

**PI AND FUZZY CONTROLLER BASED DVR TO MITIGATE
POWER QUALITY AND REDUCE THE HARMONICS
DISTORTION OF SENSITIVE LOAD**

Dissertation submitted in partial fulfilment of the requirements for the award of degree of

**MASTER OF ENGINEERING
IN
POWER SYSTEMS & ELECTRIC DRIVES**

Submitted by:

ALOK JAIN

Roll No- 801141003

Under the supervision of:

Mrs. SUMAN BHULLAR

Assistant Professor, EIED



ELECTRICAL & INSTRUMENTATION ENGINEERING DEPARTMENT

THAPAR UNIVERSITY

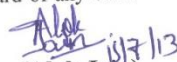
PATIALA- 147004

JULY 2013

CERTIFICATE

I hereby certify that the work which is being presented in the dissertation entitled 'PI AND FUZZY CONTROLLER BASED DVR TO MITIGATE POWER QUALITY AND REDUCE THE HARMONICS DISTORTION OF SENSITIVE LOAD' in partial fulfilment of requirement for the award of the master degree in Power Systems & Electric Drives engineering submitted in the Electrical & Instrumentation Department, Thapar University, Patiala is an authentic record of my own work carried out under the guidance of **Mrs. Suman Bhullar**, (Assistant Professor EIED, Thapar University).

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


(Alok Jain)

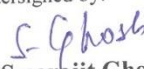
801141003

This is to certify that the above statement made by the candidate is correct and true of the best of my knowledge & belief.


(Mrs. Suman Bhullar)

Assistant Professor
Electrical & Instrumentation Engg. Department
Thapar University, Patiala

Countersigned by:


(Dr. Smarajit Ghosh)

Professor & Head
Electrical & Instrumentation Engg. Department
Thapar University, Patiala


(Dr. S.K. Mohapatra)

Sr. Professor & Dean (Academic Affairs)
Thapar University,
Patiala

ACKNOWLEDGEMENT

I would like to thank Thapar University for giving me the opportunity to use their resources and work in such a challenging environment.

First and foremost I take this opportunity to express my deepest sense of gratitude to my guide **Mrs. Suman Bhullar**, Assistant Professor, EIED, Thapar University, Patiala for her able guidance during my dissertation. This dissertation would not have been possible without her help and the valuable time that she has given me amidst of her busy schedule.

I would like to express my deep sense of gratitude towards **Dr. Smarajit Ghosh**, Professor & Head, **Ms. Manbir Kaur**, Associate Professor (P.G. Coordinator), EIED, Thapar University, Patiala who have been a constant source of inspiration for me throughout this dissertation.

I would also like to extend my gratitude to my parents, friends and senior students of this department who have always encouraged and supported me in doing my work.

Last but not the least I would like to thank all the staff members of Department of Electrical & Instrumentation Engineering who have been very cooperative with me.



ALOK JAIN

Roll No. 801141003

ABSTRACT

Power quality has been an issue that is becoming increasingly pivotal in modern industrial and commercial applications. Voltage disturbances especially the voltage sag and swell are the most common power quality problems due to increased use of a large numbers of sophisticated and sensitive electronic equipment in industrial systems.

To overcome this problem, custom power devices are used. One of the devices is the Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks. It is a series connected power electronic based device that can quickly mitigate the voltage sags in the system and restore the load voltage to the pre-fault value. The primary advantage of the DVR is keeping the users always on-line with high quality constant voltage maintaining the continuity of production.

In this dissertation, a PI controller and a fuzzy logic controller method for DVR that protects a sensitive load, to counter voltage sag under unbalanced loading conditions (linear, non-linear and induction motor load) is presented. DVR along with other parts of the distribution system are simulated using MATLAB/ SIMULINK.

LIST OF ABBREVIATIONS

SLG	-	Single Line to Ground
DLG	-	Double Line to Ground
IEEE	-	Institute of Electrical and Electronic Engineers
PWM	-	Pulse Width Modulation
SMES	-	Superconducting Magnetic Energy Storage
FACTS	-	Flexible AC Transmission Systems
DSTATCOM	-	Distribution Static Synchronous Compensators
DVR	-	Dynamic Voltage Restorer
UPQC	-	Unified Power Quality Compensator
SSSC	-	Static Synchronous Series Compensator
SVC	-	Static Var Compensator
VSI	-	Voltage Source Inverter
PCC	-	Point of Common Coupling
IGBT	-	Insulated Gate Bipolar Transistor
IGCT	-	Insulated Gate Commutated Thyristor
SVPWM	-	Space Vector Pulse Width Modulation
FLC	-	Fuzzy Logic Controller
THD	-	Total Harmonic Distortion
DOL	-	Direct-On-Line
FOC	-	Field Oriented Control
PID	-	Proportional Integral Derivative
PLC	-	Programmable Logic Controller
VSD	-	Variable Speed Drives
ESS	-	Energy Storage System

LIST OF FIGURES

Figure 2.1: Voltage sag	11
Figure 2.2: Voltage swell	11
Figure 2.3: Voltage interruption	11
Figure 2.4: Notching	14
Figure 2.5: Noise	14
Figure 2.6: Basic configuration of Distribution STATCOM	18
Figure 2.7: Basic configuration of DVR	19
Figure 2.8: Basic Configuration of UPQC	19
Figure 3.1: Schematic representation of a DVR	21
Figure 3.2: Two level switch mode inverter	22
Figure 3.3: Protection mode of a DVR	23
Figure 3.4: Standby mode of a DVR	24
Figure 3.5: Compensation techniques of a DVR	24
Figure 3.6: Pre sag compensation	25
Figure 3.7: In-phase compensation	26
Figure 3.8: Voltage tolerance method with minimum energy injection	27
Figure 3.9: Location of a DVR	27
Figure 4.1: Schematic of a typical PI Controller	28
Figure 4.2: Phase-Modulation of the control angle δ (Subsystem 1)	29
Figure 4.3: Circuit Model of DVR Test System	29
Figure 4.4: Block diagram of proposed control system	30

Figure 4.5: Membership Functions for inputs and output	31
Figure 4.6(a), (b), (c), (d), (e) and (f): Simulation Models of DVR Test System	34-39
Figure 4.7(a), (b), (e) and (f): Output load voltage of SLG Fault without and with compensation of PI Controller and Fuzzy Logic Controller (Linear Load)	40-41
Figure 4.7(c), (d), (g) and (h): Frequency Spectrum without and with compensation of PI Controller and Fuzzy Logic Controller (Linear Load)	40-41
Figure 4.8(a), (b), (e) and (f): Output load voltage of SLG Fault without and with compensation of PI Controller and Fuzzy Logic Controller (Non-Linear Load)	42
Figure 4.8(c), (d), (g) and (h): Frequency Spectrum without and with compensation of PI Controller and Fuzzy Logic Controller (Non-Linear Load)	42-43
Figure 4.9(a), (b), (e) and (f): Output load voltage of SLG Fault without and with compensation of PI Controller and Fuzzy Logic Controller (Induction Motor Load)	43-44
Figure 4.9(c), (d), (g) and (h): Frequency Spectrum without and with compensation of PI Controller and Fuzzy Logic Controller (Induction Motor Load)	44

LIST OF TABLES

Table 2.1: Classification of Oscillatory Transients	13
Table 4.1: Fuzzy rules	32
Table 4.2: System Parameters	33
Table 4.3: THD levels of the test system	45

TABLE OF CONTENTS

Certificate	i
Acknowledgement	ii
Abstract	iii
List of Abbreviations	iv
List of Figures	v-vi
List of tables	vii
Table of Contents	viii-ix
Chapter 1. Introduction	1-8
1.1 Overview	1
1.2 Literature Review	2-7
1.3 Scope of Work	8
1.4 Organisation of Dissertation	8
Chapter 2. Power Quality and Custom Power Concept	9-19
2.1 Power Quality	9
2.2 Power Quality Problems	10
2.3 Solutions to Improve the Power Quality	14
2.4 Custom Power	14
2.5 Need of Custom Power	15
2.6 Custom Power Devices	16
2.6.1 Distribution STATCOM	17
2.6.2 Dynamic Voltage Restorer/ Regulator (DVR)	18
2.6.3 Unified Power Quality Conditioner (UPQC)	19
Chapter 3. Dynamic Voltage Restorer	20-27
3.1 Introduction	20
3.2 Configuration of DVR	20
3.3 Operation of a DVR	23

3.4 Operating Modes of a DVR	23
3.5 Concept of Compensation Techniques in DVR	24
3.6 Location of a DVR	27
Chapter 4. Realization of Compensation Technique	28-45
4.1 PI Controller- Discrete PWM Based Control Scheme	28
4.2 Fuzzy Logic Controller	30
4.2.1 Input Parameters	30
4.2.2 Fuzzification	30
4.2.3 Decision Making	31
4.2.4 Defuzzification	32
4.2.5 Signal processing	32
4.3 Parameters of DVR Test System	32
4.4 Simulation Models of the Test System	34
4.4.1 Simulink Model of the Test System with Linear Load	34
4.4.2 Simulink Model of the Test System with Non-Linear Load	36
4.4.3 Simulink Model of the Test System with Induction Motor as Load	38
4.5 Simulation Results	40
Case I: Results for Linear load	40
Case II: Results for Non-Linear Load	41
Case III: Results for FOC Induction Motor Drive	43
4.6 Comparison of THD levels for different types of loads	45
Chapter 5. Conclusion and Future Scope	46
References	47

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Power quality and reliability in distribution systems have been attracting an increasing interest in modern times and have become an area of concern for modern industrial and commercial applications. Introduction of sophisticated manufacturing systems, industrial drives, precision electronic equipments in modern times demand greater quality and reliability of power supply in distribution networks than ever before. Power quality problems encompass a wide range of phenomena. Voltage sag/swell, flicker, harmonics distortion, impulse transients and interruptions are a prominent few. These disturbances are responsible for problems ranging from malfunctions or errors to plant shut down and loss of manufacturing capability. Voltage sags/swells can occur more frequently than any other power quality phenomenon. These sags/swells are the most important power quality problems in the power distribution system.

Voltage Sag or Voltage Dip is defined by the IEEE 1159 as the decrease in the rms voltage level to 10%-90% of nominal, at the power frequency for durations of $\frac{1}{2}$ cycle to one minute. The IEC (International Electro-technical Commission) terminology for voltage sag is dip. The IEC defines voltage dip as a sudden reduction of the voltage at a point in the electrical system, followed by voltage recovery after a short period, from $\frac{1}{2}$ a cycle to a few seconds. Voltage sags are usually associated with system faults but they can also be generated by energization of heavy loads or starting of large motors which can draw 6 to 10 times its full load current during starting. Sag durations are subdivided into three categories, instantaneous, momentary, and temporary-all of which coincide with utility device operation times.

Voltage Swell is defined by IEEE 1159 as the increase in the rms voltage level to 110%-180% of nominal, at the power frequency for durations of $\frac{1}{2}$ cycles to one minute. It is classified as a short duration voltage variation phenomena, which is one of the general categories of power quality problems. The term "momentary overvoltage" is used as a synonym for the term swell. Swells can occur from the temporary voltage rise on the healthy phases during a single-line-to-ground fault. Swells can also be caused by switching off a large load or energizing a large capacitor bank and are characterized by their magnitude (rms

value) and duration. The severity of a voltage swell is a function of the fault location, system impedance and grounding.

As the quality of power is strictly related to the economic consequences associated with the equipment and should therefore be evaluated considering the customers point of view. So the need for solutions dedicated to single customers with highly sensitive loads is great since a fast response of voltage regulation is required. Further it needs to synthesize the characteristics of voltage sags/swells both in domestic and industrial distributions. Alongside the variation in magnitudes, voltage sags/swells can also be accompanied by a change in phase angle. This phenomenon is known as phase angle jump (i.e. the variation of phase angle before the onset and during the voltage sag/swell events and is calculated as an argument of the complex voltage).

In order to meet these challenges, it needs a device capable of injecting minimum energy so as to regulate load voltage at its predetermined value. Dynamic Voltage Restorer (DVR) is one of the prominent methods for compensating the power quality problems associated with voltage sags/swells. Dynamic voltage restorer (DVR) can provide an effective solution to mitigate voltage sag/swell by establishing the appropriate predetermined voltage level required by the loads. It is recently being used as the active solution for voltage sag/swell mitigation in modern industrial applications.

In this dissertation, a new configuration of Dynamic Voltage Restorer (DVR) with PI controller and fuzzy logic controller is used which is capable of compensating power quality problems associated with voltage sags/swells and maintaining a prescribed level of supply voltage at the different load terminals. The simulation of the proposed DVR is accomplished using MATLAB/ SIMULINK. The performance of the proposed DVR for different supply disturbances is tested under various operating conditions.

1.2 LITERATURE REVIEW

Woodley N.H. (1999) *et al.* presented their experience to install the prototype series compensator, which they called DVR, on the existing power system. In this paper, a bypass control scheme to protect the power electronics from load current and fault current was described. When fault occurred on the transmission system the harmonic disturbance would be imposed on voltage sags or swells. These harmonics might be harmful to the customers load and might affect the DVR hardware and/or the accuracy of inverter control.

Chang C.S. (2000) *et al.* presented the performance of voltage sag mitigation devices such as the Dynamic Voltage Restorer (DVR) in highly simplified electrical environment consisting of simple line and load models. The negative influences of dynamic motor loads on the existing voltage disturbance, such as post-fault sags, further during-fault phase-angle deviations, during-fault and post-fault voltage fluctuations had often been unnoticed.

Zhan Changjiang (2001) *et al.* presented a compensation strategy based on SPLL (Software Phase-Locked Loop) algorithm for the DVR, which was applied for the dynamic compensation of voltage sags with a phase jump. In this paper, a PWM inverter control of the DVR adopted a conventional SVPWM method for the maximum utilization of the dc-link voltage supported by lead-acid batteries.

Godsk Nielsen John (2001) *et al.* presented different control strategies for dynamic voltage restorer with emphasis put on the compensation of voltage sags with phase jump. Different control methods to compensate voltage sags with phase jump were proposed and compared. Two promising control methods were tested and carried out with simulations and finally tested on a 10 kVA rated Dynamic Voltage Restorer in the laboratory. Both methods could be used to reduce load voltage disturbances caused by voltage sags with phase jump. One method completely compensated the phase jump, which was the best solution for very sensitive loads.

Jurado Francisco (2004) *et al.* presented fuzzy logic control of dynamic voltage restorer. Some basic concepts of the DVR were presented, also described the fundamentals of fuzzy logic. He presented the application of fuzzy logic control in the field of PWM converter. The voltage error and its derivative were the Fuzzy Logic controller input crisp values. When a Fuzzy Logic controller was used, the tracking error and transient overshoots of PWM could be considerably reduced. The simulations carried out, shown that the Dynamic voltage restorer provided excellent voltage regulation capabilities.

Boonchiaml Paisan (2006) *et al.* presented detailed analysis of load voltage compensation for dynamic voltage restorer (DVR) that used for enhancing power quality. A technique of determining the accurate amount of voltage injection necessary to correct a specific voltage reduction with least power injection was described. Systematic expressions for both magnitude and angle of the injected voltage were also derived. It had been shown that a voltage reduction and power factor should be analysed before compensating the voltage.

Jowder Al. Fawzi (2007) et al. presented DVR based on hysteresis voltage control. DFT was used to detect the magnitude and phase jump of the voltage sag/swell. Pre-sag compensation was adopted. Hysteresis voltage control consisted of two parts i.e. the detection of the start and end of voltage sag/swell and the hysteresis voltage controller. In hysteresis control, each phase was treated independently. The influence of the hysteresis band on the quality of the load voltage and DVR was studied for voltage sag/swell.

Kumar V. (2007) et al. presented the power quality problems such as voltage dips, swells and interruptions, consequences, and mitigation techniques of custom power electronic devices DVR and DSTATCOM. The design and applications of DVR and DSTATCOM for voltage sags, interruptions and swells, and comprehensive results were presented. A new PWM-based control scheme had been implemented to control the electronic valves in the two-level VSC used in the DSTATCOM and DVR. The simulations carried out showed that the DVR provides relatively better voltage regulation capabilities. It was also observed that the capacity for power compensation and voltage regulation of DVR and DSTATCOM depends on the rating of the dc storage device.

Ashari M. (2007) et al. presented the DVR with a fuzzy controller which was used for handling voltage sags including outage. A three phase inverter was used and was modulated by SVPWM. abc to dq0 transformation was used. A fuzzy controller with three inputs and one output was used. Simulation was carried out for a system with two feeders, 20KV system. It was observed that the DVR handled the problem of voltage sag and outage successfully.

Margo P. (2008) et al. presented the results of the simulation which showed that the DVR based on Fuzzy Polar Controller could compensate balanced and unbalanced voltage sags in the zero sequence blocking system. Simulation results showed that the proposed method compensated both balanced and unbalanced voltage sags better than PI controller.

Jayaprakash P. (2008) et al. presented the operation of a DVR under different voltage injection schemes. A comparison of the performance with different schemes had been performed with reduced rating VSC including capacitor supported DVR. The reference load voltage had been generated using the method of unit vectors. The control of DVR had been achieved which minimized the error of voltage injection. The SRF (synchronous reference frame) theory had been used for the control of DVR. It was concluded that the voltage injection in-phase with the PCC (Point of Common Coupling) voltage resulted in minimum rating of DVR but at the cost of an energy source at the dc bus.

Benachaiba Chellali (2008) *et al.* discussed that the custom power devices are used to solve the problems of voltage sags and voltage swells which are one of the most common power quality problems. In this paper, DVR having in-phase compensation technique was used to overcome these problems. Simulation was carried out for single phase voltage sag/swell and three phase voltage sag/swell. It was observed that the DVR was able to mitigate voltage sag and voltage swell effectively.

Pal Yash (2008) *et al.* presented a comprehensive review of compensating custom power devices mainly DSTATCOM (distribution static compensator), DVR (dynamic voltage restorer) and UPQC (unified power quality compensator). It was aimed at providing a broad viewpoint on the status of compensating devices in electric power distribution system to researchers and application engineers dealing with power quality problems.

