# A Study on Voltage Profile Enhancement of Smart Distribution Networks Using Dynamic Voltage Restorer (DVR)

**By**

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**Supervised by**

**Dr. Majid Ali**

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**Engr. Akif Zia Khan**

**A Thesis Submitted to the**

**U.S Pakistan Center for Advanced Studies in Energy in partial fulfillment of the requirements for the degree of**

**MASTERS of SCIENCE in**

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## THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by Mr. Ehsan ur Rehman, Registration No. NUST201361513MCES64113F, of U.S Pakistan Center for Advanced Studies in Energy has been vetted by undersigned, found complete in all respects as per NUST Statues/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

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Name of Supervisor Dr. Majid Ali

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Signature (HoD): ________________________

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# Certificate

This is to certify that work in this thesis has been carried out by **Mr. Ehsan ur Rehman** and completed under my supervision in solar thermal laboratory, U.S Pakistan Center for Advanced Studies in Energy, National University of Sciences and Technology, H-12, Islamabad, Pakistan.

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# Dedication

This Thesis is dedicated to:

The Almighty Allah, our Creator and our Master,

Prophet Muhammad (PBUH), who taught us the purpose of life,

My great parents and family who have been there for me through every hardship

My supervisor & co-supervisor who always encouraged and supported me.

Every Person that has influenced me to be what I am today

# Abstract

The world is witnessing a transition from its present centralized generation paradigm to a future with increased share of distributed generation (DG). Integration of renewable energy sources (RES) based distributed generators is a solution to decrease reliance on depleting fossil fuel reserves, increase energy security and provide an environment friendly solution to growing power demand. Major technical issues associated with DG integration are the impact on voltage regulation, harmonics, protection co-ordination, reactive power management, predictability of power output with RES based DGs. With the increasing usage of sophisticated sensitive electronic equipment in industrial, residential and commercial sectors, it is important to protect them from any power quality disturbance to avoid equipment damage and malfunction leading to economic loss for the customer. According to Leonardo Energy statistics the financial losses due to poor power quality amount to total of 150 billion Euros annually in the EU-25. The objectives of this research are to focus on the voltage stability problem in power system with DG integration keeping the harmonic content within the limits. DVR being one of the most effective series compensation utility for voltage regulation is used to reduce the overall harmonic content and better Voltage stability in medium level distribution system. DQ0 and Fuzzy Logic controller (FLC) based DVR are used in the power system to compensate for power quality issues like voltage sags/swells of several types. The DQ0 based DVR could restore the voltage levels to more than 93 % of the reference voltage when the system is subjected to 30% voltage sags whereas the FLC based DVR compensated for more than 96% of the reference voltage. The Harmonic content injected by both DVRs in power system is less than 5% which is the standard requirement for grid integration. The obtained results prove that FLC based DVR is more effective in compensating voltage sags of balanced and unbalanced nature with less number of harmonics injected in the medium level voltage distribution network

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- “**Voltage profile improvement in medium level voltage network by DQ0 and Fuzzy Logic Dynamic Voltage Restorer using low DC voltage source** “by Ehsan ur Rehman, Akif Zia Khan & Majid Ali. Under Review in IETE Journal of Research. Print ISSN: 0377-2063 Online ISSN: 0974-780X

- “**Advances in the Control & Energy Storage systems for Dynamic Voltage Restorer (DVR): An Overview “**By Ehsan ur Rehman, Akif Zia Khan, Majid Ali & Awais Hashmi. Accepted in **International Journal of Scientific and Engineering Research** (IJSER) - **(ISSN 2229-5518).**

# List of Abbreviations

Renewable Energy System (RES)

Dynamic Voltage Regulators (DVR)

Direct-Quadrature Zero (DQ0)

Grid Connected Inverter (GCI)

Institute of Electrical and Electronics Engineers (IEEE)

Root-Mean-Square (RMS)

Proportional Integral (PI)

Fuzzy Logic Controllers (FLC)

Photo Voltaic (PV)

Total Harmonic Distortion (THD)

Point of Common Coupling (PCC)

Fast Fourier Transform (FFT)

Static Synchronous Compensator (STATCOM)

Proportional Integral Derivative (PID)

Unified Power Quality Conditioners (UPQC)

Computer Business Equipment Manufacturers Association (CBEMA)

Information Technology Industry Council (ITIC)

# Chapter 1

# Introduction

## 1.1.Motivation & System Description

Modern Power Systems are moving towards the direction of Smart Grids that rely heavily on the active sources of generation embedded within the power system close to the utilizing units. The modern power system includes a substantial portion of industrial, residential and commercial sector that are using sophisticated sensitive electronic equipment and distributed generation. The introduction of sophisticated sensitive electronic equipment in power system and the integration of distributed generation, though considered very important for the future of the grid, raises the issue of continual service of superior quality power to avoid any damage to the equipment leading to economic loss for the consumer[1]. The demand for greater quality and reliability of power supply in distribution networks in modern times is higher than ever before because of sophisticated manufacturing systems, industrial drives and precision electronic equipment. The first sign that the quality of power is affected is when the voltage waveform diverges from the sinusoidal waveform or there is a change in amplitude from a standard level that the power source must provide to the utility and this disturbance from the normal operation can be of few milliseconds up to hours resulting in millions of dollars' worth of damages annually to the consumers. Improving the voltage profile along the power network is of main importance for Quality of power. Several researches have been made over the years to better the voltage profile along the power network.

## 1.2.Power Quality

In ideal case scenario, the Distribution system should be providing its consumer with a continuous supply of power at even sinusoidal voltage at desired magnitude level and frequency. But as it happens, due to the interconnection of a lot of generating station and load centers which contain many nonlinear loads, the waveform of the voltage is disrupted which creates a lot of power quality problems in current power systems. The major concern for the customers are the reliability and quality of power at the load centers. The more the sophisticated electronic devices are used in the power system, more severe this issue becomes of the power Quality. Some system events also contribute power quality problems like capacitor switching, starting of motors and faults. Any disruption in the power quality results in immediate interruption in the operation of many sensitive devices, and in some cases, cause physical damage to the devices resulting in huge losses. A few examples of sensitive loads in our households and industries today are computers, programmable logic controllers (PLC), variable speed drives (VSD) etc. Power Quality is defined in IEEE standard 1100 as "the concept of powering and grounding sensitive electronic equipment in a manner that is suitable to the operation of that equipment". The parameters on which power quality is assessed are

- fluctuations in voltage magnitude
- Harmonic content in waveform for AC power
- Transient voltages and currents
- Continuity of service

Power Quality issues generally encompass the problems such as flicker, harmonics distortion, voltage sags/swells, impulse transient and interruptions. Voltage sags and swells are the commonly occurring quality problems in the power distribution systems.

### 1.2.1. Power Quality Issues

#### 1.2.1.1. Voltage Sags/ Dips

Voltage Dips are defined by International Electro-technical Commission (IEC) as "*a sudden reduction of the supply voltage at the power frequency to a value between the ranges of 10% to 90% of the nominal voltage followed by a voltage recovery after a short duration usually from 10 milliseconds up to a minute*"[2]

The duration of voltage sag depends upon the type of the fault, where the fault is located in the system and how soon the protection devices can clear that fall out. The duration of voltage sags can be short but sensitive devices in the system like PLCs may malfunction and cause losses in production leading to financial losses. In industries, it can cause a total shutdown and recovery can take from hours to sometimes even days. 20% of the world's electrical load is lightning load which is sensitive to voltage dips[3].

**Table 1.1: Voltage disturbance characteristics defined by IEEE**

| Disturbance Type | Typical Voltage Magnitude | Typical Duration |
|---|---|---|
| **Sag** | 0.1-0.9 pu | 0.5-30 cycles |
| **Swell** | 1.1-1.8 pu | 0.5-30 cycles |
| **Flicker** | 0-1% | Steady State |
| **Interruption** | <0.1pu | 0.5 cycles |
| **Imbalance** | 0.5-3% | Steady State |
| **Harmonics** | 5% | Steady State |

Causes of Voltage sags & dips are

- Distance of the location from the power source
- Unbalanced load in the three-phase system
- Turning off/on of heavy loads in the power system
- Extended detachment from a distribution transformer with interjected loads
- Defective grid operation.
- Use of unsuitable equipment for local supply

#### 1.2.1.2. Voltage Swell

According to the IEEE 1159-1995 the voltage swell is the increase in the rms voltage level to 110%-180% of nominal, at the power frequency for durations of ½ 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 [4]. The sources of voltage swell in power systems can be due to several reasons. It can be in healthy feeder because of a single line to ground fault, disconnection of a large load or energization of a large capacitor bank. The harshness of the voltage swell is depending upon the fault location, system impedance and grounding. Accompanying Voltage sags and swells, there can be a change in the phase angle and this phenomenon is called phase angle jump.

#### 1.2.1.3. Voltage Interruption

Voltage interruption is a significant reduction in rms voltage to less than small percentile of the nominal voltage, or a complete loss of voltage. The cause can be any faults, components malfunctioning of scheduled power shut down for maintenance purposes.

#### 1.2.1.4. Voltage Fluctuations & flickers

The voltage fluctuations in the power network can be because of both the load and the generators connected. Operation of electrical devices with a fluctuating load such as controlled converters, welding machines sets, electrical resistors, arc furnaces, all consumers with pulse consumption, large load switching or asynchronous generator in wind power plants can be a cause of voltage fluctuations in the system resulting in voltage variation at the consumption side[1].

