-linear loads in the power system network has lead to the hazardous consequences suffered by the customer. This has further resulted in the slew of forward looking enhancements in system protection using Custom Power devices. They aptly enhance the stability & reliability of the system by reducing the effects of various disturbances.

2.2 DEFINITION OF POWER QUALITY

The quality assurance of electric power demands a deep research and study on the subject 'Electric Power Quality'. The interesting discussions & their respective proposals lead to various definitions of "Power Quality". It is term which different people described in different ways as follows:

1. Institute of Electrical and Electronic Engineers (IEEE) Standard IEEE1100 defines power quality as "the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment."
2. Electric Power Quality (EPQ) is a term that refers to maintaining the near sinusoidal waveform of power distribution bus voltages and currents at rated magnitude and frequency. Thus EPQ is often used to express voltage quality, current quality, reliability of service, quality of power supply, etc.
3. Power Quality is defined as the set of Parameters defining the properties of the power supply as delivered to the user in normal operating conditions in terms of continuity of supply and characteristics of voltage (symmetry, frequency, magnitude, waveform).

- Power quality is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance or life expectancy. This definition embraces two things that we demand from an electrical device: performance and life expectancy.

2.3 POWER QUALITY CONCERN

The variation in the definitions of power quality as given here are much wider than the general interpretation of power quality. This has to do with the fact that power quality in most cases is an issue due to the phrase ‘bad power quality’. A power quality disturbance is only seen as an issue when it causes problems, either for the customer or for the network operator. Voltage sags, Voltage dips and harmonics are the problems encountered which makes power quality, a matter of concern. This is due to the presence of nonlinear elements in the power system (i.e. either in the network or in the loads). The main distortion is due to power-electronic loads like computers, televisions, energy- saving lamps. Such loads can be found in increasing numbers with domestic and commercial customers in a run to increase efficiency & productivity leading to increased distortion in the network. The effect is especially severe for lower-order voltage harmonics at the terminals of rotating machines & higher-order harmonics for capacitor banks. Also adjustable-speed drives and arc furnaces are famous for the distortion they cause. This accounts for the mitigation by improving the immunity of equipment by the use of custom power devices. The ability of the equipment to perform in the installed environment is an indicator of its immunity.

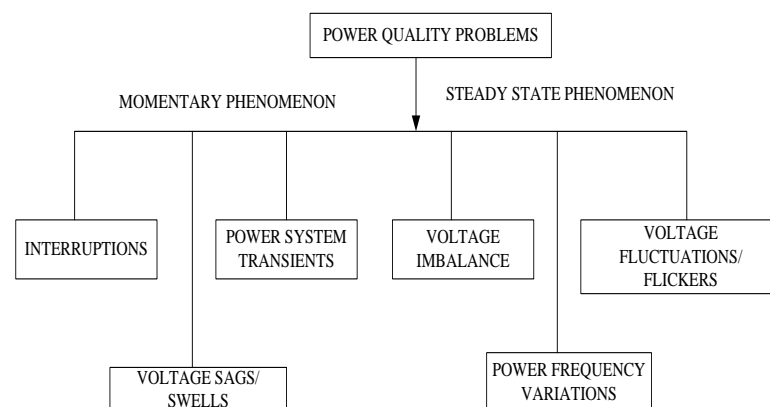


Figure 2.1: Classification of Power Quality Problems

2.4 POWER QUALITY PROBLEMS

The users demand higher power quality to use more sensitive loads to automate processes and improve living standards. Some basic criterions for power quality are constant

rms value, constant frequency, symmetrical three-phases, pure sinusoidal wave shape and limited THD. These values should be kept between limits determined by standards if the power quality level is considered to be high. The economic losses due to power interruptions and disturbances can be quite high as a result of the important processes controlled and maintained by the sensitive devices. Power quality disturbances can be summarized as follows:

1. **Interruption/under voltage/over voltage:** They are among the very common type of disturbances. During power interruption, voltage level of a particular bus goes down to zero. The interruption may occur for short or medium or long period. Such disturbances are increasing the amount of reactive power drawn or deliver by a system, insulation problems and voltage stability.
2. **Voltage/Current unbalance:** Voltage and current unbalance may occur due to the unbalance in drop in the generating system or transmission system and unbalanced loading. During unbalance, negative sequence components appear. It hampers system performance and in some cases it may hamper voltage stability.
3. **Power system harmonics:** They are low-frequency phenomena characterized by waveform distortion, which introduces harmonic frequency components. Voltage and current harmonics have undesirable effects on power system operation and power system components. In some instances, interaction between the harmonics and the power system parameters ($R-L-C$) can cause harmonics to multiply with severe consequences.
4. **Power frequency disturbances-**These are low-frequency phenomena that result in voltage sags or swells. These may be source or load generated due to faults or switching operations in a power system.
5. **Power system transients-** They are fast, short-duration events that produce distortions such as notching, ringing, and impulse. The mechanisms by which transient energy is propagated in power lines, transferred to other electrical circuits, and eventually dissipated are different from the factors that affect power frequency disturbances.
6. **Voltage sag:** It is a short duration disturbance. During voltage sag, r. m. s. voltage falls to a very low level for short period of time.

7. **Voltage swell:** It is a short duration disturbance. During voltage sag, r. m. s. voltage increases to a very high level for short period of time.
8. **Flicker:** It is visual effect and undesirable frequency variation of voltage in a system.
9. **Ringing waves:** Oscillatory disturbances of decaying magnitude for short period of time is known as ringing wave. It may be called a special type transient.
10. **Outage:** It is special type of interruption where power cut has occurred for not more than 60 s due to fault or mal-tripping of switchgear/system.