El. Shennawy Tarek (2009) *et al.* presented a simple, fast, and cost effective Dynamic Voltage Restorer (DVR) for mitigating the problem of voltage sags in industrial distribution systems, with a large portion of its load consisting of induction motors. The modeling and simulation of the proposed DVR using MATLAB/ SIMULINK had been presented. The simulation shows that the DVR performance was satisfactory in mitigating voltage sags/swells.

Ezoji H. (2009) *et al.* presented a hysteresis voltage control technique based on bipolar and unipolar Pulse Width Modulation (PWM) for Dynamic Voltage Restorer to improve the quality of load voltage. The validity of proposed method was approved by results of the simulation in MATLAB/ SIMULINK. To evaluate the quality of the load voltage during the operation of DVR, THD was calculated. The results of simulation shows that the effect of increasing the hysteresis band on THD of the load voltage under voltage swell was more than THD of the voltage sag.

Ferdi B. (2010) *et al.* presented Adaptive PI Control of Dynamic Voltage Restorer using Fuzzy Logic. PI controller was very common in the control of DVRs. However, one disadvantage of the conventional controller was the fact that by using fixed gains, the controller may not provide the required control performance, when there were variations in the system parameters or operating conditions. To overcome the problem, an adaptive PI controller using fuzzy logic was proposed. The simulation results had proved that the proposed control method greatly improved the performance of the DVR compared to the conventional PI controller.

Katole D.N. (2010) *et al.* presented the Dynamic Voltage Restorer (DVR) with ESS based PI Controller method to compensate balanced voltage sag. Voltage sag was one of the major power quality problem which resulted in a failure or a mis-operation of end use equipments. Sensitive industrial loads and utility distribution networks all suffered from various types of outages and service interruptions which could cost significant financial loss per event. The aim therefore, was to recommend measures that could improve voltage sag.

Teke A. (2010) *et al.* presented the design and analysis of a fuzzy logic (FL) controlled dynamic voltage restorer (DVR) and extended to perform quick fault detection. A new control method for DVR was proposed by combining FL with a carrier modulated PWM inverter. The proposed control method was simple to design and had outstanding voltage compensation capabilities. The proposed method for voltage sag/swell detection had the ability of detecting different kinds of power disturbances faster than conventional detection methods.

Gupta Sunil (2010) *et al.* presented the dynamic voltage restorer against voltage sag. Dynamic voltage restorer (DVR), a custom power device was used to correct the voltage sag by injecting voltage as well power into the system. The mitigation capability of these devices was influenced by the maximum load, power factor and maximum voltage dip to be compensated.

Ferdi B. (2010) *et al.* presented an adaptive neuro-fuzzy inference system based sugeno controller. According to the error signal and rate of change in error, the values of the proportional gain and integral gain was decided using if- then rule. It was observed that proposed controller that combined the fuzzy logic to the classical PI controller successfully adjusted the PI gains online.

Omar Rosli (2011) *et al.* presented a low voltage DVR based on the application of space vector pulse width modulation (SVPWM). SVPWM was preferred because of their easy digital realisation and better dc bus utilization. The proposed DVR system consists of open loop voltage system using PLL. Simulation was carried out for a linear load. DVR handled both balanced and unbalanced sag effectively. It also verified the proposed control algorithm based on SVPWM technique to generate the pulses for mitigating voltage sags.

Azim Riyasat (2011) *et al.* presented a simple, fast and efficient Dynamic Voltage Restorer (DVR) for mitigation of power quality problem associated with voltage sags/swells in industrial distribution systems with a large portion of its load comprising of induction motors. The proposed DVR employs the classical Fourier Transform technique for detection and quantification of voltage disturbances (sags/swells) events. The modeling and simulation

of the proposed DVR using MATLAB/ SIMULINK had been presented. The simulation showed that the DVR performance was efficient and satisfactory in mitigating voltage sags/swells.

Chawla Puneet (2011) et al. presented the fuzzy logic controlled DVR to response quickly and obtain a good dynamic performance. The proposed DVR had shown the ability to mitigate the voltage sags. The designed DVR had provided a regulated and sinusoidal voltage across the sensitive load and thus increased efficiency of the system. The IGBT based VSI technology and dynamic performance capability of fuzzy controlled DVR had improved the quality of critical load quantities by preventing the sags.

Khanh Q. Bach (2012) et al. presented the DVR used for mitigating voltage sags due to direct-on-line (DOL) starting of asynchronous motors. As soon as the motor reached the rated speed, terminal voltage of the motor reached close to 1 p.u. and the DVR is switched to standby mode. Two topologies were used. In the first one, DVR was connected with an independent dc supply for energy storage. In the second one, shunt rectifier was used which charges the dc link capacitor to the actual state of the supply. Feed forward control technique was used. Simulation was carried out for both the topologies. Both the topologies gave the same results. However, the effectiveness of reducing the starting current and starting torque is better in case of battery dc supply.

Kanakaraj M. (2012) et al. presented a new topology based on fuel cell and power conditioner in order to enhance the voltage restoration capability of a DVR. This topology ensured a constant dc voltage across the dc link during the process of voltage compensation. A proton exchange membrane fuel cell (PEMFC) was used. In-phase compensation was adopted. Simulation was carried for voltage sag and voltage swell and it was observed that the DVR compensated 25% of voltage sag and 30% of voltage swell.

Jain Sandesh (2012) et al. presented the compensation techniques of custom power electronic devices DVR. In this paper, the effective algorithm had been developed in order to obtain a fast response of the device. The analysis of mitigating harmonics, DVR under fuzzy controller was carried out using MATLAB Power System Block set. The results of simulation were presented and discussed. The THD and the amount of unbalance in load voltage were decreased with the application of DVR. The proposed system performed better than the traditional methods in mitigating harmonics and voltage sags.

1.3 SCOPE OF WORK

It was observed from the literature Survey that, the field of power quality and custom power devices plays an important role in power system. DVR is one of the custom power device used in distribution system for the improvement of power quality. Different types of controller namely fuzzy, hysteresis, PI, and PID are reported in literature to compensate various PQ problems.

In this dissertation, the effectiveness of PI controller and Fuzzy logic controller based DVR to mitigate power quality under static linear, static non-linear and induction motor loads, is investigated.

1.4 ORGANISATION OF DISSERTATION

The work carried out in the dissertation has been summarized in five chapters.

Chapter 1 briefs the overview, literature view and scope of work. It also contains the organization of dissertation.

Chapter 2 deliberates on definitions of power quality, its associated problems and solution strategy, introduction of custom power, need of custom power and custom power devices.

Chapter 3 deliberates on introduction of DVR, its configuration, operating modes and its principle, location of DVR.

Chapter 4 discusses tests and results, parameters of the test system, SIMULINK model of the test system with linear load and their results, SIMULINK model of the test system with non-linear load and their results and SIMULINK model of the test system with induction motor load and their results.

Chapter 5 contains the conclusion and future scope.

POWER QUALITY AND CUSTOM POWER CONCEPT

2.1 POWER QUALITY

Since the discovery of electricity 400 years ago, the generation, distribution and use of electricity have evolved steadily. New and innovative means to generate and use electricity fuelled the industrial revolution and since then the scientists and engineers have contributed to its continuing evolution. In the beginning, electrical machines and devices consumed large amounts of electricity and performed well. The machines were designed with cost concerns secondary to performance considerations. However, in the last 50 years, the industrial age led to the need for products to be economically competitive. Increased demand for electricity created extensive power generation and distribution grids. Industries demanded larger and larger shares of the generated power, which along with the growing use of electricity in the residential sector, stretched electricity generation to the limit. Today, electrical utilities are no longer independently operated entities. They are a part of a large network of utilities tied together in a complex grid. The combinations of these factors have created the electrical systems requiring power quality.

As per IEEE standard 1100 power quality is defined as “the concept of powering and grounding sensitive electronic equipment in a manner that is suitable to the operation of that equipment.”

Parameters of power quality are as follows:

1. Variation in voltage magnitude.
2. Harmonic content in the waveform for ac power.
3. Transient voltages and currents.
4. Continuity of service.

These days, power systems are complex in nature. Hundreds of generating stations and load centres are interconnected. The major concerns for the customers are the reliability and quality of power supply at the load centres. Power generation in most of the well developed countries is reliable but quality of supply is not. Customers should be provided with uninterrupted supply of energy.

A power quality problem is defined as any manifested problem in voltage or current of leading to frequency deviations that result in failure or mis-operation of customer equipment. Power quality has serious implications for the consumers. Power system, especially the distribution system, has numerous non-linear loads which significantly affect the quality of power supply. These loads may distort the supply waveform. Some system events also contribute power quality problems like capacitor switching, starting of motors and faults. The consequence of power quality problems includes a large economic loss.

Power quality problems are also associated with 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. Both, electric utilities and end users of electrical power are becoming increasingly concerned about the quality of electric power. Sensitive loads such as computers, programmable logic controllers (PLC), variable speed drives (VSD) etc. need high quality supplies.

Modernization and automation of industry involves increasing use of computers, microprocessors and power electronic systems such as adjustable speed drives. The power electronic systems also contribute to power quality problem (generated harmonics). The electronic devices are very sensitive to disturbances and become less tolerant to power quality problems such as voltage sags, swells and harmonics.

2.2 POWER QUALITY PROBLEMS

Voltage sag

It is also referred to as a voltage dip. This is the most common power quality problem. It is defined as a decrease of rms voltage to a value between 0.1 p.u. to 0.9 p.u. and lasts for duration between 0.5 cycles to 1 minute. The voltage sag magnitude depends on various factors like the type of fault, the location of the fault and the fault impedance. The duration of voltage sag basically depends on how fast the fault is cleared by the protective device. In short, voltage sag will last till the fault is cleared. Although the effect of voltage sag is only for a short duration, sensitive equipments like PLC's may malfunction. This affects the production and leads to revenue loss.

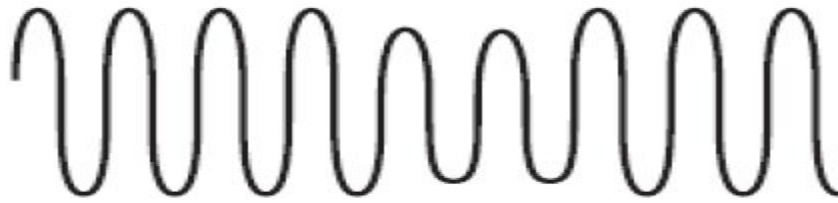


Figure 2.1: Voltage sag

Voltage swell

A voltage swell is defined as an increase in rms voltage between 1.1 and 1.8 p.u. at the power frequency for duration between 0.5 cycles to 1 minute. A voltage swell (like sag) is characterized by its magnitude (RMS) and duration. The main causes for voltage swell are switching of large capacitors or start/stop of heavy loads. Voltage swell is less common in distribution systems.

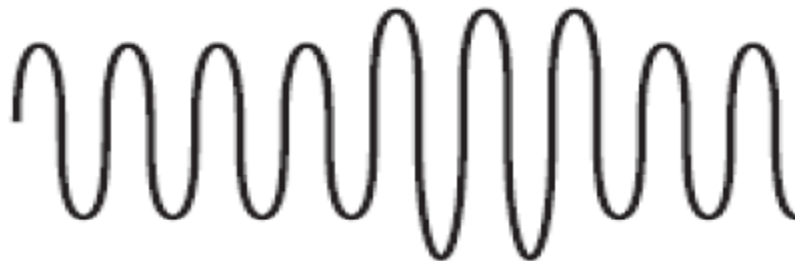


Figure 2.2: Voltage swell

Voltage interruption

A voltage interruption is a large decrease in rms voltage to less than a small percentile of the nominal voltage, or a complete loss of voltage. Voltage interruptions may come from accidents like faults and component malfunctions, or from scheduled downtime. Short voltage interruptions are typically the result of a malfunction of a switching device or a deliberate or inadvertent operation of a fuse, circuit breaker, or reclosure in response to faults and disturbances. Long voltage interruptions are usually the result of scheduled downtime, where part of an electrical power system is disconnected in order to perform maintenance or repairs.

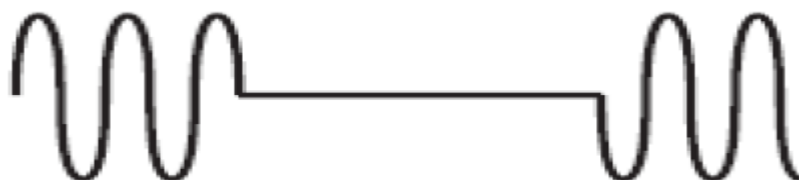


Figure 2.3: Voltage interruption

Spikes

Spikes are a sudden, short surge in voltage. Voltage spikes can be caused by lightning, power outages, short circuits, or power transitions in large equipment on the same power line.

Transients

Transients are also known as surge. Transients are power quality disturbances that involve destructive high magnitudes of current and voltage or even both. It may reach thousands of volts and amps even in low voltage systems. However, such phenomena only exist in a very short duration from less than 50 nanoseconds to as long as 50 milliseconds.

Sources of Transients

- Lightning Strikes
- Switching activities
 - ✓ Opening and closing of disconnects on energized lines
 - ✓ Capacitor bank switching
 - ✓ Reclosing operations
 - ✓ Tap changing on transformers
- Loose connections in the distribution system that results to arcing
- Accidents, human error, animals and bad weather conditions
- Neighbouring facilities

Transients are classified as follows:

Impulsive transient

It is a type of transient disturbance that may enter the power system. It is defined by IEEE 1159 as a sudden, non-power frequency change in the steady-state condition of voltage, current, or both that is unidirectional in polarity– either primarily positive or negative. It is normally a single, very high impulse like lightning. Impulsive transients are not usually transmitted far from the source of where they enter the power system. However, in some cases, they may propagate for some distance along distribution utility lines. Also, it may considerably have different characteristics when viewed from different parts of the electrical system (i.e. from one building to another).

Causes

Lightning is an example of an impulsive transient. Currents produced from a lightning strike can go as high to several thousand amps in about 2-3 μ s. In addition, the sudden rise has frequency components in the high MHz range. Electrostatic discharge is another form of an impulsive transient.

Oscillatory transients

Oscillatory Transient is described as a sudden, non-power frequency change in the steady-state condition of voltage, current, or both that has both positive and negative polarity values (bidirectional). The oscillatory transient is subdivided into three classes which are as follows:

Table 2.1: Classification of Oscillatory Transients

Oscillatory transients	Spectral content	Typical duration	Typical voltage magnitude
Low frequency	<5 kHz	0.3-50 ms	0-4 p.u.
Medium frequency	5-500 kHz	20 μ s	0-8 p.u.
High frequency	0.5-5 MHz	5 μ s	0-4 p.u.

Voltage fluctuations and flickers

Voltage fluctuations are systematic variations of the voltage envelope or a series of random changes in the voltage magnitude (which lies in the range of 0.9 p.u. to 1.1 p.u.). High power loads that draw fluctuating current, such as large motor drives and arc furnaces, cause low frequency cyclic voltage variations that result in flickering of light sources (incandescent and fluorescent lamps) which can cause significant physiological discomfort or irritation in human beings. The typical frequency spectrum of voltage flicker lies in the range from 0 Hz to 30 Hz.

Waveform distortion

This is defined as a steady-state deviation from an ideal sine wave of power frequency. Different types of waveform distortion are as follows:

a) Harmonics

A harmonic is any sinusoidal frequency, which is a multiple of the fundamental frequency. Harmonic frequencies can be even or odd multiples of the sinusoidal fundamental frequency. The main causes for harmonic distortion are rectifiers and all non-linear loads, such as power electronics equipment.

b) Notching

Notching is a periodic voltage disturbance caused by the normal operation of power electronic devices when current is commutated from one phase to another.



Figure 2.4: Notching

c) Noise

Noise is defined as unwanted electrical signal with broadband spectral content lower than 200 kHz superimpose upon the power system voltage or current in phase conductors, or found on neutral conductors or signal lines. Noise power systems can be due to power electronic devices, control circuits, arcing equipment, loads with solid state rectifiers and switching power supplies.



Figure 2.5: Noise

2.3 SOLUTIONS TO IMPROVE THE POWER QUALITY

The solution to the power quality can be done from customer side or from utility side. Approaches that are used to improve the power quality are as follows:

- **Load conditioning:** It ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion.
- **Line conditioning systems:** They suppress or counteract the power system disturbances. To achieve improve power quality is to use passive filters connected at the sensitive load terminals. The challenge is to regulate the sensitive load terminal voltage so that its magnitude remains constant and any harmonic distortion is reduced to an acceptable level.

2.4 CUSTOM POWER

Custom Power is a concept based on the use of power electronic controllers in the distribution system to supply value-added, reliable, high quality power to its customers. For many customers, this is a preferred alternative to the customer improvising utility power by their own means, mostly in a band aid manner with numerous uninterruptible power supplies,

as is done now. Many utilities are moving in the direction of value-added Custom Power service to their large customers.

Custom Power means that the customer receives specified power quality from a utility or a service provider or at-the-fence equipment installed by the customer in coordination with the utility, which includes an acceptable combination of the following features:

- No (or rare) power interruptions.
- Magnitude and duration of voltage reductions within specified limits.
- Magnitude and duration of overvoltages within specified limits.
- Low harmonic voltage.
- Low phase unbalance.
- Acceptance of fluctuating, nonlinear and low power factor loads without significant effect on the terminal voltage.

This can be done on the basis of an individual, large customer, industrial or a supply for a high tech community on a wide area basis.

2.5 NEED OF CUSTOM POWER

The need for the Custom Power concept arises from the fact that:

- Most of the interruptions and voltage reductions occur in the utility system on account of lightning faults on transmission and distribution lines, low frequency dynamic swings of the transmission system, trees touching the wires, equipment failure, switching, etc. Voltage sags may also be a consequence of large load changes affecting customers own equipment or affecting other equipment via the utility system.
- Impulses, switching surges and overvoltages affecting the insulation, would most likely result from lightning strikes and switching events in the transmission and distribution system.
- Temporary overvoltages lasting from several cycles to several seconds would largely result from large load changes, capacitor switching, transformer switching, dynamic stability swings, excessive leading-VARs during light loads, etc. in the utility system.
- Voltage unbalances in a three-phase supply would occur mostly due to large unbalanced loads on a utility's distribution lines and long lines with unbalanced phase impedances.
- Harmonics would most likely be the consequence of high harmonics in the customer load, or the saturation of a utility's transformers. These harmonics would then be amplified by the natural resonances in the utility system and/or the customer system.