#### 1.2.1.5. Waveform distortion

Waveform distortion is phenomenon when the load voltage waveform deviates from the steady state ideal sine wave of power frequency. The several types of waveform distortion are harmonics, notching and noise discussed below

#### 1.2.1.6. Harmonics

Harmonics are sinusoidal waves of voltage and currents with integer multiple of fundamental power frequency and one of the most occurring power quality problem that causes added pressure to other devices connected to the electrical system[5]. Many industrial and commercial loads such as power converters, fluorescent lamps, computers, light dimmers and variable speed motor drives used in conjunction with industrial pumps fans, compressors and also in air conditioning equipment are non-linear in nature and have made the harmonic distortion a common occurrence[6][7]. In three phase power systems, we only have to cope with the odd harmonics problem, especially the third harmonic which is a particular problem in large power systems, as the even harmonics cancel each other out. IEEE-519 Standard informs us about the limitations of the current and voltage harmonics that can have a undesirable effect on the power system and its equipment[8]. There are several harmonic standards and engineering practices and commendations in the form of IEC 1000-3-2, AS 2279, D.A.CH.CZ, EN 61000-3-2/EN 61000-3-12, and ER G5/4 (UK) that allow individual voltage harmonics, especially5th and $7^{th}$ to be up to 3% in the voltage level of 6.6kV, 11kV and 20 kV

- Effects

The harmonics that are introduced in the power system through DGs might have negative effects on the power system's and its apparatus's operation and in a way, are alike to the effects of stress and high blood pressure on the human body. Some are listed below[9][10][11][12], [13]

1. Overloading of neutrals, insulation failure
2. Reduction of life time of capacitors
3. Capacitors and motors overloading that causes their failure
4. Ripple control receivers malfunctioning
5. Increased iron and copper losses or eddy currents, overheating the transformers and wiring of power system
6. Skin effect on undersized conductors
7. Torque and speed ripple of induction motor
8. Reliability issues due to vibration, torque pulsation and mechanical fatigue
9. Overs stressing of power factor improving capacitors
10. Nuisance tripping of circuit breakers, damaging or blowing components for no apparent reason
11. Larger RMS voltage drops in the lines
12. Negative effect on arc extinction
13. Faulty utility meter reading causing higher billing to consumers
14. Failure of Commutation circuits founds in DC drives and AC drives with SCRs
15. Increase in switching losses of semiconductor switches

#### 1.2.1.7. Notching

Notching arises because of the regular operation of the power electronic devices. It's a periodic voltage disturbance when the current through the power electronic devices is commuted from one phase to another.

#### 1.2.1.8. 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.

## 1.3.Causes of transients & Spikes

- Lightning
- Arc welding
- Switching on heavy or reactive equipment such as motors transformer, motor drives
- Electric grade switching

## 1.4.Standards associated with Voltage Sag

IEEE, IEC, CBEMA and SEMI have all standards associated with Voltage sag that are in use in the industry. All the power system components and the systems should meet the requirement of these standards as a reference for their performance. Both the manufacturers and the Buyers need to comply with the standards in manufacturing and the usage of the devices and systems for overall system reliability. Computer Business Equipment Manufacturers Association (CBEMA) curve gives the duration and severity of voltage variations that can be tolerated by the data process equipment .CBEMA along with Information Technology Industry Council (ITIC) are the commonly used voltage-tolerance curves of the sensitive devices[14].

**Table 1.2: IEEE & SEMI Standards**

| | | |
|---|---|---|
| ***IEEE Standards*** | | |
| ***1)*** | **IEEE 446-1995** | "IEEE recommended practice for emergency and standby power systems for industrial and commercial applications range of sensibility loads" |
| ***2)*** | **IEEE 493-1990** | "Recommended practice for the design of reliable industrial and commercial power systems" |
| ***3)*** | **IEEE 1100-1999,** | "IEEE recommended practice for powering and grounding Electronic equipment" |
| ***4)*** | **IEEE 1159-1995** | "IEEE recommended practice for monitoring electric power quality" |
| ***5)*** | **IEEE 1250-1995** | "IEEE guide for service to equipment sensitive to momentary voltage disturbances" |
| ***SEMI Standards*** | | |

| | | |
|---|---|---|
| *1)* | **SEMI F47-0200** | "Specification for semiconductor processing equipment voltage sag immunity" |
| *2)* | **SEMI F42-0999,** | "Test method for semiconductor processing equipment voltage sag immunity" |

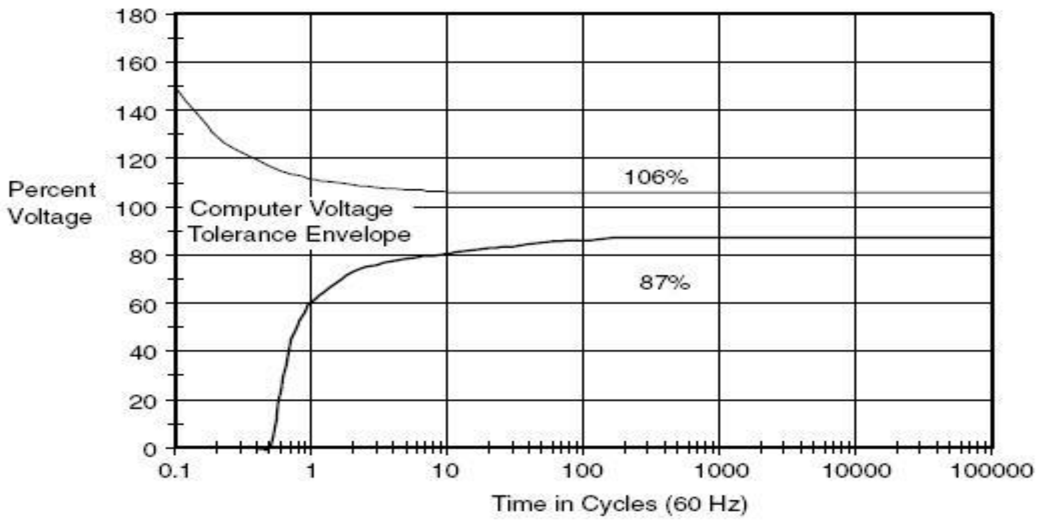


**Figure 1.1: CBEMA Curve**

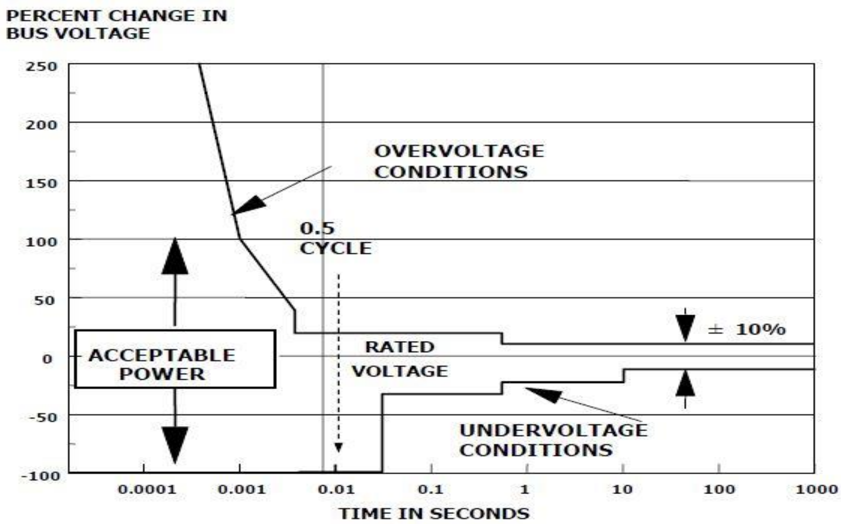


**Figure 1.2: The ITIC Curve**

## 1.5.Dynamic Voltage restorer

The power Quality issues discussed above need to be resolved as the economic consequences related to the equipment and systems due to power quality are of significance importance for the consumers. Dynamic Voltage Restorer is a power electronics device capable of regulating the load voltage at its predetermined voltage level with minimum voltage injection and is recently being used as one of the prominent method for the vigorous answer for voltage sag/swell vindication in modern industrial applications.