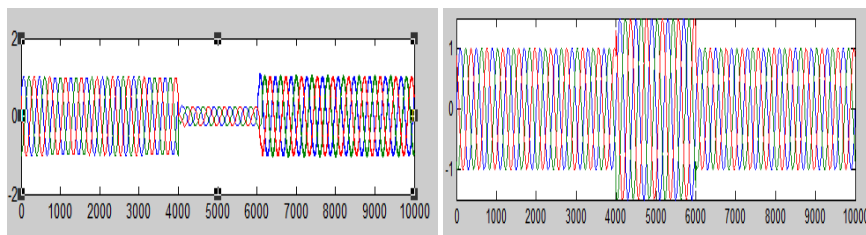


Figure 2.2: (a) Voltage Sag (b) Voltage Swell

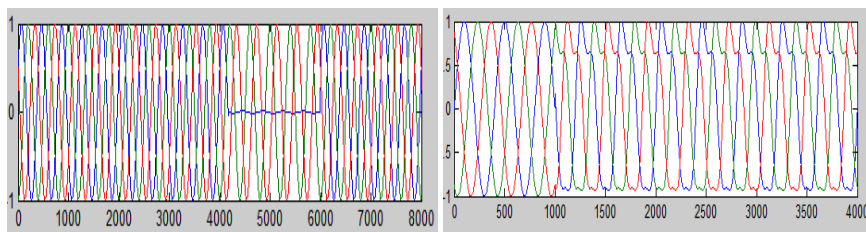


Figure 2.2: (c) Outage (d) Harmonics

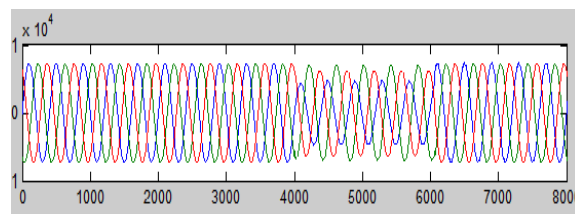


Figure 2.2 (e): Unbalance

Figure 2.2: Power Quality Problems

2.5 POWER QUALITY SOLUTIONS

The integrated solution to the power quality problems encountered in the distribution area is “Custom Power”. It focuses on reliability & quality of power flow. Custom power technology, the low-voltage counterpart of the more widely known flexible ac transmission system (FACTS) technology, aimed at high-voltage power transmission applications, has emerged as a credible solution to solve many of the power quality problems relating to continuity of supply at the end-user level [4]. Mitigation is in the harmonic context which is often seen as reduction of harmonic voltage or current distortion.

However the problem can also be mitigated by improving the immunity of equipment. The mitigation methods includes reducing the number of faults, faster fault clearing, improved network design & operation, improved end-user equipment [5].The higher index of reliability & power quality to satisfy the customer has reflected the need for the development & application of compensation systems. Compensating systems also known as the custom power devices offer a handful of protection & security to the system under observation. A custom power device is a reliable & flexible solution to the consumers regarding the power supply. They tend to absorb the various disturbances by injecting appropriate voltage, current or both into the system; thereby relieving the main source from meeting the reactive power demand of the load. Various custom power devices covering a wide range of flexible controllers & capitalize on evolution of power electronic controllers are widely used to compensate voltage sag/swells in the system [3].The custom power devices used for transmission system includes static synchronous compensator (STATCOM), static synchronous series compensator (SSSC), interline power flow conditioner (IPFC) & unified power flow conditioner(UPFC) and for distribution system are distribution static synchronous compensator(DSTATCOM), dynamic voltage restorer(DVR), active power filter(APF),unified power quality conditioner(UPQC) etc. There are various other custom power devices such as Battery Energy Storage Systems (BESS), Surge Arresters (SA), Super conducting Magnetic Energy Systems (SMES), Static Electronic Tap Changers (SETC), Solid-State Transfer Switches (SSTS) and Solid State Fault Current Limiter (SSFCL).

In this work, the effectiveness of DVR to compensate load voltage is investigated. It is a series compensating device that helps in increasing the immunity of the equipment & reliability of the system by regulation of voltage in the system. The whole work is concentrated around DVR & its various control strategies.

DYNAMIC VOLTAGE RESTORER

3.1 INTRODUCTION

Power quality is an issue; gaining significant interest due to huge economic losses which is the result of various voltage disturbances occurring in the system. Among the voltage disturbances, voltage sag is most severe that adversely affects the performance of the system. The one such efficient & reliable solution is the DVR.

DVR is a static series compensator that injects voltage in series to the distribution system, regulating the load side voltage. It is connected between the supply and the sensitive load to compensate the line voltage harmonics, reduction of transients in addition to compensation of voltage sags & swells.

3.2 PRINCIPLE OF DVR OPERATION

The main aim of DVR is to regulate the voltage at the load terminals irrespective of sag, distortion or unbalance in the supply voltage. The basic operating principle is to inject a voltage of required magnitude & frequency to restore the load voltage under voltage sag or distortion. Generally; it employs solid state power electronic switches such as GTO, IGBT or IGCT in the VSI, which can be operated in various pulse width modulation techniques such as SPWM (sinusoidal pulse width modulation), MSPWM (multiple sinusoidal pulse width modulation). They inject a set of three phase AC voltage in series & synchronism with the distribution system.

In normal condition it operates in the standby mode. During the disturbance, the nominal voltage is compared with the voltage variation in order to calculate the voltage to be injected by the DVR to maintain the supply voltage within limits. The DVR is capable of providing the reactive power compensation but the real power is provided by the energy storage system.

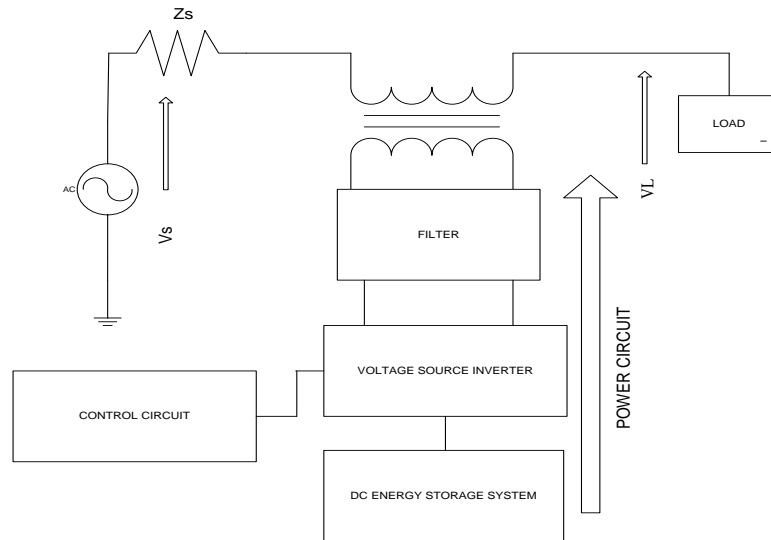


Figure 3.1: Block Diagram of Dynamic Voltage Restorer

3.3 CONFIGURATION OF DVR

The vital components of DVR are the power circuit which injects the desired voltage & control circuit that controls the load voltage of the system within prescribed limits. It consists of the following main components whose description is given below:

3.3.1 VOLTAGE SOURCE INVERTER

It forms the building block of compensating device. It performs the power conversion process from DC to AC. VSI consists of fully controlled semiconductor power switches to form a single phase or three phase topologies. For medium power inverters, IGBT's are used and GTO's or IGCT's due to compact size & fast response for high power inverters are employed. The single phase VSI topology encompasses a low-range power applications and medium to high power applications are covered by the three phase topology [10]. Single phase VSI consists of four semiconductor switches (in 2 legs) to generate the ac output waveform as in fig.3.1. Three phase VSI is a six step bridge inverter that uses a minimum of six thyristors as in fig 3.2, where a step means a change in the firing from one thyristor to the next thyristor in proper sequence. For one cycle of 360 degree, each step is of 60 degree for a six step inverter.