There are a number of reasons for the choice of the Custom Power concept for many customers, and on a long term basis for most customers. These reasons are:

- The customers are better served if they receive a comprehensive solution to their power supply problems from the power supply service providers.
- Most of the voltage reductions and interruptions result from events that involve the utility system.
- In general, the total cost of the solutions that involve the utilities own systems would be much less than the cost of solutions put in place by the individual customers.
- At least from the point of view of reliability, migration to the Custom Power concept seems to be inevitable.

2.6 CUSTOM POWER DEVICES

The introduction of power electronic loads has raised much concern about power quality problems caused by harmonics, distortions, interruptions, and surges. The use of electronic devices increases the power quality problems. Equipments such as large industrial drives (e.g., cycloconverters) generate significantly high voltage and current harmonics and create extensive voltage fluctuation.

The application of harmonic filters and SVCs to radial transmission systems can offer partial solution to high THD levels and voltage fluctuations. Yet, the lack of dynamic capabilities of these devices limits them to bulk correction. In addition, they might be effective in one application but fail to correct other power quality issues.

Hingorani introduced the concept of custom power as the solution to V, P, and Q (voltage, active power, reactive power) compensation and power quality problems at the expense of high cost and network complexity. FACTS controllers improve the reliability and quality of power transmission by simultaneously enhancing both power transfer capacity and stability whereas custom power devices enhance the quality and reliability of power delivered to the customer. With a custom power device, a customer (e.g., a sensitive load) will be able to receive a pre-specified quality of electric power with a combination of specifications including but not limited to:

- Magnitude and duration of over and under voltages with specified limits,
- Low harmonic distortion in the supply, load voltages, and currents.
- Small phase imbalance,
- Low flicker in the supply voltage,

- Control of power interruptions, and
- Control of supply voltage frequency within specified limits.

Classification of Custom power devices are based on their power electronic controllers, which can be either of the network reconfiguration type or of the compensation type. The network reconfiguration devices also called switchgear include the solid state and or static versions or current limiting, current breaking, and current transferring components. The compensation type custom power devices either compensate a load (e.g., correct its power factor, imbalance) or improve the quality for the supply voltage (e.g., eliminate its harmonics). They are either connected in shunt or in series or a combination of both. Custom power devices are classified as follows:

Network – reconfiguration custom power devices includes

- Solid state current limiter (SSCL),
- Solid–state breaker (SSB), and
- Solid state transfer switch (SSTS)

Compensation-custom power devices includes

- Distribution STATCOM,
- Dynamic voltage restorer / regulator (DVR), and
- Unified power quality conditioner (UPQC).

Custom power devices are designed to improve the quality of power at their point of installation of the power distribution system. They are not primarily designed to improve the power quality of the entire system.

2.6.1 Distribution STATCOM

The distribution STATCOM is similar to a transmission STATCOM in that it uses a VSC of the required rating. However, the VSC used in a DVR is a Type 1 converter with PWM control over the magnitude of the injected AC voltage while maintaining a constant DC voltage across the capacitor. Faster power semiconductor devices such as IGBT or IGCT are used instead of GTO. The rapid switching capability provided by IGBT (or IGCT) switches enable the use of more sophisticated control schemes to provide functions of balancing (by injecting negative sequence current), active filtering (by injecting harmonic currents) and flicker mitigation. By connecting an energy storage device such as a Superconducting Magnetic Energy Storage (SMES) on the DC side through a DC/DC power conditioner, it is possible to exchange real power with the network for a limited time (during momentary interruptions or large voltage sags).

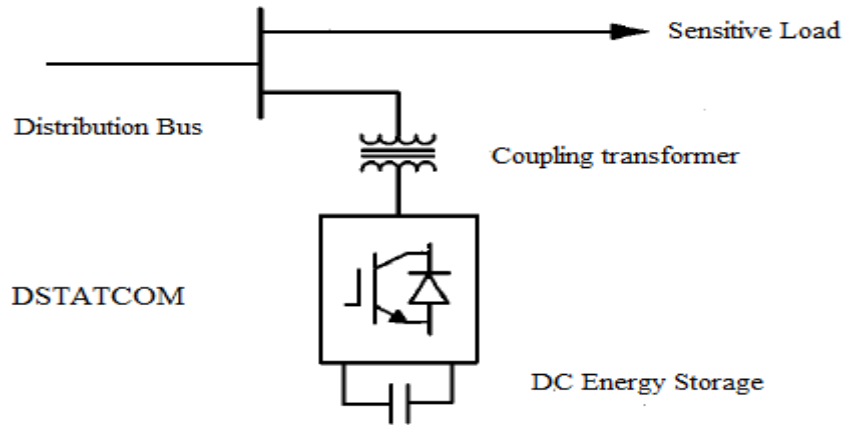


Figure 2.6: Basic configuration of Distribution STATCOM

2.6.2 Dynamic Voltage Restorer/ Regulator (DVR)

The Dynamic Voltage Restorer (DVR) is a series connected device analogous to a SSSC. The main function of a DVR is to eliminate or reduce voltage sags seen by sensitive loads such as semiconductor manufacturing plant or IT industry. DVR that have been installed so far are modular with ratings of 2 MVA per module. They have been designed to compensate three phase voltage sags up to 35% for duration of time less than half a second (depending on the requirement). If the voltage sag occurs only in one phase (caused by SLG faults) then the DVR may be designed to provide compensation for sags exceeding 50%. The energy storage required in capacitors is typically in the range of 0.2 to 0.4 MJ per MW of load served.

A DVR is connected in series with the feeder using a transformer. The low voltage winding is connected to the converter. If the objective of a DVR is mainly to regulate the voltage at the load bus, it remains for most of the time in stand-by mode during which the converter is bypassed (no voltage is injected). Only when sag is detected, the DVR injects a series voltage of the required magnitude. It is necessary to protect a DVR against the fault currents (as in the case of a SSSC). A DVR with IGBT/IGCT devices can be controlled to act as a series active filter to isolate the load from voltage harmonics on the source side. It is also possible to balance the voltage on the load side by injecting negative and/or zero sequence voltages in addition to harmonic voltages.

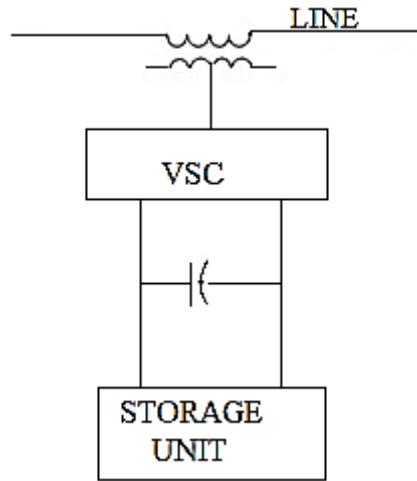


Figure 2.7: Basic configuration of DVR

2.6.3 Unified Power Quality Conditioner (UPQC)

Unified power quality conditioners are viable compensation devices that are used to ensure that delivered power meets all required standards and specifications at the point of installation.

The ideal UPQC can be represented as the combination of a voltage source converter (injecting shunt current) and a common DC link (connected to a DC capacitor).

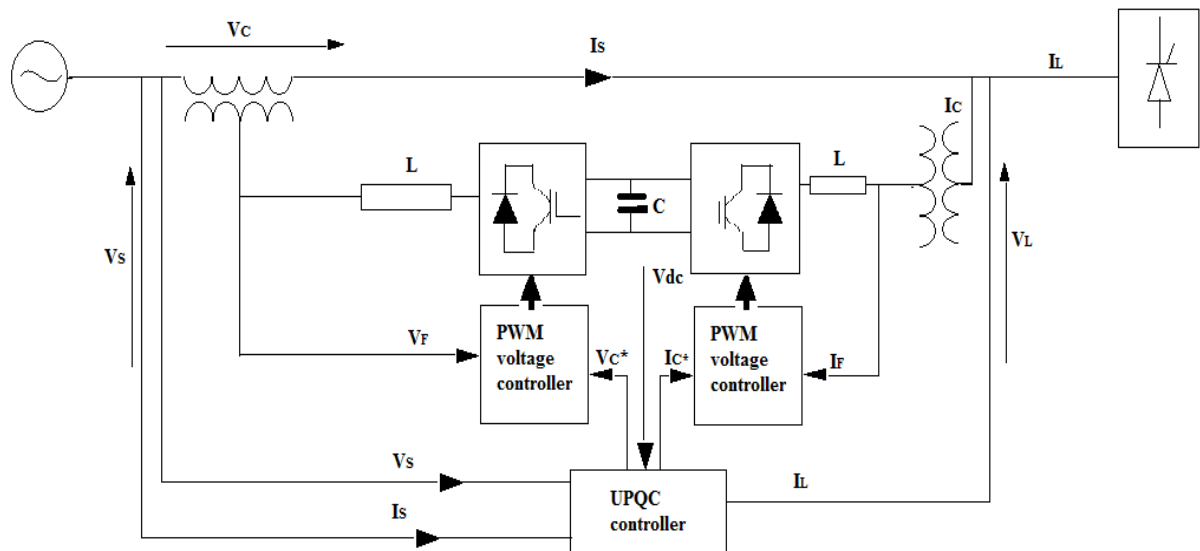


Figure 2.8: Basic Configuration of UPQC

UPQC consist of combined series active power filter that compensates voltage harmonics of the power supply, and shunt active power filter that compensates harmonic currents of a non-linear load. This dual functionality makes the UPQC as one of the most suitable devices that could solve the problems of both consumers as well as of utility. UPQC, thus can help to improve voltage profile and hence the overall health of power distribution system.

CHAPTER 3

DYNAMIC VOLTAGE RESTORER

3.1 INTRODUCTION

It is also known as a static voltage booster (SVB) or a static series compensator (SSC). It is generally installed in distribution systems. It is a series custom power device intended to protect the sensitive loads at the point of common coupling (PCC) from various power quality problems.

DVR has the capability to deal with line voltage harmonics, reduction of transients in voltage, fault current limitations, voltage sags, voltage swells. Problems facing industries regarding the power quality are mainly voltage sags and swells. This may occur in developing countries where the grid quality is unsatisfactory. These problems can cause the sensitive equipment to fail or shutdown as well as create a large current imbalance that could blow up the fuses or trip the breakers. These effects can be very expensive for the customers, ranging from minor quality variations to production downtime and equipment damage. Use of DVR to mitigate voltage sags voltage swells is considered to be the most cost efficient method.

DVR works independently of the type of fault or any event. For 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. Step down transformer offers infinite impedance for the zero sequence part of the disturbance. The DVR supplies the active power with help of DC energy storage and required reactive power is generated internally. The injected active power should be minimised.

3.2 CONFIGURATION OF DVR

The configuration of a DVR consists of:

1. Injection/Booster/Isolation transformer
2. Harmonic/Passive filter
3. Storage devices/Energy storage systems
4. Voltage source converter/inverter
5. DC charging set
6. Control and Protection system

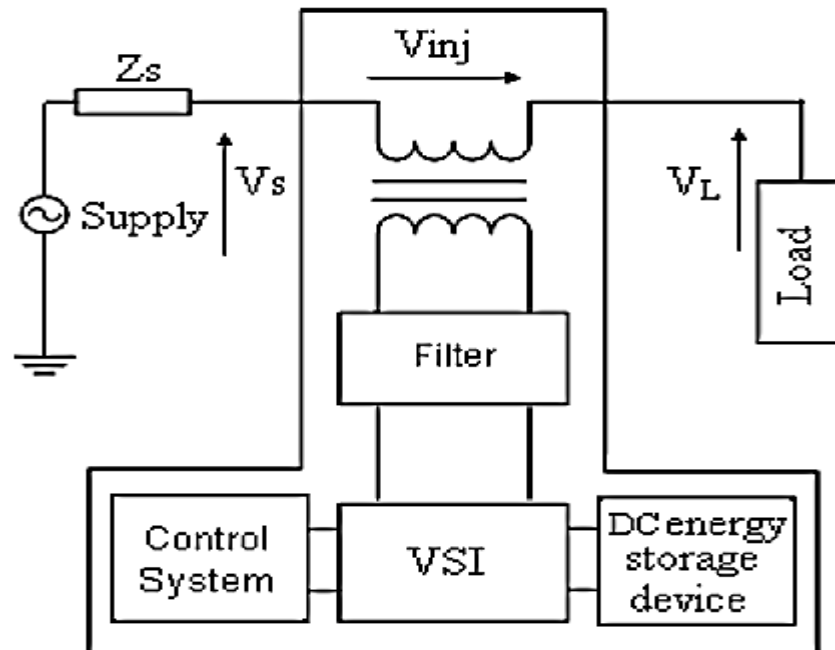


Figure 3.1: Schematic representation of a DVR

1. Injection Transformer

It consists of a three phase transformer or three single phase transformers which limit the coupling of noise and transient energy from primary side to the secondary side. It connects the DVR to the distribution network via high voltage windings. Transformer can be connected in star/star configuration or delta/star configuration. If the system is connected in star/star configuration then zero sequence voltage compensation is required. If a delta/star configuration is used then no zero sequence voltage compensation is required as it offers infinite impedance for zero sequence components.

It isolates the load from rest of the system and couples the injected voltages generated by the voltage source converter to the incoming supply voltage. The transformer winding ratio is determined according to the voltage requirement in its secondary side. Usually, winding ratio is kept equal to the supply voltage so as to allow the DVR to provide full voltage sag compensation. The rating of the transformer is an important factor to determine the performance of a DVR as it limits the maximum compensation ability of the DVR.

2. Harmonic/Passive filter

Usually, a filter unit consists of inductor and capacitor. It eliminates the unwanted harmonic components produced by the voltage source converter.

3. Storage devices/Energy storage systems

They fulfil the active requirement of the load. Various systems can be used for this purpose like flywheel, super conducting magnetic energy storage systems (SMES), lead acid batteries.

4. Voltage source converter/inverter

It basically consists of a storage device and switching devices. It produces sinusoidal voltage of desired phase angle and magnitude. There are four main types of storage devices: MOSFET, GTO, IGBT and IGCT. Highly sophisticated converter design with IGBT's are used which allows the DVR to compensate large voltage dips.

A voltage source converter is used to temporarily replace the supply voltage or to produce a part of the supply voltage which is missing. The most popular three phase inverter topology is a two level inverter.

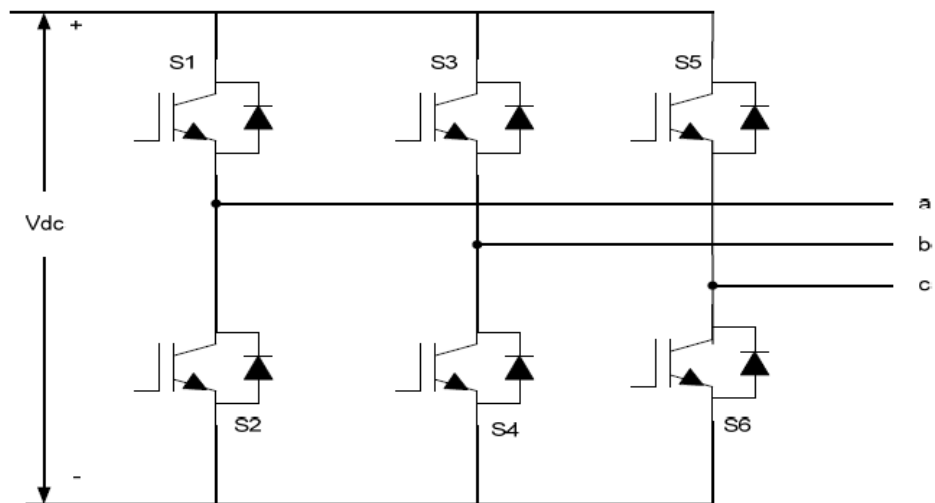


Figure 3.2: Two level switch mode inverter

5. DC charging set

It performs two main tasks which are as follows:

- It charges the dc source after a sag compensation event.
- It maintains dc link voltage at the nominal dc link voltage.

Excess of dc link voltage will damage the dc storage capacitor and switching device.

6. Control and Protection system

As there exists different operating modes of DVR so all protective functions of DVR are implemented in combination of hardware and programmable logic control. The control system determines the voltage that should be injected by the DVR. Transformer can be provided with differential current protection.

3.3 OPERATION OF A DVR

It injects dynamically controlled voltages in series with the bus voltage through the booster transformer. The amplitudes of the injected phase voltages are controlled so as to eliminate the detrimental effects of a bus fault to the load voltage.

The system impedance Z_{th} depends on the fault level of the load bus. When the system voltage (V_{th}) drops, the DVR injects a series voltage V_{DVR} through the injection transformer so that the desired load voltage magnitude V_L can be maintained. The series injected voltage of the DVR can be written as:

$$V_{DVR} = V_L + Z_{th}I_L - V_{th} \quad (3.1)$$

$$I_L = \left(\frac{P_L + jQ_L}{V_L} \right) \quad (3.2)$$

Where,

V_L = Desired load voltage magnitude

Z_{th} = load impedance

I_L = Load current

V_{th} = system voltage during fault condition

3.4 OPERATING MODES OF A DVR

Different operating modes of DVR are as follows:

Protection mode:

If the over current on the load side exceeds a permissible limit due to short circuit on the load or large inrush current, the DVR will be isolated from the systems by using the bypass switches (S2 and S3 will open) and supplying another path for current (S1 will be closed).