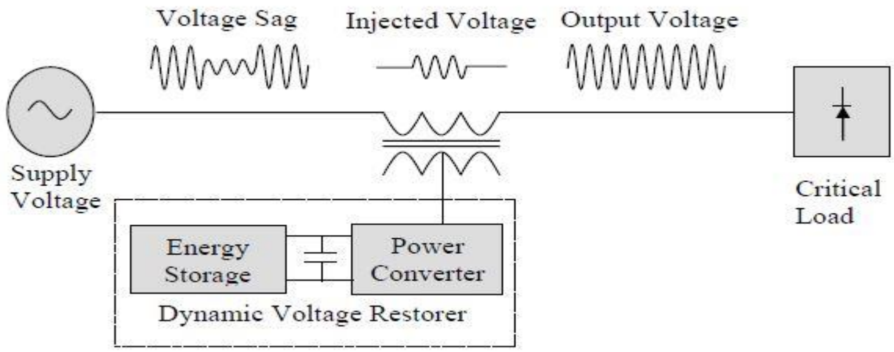


**Figure 1.3: Block diagram of DVR**

In this dissertation, a new configuration of Dynamic Voltage Restorer with DQ0 controller and Fuzzy logic controller (FLC) are used which are capable of compensating power quality problems associated with Voltage sags/swells and harmonics at the medium voltage distribution system level. The modelling and simulation of DVR

## 1.6.Research objectives

The main objectives of this research work could be following:

- To investigate performance limitations of classical DVR under unbalanced Load condition
- Modeling of Dynamic voltage restorer (DVR) using MATLAB /Simulink/Simpowersystem
- Design of MV-level DVR with low voltage source
- To investigate performance comparison of different contollers used in DVR
- Design and analysis of suitable DVR which could provide better voltage quality under various voltage sag conditions

## 1.7. Organization of thesis

The different sections of this thesis are presented below

| | |
|---|---|
| **Ch#1 Introduction** | • Comprehensive background<br>• Motivation, Research objectives |
| **Ch#2 Literature Review** | • Elements of DVR<br>• Recent work in DVR |
| **Ch#3 Methodology** | • Designing of Specific DVR elements<br>• Designing of MV-DVR |
| **Ch#4 Control system of DVR** | • Detection Scheme & Control algorithm for DVR |
| **Ch#5 Simulation results and discussion** | • Analysis of different voltage sags in power system<br>• Simulation results and discussion |
| **Ch#6 Conclusion** | • Conclusions and Future Recommendations |

## 1.8. Conclusion

This chapter introduces the power quality issues that are faced by the power system which include voltage sag, voltage swells, fluctuations, harmonics, noise, notching and waveform distortion .it also discussed the different power quality standards associated with power quality standards in power systems. A brief introduction of DVR is given in the Chapter as well. The motivation, problem statement, research objectives are also described in this chapter

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# Chapter 2

# Literature Review

The two custom power devices, UPS and DVR are the Power electronic apparatus that inoculate a voltage waveform to the distribution line. The difference between UPS an DVR is that a UPS is always operating in its maximum power and injects a full voltage to the load whether the waveform is distorted or not, whereas the DVR only injects the missing voltage from the load voltage and delivers only when the sag or swell occurs so the time of its operation is also less. This results in less operating losses and low power rating for the DVR. The Dynamic voltage restorer, also known as static voltage booster (SVB) or Static series compensator (SSC), is an effective and active modern custom power device that is used in voltage distribution networks. It is a series connected solid state device that injects a certain amount of missing voltage from the load voltage and regulate it to the standard level. Generally, DVR is connected between the supply and the critical load in the distribution system so that the critical load might be protected from the different power quality issues such as voltage sags, swell, line voltage harmonics compensation, reduction of transients in voltage and fault current limitations. This might result into the failure of sensitive equipment as well as an introduction of large current imbalance that might blow up the fuses or trip the breakers. A DC voltage source is required by the DVR to supply active power and the reactive power is produced within. The injected active power should be minimized.

## 2.1.Basic Operation of DVR

The Basic Operation of the DVR remains to inject three single phase AC voltages in series with the three incoming network voltages that are of manageable amplitude and phase during a voltage sag. This voltage sag can be the result of any fault in the distribution system that will create a difference between the standard voltage requirement of the system and the current faulty voltage levels. A Pulse width modulated (PWM) Voltage source converter (VSC) is fed through a DC link Supply for the active and reactive power compensation [1]. This DVR operates continuously monitoring the load voltage but only generates and inject the compensation signal when a difference between the load voltage and the supply voltage in detected. During normal operation, i.e. under no sag condition, DVR operated in the standby mode in which losses are very low because the low voltage side of the injection transformer is bypassed using switches and it acts as a short-circuited current transformer. The losses during the standby mode are less and should be kept that way to make sure that there are no steady state power losses[2]–[9]. The Energy required for the compensation signal generation is provided by an energy source. The size of the energy source depends on the load MVA requirement, Control strategy used and level of voltage interruption to be dealt with. The injection transformer used for injecting the compensation signal should have low short circuit impedance as it determines the voltage drop on the DVR in the standard operation of the system. This Short circuit impedance also effects the filtration schemes used for the VSC generated harmonic suppression. DVR must also be protected in case of abnormal condition that may affect the DVR ratings by harming the equipment of the DVR. This protection can be provided through solid-state bypass switches or electromechanical bypass switches. When designing a DVR, the following factors should be considered in case of rating and performance of the DVR.

- Maximum limit of the MVA-load and power factor
- Maximum voltage sags to be compensated in single and three phases
- The duration of voltage sag handling capability should be maximum
- The maximum allowed voltage drops in standby mode of the DVR
- Injection transformer's short circuit impedance
- The connections of the transformers connected with DVR
- Short circuit power

## 2.2. Structure of the DVR

A DVR mainly consists of following components [10]–[14].

- Energy Source
- Voltage Source Converter
- Injection/Booster Transformer
- Harmonic Filter

### 2.2.1. Energy Source

Power Systems can experience severe voltage interruptions likes sags and swells and to compensate these sags and swells effectively, active power is required. This active power traded at the DVR AC terminals must be made available at the DVR DC terminal by an energy source. This can be from the grid itself or from an auxiliary supply. In Short, a DC Link Voltage is required by the VSC to produce an AC voltage into the Grid. This Energy can be attained by any of the following means [1], [10], [15]

#### 2.2.1.1. Auxiliary Supply

If the system that the DVR is connected to is weak then this topology is preferred to increase the performance. There are two topologies when using auxiliary supply, variable DC link Voltage or DC link Voltage.

#### 2.2.1.2. Variable DC link Voltage

In this topology, a low rating DC link is used that incorporates a capacitor. This deals with the short-term voltage sags because its capacitor decays exponentially and it cannot handle long time sags. The amount of energy that a capacitor can store is given by following equation.

$$E_{st} = \frac{1}{2} C_{DC} V^2{}_{DC} \tag{2.1}$$

$$P_{Series} = \left(1 - \frac{V_{pcc}}{V_{rs}}\right) P_{load} \tag{2.2}$$

In the above equations, the DC link voltage is represented by $\boldsymbol{V_{DC}}$ and the $\boldsymbol{C_{DC}}$ is the capacitor capacitance. $\boldsymbol{V_{PCC}}$ gives the sag voltage at the point of common coupling whereas $\boldsymbol{V_{rs}}$ is the Source voltage. $\boldsymbol{P_{series}}$ and $\boldsymbol{P_{load}}$ are the powers handled by the series converter and the load respectively.

#### 2.2.1.3. Constant DC Link Voltage

This topology is used for a better performance through continuous supply of constant voltage the energy is provided through a high-energy storage to the small rated DC link that helps in ensuring that the DC link voltage is kept constant. The complexity of this topology increases though. When the DVR is coupled to the strong grid, the remaining voltage can be used to provide the required power to the system through line connected Shunt converter & DVR.

#### 2.2.1.4. Supply Side Connected Converter

In this topology, the DC link capacitor is charged through the shunt converter which is coupled to the supply side, an uncontrollable DC link voltage. The DC link voltage is effected while performing the compensation of the voltage sags and its voltage will drop according to the:

$$V_{DC} = \sqrt{6}V_s = \sqrt{6}V_{pcc} \quad (2.3)$$

$$P_{shunt} = P_{series} = 3(1 - \frac{V_{pcc}}{V_{rs}})P_{load}) \quad (2.4)$$

$$I_{shunt} = \frac{\left(1 - {V_{pcc}}/{V_{rs}}\right)}{{V_{pcc}}/{V_{rs}}} I_{load} \quad (2.5)$$

The power felt by the shunt converter is equivalent to the voltage difference between the supply voltage and the load voltage.

2.2.1.5. Load Side Connected Converter

In this topology, the shunt converter used to charge the DC link is connected on the load side which means that the load voltage will provide the energy required to compensate its missing part. The DC link voltage remains constant as its being provided from the corrected constant load voltage. however, the currents drawn by the shunt converter on the load side will be distorted in nature and its will seriously degrade the power quality of the load voltage.

$$V_{DC} = \sqrt{6}V_L \quad (2.6)$$

$$P_{shunt} = P_{series} = \frac{\left(1 - {V_{pcc}}/{V_{rs}}\right)}{{V_{pcc}}/{V_{rs}}} P_{load} \quad (2.7)$$

The Problem with energy Storage systems are their costs. Large Energy Storage systems cost too much to be incorporated for systems like DVR. The size of the energy storage effects the performance limitation of dealing with longer voltage interruptions. Therefore, we see majority of the solutions put forward are realized through a shunt converter supplied from the line itself.

### 2.2.2. Voltage Source Converter

Pulse width modulated Voltage Source Converter is a power electronic device that is used for generating the sinusoidal voltage at any required frequency, magnitude and phase angle. It mainly consists of the Storage device and switching devices.it requires an injection transformer and a line filter to limit the higher order harmonics produced from switching. Integrated Gate Commutated Thyristors (IGCT) gives VSC a higher power rating through its improved performance and dependability. DVRs, Equipped with VSCs Having IGCT can compensate dips more severe than their predecessor DVRs. VSC is energized through a low impedance DC stiff Voltage supply and the output voltage does not depend on the current drawn by load. The technique called Pulse width modulation is used to create gate signals for the VSC to operate.