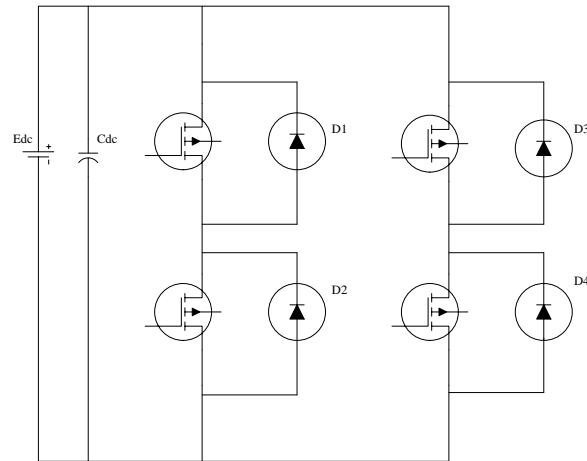


Figure 3.2: Single Phase VSI

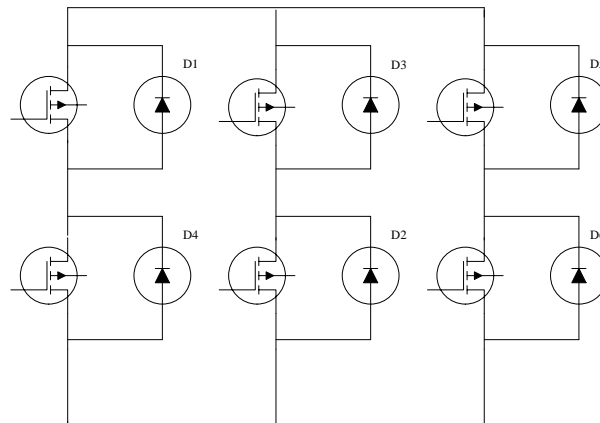


Figure 3.3: Three Phase VSI

3.3.2 SERIES INJECTION TRANSFORMER

It provides electrical isolation & voltage boost to the system. In a 3-phase system, either 3 single phase units of isolating transformer or 3-phase isolating transformer can be employed for the purpose of voltage injection. While selecting the injection transformer, the determination of expected maximum output voltage is prime significance, both economically & technically. Prior to the level of the distribution system being compensated by DVR & largest sag to be compensated by VSI at the minimum Dc-link voltage decides the turn ratio of the series injection transformer. The effects of higher order harmonics on the transformer are related to the positioning of filtering system, i.e. inverter filtering side system & line side filtering. Proposed system uses 3 single phase units of isolating transformer with unity turns ratio. The LC type filters are provided on the inverter side to deliver the filtered & controlled VSI voltage to the injection transformer.

3.3.3. FILTER

These are electronic circuits comprising of combination of passive elements; resistors, inductors & capacitors. They perform signal processing functions to remove the unwanted frequency signals to enhance the desired signal output. LC type of filters corrects the harmonic output from VSI to provide compensation in the required phase of the 3 phase system boosted by DVR.

3.3.4 ENERGY STORAGE UNIT

The purpose of storage systems is to protect sensitive equipments from shutdowns caused by voltage sags or interruptions. They provide necessary energy to the VSI via a dc link for the generation of injected voltages. There are different types of storage systems such as superconducting magnetic energy storage system (SMES), DC batteries, flywheel energy storage system, battery energy storage system (BESS) etc. Capacity of the storage system directly determines the duration of the sag which can be mitigating by the DVR. Among the above mentioned storage systems, Batteries are more common & can be highly effective if high voltage configuration is used. There are different types of battery energy storage technologies such as lead-acid battery, flooded type battery, valve regulated type battery (VRLA), sodium sulphur battery (NaS) etc [6].

3.4 CONTROL CIRCUIT

Several techniques & control philosophy of the DVR have been implemented for power quality improvement in the distribution system. The DVR is equipped with a control system to mitigate voltage sags/swells. The control of the DVR is very important as it involves the detection of voltage sags (start, end & depth of voltage sag) by appropriate detection algorithm [7]. The control strategy can depend on the type of load connected. Its main purpose is to maintain constant voltage magnitude at the point where the sensitive load is connected under system disturbances. Three basic control strategies of DVR can be stated as:

3.4.1 PRE-SAG COMPENSATION METHOD

In this method, both magnitude & phase angle are to be compensated. The supply voltage is continuously tracked & load voltage is compensated to the pre-sag condition by injecting voltage equal to the difference of voltage under pre-sag & sag condition as in fig

3.3. Though, it gives a nearly undisturbed load voltage but suffers a drawback of exhausting the rating of the DVR.

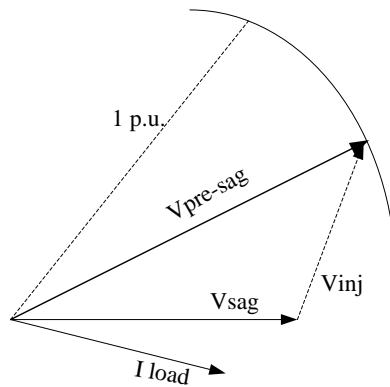


Figure 3.4:Pre-Sag Compensation Method

3.4.2 IN PHASE COMPENSATION METHOD

In this method, when the source voltage drops due to sagging condition, the VSI injects a voltage called missing voltage based on the drop of voltage magnitude as in fig 3.5. The generated Voltage of the DVR is always in phase with the measured supply voltage regardless of the load current and the pre-sag voltage.

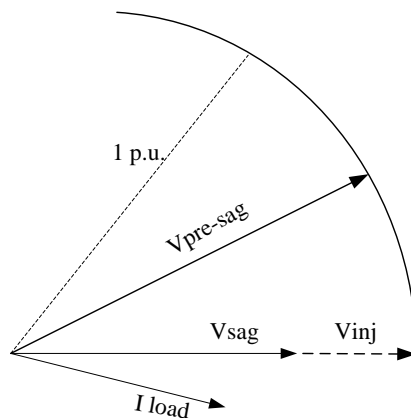


Figure 3.5: In-Phase Compensation Method

3.4.3 REACTIVE POWER COMPENSATION

This is also known as the minimum energy injection, which depends on maximizing the active power supplied by the network (keeping the apparent power constant and decreasing the network reactive power) by minimizing the active power supplied by the

compensator (increasing the reactive power supplied by the compensator). In this injection method the injected voltage is in quadrature with load current.