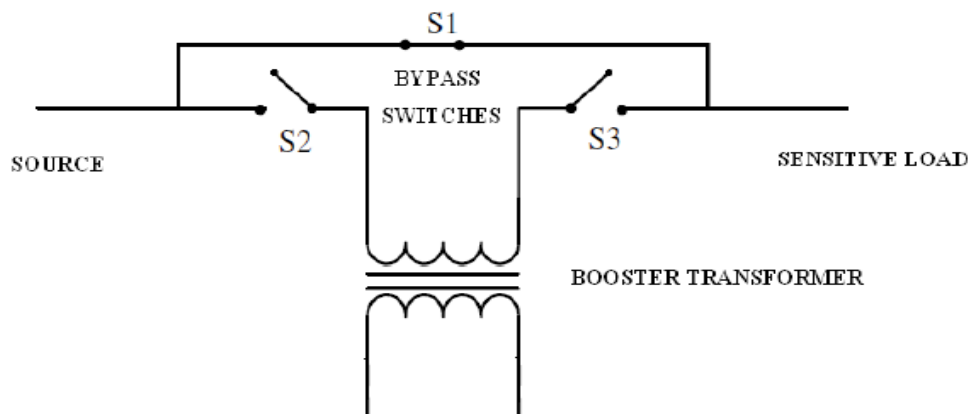


Figure 3.3: Protection mode of a DVR

Injection/Boost Mode:

In this mode, $V_{DVR} > 0$. In the Injection/Boost mode the DVR is injecting a compensating voltage through the booster transformer due to the detection of a disturbance in the supply voltage.

Standby Mode:

In this mode, $V_{DVR} = 0$. The booster transformers low voltage winding is shorted through the converter. No switching of semiconductors occurs in this mode of operation and the full load current will pass through the primary. Losses of the DVR during this mode should be minimised.

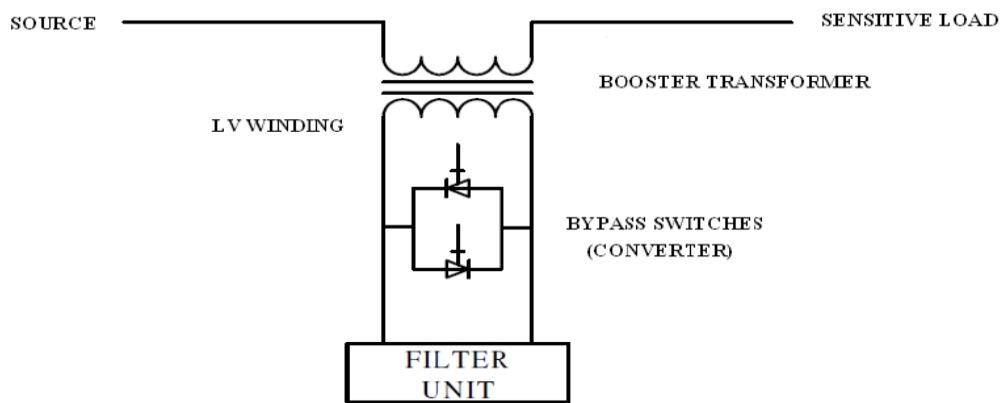


Figure 3.4: Standby mode of a DVR

3.5 CONCEPT OF COMPENSATION TECHNIQUES IN DVR

The concept of compensation techniques in DVR can be divided into two categories which are as follows:

- Reactive power compensation
- Active and reactive power compensation

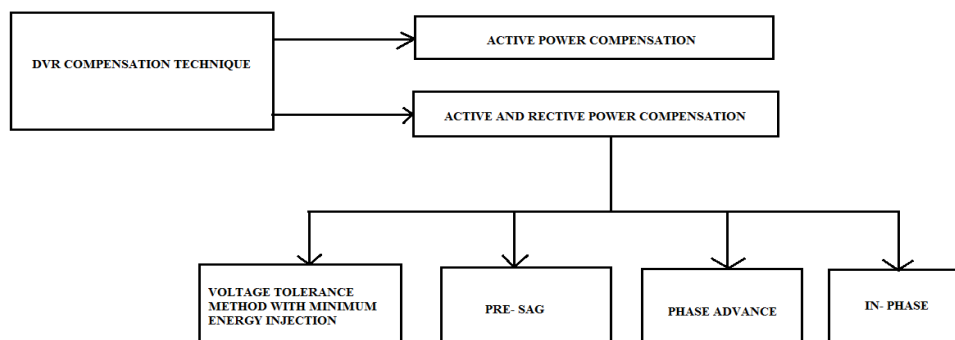


Figure 3.5: Compensation techniques of a DVR

Voltage injection or compensation methods by means of a DVR depend upon the limiting factors such as DVR power ratings, various conditions of load, and different types of voltage sags. Some loads are sensitive towards phase angle jump and some are sensitive towards change in magnitude and others are tolerant to these. Therefore the control strategies depend upon the type of load characteristics.

There are four different methods of DVR voltage injection which are as follows:

1. Pre-sag compensation method
2. In-phase compensation method
3. In-phase advanced compensation (IPAC) method
4. Voltage tolerance method with minimum energy injection

1. Pre-sag/dip compensation method

The pre-sag method tracks the supply voltage continuously and if it detects any disturbances in supply voltage then it will inject the difference voltage between the sag or voltage at PCC and pre-fault condition, so that the load voltage can be restored back to the pre-fault condition.

Compensation of voltage sags in the both phase angle and amplitude sensitive loads would be achieved by pre-sag compensation method. In this method, the injected active power cannot be controlled and it is determined by external conditions such as the type of faults and load conditions.

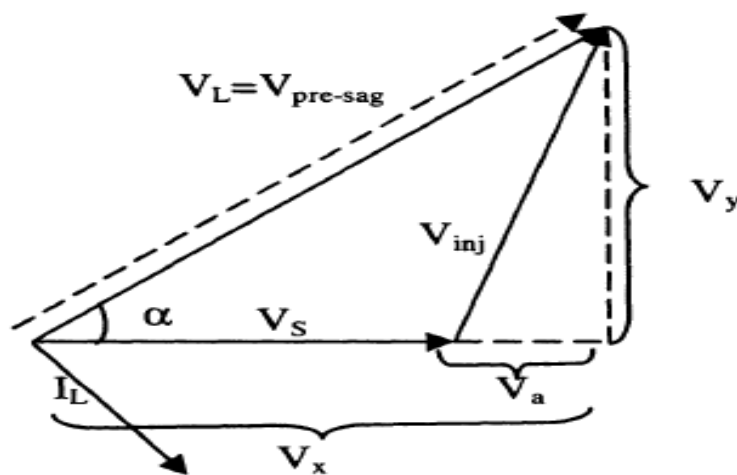


Figure 3.6: Pre sag compensation

$$V_{DVR} = V_{prefault} - V_{sag} \quad (3.3)$$

2. In-phase compensation method

This is the most straight forward method. In this method, the injected voltage is in phase with the supply side voltage irrespective of the load current and pre-fault voltage. The phase angles of the pre-sag and load voltage are different but the most important criteria for power quality that is the constant magnitude of load voltage are satisfied.

When the source voltage drops to voltage sag then the voltage source inverter (VSI) injects the missing voltage based on magnitude of the voltage drop. One of the advantages of this method is that the amplitude of DVR injection voltage is minimum for certain voltage sag in comparison with other strategies. Practical application of this method is in non-sensitive loads to phase angle jump.

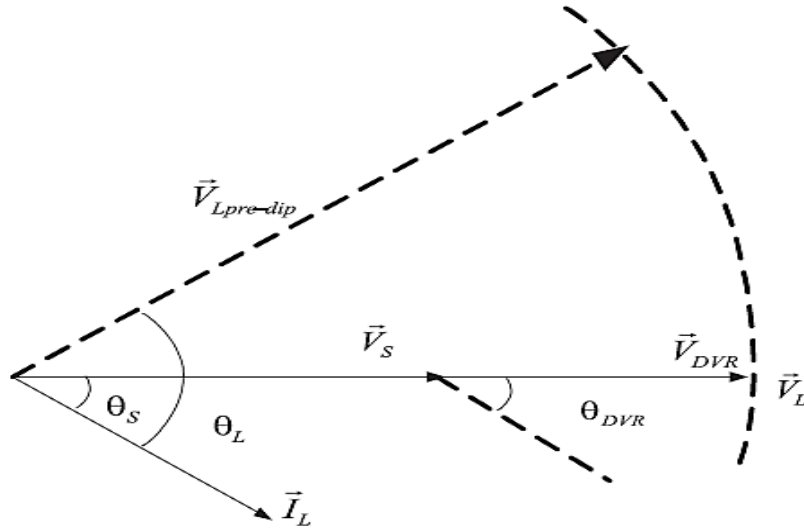


Figure 3.7: In-phase compensation

3. In-phase advanced compensation (IPAC) method

In this method, the real power spent by the DVR is decreased by minimizing the power angle between the sag voltage and load current. In case of pre-sag and in-phase compensation method the active power is injected into the system during disturbances. The minimization of injected energy is achieved by making the active power component zero by having the injection voltage phasor perpendicular to the load current phasor. In this method, the values of load current and voltage are fixed in the system. So we can change only the phase of the sag voltage.

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.

4. Voltage tolerance method with minimum energy injection

A small drop in voltage and small jump in phase angle can be tolerated by the load itself. If the voltage magnitude lies between 90%-110% of nominal voltage and 5%-10% of nominal state that will not disturb the operation characteristics of loads. Both magnitude and phase are the control parameter for this method which can be achieved by small energy injection.

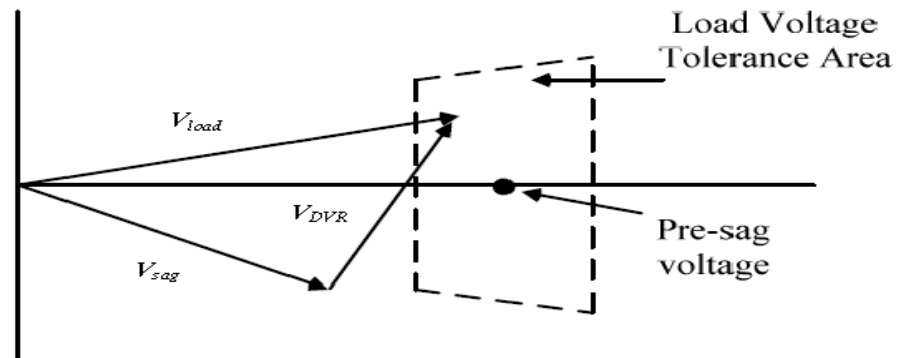


Figure 3.8: Voltage tolerance method with minimum energy injection

3.6 LOCATION OF A DVR

If a fault occurs on the line feeding load 1 then its voltage collapses to zero. Load 2 experiences voltage sag whose magnitude is equal to the load voltage at the point of common coupling. The voltage of the sensitive load is protected by the DVR and is restored to its pre-fault value. DVR is located downstream of a delta/star distribution transformer. Hence, there is no need to provide zero sequence voltage compensation.

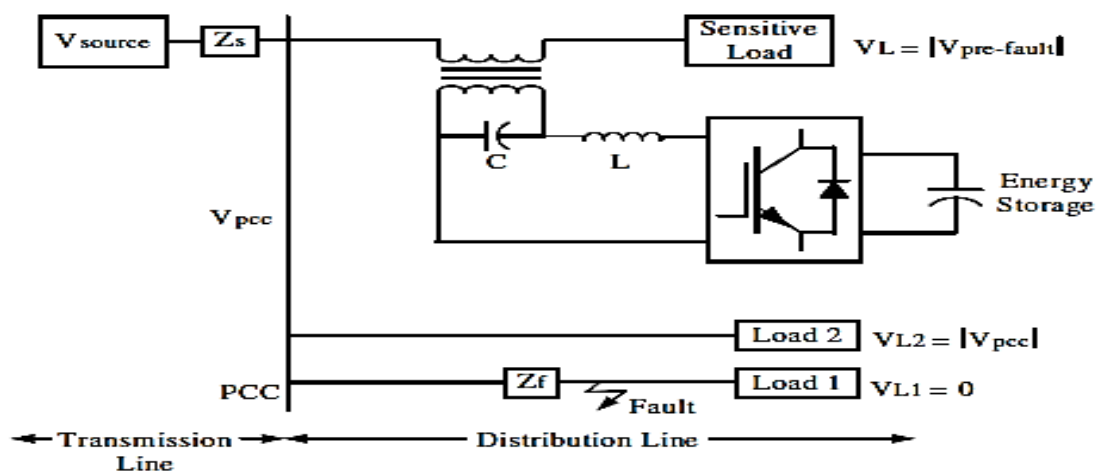


Figure 3.9: Location of a DVR

REALIZATION OF COMPENSATION TECHNIQUE

4.1 PI CONTROLLER-DISCRETE PWM BASED CONTROL SCHEME

In order to mitigate the simulated voltage sags in the test system of each compensation technique, also to compensate voltage sags in practical application, a discrete PWM-based control scheme is implemented, with reference to DVR.

Voltage sag is created at load terminals by a SLG fault as shown in figure 4.3. Load voltage is sensed and passed through a sequence analyzer. The magnitude is compared with reference voltage (V_{ref}). Pulse width modulated (PWM) control technique is applied for inverter switching so as to produce a three phase 50 Hz sinusoidal voltage at the load terminals. Chopping frequency is in the range of a few KHz. The IGBT inverter is controlled with PI controller in order to maintain 1 p.u. voltage at the load terminals i.e. considered as base voltage =1p.u.

A proportional-integral (PI) controller shown in figure 4.1 drives the plant to be controlled with a weighted sum of the error (difference between the actual sensed output and desired set-point) and the integral of that value. An advantage of a proportional plus integral controller is that its integral term causes the steady-state error to be zero for a step input. PI controller input is an actuating signal which is the difference between the V_{ref} and V_{in} . Output of the controller block is of the form of an angle δ , which introduces additional phase-lag/lead in the three-phase voltages.

The output of error detector is $V_{ref} - V_{in}$.

V_{ref} equal to 1 p.u. voltage

V_{in} voltage in p.u. at the load terminals.

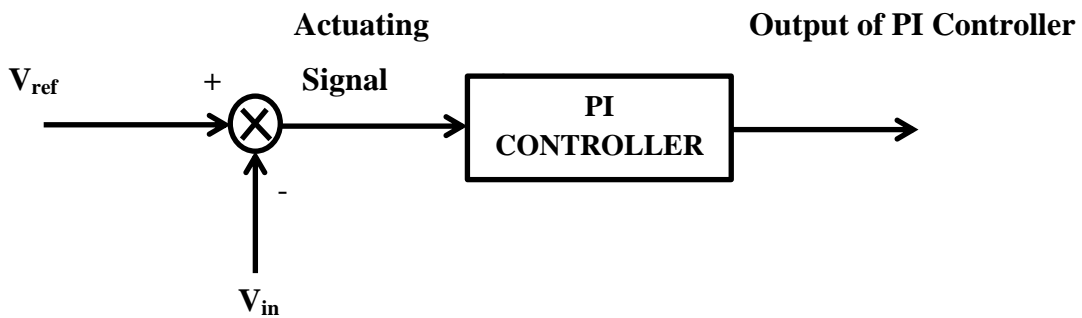


Figure 4.1: Schematic of a typical PI Controller

The controller output when compared at PWM signal generator results in the desired firing sequence. The sinusoidal voltage V_{control} is phase-modulated by means of the angle δ or delta as shown in figure 4.2 and the modulated three-phase voltages are given by

$$V_A = \text{Sin}(\omega t + \delta) \quad (4.1)$$

$$V_B = \text{Sin}(\omega t + \delta - 2\pi/3) \quad (4.2)$$

$$V_C = \text{Sin}(\omega t + \delta + 2\pi/3) \quad (4.3)$$

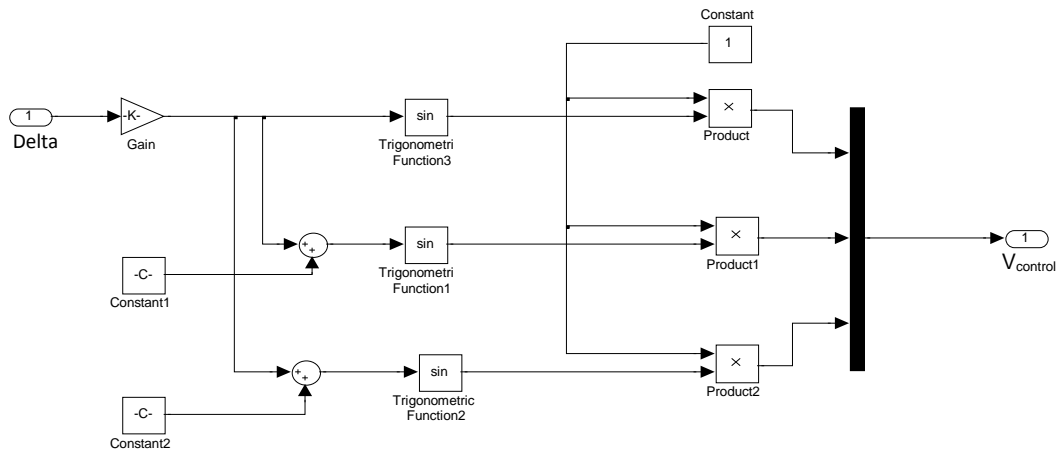


Figure 4.2: Phase-Modulation of the control angle δ (Subsystem 1)

The modulated angle is applied to the PWM generators in phase A. The angles for phases B and C are shifted by 120° and 240° . In this PI controller, only voltage magnitude is taken as a feedback parameter in the control scheme.