### 2.2.3. Harmonic Filter Unit

Harmonic Filter have a significant importance in the design of the DVR system as it is important for the dynamic response of the system. Semiconductor switching devices are used in wide variety of industrial applications as well as DVR. The use of such devices causes waveforms to be distorted because of the nonlinear nature of the switching devices. Harmonic filer unit is used to overcomes these complications in the system. It is used to keep the harmonics level generated by the VSC in to the Grid to a permissible level. The LC type harmonic filters are preferred but the designing of such filters require a deep analysis. The values cannot be simply calculated based on the harmonics of the capacitor voltage alone. The two filtering schemes that are discussed in the literature are

- Inverter side Filter
- Line Side Filter

The choice of filtering schemes significantly affects the performance of the DVR, both filtering schemes have their advantages and disadvantages. The inverter side filter is preferred to the line side filter for its harmonic isolation i.e. it doesn't allow the higher order harmonics to penetrate the power system whereas using the line side filter will introduce harmonics into the power system for which other significant measure will be required. Yet, the inverter side filter may introduce an additional voltage drop on the low voltage side of the injection transformer and effect the compensation signal voltage that will be injected by the transformer because of the inductor of the filter. Additionally, magnitude and phase difference is also experienced on the grid side with inverter side filter scheme.

#### 2.2.3.1. Inverter Side Filter

LC harmonic filters are typically designed based on the fourier series of the inverter voltage output waveform. For precise outcomes you have to consider a significant quantity of harmonics with the related additions and multiplications. The figure below shows the equivalent circuit of the inverter side filter.

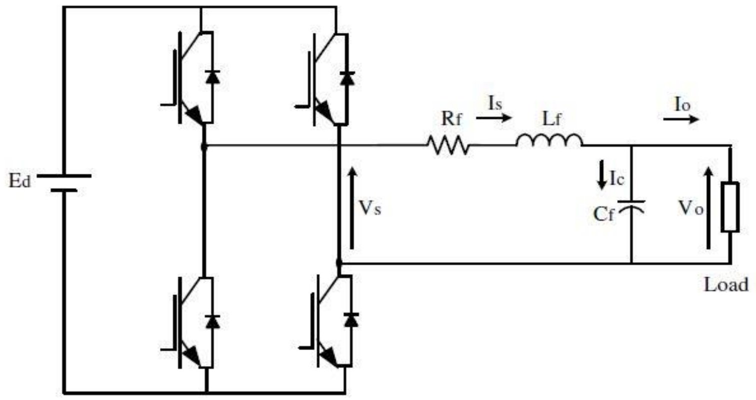


**Figure 2.1: Equivalent circuit of the inverter side filter [15]**

The Inverter output voltage equation will be:

$$V_s = V_o + R_f I_s + L_f \frac{dI_s}{dI_f} \tag{2.8}$$

The criteria used in this paper is based on the minimum injection of reactive power which in also minimizes the size, losses and cost of the filter. There are three stages of designing an LC filter. Following equations are derived through comprehensive analysis described in the paper.

Step 1: Calculation of modulation index, K.

The modulation index depends on the DC voltage source Ed and the nominal load voltage given by the following equations:

$$K = [\frac{k^2 - \frac{15}{4}k^4 + \frac{64}{5\pi}k^5 - \frac{5}{4}k^6}{1440}]^{1/2} \tag{2.9}$$

Where k is

$$k = \sqrt{2}\frac{V_0}{E_d} \tag{2.10}$$

Step 2: Calculation of the filter inductance

Once the modulation index is calculated the filter inductance can be found by using equation (2)

$$L_f = \left(\frac{V_o}{I_o f_s}\right)\sqrt{\{K\frac{E_d}{V_{o,av}}\left(1 + 4\pi^2\left(\frac{f_r}{f_s}\right)^2 K\frac{E_d}{V_{o,av}}\right)\}} \quad (2.11)$$

Step 3: Calculation of the filter Capacitance

The capacitance of the LC filter is calculated by the following relation:

$$C_f = K\frac{E_d}{L_f {f_s}^2 V_{o,av}} \quad (2.12)$$

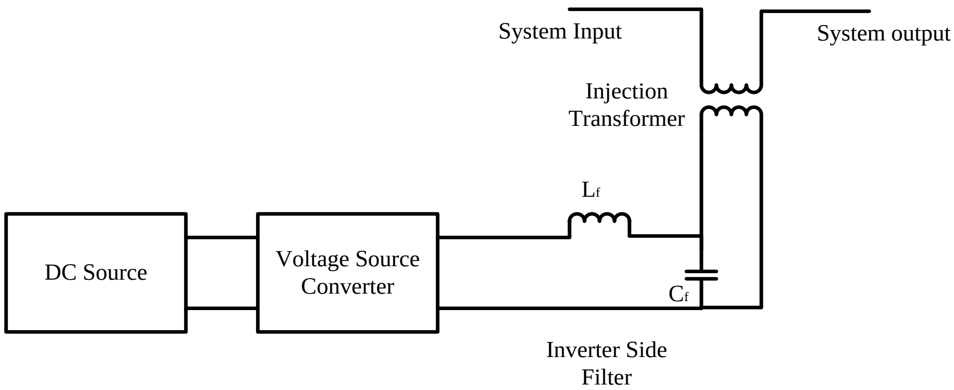


**Figure 2.2: Inverter side filter**

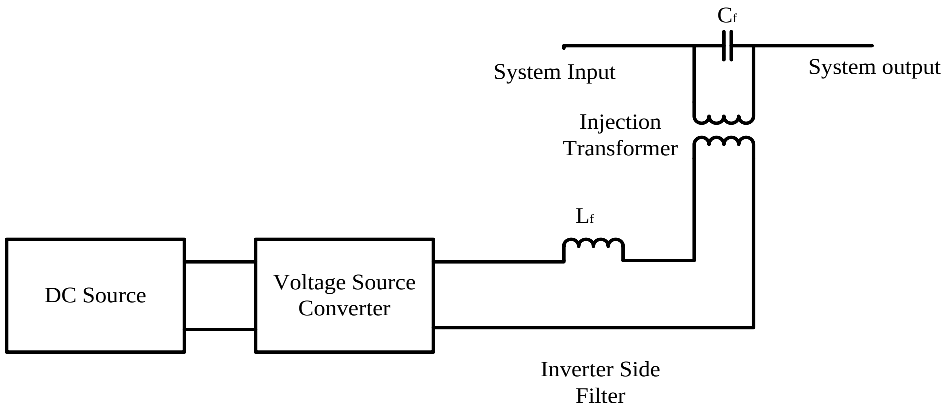


**Figure 2.3: Line Side Filter**

### 2.2.4. Series Injection/Booster Transformer

The relationship between the different parameters of the transformer is given by the following relation:

$$\frac{V_p}{V_s} = \frac{I_s}{I_p} = \frac{N_{pr}}{N_{se}} = m \quad (2.13)$$

The Primary and secondary voltages are represented by $V_P$ and $V_S$ respectively, $I_S$ gives the secondary current and $I_P$ gives the primary current in the transformer. $N_{pr}$ is the number of turns on the primary side whereas $N_{se}$ gives the number of turns on the secondary side of the transformer. The factor m, in the above relation is called the turn-ratio of the transformer. The injection/ Booster Transformer is required to couple the DVR to the distribution system via the HV windings.[16]–[18]. The Compensation signals are generated by the voltage Source Converters. Additionally, it keeps the link of noise and transient from the primary side to penetrate the secondary side in limit through galvanic isolation. Selection of injection transformer is considered very important for effective and reliable restoration scheme. Selection for the injection transformer requires intelligent decision making and considering the following issues

- The MVA rating
- The primary winding voltage and current ratings
- The turn-ratio which, in turn, determines the secondary winding voltage and current rating
- The short-circuit impedance

For a transformer to protect its series connected sensitive load, the rated current rating of the transformer should be in accordance with the rated sensitive load capacity.

#### 2.2.4.1. MVA Ratings

Injection transformers MVA ratings can be determined by the primary voltage ratings and the maximum current handling capacity of the DVR, which is only a fraction of the total MVA ratings of the load's rating that is under protection. The MVA rating can be calculated using the power equation give

$$P = K_s V_p I_p \tag{2.14}$$

$K_S$ is the Safety margin, $V_{pr}$ is the primary voltage of the injection transformer and $I_{pr}$ is the current rating of the injection transformer.

#### 2.2.4.2. Primary Winding Ratings

The primary side voltage rating of the injection transformer is dependent on the energy storage capacity, as the maximum voltage sag/swell that can be compensated by the DVR is usually the rated energy storage capacity. Minimum Energy injection allows for us to use the most efficient primary side voltage ratings. The ratings of the injection transformer can be calculated by the following equation:

$$V_{inj} = DV_r \quad (2.15)$$

$$V_s = (1 - D)V_r \quad (2.16)$$

Primary feeder rated rms voltage is given by Vr, D is the maximum single-phase voltage sag that is to be compensated and the injection voltage is represented by $V_{inj.}$ The primary voltage ratings may change if the injected power is requested to be minimized. In-phase method reduces the injected active energy by increasing the scale of the injected voltage

2.2.4.3. Turn Ratio

Injection transformers secondary voltage, current ratings and the turn ratio are interconnected. The turn ratio of the injection transformer can be determined, with the primary side ratings known and secondary side ratings are also calculated. In Practice, the turn ratio is adjusted until finding available switching devices with minimum cost of storage devices.

2.2.4.4. Short Circuit Impedance

Though the system operates for most of the time in steady state conditions but the characteristics of the system under a system fault, short circuit or any other abnormal condition must be known. The short circuit impedance of the injection transformer causes a voltage to drop across its terminal in the normal operation of the power system. It also effects the selection of filtering scheme for the system Fig 2.4 shows the equivalent circuit of the DVR with inverter side- filtering scheme.