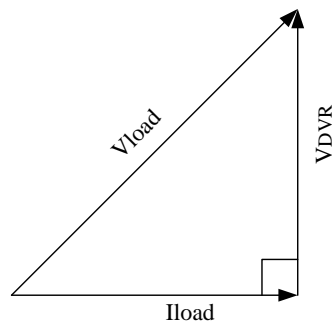


Figure 3.6: Reactive Power Compensation Method

3.5 APPLICATIONS OF DVR

The first DVR was installed in North America in 1996 - a 12.47 kV system located in Anderson, South Carolina [13]. Practically, the capability of injection voltage by DVR system is 50% of nominal voltage. This allows DVRs to successfully provide protection against sags to 50% for durations of up to 0.1 seconds. Furthermore, most voltage sags rarely reach less than 50%. The dynamic voltage restorer is also used to mitigate the damaging effects of voltage swells, voltage unbalance and other waveform distortions. DVRs of capacities up to 50 MVA have seen applications to critical loads in food processing, semiconductor and utility supply. Cost and installation constraints limit these to where there is clear need for constant voltage supply.

CONTROL PHILOSOPHIES OF DVR

4.1 INTRODUCTION

Voltage sags are one of the most severe power quality problems & DVR is an effective solution to mitigate it. The purpose of control scheme is to control the system output by generating an appropriate control signal prior to the unbalanced condition prevailing in the system. It generates the signals to enable the VSI (voltage source inverter) by providing proper firing sequence to the circuit. In this work, different control strategies for dynamic voltage restorer are investigated with emphasis on voltage sag compensation. Three promising control methods to compensate voltage sags are tested & compared with simulation of DVR on 11kV system. The comparison of the performance of three control strategies is made on basis of voltage waveforms & its frequency spectrum analysis. Their performance level is presented in the decreasing order of their compensation capability & better performance in mitigating voltage sag over a broader range for static linear & static non-linear load. Three control philosophies have been used namely, PI, Fuzzy & PI-Fuzzy. These are discussed as below:

4.2 PROPORTIONAL-INTEGRAL (PI) CONTROLLER BASED DVR

PI is a feedback controller that uses the weighted sum of error & 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. 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 [8]. The input to the PI controller is difference between the reference value & error value of voltage. As per the comparison of reference value & error value of voltage, linear PI adjusts its proportional & integral gains K_p & K_i in order to reduce the steady state error to zero for a step input as shown in fig.4.1. It is widely used due to simple control structure but suffers a disadvantage of fixed gains i.e. it cannot adapt itself to the varying parameters & conditions of the system.

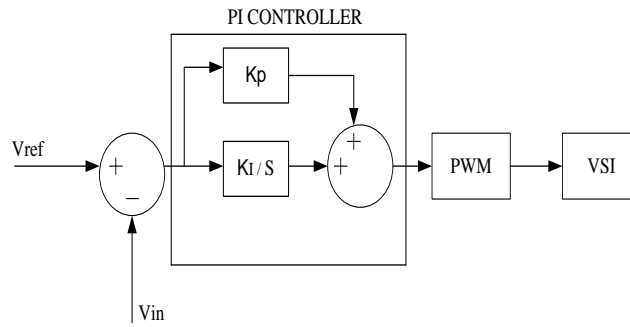


Figure 4.1: Control Strategy of PI Controller

4.3 FUZZY CONTROLLER BASED DVR

The drawback suffered by PI controller is overcome by Fuzzy. In comparison to the linear PI controller, this is a non-linear controller that can provide satisfactory performance under the influence of changing system parameters & operating conditions [8][9]. The function fuzzy controller is very useful as relieves the system from exact & cumbersome mathematical modeling & calculations. The performance of fuzzy controller is well established for improvements in both transient & steady state [10]. The fuzzy controller comprises of four main functional modules namely; Knowledge base, Fuzzification, Inference mechanism & Defuzzification as in fig 4.2.

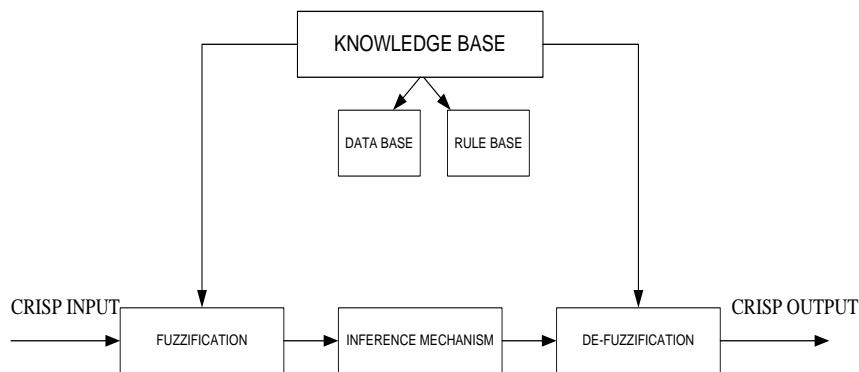


Figure 4.2: Schematic Diagram of Fuzzy Logic

4.3.1 Knowledge Base

It consists of data base & rule base that maps all the input & output with certain degree of uncertainty in process parameters & external disturbances to obtain good dynamic

response. Data base scales the input-output variables in the form of membership functions that defines it in a range appropriate to provide information to the fuzzy rule-based system & output variables or control actions to the system under observation. Fuzzy rule-based system utilizes a collection of fuzzy conditional statements derived from a knowledge base to approximate and construct the control surface.

4.3.2 Fuzzification

It is the process of defining a crisp data or digital data operating on discrete values of either 0 or 1 in terms of logical variables that take on continuous values between 0 and 1 i.e. fuzzy set. Fuzzy set maps the input-output variables into membership functions & truth values as in fig 4.3- 4.5.

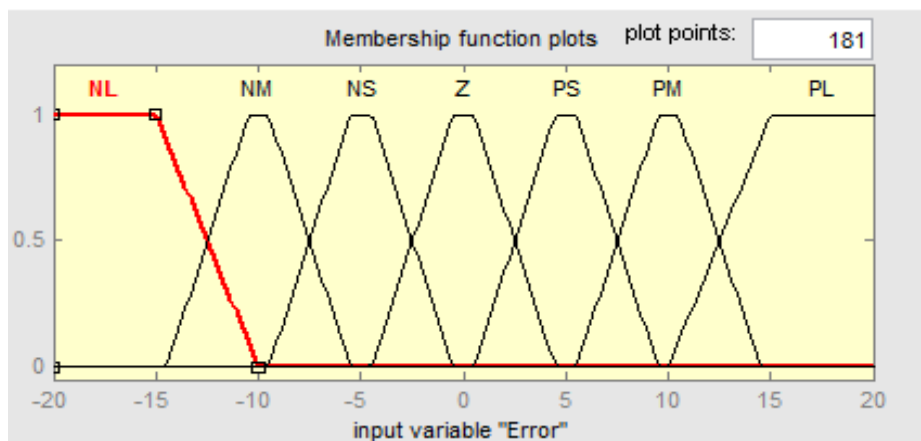


Figure 4.3: Input Membership Function of “Error”