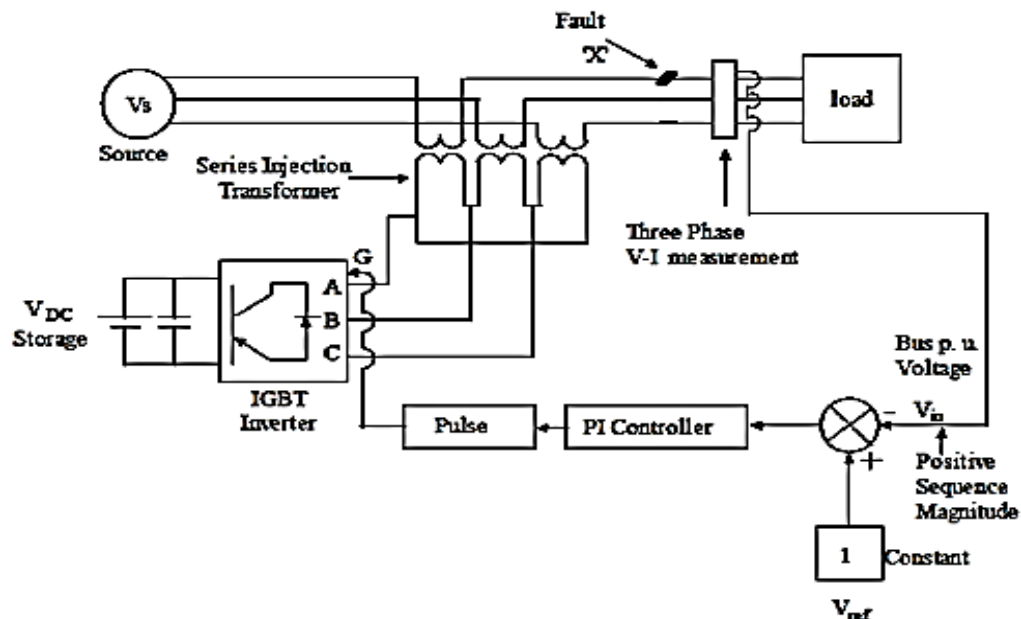


Figure 4.3: Circuit Model of DVR Test System

4.2 FUZZY LOGIC CONTROLLER

In fuzzy logic, basic control is determined by a set of linguistic rules which are determined by the system. Since numerical variables are converted into linguistic variables, mathematical modelling of the system is not required. The fuzzy logic control is being proposed for controlling the inverter action. The fuzzy logic controller has two real time inputs measured at every sample time, named error and error rate and one output named actuating signal for each phase. The input signals are fuzzified and represented in fuzzy set notations as membership functions. The defined ‘If ... Then ...’ rules produce output (actuating) signal and these signals are defuzzified to analog control signals for comparing with a carrier signal to control PWM inverter.

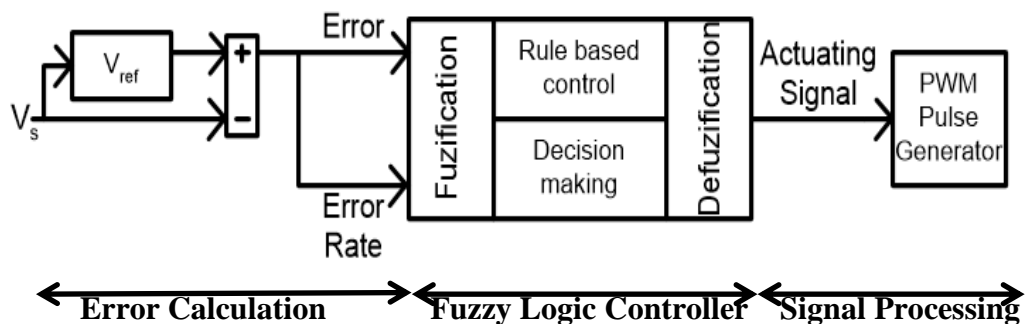


Figure 4.4: Block diagram of proposed control system

4.2.1 Input Parameters

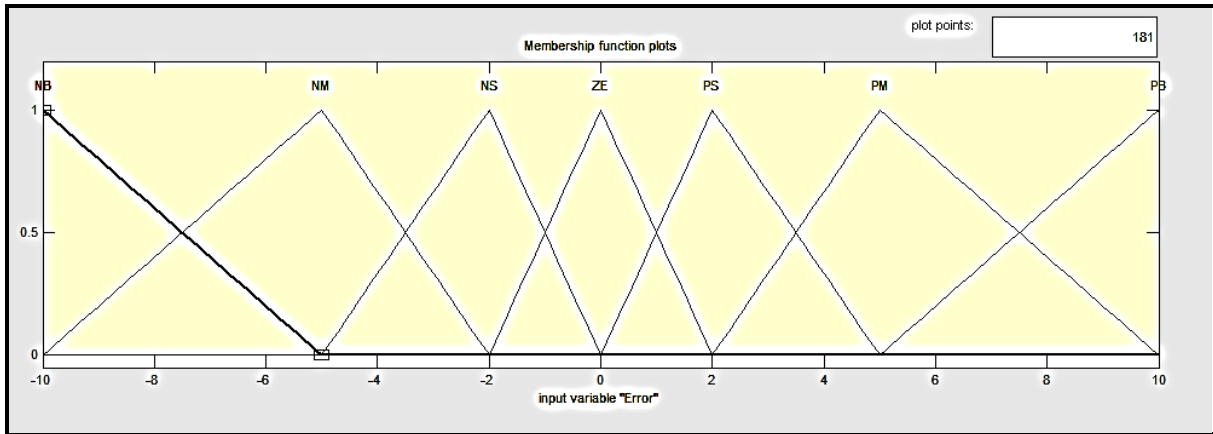
Two variables, error in voltage i.e. difference between supply voltage and the reference voltage and error rate i.e. the rate of change of error of voltage are taken as input to fuzzy logic controller Error and error rate are defined as:

$$\text{Error} = V_{ref} - V_s \quad (4.4)$$

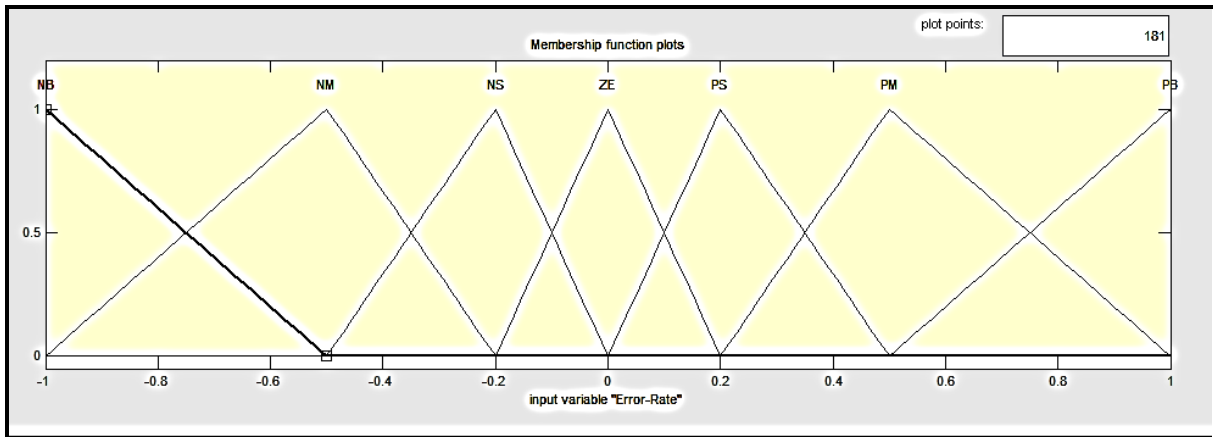
$$\text{Error rate} = \text{error}(n) - \text{error}(n-1) \quad (4.5)$$

4.2.2 Fuzzification

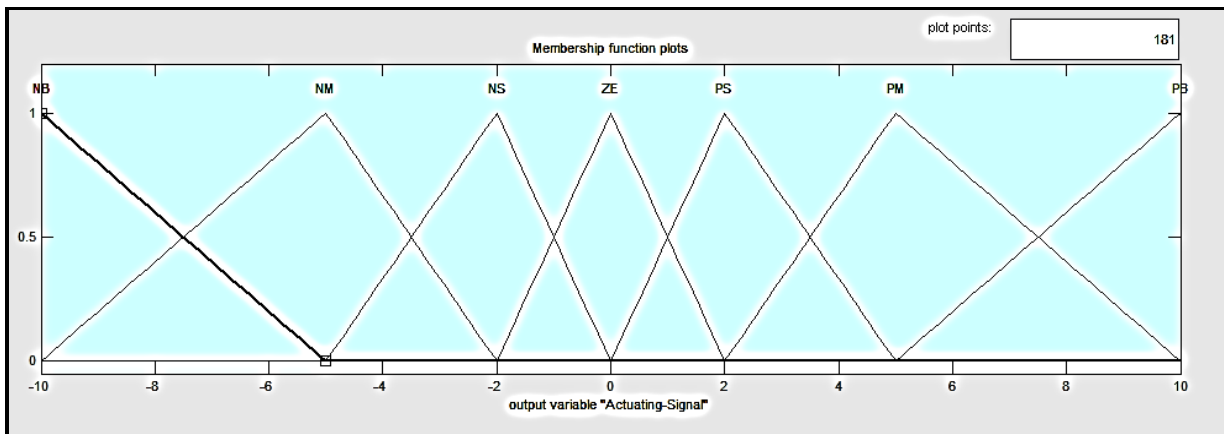
In this simulation study, the error and error rate are defined by linguistic variables such as negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM) and positive big (PB) characterized by triangular membership functions. These functions have been chosen to satisfy the output needs of the fuzzy controller. The output is also defined by seven linguistic variables such as negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM) and positive big (PB) characterized by membership functions given in figure 4.5.



Input Variable 'Error'



Input Variable 'Error Rate'



Output Variable 'Actuating Signal'

Figure 4.5: Membership Functions for inputs and output

4.2.3 Decision Making

Fuzzy process is realized by Mamdani method. Mamdani inference method has been used because it can easily obtain the relationship between its inputs and output. The set of rules for fuzzy controller are represented in Table 1. There are 49 rules for fuzzy controller. The output membership function for each rule is given by the Min (minimum) operator.

The Max operator is used to get the combined fuzzy output from the set of outputs of Min operator. The output is produced by the fuzzy sets and fuzzy logic operations by evaluating all the rules.

A simple if-then rule is defined as follows: If error is Z and error rate is Z then output is Z.

Table 4.1: Fuzzy rules

Ce\e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NM	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PM	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PM	PM	PB	PB	PB

4.2.4 Defuzzification

It is the process of converting the controller outputs in linguistic labels represented by fuzzy set to real control (analog) signals. Centroid method is used for defuzzification in this work.

4.2.5 Signal Processing

The outputs of FLC process are the control signals that are used in generation of switching signals of the PWM inverter by comparing with a carrier signal.

4.3 PARAMETERS OF DVR TEST SYSTEM

Electrical circuit model of DVR test system is shown in figure 4.3. System parameters are listed in Table 2. Voltage sag is created at load terminals via SLG fault as shown in figure 4.3. Load voltage is sensed and passes through a sequence analyser. The magnitude is compared with V_{ref} .

MATLAB Simulation diagram of the test system for DVR is shown in figure 4.6. System comprises of 11 kV, 50 Hz generator, feeding transmission lines through a three-phase, three-winding transformer connected in $\Delta/Y/Y$, 11000/400/400V.

In this test system, two similar loads with different feeders are considered. One of the feeders is connected to DVR and the other is kept as it is. This test system is analyzed under SLG fault condition.

Table 4.2: System Parameters

Serial number	System Quantities	Parameters
1.	Source	3 phase, 11kV rms (phase-phase), 50Hz, $500e^6$ Short circuit level(VA), 11kV Base voltage, $\frac{X}{R} = 0.5$.
2.	Convertor	IGBT based, 3 arms, 6 pulse, $R_{on} = 1e^{-3}$ ohms
3.	Discrete 3-phase PLL	$K_P = 20, K_i = 50$, sampling time $50\mu s$
4.	Linear Load	400V rms (phase-phase), 50 Hz, 10 kW, 10 kVar.
5.	Non Linear Load	Non-linear Resistance (100ohm), Inductance ($50e^{-3}H$), 400V rms (phase-phase), 50 Hz.
6.	FOC Induction Motor Drive	Stator Resistance ($14.85e^{-3}$), Rotor Resistance ($9.295e^{-3}$), Leakage Inductance ($0.3027e^{-3}$), Mutual Inductance ($10.46e^{-3}$), Nominal power $200e^3$ VA, 400V rms (phase-phase), 50 Hz.
7.	Transformer	Nominal power $200e^3$ VA, 50 Hz, $\Delta/Y/Y$ (grounded) 11000/400/400V, $(R_1/R_2/R_3, L_1/L_2/L_3) = (0.002/0.002/0.002, 0.08/0.08/0.08)$ p.u.

4.4 SIMULATION MODELS OF THE TEST SYSTEM

4.4.1 SIMULINK MODEL OF THE TEST SYSTEM WITH LINEAR LOAD

In this SIMULINK model, systems with two parallel feeders are shown. In both the feeders further similar loads are connected. In one feeder DVR is connected in series with line and the other feeders is kept as it is.