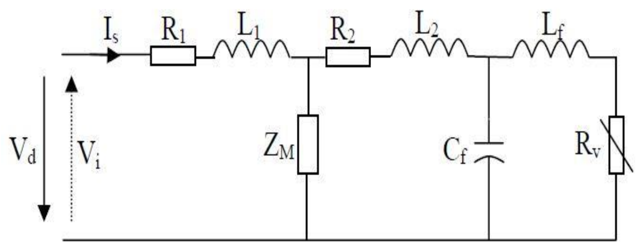


**Figure 2.4: Equivalent Circuit of DVR with Inverter-Side Filter [14]**

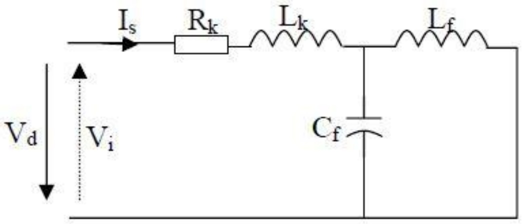


**Figure 2.5: Simplified Equivalent Circuit of DVR with Inverter-Side Filter [14]**

Fig 2.5 shows the simplified equivalent circuit of DVR with inverter side- filtering scheme. $V_d$ gives us the voltage drop across the injection transformer under steady state operation, $R_k$ and $L_k$ are the short circuit resistance and reactance. $L_f$ is the filter reactance value and the filter capacitance is given by $C_f$.

$$R_k = R_{ps} + m^2 R_{ss} \tag{2.17}$$

$$L_k = L_{ps} + m^2 L_{ss} \tag{2.18}$$

During the standby mode, the voltage drop across the transformer must be less than the specified value and it should meet the following condition

$$\sqrt{{R_k}^2 + w^2(L_k + L_f/(1 - w^2 L_f C_f))^2} < \left( {V_T}/{I_T} \right) \tag{2.19}$$

2.2.4.5. Winding Parameters

The Equivalent circuit of a transformer shows us that it has winding resistances on primary and secondary side represented by $R_{ps}$ and $R_{ss}$, Leakage inductances on primary and secondary side represented by $L_{ps}$,$L_{ss}$ and the magnetizing characteristics of the core $R_c$,$L_m$. These resistance and inductance values are usually given in per-unit systems. The values are based on the transformer rated power $P_n$, nominal frequency $f_n$ and nominal voltage $V_n$ (rms) of the corresponding winding. the per unit resistance and inductance values, for each winding, are defined as:

$$R_{(pu)} = \frac{R(\Omega)}{R_{base}} \tag{2.20}$$

$$L_{(pu)} = \frac{L(H)}{L_{base}} \tag{2.21}$$

The Base resistance and base inductance used for each winding are

$$R_{base} = \frac{(V_n)^2}{P_n} \quad (2.22)$$

$$L_{base} = \frac{R_{base}}{2\pi f_n} \quad (2.23)$$

To specify a magnetizing current of 0.5% based on nominal current, the per unit values of 1/0.005=200pu for the resistance and the inductance of the magnetizing branch should be entered.

## 2.3.DVR Operating Sites

The Idea behind DVR is to compensate for the detrimental effects of a fault in the power system in the shape of a voltage interruption. For a DVR to Perform efficiently it must compensate the Fault voltage immediately so that the effects of the Voltage sags and swells don't interrupt the normal load operation. For this Reason, DVR should monitor the voltage profile continuously. There are three basic modes of operation of a DVR which are explained as follows[12], [19]–[21].

### 2.3.1. Protection mode

DVR can operate in both medium level and low-level voltage distribution system depending on the DVR ratings which in turn depend on the equipment used in the DVR. The DVR must be robust enough to handle the abnormal conditions on the load side of the DVR and even the loss of entre grid connection. There are two types of protection provided for the DVR, through passive control of the DVR and through the active control of DVR. Passive protection is provided through the uses of bypass switches that will isolate the DVR from the power system when unusual conditions result in excessive inrush current. The Switches will provide an alternate path for the current while disconnecting the DVR from the system. This passive control scheme is favored for the series protection of the DVR because by using this the VSC can be rated for low currents. This is done using switches S2 and S3. Switches S2 & S3 will be open and the Switch S1 will be closed to provide another path from the abnormal levels of current.

### 2.3.2. Standby mode

This is the non-fault mode i.e. the system is operating under normal conditions with no faults occurring. The primary side of the injection transformer is shorted through the converter and all the load current passes through the secondary. No voltage is injected through the DVR in the power system

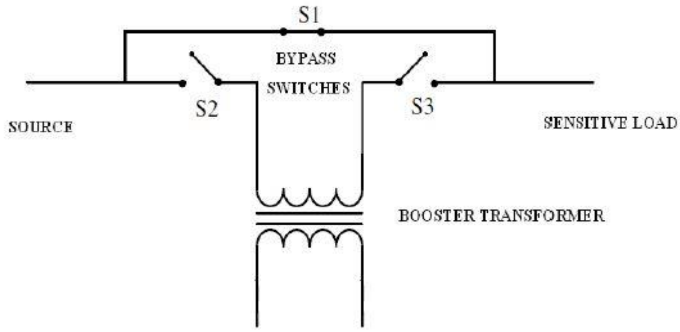


**Figure 2.6: Protection Mode with the help of switches S1, S2& S3 [1]**

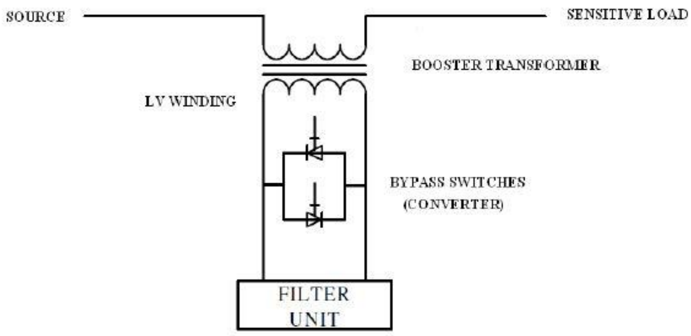


**Figure 2.7: Standby Mode of operation [1]**

DVR operates in the standby mode for the most part of the time. the voltage drop across the transformer will be determined by the short circuit impedance of the boot transformer. If the distribution network that the DVR is connected to is weak, a small compensation voltage needs to be injected for the system to operate correctly.

### 2.3.3. Injection/Boost mode

This is the mode of operation when a fault is detected in the system and its results in voltage sags or swell. DVR detects the Voltage sags/ swells level and generate the compensation signal which is then fed into the system through the injection transformer.

## 2.4. DVR Compensation Techniques

There are a lot of factors that needs to be taken into consideration when planning a compensation scheme for the DVR. Some of the factors include the requirement for a faster response, the type of load connected that can vary largely and the diverse types of sags that are to be dealt with, the symmetrical and non-symmetrical voltage sags and the phase jumps that accompany sags and the background power problems. The main task is to keep the voltage levels at their nominal levels across all the three phases of the power system. The type of voltage compensation techniques in literature are described below [1], [22].

### 2.4.1. Pre-sag compensation method

In pre-sag compensation technique, the supply voltage is continuously monitored and the load voltage on occurrence of a voltage sag or swell is compensated back to its pre-sag condition. In this method, the active power injected cannot be controlled and depends mainly on the external factors.

$$V_{DVR} = V_{prefault} - V_{sag} \tag{2.24}$$

### 2.4.2. In-phase compensation method

This method gets its name from the fact that the voltage generated by the DVR is always in phase with the measured supply voltage and it is not effected by the load current and pre-sag voltage. The load voltage is kept at a constant voltage magnitude but there is a change in the phase angles of the pre-sag and load voltages[23], [24].

$$|V_L| = |V_{prefault}| \tag{2.25}$$

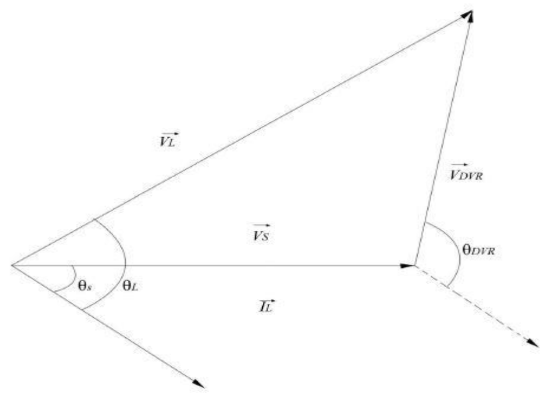


**Figure 2.8: Pre-Sag Compensation Scheme [7]**

### 2.4.3. In-phase advanced compensation method

In-Phase Advanced Compensation method uses only the reactive power to compensate for the voltage sags but most of the voltage sags type require injection of real power into the system through an energy storage DC links. This makes this technique only limited to a few types of voltage sags but it cuts the cost of having an energy storage device for the DC link, which is the most expensive part of the DVR. Another disadvantage of this scheme is the increased values of the injected voltage, phase shift, waveform discontinuity and the complexity of the control system. This scheme is not effective for deep voltage sags or large phase angle shifts but it requires lower magnitude of injected voltage which in turns reduces the requirement of the energy storage capacity. Thus, it injects minimum energy when compared to the pre-sag and in phase methods.