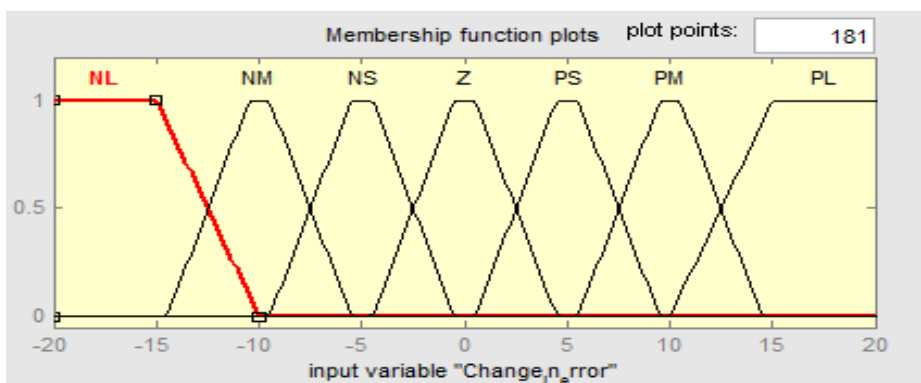


Figure 4.4: Input Membership Function of “Change in Error”

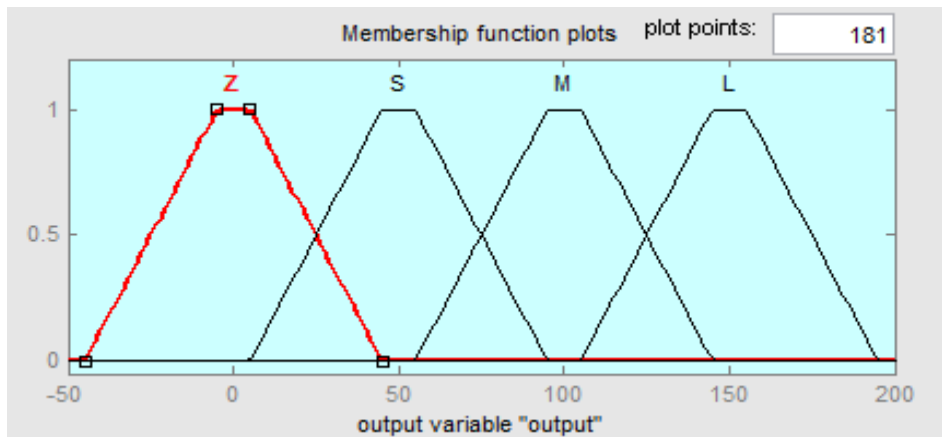


Figure 4.5: Output Membership Function

4.3.3 Inference Mechanism

It is referred to as approximate reasoning that uses knowledge to conduct deductive inference of IF-THEN rules. This mechanism encodes knowledge about a system in statements form of linguistic IF -THEN propositions with antecedents & consequents. There are three types of fuzzy inference mechanism:

1. Mamdani System (1975)
2. Sugeno models: Takagi and Sugeno(1985) & Sugeno & Kang(1988)
3. Tsukamoto models(1979)

4.3.4 Defuzzification

It is a conversion process of fuzzy quantity to a precise quantity and is reverse process of fuzzification. A logical union of two or more membership functions in the universe of discourse requires a crisp decision with approximate solution for the output of fuzzy which is uncertain in nature to be a single scalar quantity. Various methods for defuzzifying the output membership functions have been proposed; out of them four of widely used are summarized as follows:

1. Centroid method
2. Centre of sums method(cos)
3. Weighted average method
4. Mean-max membership

The FLC controller of the tested system exploits the Mamdani type of inference method. It defuzzifies the crisp input-output variables into fuzzy trapezoidal membership function and reverse process of Defuzzification is based upon the Centroid method. The

controller core is the fuzzy control rules as shown in table I. which are mainly obtained from intuitive feeling and experience [11].

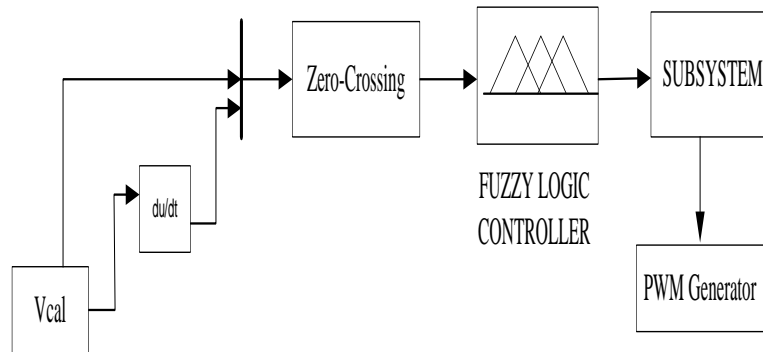


Figure 4.6: Control Strategy of Fuzzy Controller

Table 4.1: Fuzzy Rule Based System

$\begin{matrix} \text{"e"} \\ \text{"ce"} \end{matrix}$	NL	NM	NS	Z	PS	PM	PL
NL	L	L	L	M	Z	S	Z
NM	L	L	M	Z	Z	Z	S
NS	L	M	S	Z	Z	S	S
Z	M	S	S	Z	S	S	M
PS	S	S	Z	Z	S	M	L
PM	S	Z	Z	Z	M	L	L
PL	Z	S	Z	M	L	L	L

4.4 HYBRID PI-FUZZY BASED DVR

The hybrid PI-Fuzzy control scheme uses fuzzy as adjustor discussed in section 4.3 to adjust the parameters of proportional gain K_p and integral gain K_i based on the error e and the change of error Δe [11]. 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 ΔK_p and ΔK_i as output for voltage regulator where K_p and K_i are proportional gain and integral gain respectively [12] as shown in fig.4.4.

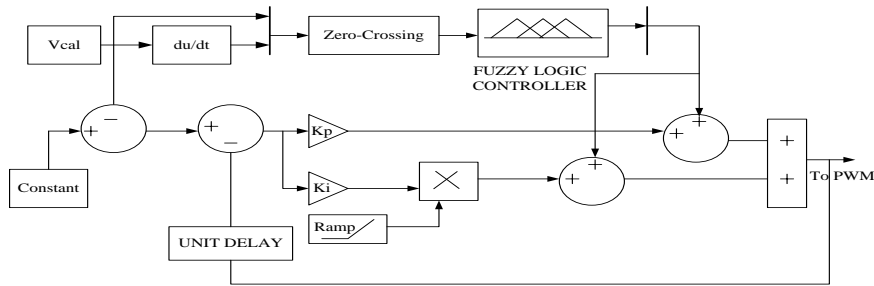


Fig.4.7: Control Strategy of PI-Fuzzy Controller

4.5 COMPARISON B/W CONTROLLERS

As given in table 4.1, all the three control strategies namely, PI controller based DVR, Fuzzy controller based DVR & hybrid PI-Fuzzy based DVR give equal satisfactory performance by reducing the THD level from 25% for uncompensated system as in fig. 5.3 to 15% as in fig. 5.4, fig. 5.7 & fig. 5.10 with maximum fundamental component of 0.4395 respectively, for static linear load.