- **PI Controller** is used for the control purpose-

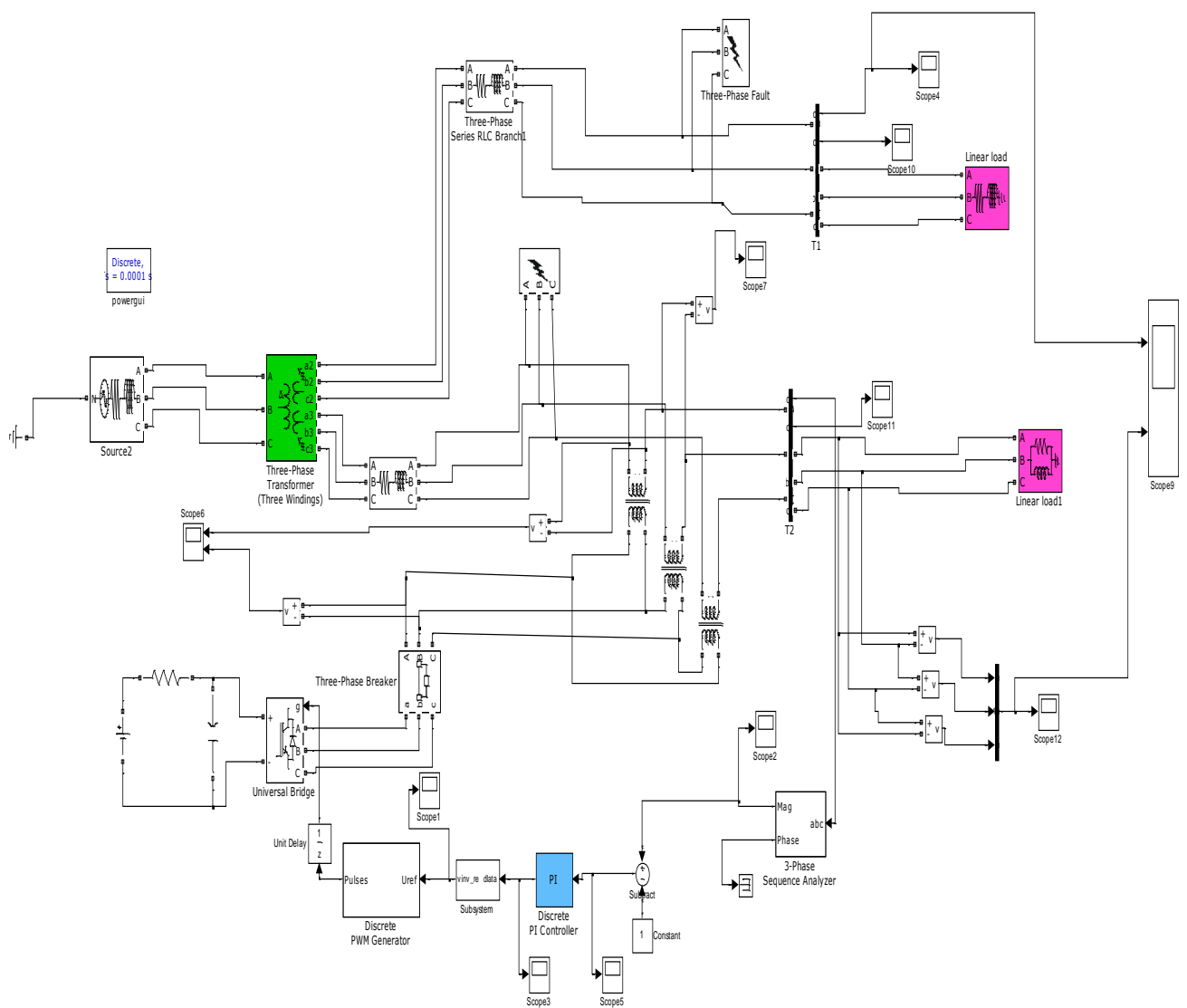


Figure 4.6(a): Simulation Model of DVR Test System

- **FUZZY LOGIC Controller** is used for the control purpose-

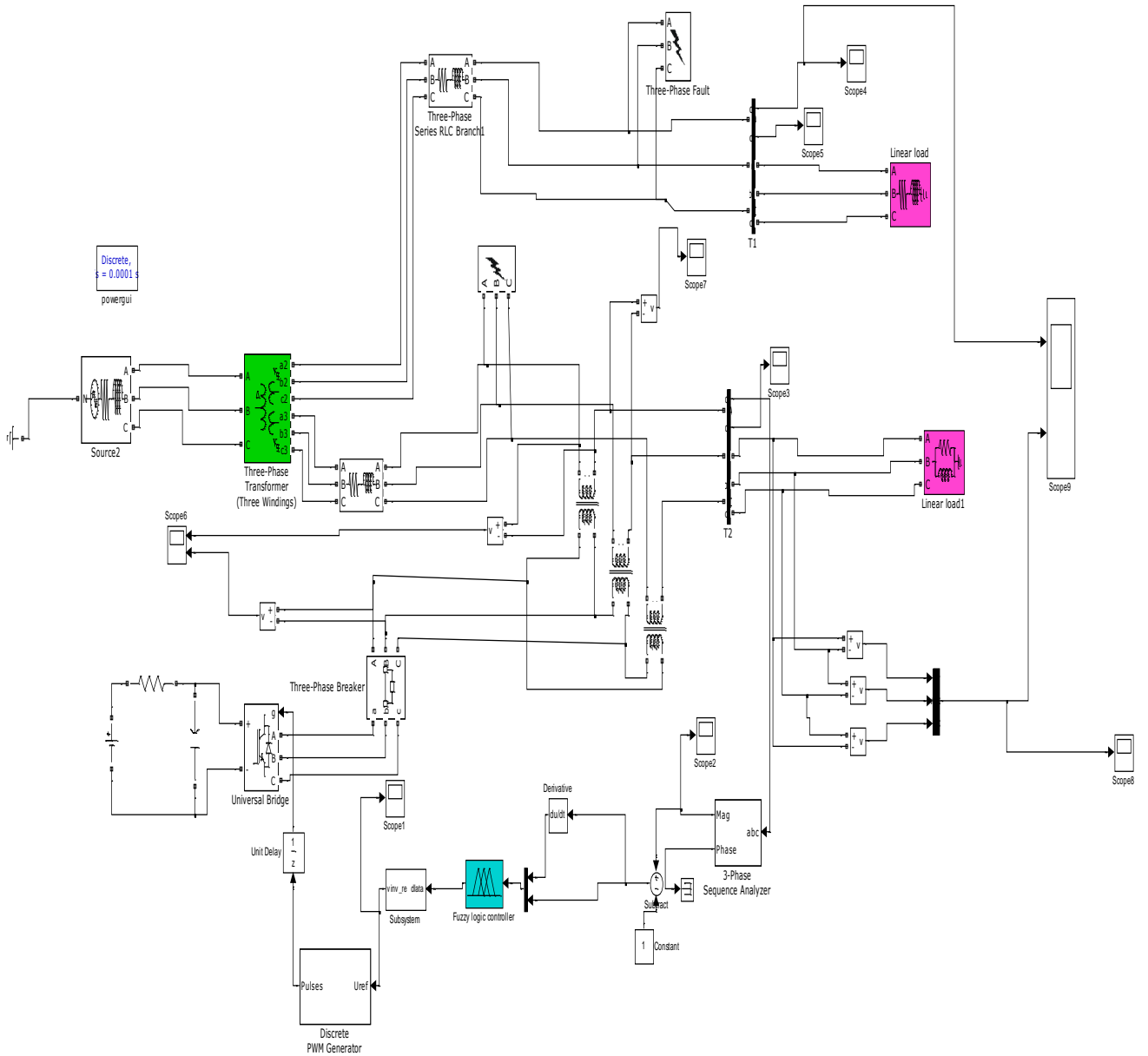


Figure 4.6(b): Simulation Model of DVR Test System

4.4.2 SIMULINK MODEL OF THE TEST SYSTEM WITH NON-LINEAR LOAD

- **PI Controller** is used for the control purpose-

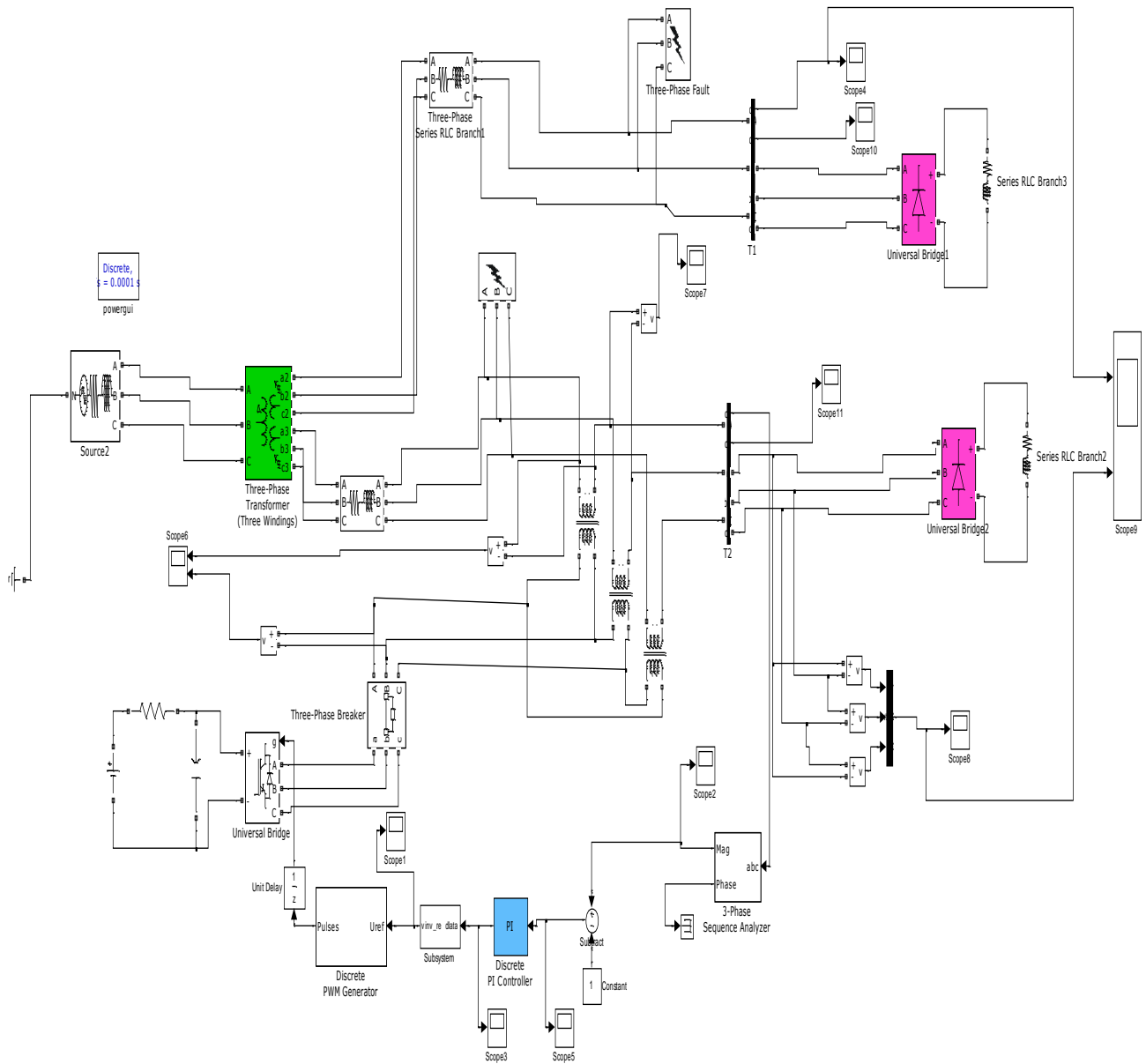


Figure 4.6(c): Simulation Model of DVR Test System

- **FUZZY LOGIC Controller** is used for the control purpose-

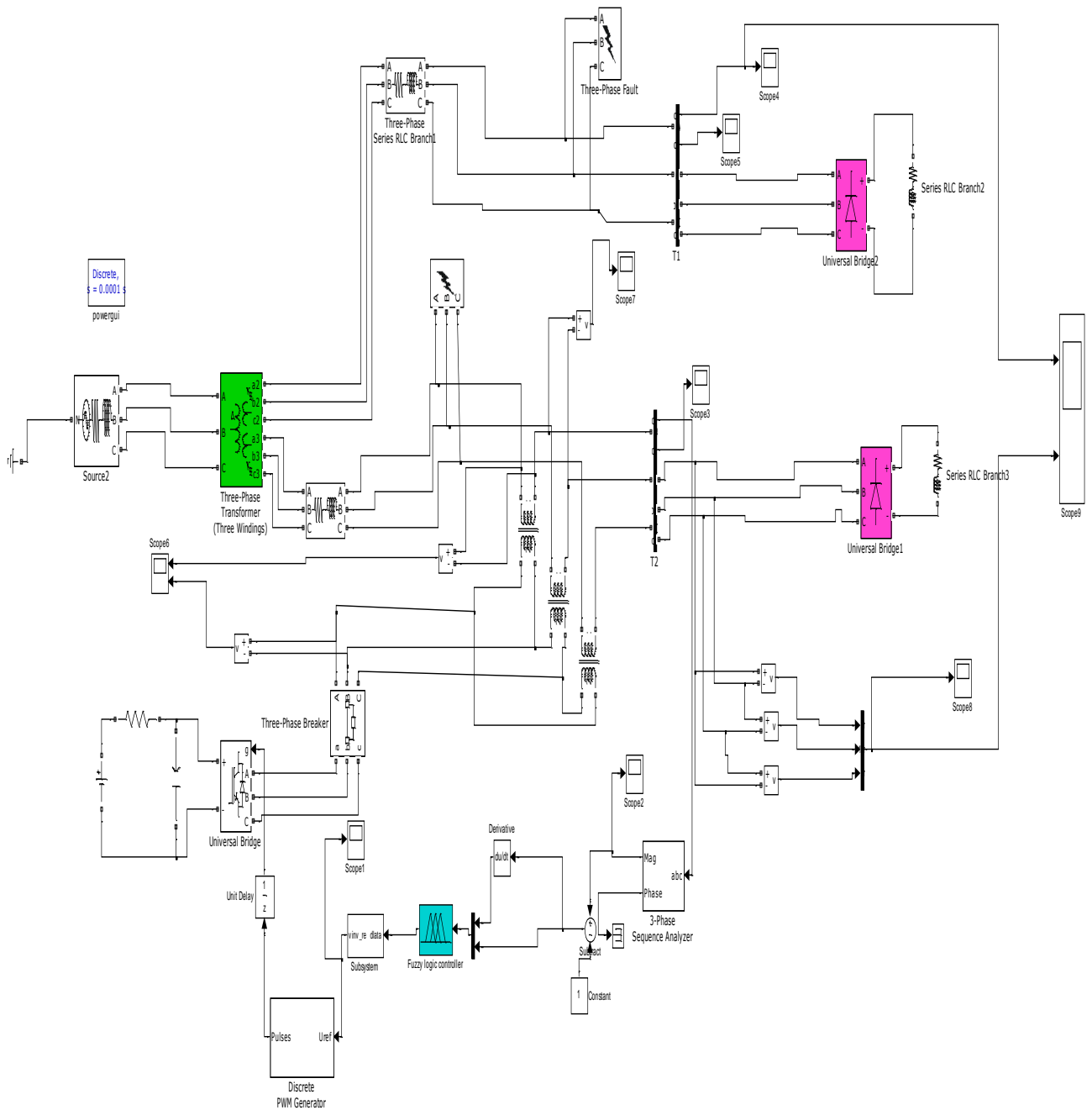


Figure 4.6(d): Simulation Model of DVR Test System

4.4.3 SIMULINK MODEL OF THE TEST SYSTEM WITH FOC INDUCTION MOTOR AS LOAD

- **PI Controller** is used for the control purpose-

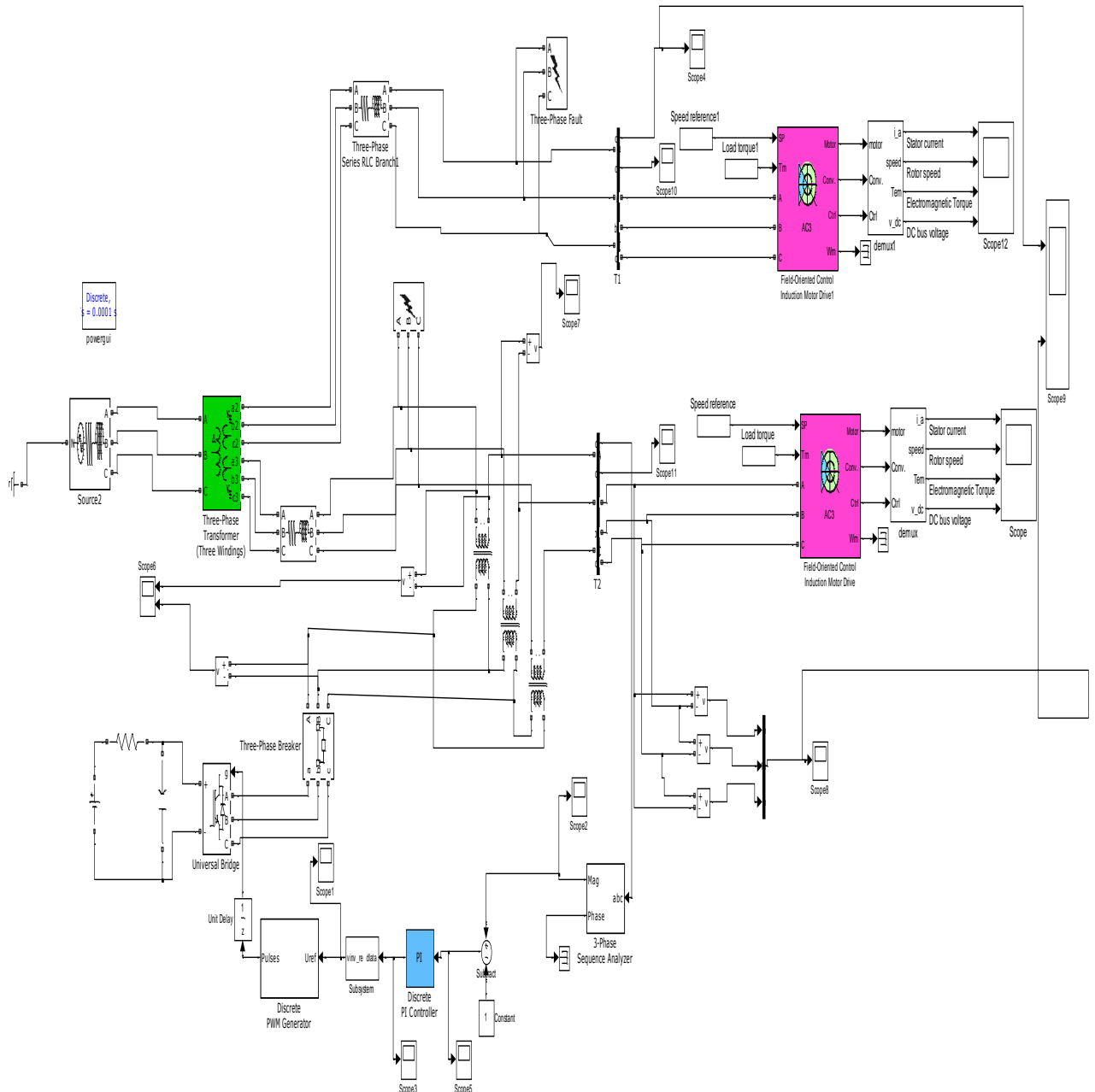


Figure 4.6(e): Simulation Model of DVR Test System

- **FUZZY LOGIC Controller** is used for the control purpose-

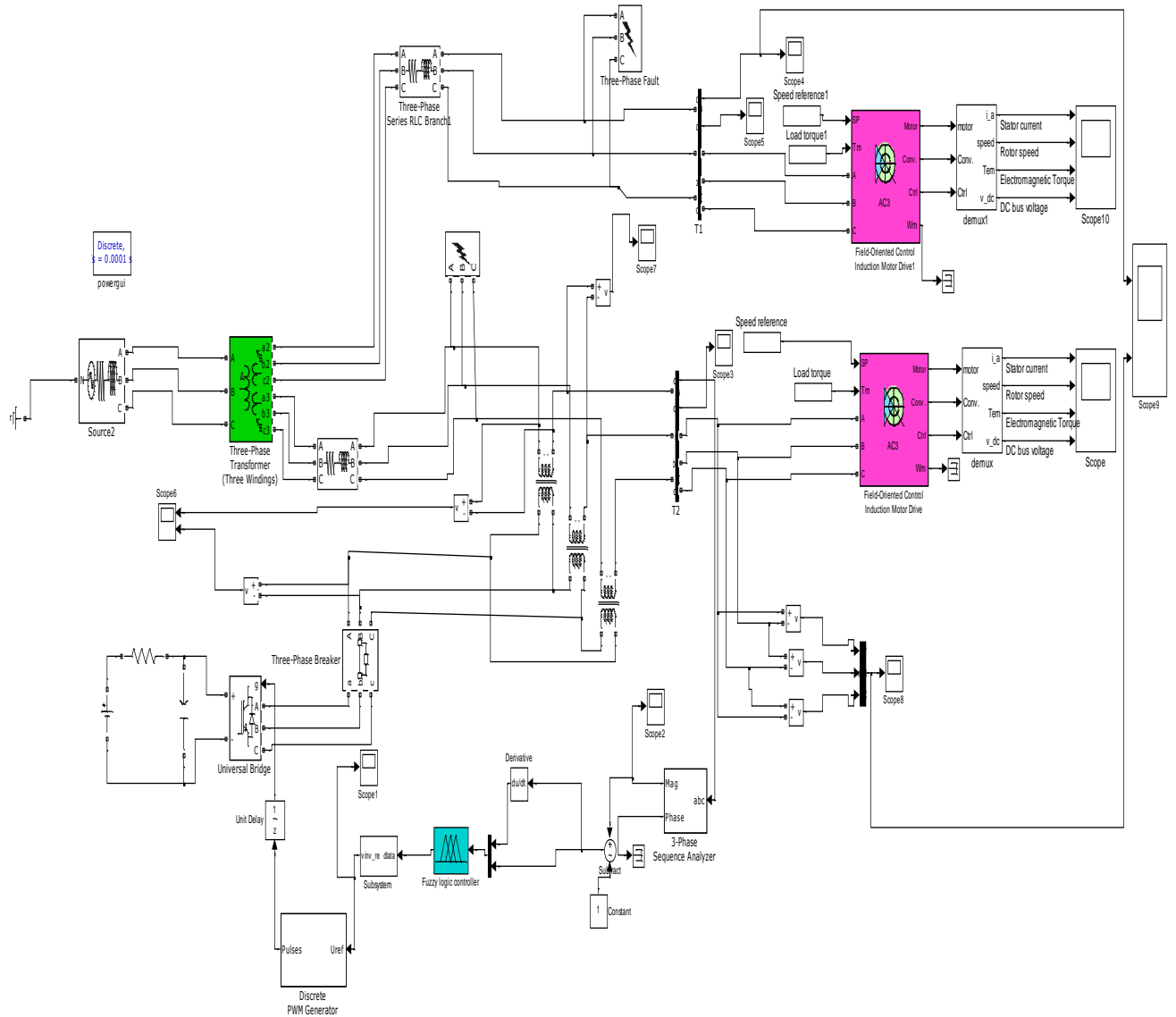


Figure 4.6(f): Simulation Model of DVR Test System

4.5 SIMULATION RESULTS

Here simulations are performed on the DVR test system using MATLAB/SIMULINK. The system performance is analysed for compensate the load voltage in distribution networks under SLG fault condition. Three cases of different load conditions are considered to study the impact of DVR in distribution system. Different cases are listed below:

Case I: Results for Linear load

SLG fault is considered for the test system delivering linear load. Here the fault resistance is 0.001 ohm and the ground resistance is 0.001 ohm. The fault is created for the duration of 0.4s to 0.6s. The output waves for the load voltage without and with compensation are shown in Figure.4.7(a) & Figure.4.7(b) (With PI Controller); Figure.4.7(e) & Figure.4.7(f) (With Fuzzy Controller) and the frequency spectrum with and without compensation is shown in Figure.4.7(c) & Figure.4.7(d) (With PI Controller); Figure.4.7(g) & Figure.4.7(h) (With Fuzzy Controller). Here it is clear from the output wave shapes that the voltage in the phase where fault is created is increasing during the fault duration in the uncompensated feeder. When DVR is connected in the system the unbalancing is reduced.