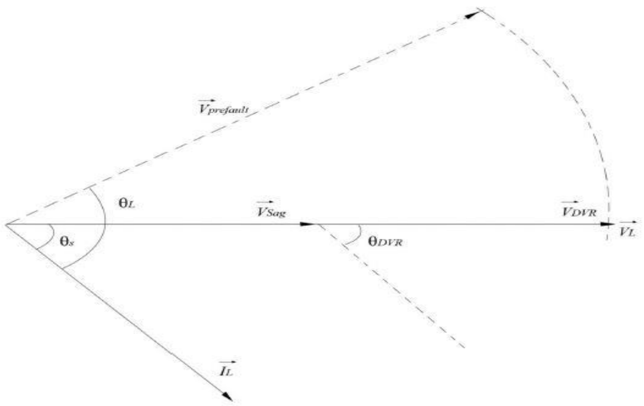

**Figure 2.9: In-phase compensation scheme [7]**

### 2.4.4. Voltage tolerance method with minimum energy injection

In this method, the Voltage and the phase jump are not required to be at their optimal level, rather there is a window of tolerance from the load side on both the magnitude of the voltage and the phase angel of the voltage. This method utilizes this window of tolerance in which the load's operational characteristics are not disturbed by injecting enough energy into the system that keeps the load voltage and the phase angle in between the tolerance window limits. The window of tolerance for the normal load operation is in between 90%-110% of the load voltage magnitude and 5%- 10% of the phase angle jump

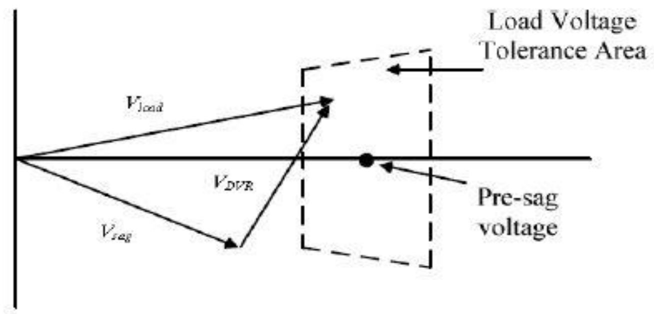


**Figure 2.10: Voltage Tolerance with minimum energy Injection Scheme [7]**

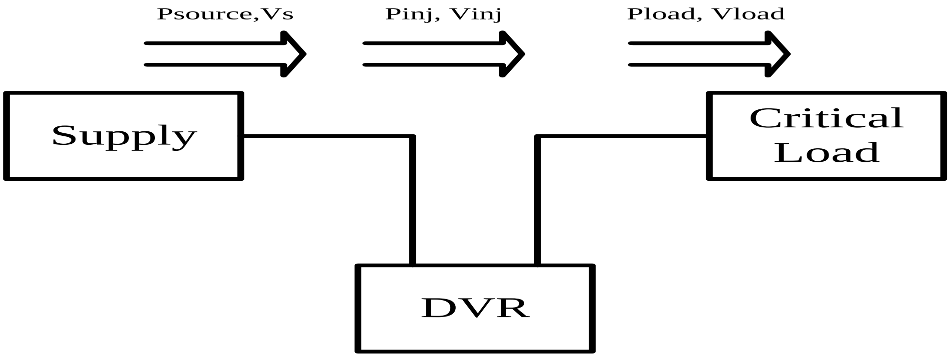


**Figure 2.11: Power flow [11]**

$$P_{load} = V_L I_L \cos\alpha \quad (2.26)$$

$$P_{source} = V_s I_L \cos\beta \quad (2.27)$$

$$P_{inj} = P_{source} - P_{load} = I_L(V_S \cos\beta - V_L \cos\alpha) \quad (2.28)$$

$I_L$ is the load current; α is the angle between $V_L$ and $I_L$; b is the angle between *Vs* and $I_L$.

## 2.5.Location of the DVR

The point of installation of a DVR in the power system is of importance as well. The Location of DVR depends on the number of loads that are to be protected. DVR can be installed to protect a single consumer and it can also be installed at a location where it provides protection to a group of consumers with value added power. The DVR can be installed either at the MV distribution level to protect all the customers connected to this MV distribution network or it can be connected at a LV distribution network close to the LV customer for its protection [17].

### 2.5.1. MV-level DVR

The DVR can be connected in the medium voltage level distribution system to protect a big consumer or set of consumers as shown in the figure. The use of DVR in MV-level will only slightly increase the supply impedance for the load connected to the LV level. For MV connected load closer to the DVR the impedance increase is quite significant as compared to the LV connected load. The summation of all these impedance for the LV load gives the impedance that is seen by the load before connecting the DVR to the system. After the insertion of DVR this impedance slightly increases as shown by the following equations.

$$Z_{supply\ before} = Z_{50/10} + Z_{line,10} + Z_{10/0.4} + Z_{line,0.4} \qquad (2.29)$$

$$Z_{supply\ after} = Z_{DVR} + Z_{supply,before} \qquad (2.30)$$

$$Z_{increase,\%} = \frac{Z_{DVR}}{Z_{supply,before}} 100\% \qquad (2.31)$$

There are advantages and disadvantages of connecting the DVR to the MV-level system in the literature. some of them are discussed below[15]

- The impedance increase seen by the LV load is relatively smaller when connected to the MV level.
- When one large DVR is connected to the MV-level, the cost per MVA are lower as compared to the decentralized low voltage unites used in LV-systems
- A Simpler DVR topology is needed when connecting DVR in MV-level three wire systems with isolated or inductor grounded systems.

Some of the disadvantages that come with MV-level integration are

- Protecting many consumers can result in utilizing a part of the DVR ratings on loads that do not require supreme voltage quality
- The DVR ratings are going to be high otherwise a not sufficient ratings DVR will increase losses in the system when connected to MV-level.
- A Higher level of isolation on injection transformer is required for the time the MV systems experiences ground faults because the phase to ground voltage can increase up to 1.73 times.
- Short circuit level and isolation level are required to be higher than normal

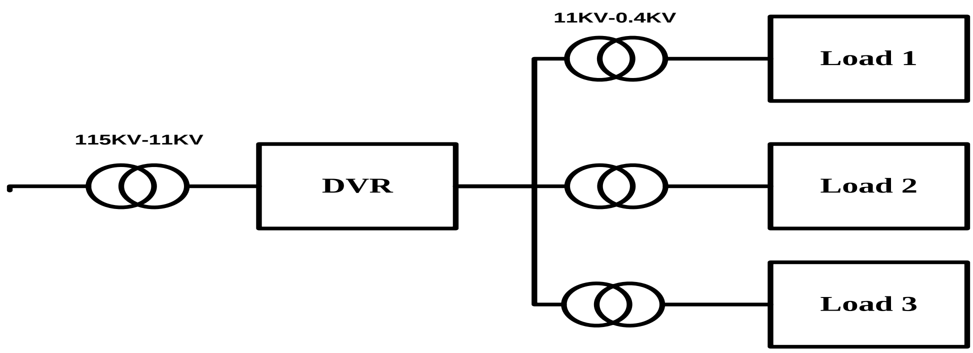


**Figure 2.12: DVR Located at MV- Level [15]**

### 2.5.2. LV-level DVR

The LV- DVR are connected to the low voltage distribution system where it is used to protect a lower number of consumers whether it be a group or an induvial considerably significant sensitive load. Adding a DVR to the lower side of the distribution system closer to the load increases the impedance seen by the load and this change can be several hundred percent of the normal impedance.

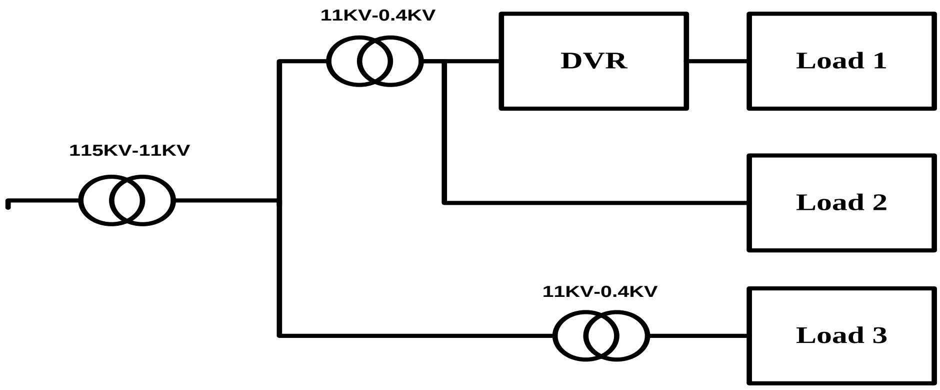


**Figure 2.13: DVR Located at LV-Level [15]**

## 2.6. Conclusion

In this chapter, an extensive literature review has been presented covering the topic of Dynamic voltage restorer. The structure of the DVR is discussed in detail with each component of the DVR described in detail. The operating sites of DVR are then discussed in which different modes of DVR are presented such as protection mode, standby mode and injection mode. Then the chapter introduces the different compensation techniques that are used in the DVR including pre-sag compensation, in phase compensation, in phase advanced compensation method and voltage tolerance method. It is also discussed how the location of the DVR in the power system affects its performance and its effectiveness. The low voltage levels DVR and Medium voltage level DVR is discussed along with their advantages and disadvantages.

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# Chapter 3

# Methodology

Simulink is a software package for modeling, simulating and analyzing dynamic systems. It supports linear and non-linear systems modeled in continuous time, sampled time or a hybrid of the two.