Table 4.2: Static Linear Load

Controllers	Load voltage(50Hz)	THD (%)
PI	0.4395	15
Fuzzy	0.4395	15
Hybrid PI-Fuzzy	0.4395	15

For static non-linear load, hybrid PI-Fuzzy gives better compensation by reducing the THD level of uncompensated system from 25% as in fig 5.3 to a much reduced value of 16.68% as compared to 17.49% with Fuzzy & 23.70% with PI controller.

Table 4.3: Static Non-Linear Load

Controllers	Load voltage(50Hz)	THD (%)
PI	0.3287	23.70
Fuzzy	0.404	17.49
Hybrid PI-Fuzzy	0.4143	16.68

SIMULATION TEST MODELS

5.1 INTRODUCTION

Dynamic voltage restorer is a custom power concept used to mitigate the voltage sags by injecting a voltage in series with the load voltage of the system. The mitigation capability of DVR is reflected by maximum load, power factor & maximum voltage dip to be compensated.

In the SIMULINK test model, two feeders are drawn from the same supply using 3-winding transformer. One of the feeders is compensated using DVR while the other uncompensated. These are further connected to identical loads so that their performances are fairly compared. The controllers PI, Fuzzy, hybrid PI-Fuzzy are employed step by step in the compensated feeder to compare their performances. The loads investigated in this work are static linear and static non-linear loads.

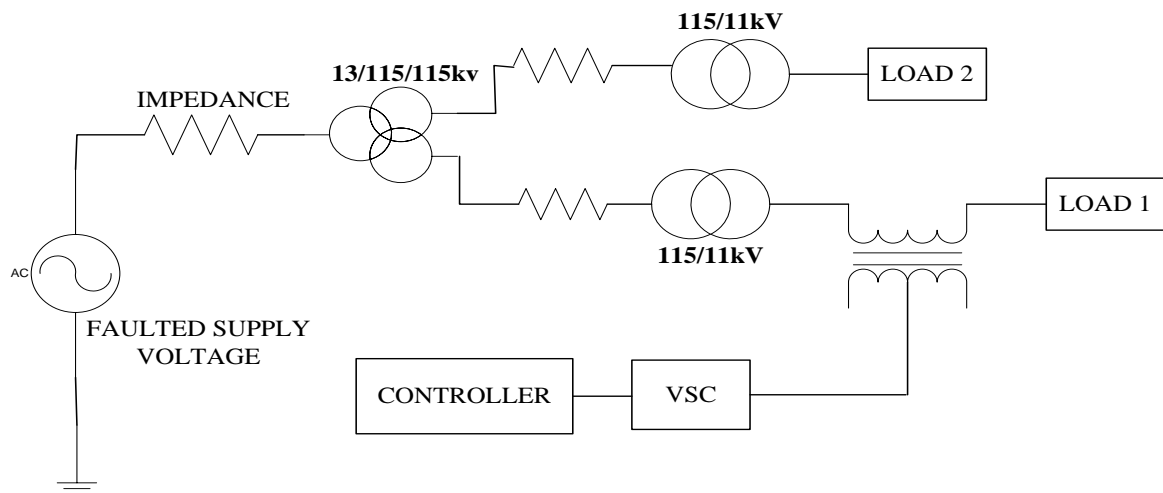


Figure 5.1: Single Line Diagram of Test System

Table 5.1: System Parameters

Sr.No	System Quantities	Standards
1.	Source	3-Phase,13kV,50Hz
2.	Inverter Parameters	IGBT based,3arms,6 Pulse, Carrier frequency-1080Hz Sample time=50 μ sec
3.	PI Controller	Kp=0.5,Ki=50,sample time=50 μ sec
4.	RL Load	Active power=1KW,Reactive power=400VAR
5.	Three Winding Transformer	Y/ Δ / Δ 13/115/115kV
6.	Two Winding Transformer	Δ /Y 115/11 kV

5.2 SIMULINK MODEL OF THE TEST SYSTEM WITH PI CONTROLLER

In the SIMULINK model, two feeders are drawn from the same supply using 3-winding transformer. One of the feeders is compensated using DVR while the other uncompensated. The PI controller based DVR is investigated for static linear and static non-linear loads. From the simulation results, it is seen that that the PI controller based DVR reduces the THD level of uncompensated system from 25% as in fig 5.3 to 15% in fig 5.4 for static linear load and for static non-linear load, it is reduced from 25% to 23.70% as in fig 5.5.

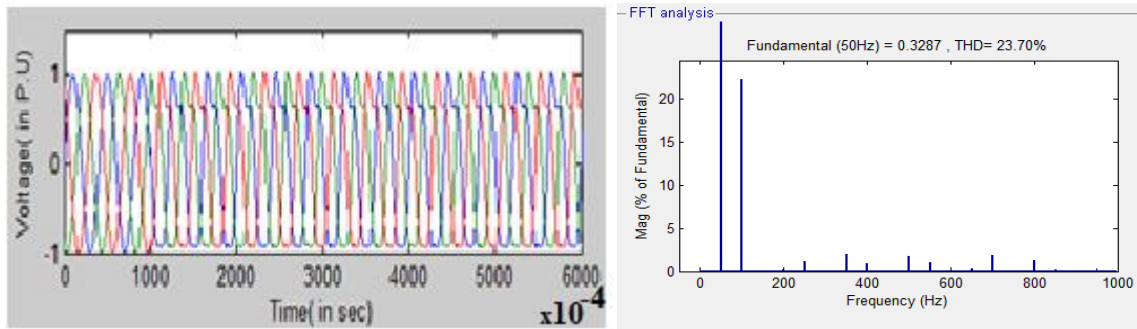


Figure 5.5: Load Voltage Waveform and its Frequency Spectrum when Compensated using PI Controller Based DVR

5.3 SIMULINK MODEL OF TEST SYSTEM WITH FUZZY CONTROLLER

In this case, fuzzy logic controller is employed to compensate the uncompensated system shown in fig. 5.3. Unlike, linear PI control scheme as discussed in section 5.2, it is a non-linear technique that uses trapezoidal membership function & rule base system as given in table 4.1 to adjust accordingly to the varying system parameters & conditions. It overcomes the disadvantage suffered with linear PI controller by providing better compensation & reducing the THD level of uncompensated system from 25% as in fig.5.3 to 17.49% of compensated system as in fig.5.8 for static non-linear load. The voltage waveform & its frequency spectrum depict the effectiveness of fuzzy in reducing harmonics as compared to PI for static non-linear load.