- **PI Controller** is used for the control purpose-

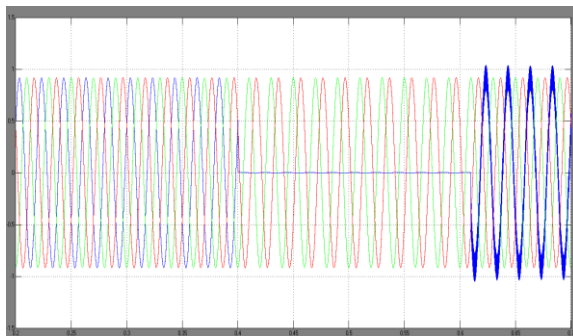


Figure 4.7(a): Output load voltage of SLG Fault without compensation

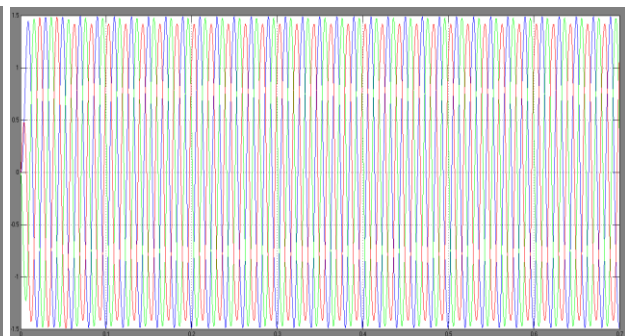


Figure 4.7(b): Output load voltage of SLG Fault with compensation

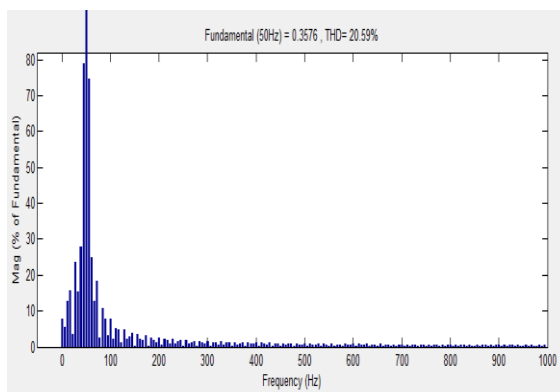


Figure 4.7(c): Frequency Spectrum without compensation

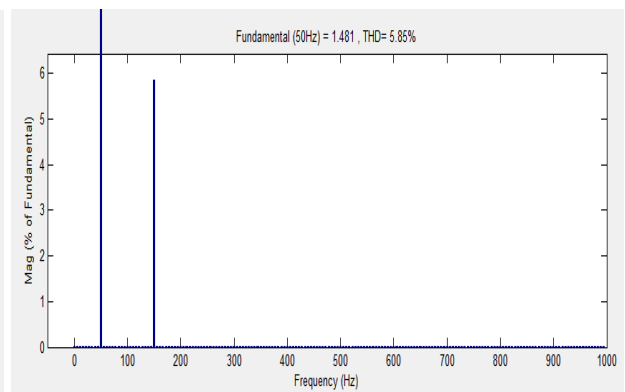
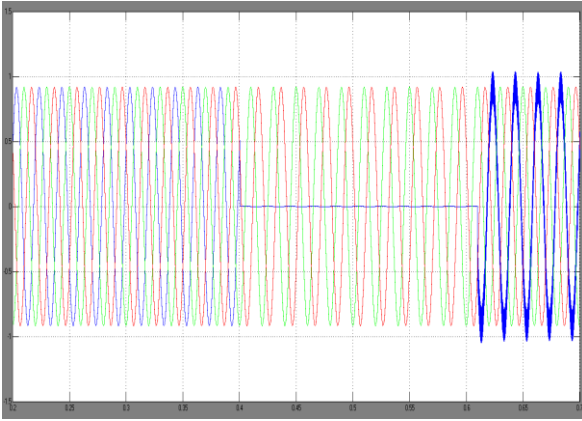
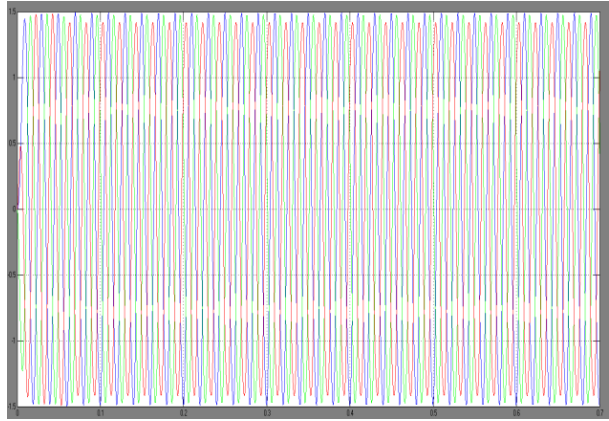


Figure 4.7(d): Frequency Spectrum with compensation

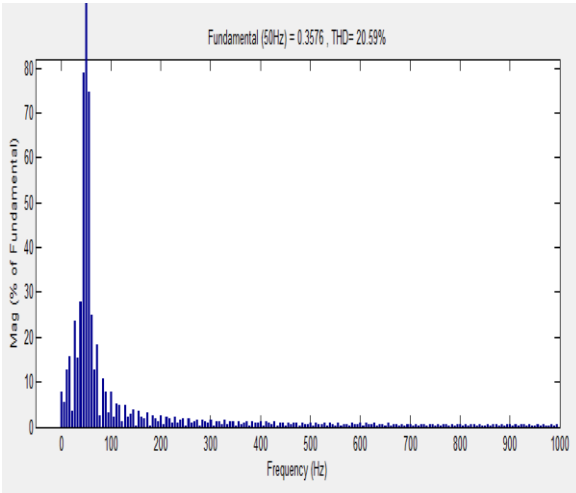
- **Fuzzy Logic Controller** is used for the control purpose-



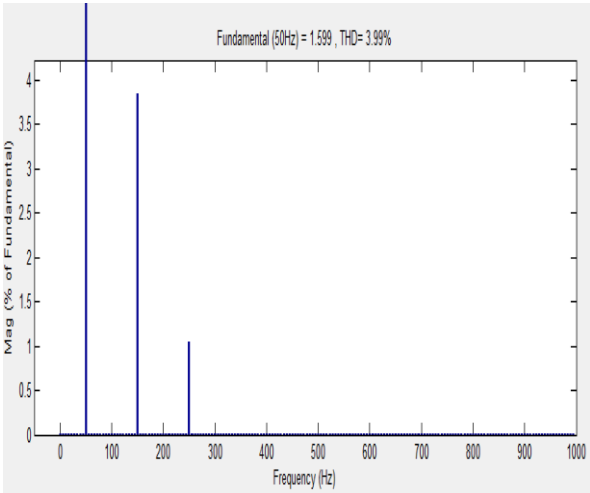
**Figure 4.7(e): Output load voltage of SLG
Fault without compensation**



**Figure 4.7(f): Output load voltage of SLG
Fault with compensation**



**Figure 4.7(g): Frequency Spectrum
without compensation**

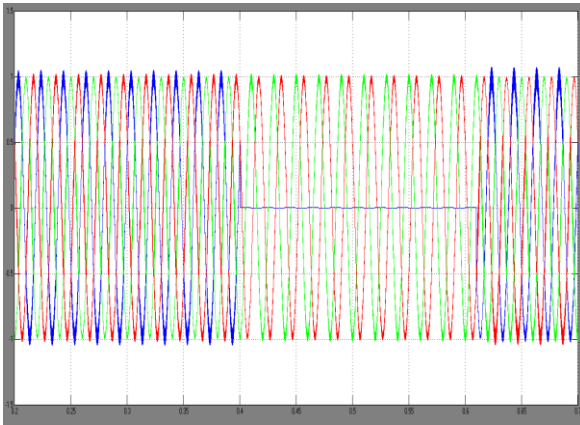


**Figure 4.7(h): Frequency Spectrum
with compensation**

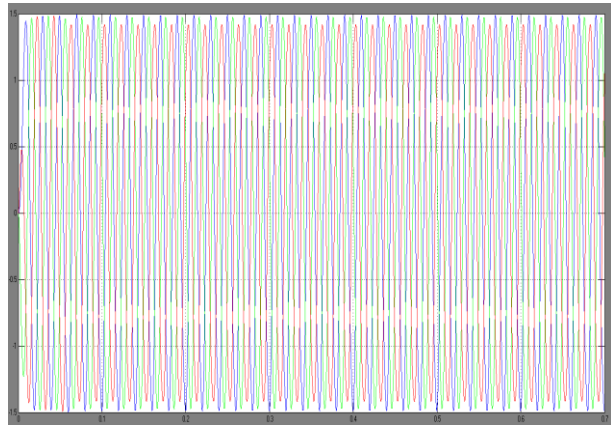
Case II: Results for Non-Linear Load

SLG fault is considered for the test system delivering non-linear load. Here the fault resistance is 0.001 ohm and the ground resistance is 0.001 ohm. The fault is created for the duration of 0.4s to 0.6s. The output waves for the load voltage without and with compensation are shown in Figure.4.8(a) & Figure.4.8(b) (With PI Controller); Figure.4.8(e) & Figure.4.8(f) (With Fuzzy Controller) and the frequency spectrum with and without compensation is shown in Figure.4.8(c) & Figure.4.8(d) (With PI Controller); Figure.4.8(g) & Figure.4.8(h) (With Fuzzy Controller). Here it is clear from the output wave shapes that the voltage in the phase where fault is created is increasing during the fault duration in the uncompensated feeder. When DVR is connected in the system the unbalancing is reduced.

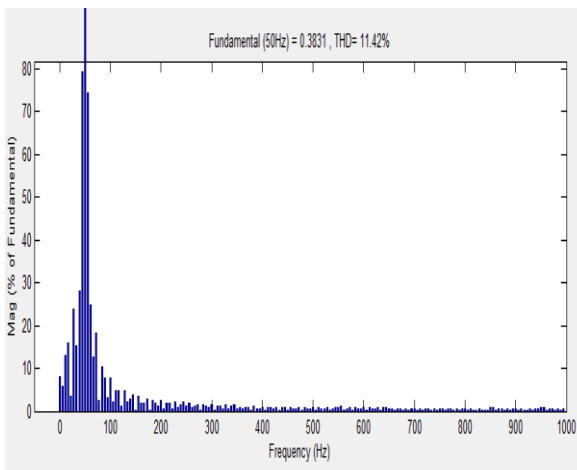
- **PI Controller** is used for the control purpose-



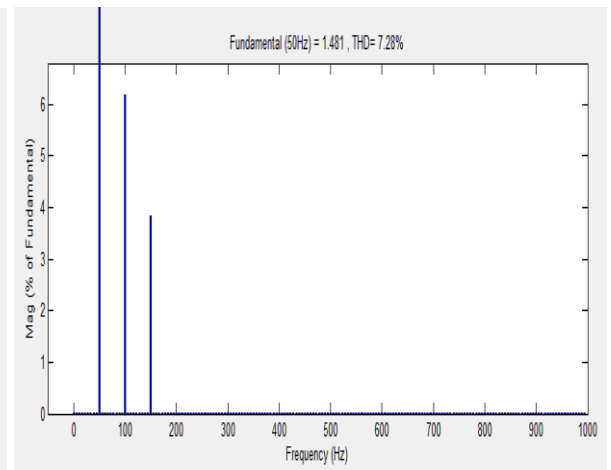
**Figure 4.8(a): Output load voltage of SLG
Fault without compensation**



**Figure 4.8(b): Output load voltage of SLG
Fault with compensation**

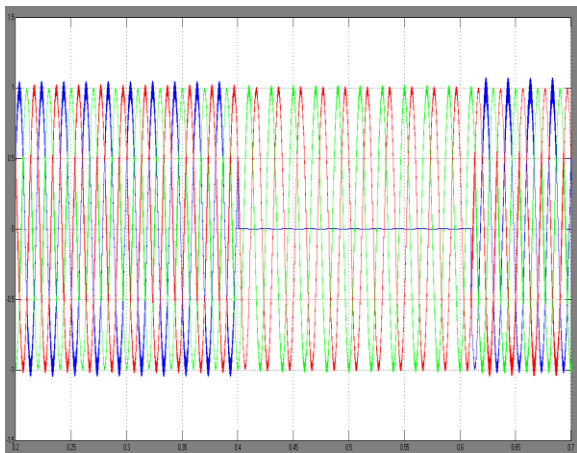


**Figure 4.8(c): Frequency Spectrum
without compensation**

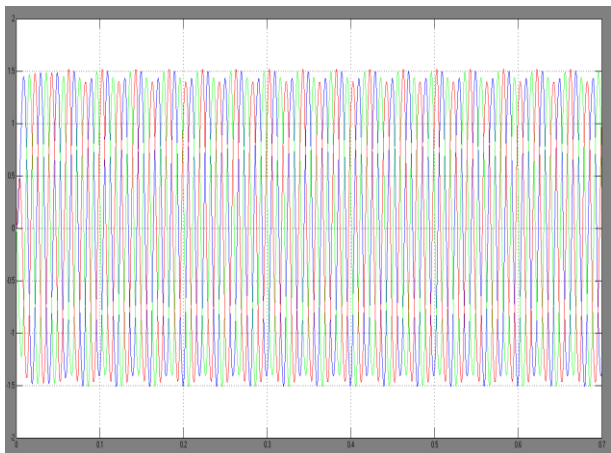


**Figure 4.8(d): Frequency Spectrum
with compensation**

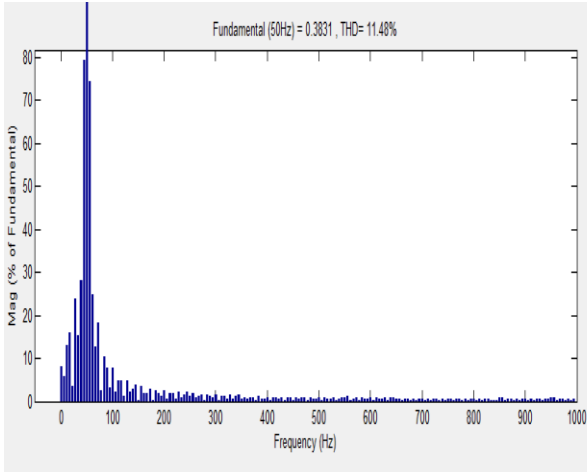
- **Fuzzy Logic Controller** is used for the control purpose-



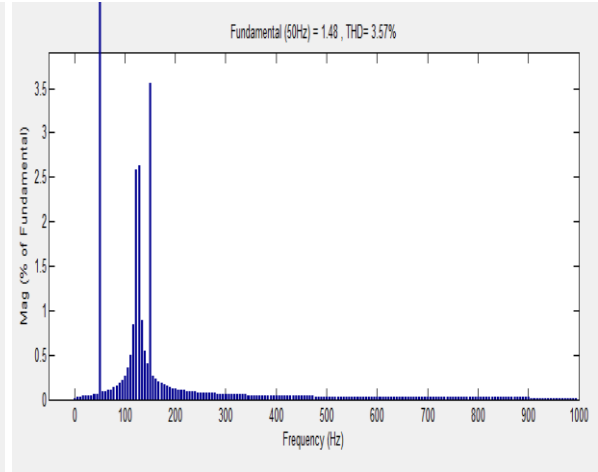
**Figure 4.8(e): Output load voltage of SLG
Fault without compensation**



**Figure 4.8(f): Output load voltage of SLG
Fault with compensation**



**Figure 4.8(g): Frequency Spectrum
without compensation**

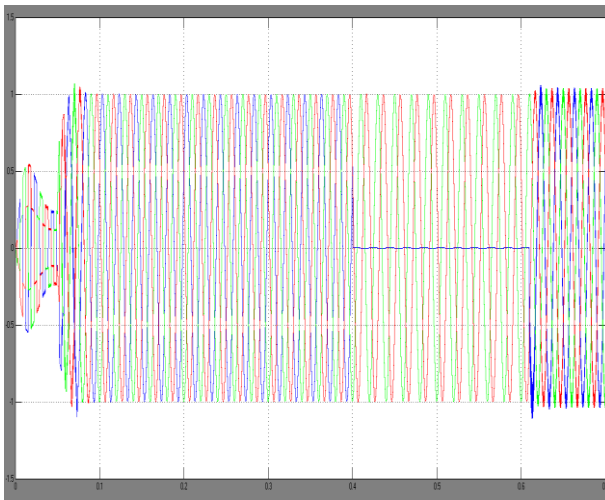


**Figure 4.8(h): Frequency Spectrum
with compensation**

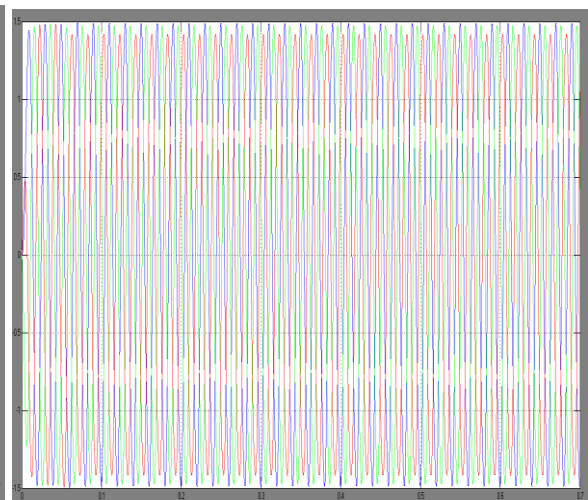
Case III: Results for FOC Induction Motor Drive

SLG fault is considered for the test system delivering induction motor as load. Here the fault resistance is 0.001 ohm and the ground resistance is 0.001 ohm. The fault is created for the duration of 0.4s to 0.6s. The output waves for the load voltage without and with compensation are shown in Figure.4.9(a) & Figure.4.9(b) (With PI Controller); Figure.4.9(e) & Figure.4.9(f) (With Fuzzy Controller) and the frequency spectrum with and without compensation is shown in Figure.4.9(c) & Figure.4.9(d) (With PI Controller); Figure.4.9(g) & Figure.4.9(h) (With Fuzzy Controller). Here it is clear from the output wave shapes that the voltage in the phase where fault is created is increasing during the fault duration in the uncompensated feeder. When DVR is connected in the system the unbalancing is reduced.