Some advantages of Simulink program are as following:

- Requires less memory space and CPU run time
- Circuit equations are solved much faster than PSPICE.
- Some mathematical calculations e.g. harmonic magnitude spectrum, are computed with higher steps than PSCAD / EMTDC.
- Access to sophisticated routines embedded in MATLAB toolboxes
- Well suited for the design of industrial applications

## 3.1. Design Parameters

There are many factors that are needed to be considered when designing a DVR for the power system. these include the load requirements, the supply characteristics and the maximum voltage sag/swell that is to be compensated by the DVR[1]–[5].

### 3.1.1. Maximum Load Power & Power Factor

The magnitude of the load is important when considering the current ratings of the VSC and the injection transformer. The magnitude of the energy storage devices needs to be selected according to the size of the load. The Voltage injection capability is selected as low as needed to decrease apparatus price and standby losses.

### 3.1.2. Maximum Depth & duration of Voltage Dips

The size of the energy storage and the voltage ratings of the injection transformer are influenced by the maximum voltage sag requirement. The voltage ratings of the transformer should be according to the maximum voltage sag that is to be compensated. The maximum voltage sag and its average duration is determined by the statistics at the DVR site and by the satisfactory amount of the equipment trips.

### 3.1.3. Maximum Allowed Voltage drops of the DVR during the Standby Mode

When the DVR is in the standby mode, there is going to be a voltage drop across the transformer terminals and it effects the control mode chosen for the DVR. It also indirectly affects the dynamic response of the DVR at the beginning of the voltage sag. The transformer, filter and the converter losses make up the losses in the DVR.

### 3.1.4. Parameters of the Step-down transformer

The parameters of the injection transformer on the primary side winding and the secondary side winding are to be designed properly for the coupling of the transformer at the input and the output side of the DVR[5].

### 3.1.5. Harmonic Requirements of the load and the system

DVR must not be allowed to inject higher order harmonics into the power system above the specified limit set by different standards of the power system. This factor influences the type of filtering scheme to be applied for the DVR and the charging techniques for the DC link Capacitor.

The key purpose of the DVR is to offer a solution to the power system problems in a cost-effective manner. The Statistics of the yearly Voltage sags/swells occurrence, their duration and the cost of the lost production helps in designing an economical DVR for the system. It must be kept in mind that a DVR is not designed to support complete outages. the DVR, being a protective device, also needs protection from the abnormal conditions in the power system so it should be incorporated with bypass switches and circuit breakers for its own protection[6], [7].

## 3.2.Proposed DVR Configuration

The DVR is used in the power system to compensate for voltage sags/swells caused by any fault. It uses self-commutating IGBT solid state power electronics switches to generate the compensation voltage. PWM-VSC is used in this study and the switching frequency is selected to be 2KHz. The VSC is linked to the DC voltage source on one side and to the injection transformer through a harmonic filter. The VSC uses the power from the DC voltage source to generate the compensation signal. The use of solid state power electronic switches to convert the DC input to AC output signal introduces harmonics of higher order in the compensation signal and to block these higher order harmonics from penetrating into the power system an LC filter is used. This LC filter can be on the inverter side or the line side (high voltage). For reasons discussed earlier, the inverter side filter is used in this study. The three-phase injection transformer is used to convert the low voltage into a high voltage compensation signal (180/2540V) and couple it into the power system. The DVR is protected by placing the bypass switches and circuit breakers in parallel with the injection transformer.

The DVR and power system modelling is done in MATLAB/Simulink. The DVR is installed in a simple power system where it protects a sensitive load in the distribution system. A source of 15 kV energizes the 11-kV distribution system to which this sensitive load is connected. The load is connected to the distribution transformer on the low voltage side. The distribution transformer (Δ/Yn) steps down the voltage to the 380V(rms). The DC energy source is 200V. System frequency is 50Hz. The Voltage Sags/swells are generated through the three-phase programmable voltage source. The proposed DVR can mitigate the voltage sags, balanced and unbalanced, up to 30% of the rated distribution system voltage. The single phase equivalent diagram of the power circuit is represented by the following figure

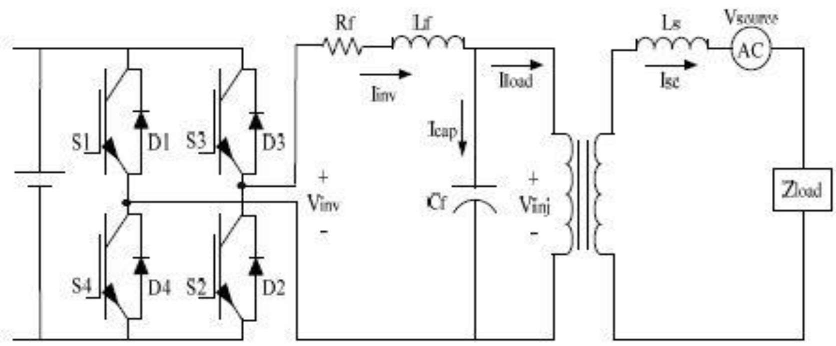


**Figure 3.1: Single-phase equivalent circuit of DVR system [16]**

The above figure represents the single phase equivalent circuit of the DVR system and all the voltages and currents involved in the system. $V_{inj}$ is the injected voltage from the DVR, $V_{inv}$ is the voltage output of the VSC which then passes through the filter inductance and capacitance represented by $L_f$ and $C_f$. A DVR must be able respond in less than 0.5 cycles to ensure that the dynamic capabilities of the DVR are up to the mark. The installation of the DVR must be done in such a way that it doesn't has any effect on the power system during the normal operation and even when there is a fault in the system[8]–[10]. Therefore, designing of the DVR components into the power system takes significance to ensure fast and reliable response. It should be made assured that the system is not affected by the installation of the DVR**,** other than the voltage sag compensation. There are four main elements, which deserve consideration in the design of a DVR.

- Voltage source PWM inverter
- Injection transformer
- Harmonic filter
- Control system

## 3.3.Design of DVR Elements

The designing of the DVR for this study is explained in this section.

### 3.3.1. Design of the converter

The converter applied in this study is a pulse width modulated Voltage source converter (PWM-VSC). This VSC is connected to the energy storage device on one end and to a harmonic filter on the other end, The VSC is the most important part of the DVR. The DC energy Storage device can be a DC link capacitor or any of the earlier mentioned technology. This DC capacitor is kept charged before and during the operation of the DVR so that it can constantly feed the DVR with a constant level of voltage. Th function of the VSC is to generate the compensation signal by accurately controlling the switches of the inverter. IGBT based VSC is used in this study. The selection of IGBT switches was mainly because they are easily controllable and the power range is suitable. The drawback of using IGBT is the current limiting behavior which is undesirable in case of DVR [11], [12]. The shape of the compensation signal depends on the switching frequency of the inverter. The switching of the IGBTs is controlled by the logical signal generated by the PWM generator. The PWM generator is fed a reference voltage signal of the voltage difference between the faulty load voltage and the supply voltage. The Three phase VSC is modelled through the universal bridge block in the Simpowersystems. The Universal bridge can be used to simulate all kind of switching devices including switching based VSC.

### 3.3.2. Design of the injection transformers

The function of the injection transformer in the DVR system is to couple the compensation signal voltages generated by the VSC with the incoming supply voltage through high voltage windings. In this study, the transformer also transforms the voltage from the primary side low voltage to a higher voltage level at the secondary voltage side. The ratings of the transformer as discussed earlier depends on the value of the voltage sags, supply current and the capacity of the DC link [11]–[14]. The turn ratio is determined by the maximum injection voltage and the capacity of the DC energy storage. In this study, a three-phase injection transformer with the turn ratio of 140-2540 V is used. All the parameters are calculated considering the worst-case performance so that the system can withhold its operation when conditions get worse. This study is designing a DVR that can compensate up to 30% voltage sag of the standard voltage of the supply. Using Eq we can calculate the higher side voltage ratings. Taking D=0.3 (30% voltage sag). The rms voltage of the supply is rms. the secondary side voltage side rating is calculated to be $V_{rms}$. The core parameters of the windings of the injection transformer are represented in per unit values in the MATLAB/Simulink environment. The power rating of the injection transformer is 250 kVA, nominal frequency is 50Hz and the voltage on the secondary side is 2540 V. The default parameters for secondary side gives the following bases for the secondary side winding. The secondary winding parameters per unit value the resistance and inductance as

$$R(pu)= 0.000286, L(pu)= 0.000356$$

Similarly, the parameters of the primary side of the transformer can be calculated which are:

$$R(pu)= 0.0189, L(pu)= 0.0071$$

To specify a magnetizing current of 0.5% (resistive and inductive) based on nominal current, the per-unit values of 1/0.005=200 pu for the resistance and the inductance of the magnetizing branch must be entered. Using the base values calculated for secondary side winding, these per-unit values correspond to:

$$R_m = 588, L_m = 588$$

The injection transformer in this study not only provides the isolation between the inverter, it also reduces the voltage requirement of the system through transforming the voltage on the primary side. The DVR must be provided protection from any abnormal condition in the power system. This is done by placing the bypass breakers in parallel with the injection transformer’s primary winding. The switchgear in the medium voltage system acts as a bypass circuit breaker when the DVR is under maintenance. The Transformer must be protected from saturation as well. For this reason, the transformer is sized to handle about twice the nominal steady state flux requirement at minimum rms injection voltage without saturation.