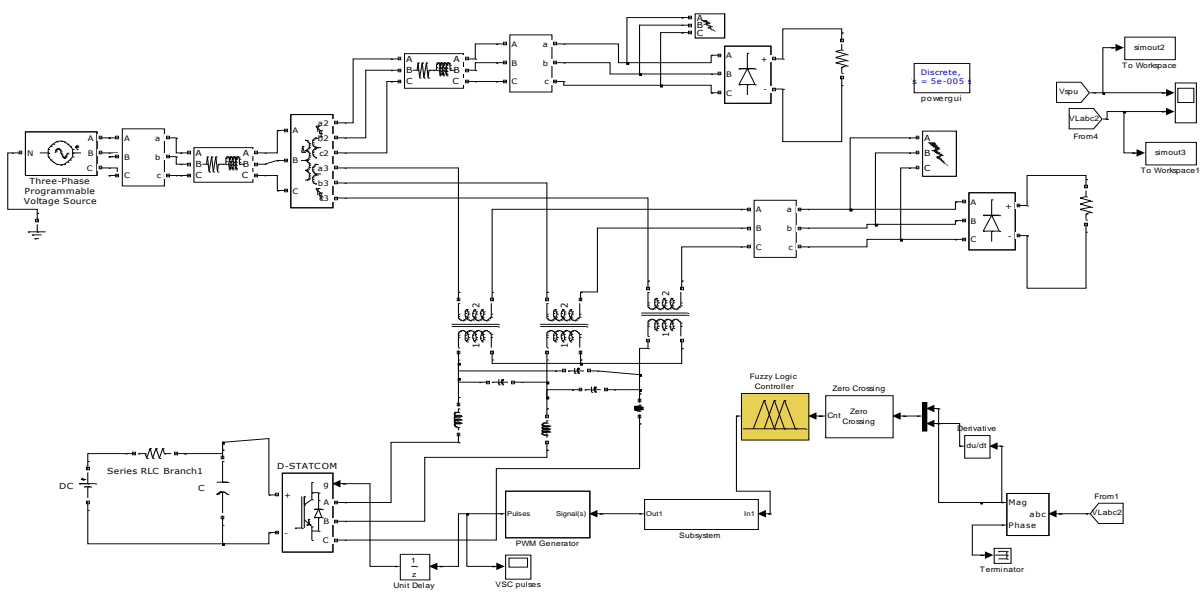


Figure 5.6: Simulink Model of Fuzzy Based DVR

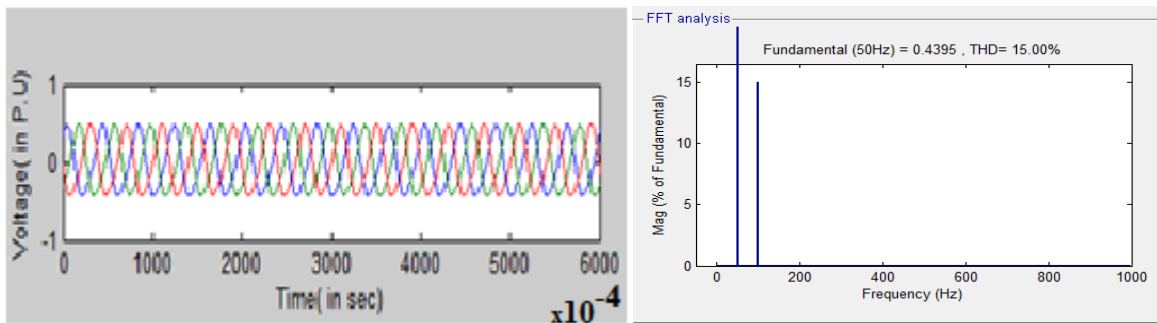


Figure 5.7: Load Voltage Waveform and its Frequency Spectrum when Compensated using Fuzzy Controller Based DVR

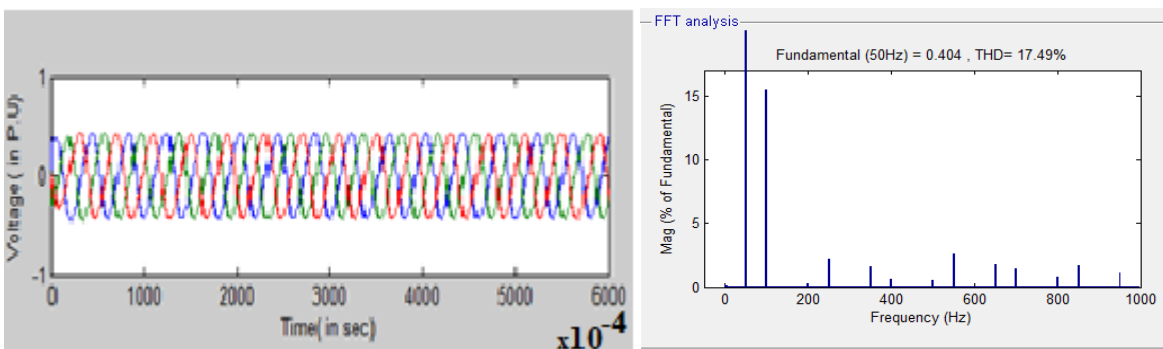


Figure 5.8: Load Voltage Waveform and its Frequency Spectrum when Compensated using Fuzzy Controller Based DVR

5.4 SIMULINK MODEL OF TEST SYSTEM WITH HYBRID PI-FUZZY CONTROLLER

In this case, hybrid PI- Fuzzy control scheme is employed & tested for static linear & non-linear loads. This hybrid controller adjusts the proportional & integral gains K_p & K_i of PI using the trapezoidal membership function & the rule base system for regulating the voltage of the system. As seen from the load voltage waveform & frequency spectrum of uncompensated system in fig 5.3, the THD level is reduced effectively from 25% to a much less value of 16.68% as in fig 5.11. Load voltage waveforms & frequency spectrum of hybrid control scheme for static non-linear load in fig 5.11 depicts that the harmonics are effectively reduced to a less value as compared to 23.70% with PI controller in fig 5.5 & 17.49% with Fuzzy controller in fig 5.8.