- **PI Controller** is used for the control purpose-



**Figure 4.9(a): Output load voltage of SLG
Fault without compensation**



**Figure 4.9(b): Output load voltage of SLG
Fault with compensation**

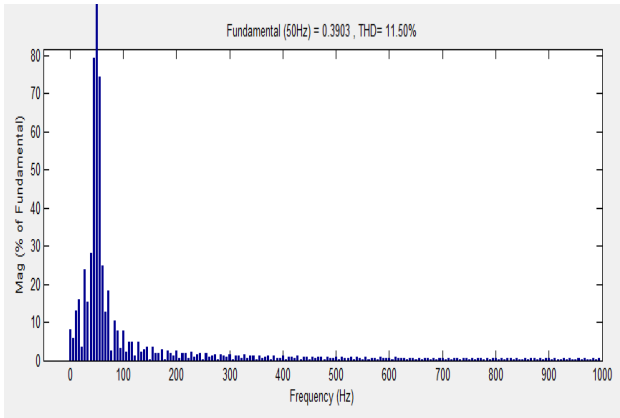


Figure 4.9(c): Frequency Spectrum without compensation

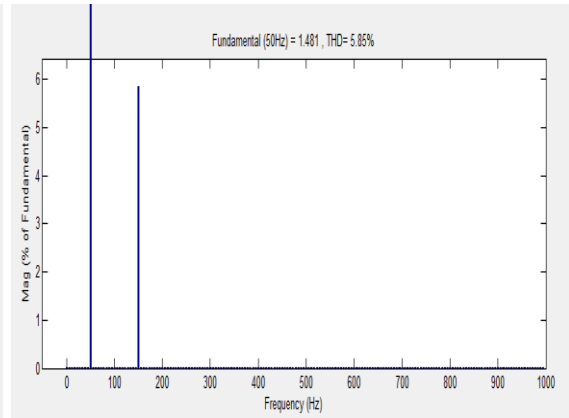


Figure 4.9(d): Frequency Spectrum with compensation

- **Fuzzy Logic Controller** is used for the control purpose-

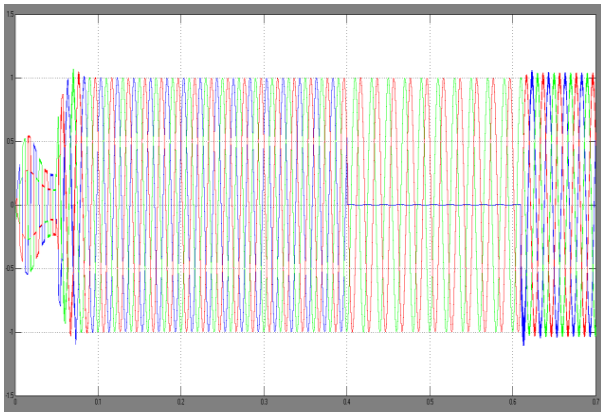


Figure 4.9(e): Output load voltage of SLG Fault without compensation

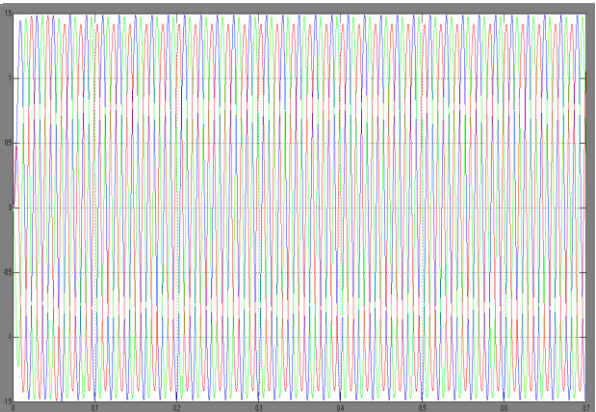


Figure 4.9(f): Output load voltage of SLG Fault with compensation

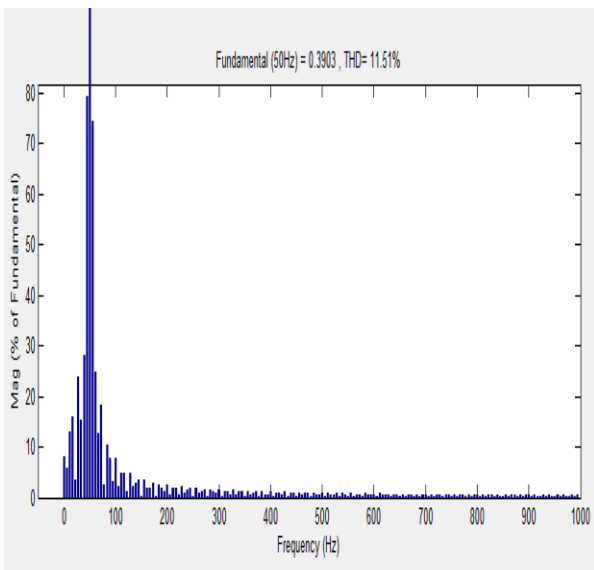


Figure 4.9(g): Frequency Spectrum without compensation

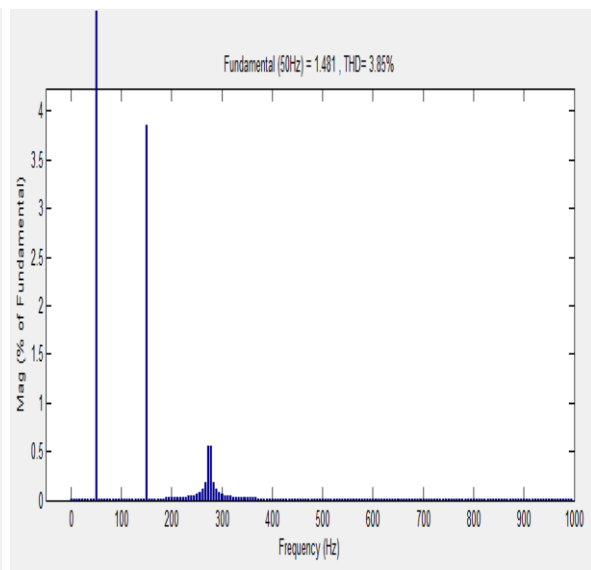


Figure 4.9(h): Frequency Spectrum with compensation

4.6 COMPARISON OF THD LEVELS FOR DIFFERENT TYPES OF LOADS

The Comparison of THD levels for different types of loads under SLG fault condition with or without DVR is shown in table 4.3. It is clear from the THD analysis that DVR effectively removes harmonics from load voltage and makes it smooth.

Table 4.3: THD levels of the test systems

Sr.No.	System Conditions	PI CONTROLLER				FUZZY CONTROLLER			
		Without DVR		With DVR		Without DVR		With DVR	
		LOAD VOLTAGE (fundamental in p.u.)	THD (%)	LOAD VOLTAGE (fundamental in p.u.)	THD (%)	LOAD VOLTAGE (fundamental in p.u.)	THD (%)	LOAD VOLTAGE (fundamental in p.u.)	THD (%)
1.	Linear Load								
	SLG fault	0.3576	20.59	1.481	5.85	0.3576	20.59	1.599	3.99
2.	Non-linear Load								
	SLG fault	0.3831	11.42	1.481	7.28	0.3831	11.48	1.48	3.57
3.	FOC Induction Motor Drive								
	SLG fault	0.3903	11.50	1.481	5.85	0.3903	11.51	1.481	3.85

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1 CONCLUSION

In this dissertation, DVR has been modeled and simulated in MATLAB environment. The performance of DVR has been analyzed for varying linear loads, non-linear loads and FOC induction motor drive. DVR has been found to regulate voltage under varying load condition and load unbalancing. It is clear from comparison of THD analysis for different types of loads under SLG fault condition that DVR reduces harmonics from load voltage very effectively and makes it smooth. Hence, it is concluded that DVR has a huge scope in improving power quality in distribution systems.

5.2 FUTURE SCOPE

In this dissertation, it is shown that DVR can compensate harmonics in voltage. The work can be expanded in the following area:

1. Other advanced controllers adaptive fuzzy controller, ANFIS, SVPWM Technique can be employed with DVR to increase the effectiveness of DVR in distribution networks.
2. Dynamic loads can be considered in future work and then the effect of DVR can be studied.

REFERENCES

1. Woodley N.H., Senior Member, IEEE, Morgan L., Member, IEEE, Sundaram A., Member, IEEE, "Experience with an Inverter-Based Dynamic Voltage Restorer" *IEEE Transaction on Power delivery*, Vol. 14, No. 3, July 1999.
2. Chang C.S., Ho Y.S., "The Influence of Motor Loads on the Voltage Restoration Capability of the Dynamic Voltage Restorer" *PowerCon, International Conference*, Vol. 2, pp. 637-642, 2000.
3. Zhan Changjiang, Ramachandaramurthy Vigna, Arulampalam Atputharajah, Fitzer Chris, Kromlidis Stylianos, Barnes Mike, Jenkins Nicholas, "Dynamic Voltage Restorer Based on Voltage SVPWM Control" *IEEE Transactions on Industry Applications*, Vol. 37, No. 6, Nov-Dec. 2001.
4. Godsk Nielsen John., Blaabjerg Frede, "Control Strategies for Dynamic Voltage Restorer Compensating Voltage Sags with Phase Jump" *Applied Power Electronics Conference and Exposition, IEEE*, Vol. 2, pp. 1267-1273, 2001.
5. Jurado Francisco, Member, IEEE, Manuel Valverde, University of Jaen, "Fuzzy Logic Control of a Dynamic Voltage Restorer" *IEEE-ISIE*, Vol. 2, pp. 1047-1052, 2004.
6. Boonchiaml Paisan, Mithulananthan Nadarajah, Rajamangala University of Technology, Thanyaburi, Thailand, "Detailed Analysis of Load Voltage Compensation for Dynamic Voltage Restorers" *TENCON, IEEE region 10 conference*, pp. 1-4, 2006.
7. Jowder Al. Fawzi, "Modeling and Simulation of Dynamic Voltage Restorer Based on Hysteresis Voltage Control" *33rd Annual Conference of the IEEE Industrial Electronics Society (IECON)*, Nov. 5-8, 2007, Taipei, Taiwan.
8. Kumar Ravi, Nagaraju Siva, J.N.T.U. College of Engineering, Kakinada, A.P, India, "Simulation of D-STATCOM and DVR in Power" *APRN Journal of Engineering and Applied Sciences*, ISSN 1819-6608, Vol. 2, No. 3, June 2007.
9. Ashari M., Hiyama T., Pujiantara M., Suryoatmojo H., Purnomo M.H., "A Novel Dynamic Voltage Restorer with Outage Handling Capability Using Fuzzy Logic Controller" *Innovative Computing, Information and Control*, pp.51, 5-7 Sept. 2007.
10. Margo P., Heri P.M., Ashari M., Hendrik M., Hiyama T., "Compensation of Balanced and Unbalanced Voltage Sags using DVR Based on Fuzzy Polar Controller"

International Journal of Applied Engineering Research, ISSN 0973-4562, Vol. 3, No. 3, pp. 879-890, 2008.

11. JayaPrakash P., Member, IEEE, Singh bhim, Senior Member, IEEE, Kothari D.P., Senior Member, IEEE, Chandra Ambrish, Senior Member, IEEE, Al-Haddad Kamal, Fellow, IEEE, "Control of Reduced Rating DVR with Battery ESS" *IEEE*, 2008.
12. Chellali Benachaiba, Brahim Ferdi, "Voltage Quality Improvement Using DVR" *Electrical Power Quality and Utilisation*, Vol. 14, No. 1, pp. 39-46, 2008.
13. Pal Yash, Swarup A., Senior Member, IEEE, Singh Bhim, Senior Member, IEEE "A Review of Compensating Type Custom Power Devices for Power Quality Improvement" *IEEE Power India Conference*, pp. 1-8, 2008.
14. El. Shennawy Tarek, El-Kamar Wady, El-Gammal Mahmoud, Abou-Ghazala Amr, Monem Moussa Abdel, Electrical Power Engineering Dept., Faculty of Engineering, Alexandria University, Egypt, "Mitigation of Voltage Sags in a Refinery with Induction Motors Using DVR" *European Journal of Scientific Research*, ISSN 1450-216X, Vol. 36, No, 1, pp. 118-131, 2009.
15. Ezoji H., Sheikholeslami A., Tabasi., Saeednia M.M., Electrical & Computer Engineering Department, Babol University of Technology, "Mitigation of DVR Using Hysteresis Voltage Control" *European Journal of Scientific Research*, ISSN 1450-216X, Vol. 27, No, 1, pp. 152-166, 2009.
16. Ferdi B., Dib S., Dehini R., University of Bechar, Algeria "Adaptive PI Control of Dynamic Voltage Restorer Using Fuzzy Logic" *Journal of Electrical Engineering: Theory and Application* Vol.1, pp. 165-173, 2010.
17. Katole D.N., Research scholar: Department of Electrical Engg, G.H. Rasoni College of engineering, Nagpur, Maharashtra, India, "Analysis and Mitigation of Balanced Voltage Sag with the Help of Energy Storage System" *ICETET*, pp. 317-321, 2010.
18. Teke A., Bayindir K., Tumay M., Department of Electrical and Electronics Engineering, Cukurova University, Adana, Turkey, "Fast sag/swell detection method for fuzzy logic controlled dynamic voltage restorer" *generation transmission and distribution IET*, Vol. 4, pp. 1-12, 2010.
19. Gupta Sunil, "Dynamic Voltage Restorer against Voltage Sag" *International Journal of Innovation, Management and Technology*, Vol. 1, No. 3, pp. 232-237, 2010.
20. Omar Rosli, Rahim N.A., Sulaiman Marizad, "Dynamic Voltage Restorer Application for Power Quality Improvement in Electrical Distribution System: An Overview" *Australian Journal of Basic and Applied Sciences*, pp. 379-396, 2011.

21. Md.Azim Riyasat, Md.Hoque Ashraful, Dept. of EEE, Islamic University of Technology, Boardbazar, Gazipur, Bangladesh, "A Fuzzy Logic Based DVR for Voltage Sag and Swell Mitigation for Industrial Induction Motor Loads" *International Journal of Computer Applications*, Vol. 30, No. 8, Sept- 2011.
22. Chawla Puneet, Khanna Rintu, Singh Abinash, "Fuzzy Logic Control for DVR to Counter Voltage Sag on a Distribution Network" *Proceedings of the World Congress on Engineering, London*, Vol. 2, July 2011.
23. Khanh Q. Bach, Lian, J., Ramachandran, B., Srivastava, S., Cartes, D., "Mitigating Voltage Sags due to DOL Starting of Three Phase Asynchronous Motors using Dynamic Voltage Restorer" *IEEE*, 2011.
24. Kanakaraj M., Thirukkovai S., "Voltage Sag/Swell Compensation using Fuel Cell Fed Inverter Based Dynamic Voltage Restorer" *Advances in Engineering, Science and Management (ICAESM), International Conference*, pp.176,182, 30-31 March 2012.
25. Jain Sandesh, Thakur Shivendra, Phulambrikar S.P., "Fuzzy Controller Based DVR to Mitigate Power Quality and reduce the Harmonics Distortion of Sensitive Load" *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, Vol. 1, Issue 5, pp. 351-361.
26. Tiwari H.P., Kumar Gupta Sunil, Pachar Ramesh, "Study of Major Issues and Their Impact on DVR System Performance" *International Journal of Computer and Electrical Engineering*, Vol. 2, No. 1, February, 2010.
27. Fuchs Ewald, Md.Masoum A.S., "Power Quality in Power Systems and Electrical Machines" *Elsevier Academic Press*, 2008.
28. Md.Shazly A., Cerrada Aurelio G., A.Abdel-Moamen M., Hasanin B., "Dynamic Voltage Restorer (DVR) System for Compensation of Voltage Sags, State-of-the-Art Review" *International Journal of Computational Engineering Research*, Vol. 3, Issue.1, pp. 177- 183, 2013.
29. De Almeida A., Moreira L., Delgado J., "Power Quality Problem and New Solutions" *International Conference on Renewable Energies and Power Quality*, Vigo, Spain, Vol. 1, 2003.
30. Omar Rosli, Rahim N.A., "Implementation and Control of a Dynamic Voltage Restorer Using Space Vector Pulse Width Modulation (SVPWM) for Voltage Sag Mitigation" *International Conference for Technical Postgraduates (TECHPOS)*, pp. 1-6, 2009.

PUBLICATIONS

- ‘PI and Fuzzy Controller based DVR to mitigate power quality and reduce the harmonics distortion of linear and non- linear loads’- accepted in CONVENER-ICACCT 2013, IEEE Sponsored Conference in APIIT, PANIPAT, HARYANA.
- ‘PI and Fuzzy Controller based DVR to mitigate power quality and reduce the harmonics distortion of Induction Motor as load’- Published in IJAR (INTERNATIONAL JOURNAL OF ADVANCED RESEARCH), Volume 1, Issue 7, 197-201, October 2013 edition with IMPACT FACTOR- 1.659.