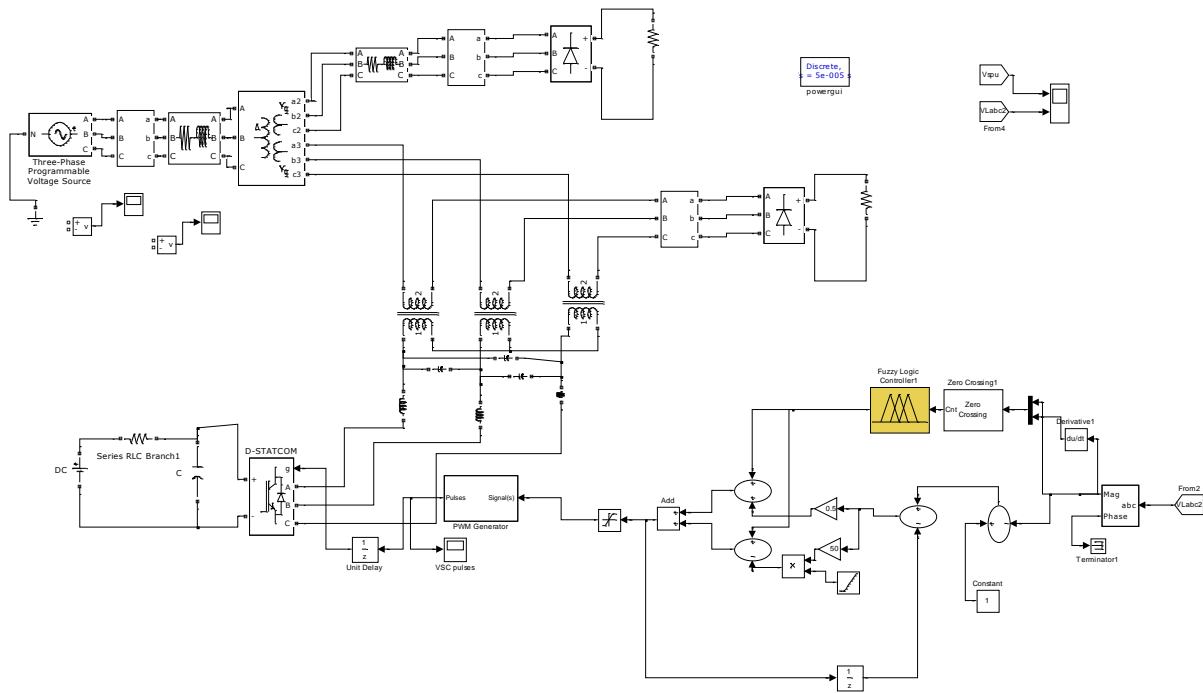


Figure 5.9: Simulink Model of Hybrid PI-Fuzzy Based DVR

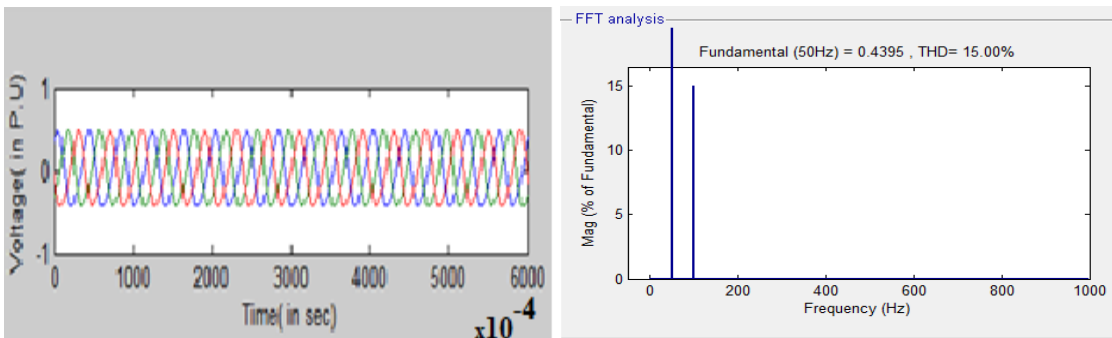


Figure 5.10: Load Voltage Waveform and its Frequency Spectrum when Compensated using PI-Fuzzy Controller Based DVR

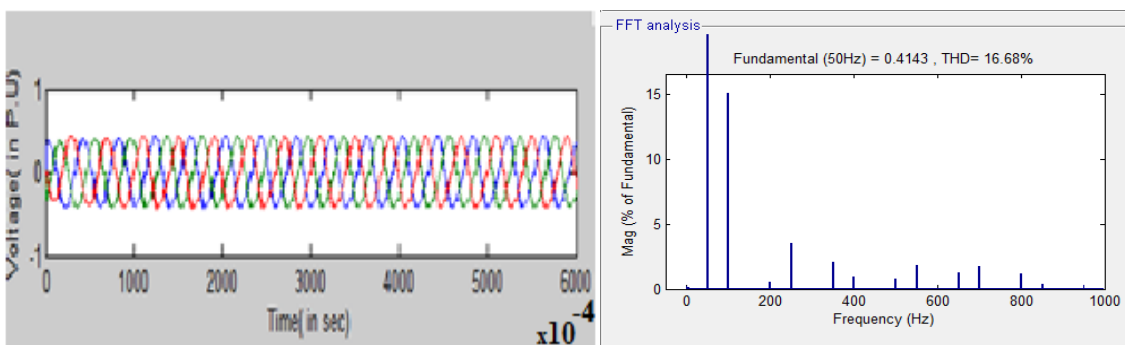


Figure 5.11: Load Voltage Waveform and its Frequency Spectrum when Compensated using PI-Fuzzy Controller Based DVR

CONCLUSIONS AND FUTURE SCOPE OF WORK

6.1 CONCLUSIONS

In this work, cost effective & reliable custom power concept, dynamic voltage restorer is used to mitigate the voltage sags in the distribution system, thereby improving the performance of the system. The various control strategies are employed & tested for 11kV distribution system. The PI controller based DVR, fuzzy controller based DVR and PI-fuzzy controller based DVRs are connected step by step in the compensated feeder to compare their performances. The effectiveness of different control techniques based DVRs for static linear & static non-linear loads have been investigated. As seen from the load voltage waveform & frequency spectrum of uncompensated system in fig 5.3, the THD level is reduced effectively from 25% to a much less value of 16.68% as in fig 5.11. Load voltage waveforms & frequency spectrum of hybrid control scheme for static non-linear load in fig 5.11 depicts that the harmonics are effectively reduced to a less value as compared to 23.70% with PI controller in fig 7 & 17.49% with Fuzzy controller in fig 9. Simulation results indicate that the non-linear control techniques provide better compensation to the system as compared to the linear PI technique based DVR connected to the feeder during static non-linear loads.

6.2 FUTURE SCOPE OF WORK

With the increase use in number of sophisticated electronic devices by the industrial customers to increase their efficiency & productivity, it is important to ensure reliable power supply even under the system disturbances. To meet the varying system parameters & conditions, various other non-linear controllers can be used. Among the investigated fuzzy non-linear technique, Neural network (NN), Genetic algorithm (GA), SVPWM (space vector PWM), VVPWM (voltage vector PWM) can be used. Any of the above mentioned controllers based DVR can be used for voltage harmonic compensation in distribution networks with other types of linear, non-linear loads and active/passive loads.

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