### 3.3.3. Design of the line-filter

The Dynamic Voltage Restorer equips power semiconductor switches in its voltage source converter which gives it nonlinear properties. These semiconductor switches generate modulation components which must be isolated from entering the power system. This requires output filters consisting of inductors and capacitors to provide high quality waveforms. This filter allows some frequencies to pass through while locking majority of the high order harmonics. Ideally the DVR should not be generating any harmonics but during the voltage sag period the DVR tends to produce harmonics[15][16]. In This study inverter side filter is preferred to the line side filter because it is closer to the source of harmonics at the low voltage side of the injection transformer. This Filter is generally a low pass filter made up of an arrangement of inductor and capacitor. The parameters of this LC filter depend upon the maximum injection limit of the DVR. Designing of the LC filter is discussed in section 2.3.1. if any parameters values required for the design of LC filter vary during the operation then the worst-case condition should be considered and the LC parameters should be calculated accordingly. The following table shows the parameter values used for the design of the LC filter.

**Table 3.1: Parameters for LC Calculations**

| $E_d$ (V) | $V_0$(V) | $F_r$(Hz) | $F_s$(Hz) | $I_0$(A) | $V_{0,av}$ |
|---|---|---|---|---|---|
| 200 | 380 | 2000 | 50 | 40 | 220 |

This method saves us the blushes of going through a Fourier series method, though the values obtained through this technique may not give us the optimum performance because of the assumptions made at the start of the designing procedure. These parameters must be fine-tuned through analyzing the total harmonic distortion (THD) and harmonic components of the output. The use of I line filter not only dampens the switching harmonics but it has several other effects on the performance of the system. Some of these potential problems are listed below taking into consideration an LCL-filter[14]:

- A voltage step increase in converter voltage can initiate the line-filter resonance frequency and this may lead to a distortion of the load voltage. The bandwidth of the injected voltage may have to be reduced to avoid high oscillations.
- There is a voltage drop introduced by the line filter components.
- The filter resonance frequency can be excited by a nonlinear load which results in distorted load voltage.
- The supply should be cleaned of any harmonic voltage component otherwise there is a potential risk of a resonance in the line-filter.

During the active mode of the DVR, where it is injecting a compensating voltage signal into the power system, the inductor closest to the converter experiences a high ripple current and a large part of this current's components are absorbed by the capacitor. It also absorbs the reactive power from the VSC. The harmonics are dampened by the inductor closest to the supply and the voltage injected by the DVR is manly free of the switching harmonics.

## 3.4.DVR parameters and system description

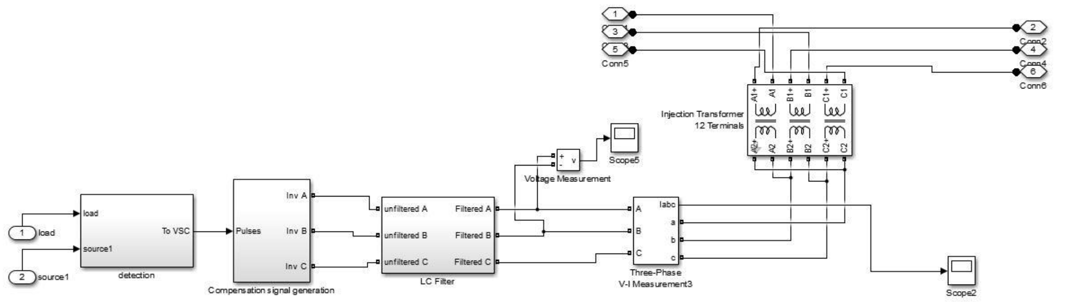


**Figure 3.4: DVR Blocks**

### 3.4.1. MV-DVR parameters

**Table 3.2: MV-DVR test system parameters**

| | |
|---|---|
| Fundamental Frequency | 50 Hz |
| Sampling frequency | 20 kHz |
| Supply Voltage(Ph-Ph) | 15 kV $V_{Ph\text{-}Ph}$ ($V_{rms}$) |
| MV Level Network Voltage (Ph-Ph) | 11 kV $V_{Ph\text{-}Ph}$ ($V_{rms}$) |
| Three Phase Injection Capability | 2540 V $V_{Ph\text{-}Ph}$ ($V_{rms}$) |
| Max Voltage injection (Single phase) | $\leq$ 30 % |

| | |
|---|---|
| DC Voltage Source | 200 V |
| Switching Frequency | 4350 Hz |
| Filter Inductance | 0.5 micro H |
| Filter Capacitance | 0.84 milli F |
| Injection Transformer Nominal Power | 100MVA |
| Injection Transformer winding rating | 140-2540 $V_{Ph-Ph}$ ($V_{rms}$) |
| Load Transformer nominal power | 100 kVA |
| Load Transformer windings rating | 11000-380 $V_{Ph-Ph}$ ($V_{rms}$) |

## 3.5. Conclusion

In this chapter, the design parameters of the DVR are discussed that are to be kept in mind during the designing. The proposed DVR configuration is put forward and then the designing procedure of each element of the DVR in this study is explained. Finally, the calculated specifications of the MV-DVR system are presented in the form of the table

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# Chapter 4

# Control system of Dynamic Voltage Restorer

Voltage sags is the most common occurring power quality problem that industrial customers face. It results in performance degradation eventually leading to the production losses. The duration of voltage sags should be kept to its minimum for better industrial performance. the cause of voltage sags can be the short circuit faults in the grid system[1]. There are two approaches to deal with the voltage sags. Either the sensitive devices connected to the grid supply be modified or the grid be equipped with Dynamic Voltage Restorer to protect those sensitive devices from experiencing voltage sags. The later approach is preferred as modifying the sensitive devices to deal with voltage sags is almost impossible.

The control of the Dynamic Voltage Restorer is the most important part of DVR scheme and it should satisfy that its able to[2]–[4]:

- Provide a fast response for the transient states as well as steady states
- Provides reliable and Efficient operation
- Compensate the voltage sags/swells experienced by the grid of deep variation and different load conditions
- Provide robust support for the sudden system variations in the form of load changes or the non-linear nature of the load.

Different compensation techniques used in DVR are discussed earlier and the selection of the proper compensation technique will depend on the voltage and the power limit of the DVR. The load characteristics also influence the selection process. These limitations not only affect the compensation technique but in turn limit the overall capability of the DVR. These limitations are Voltage, Power and Energy limitations[5].

- **Voltage Limitation**

the DVR cannot support a complete black out of power and its voltage injection capability is limited due to the cost factor. Also, the voltage drop across the device should be kept as low as possible during the normal operation.

- **Power Limit**

Power is supplied from the DC link but the bulk power is often converted from the supply itself or from a larger DC storage. To maintain the constant DC link voltage, an additional converter is used which increases the cost of the system. The Rating of the converter also limits the power rating of the DVR.

- **Energy Limit**

The amount of energy available for the voltage sags/swells compensation depends on the energy storage device. The cost of energy storage devices is usually the most in the DVR system. To keep the cost down of the system, the energy storage devices are sized as low as possible. The nature of the sags can affect the energy storage as some sags tend to drain the storage faster. A control system should incorporate all these limitations to make sure that the investment made in the DVR is not blown away. Some of the other limitations are important too which include additional hardware constraints.

- **Saturation:** there is a danger of transformer starting to saturate when it must inject high voltage levels, the result of this is that the voltage quality is degraded and the series converter has to deal with increased levels of the current.
- **In Rush Currents**: When the DVR starts to inject compensation voltages the pre-flux level might cause the injection transformer to attract additional high in-rush currents.
- **line-filter impedance**: The line filter reduces the switching harmonics in the compensating voltages but it causes a voltage drop which is undesirable.

## 4.1. Detection Scheme

Literature survey puts forward many detection techniques that are used for the finding of voltage sags and swell in the voltage profile of the power system. But the detection technique that we are going to focus during our study is DQ0 transformation also known as parks transformation. The direct-quadrature-zero transformation is a tensor that rotates the reference frame of a three-element vector or a three by three element matrix to simplify analysis. the DQ0 transform is used to convert the reference frames of three phase AC waveforms into DC signals which then simplifies the calculations for the signals. The inverse transform is then performed to recover the actual three phase AC results[6]–[10].

DQ0 transformation has been covered extensively in the literature and is preferred due to its simple applicability and easiness of the process[11]. In the DQ0 transformation the three-phase system is converted into D and Q equations where they can be easily operated on. The relation used to convert three phase voltages into D and Q components is given by

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{4.1}$$

Once the sag detection is done the D and Q components are then converted back to the three phase abc system through

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) & 1 \\ \cos(\omega t - \frac{2\pi}{3}) & -\sin(\omega t - \frac{2\pi}{3}) & 1 \\ \cos(\omega t + \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} \tag{4.2}$$

The control scheme involving the Parks transformation is simple the voltage sags and swell are detected through the DQ0 Transformation when both the source voltage and the defected load voltage are compared with each other and the correction voltage is computed. The correction signal is then forwarded to the PWM generator that is used to convert the compensating signal waveform into gate signals for the Voltage Source converter. The voltage source converter then operates according to the gate pulses and generates the compensating signal that is then injected into the power system through injection transformer. A three phase “Phase Locked Loop” (PLL) is used to track the frequency and phase of the sinusoidal three phase input signal by using the internal frequency generator. The control system adjusts the internal oscillator frequency to keep the phase difference to 0. The PLL also uses the dq0 rotating frame internally for the said controlling of the input signal. The output of the dqo-abc converter block is then fed to the three phase PWM generator which generates the pulses for the converter using the three-level topology. The output signal of dq0-abc converter bloc acts as the modulating signal which is the naturally sampled and compared with two symmetrical level-shifted triangle carriers.

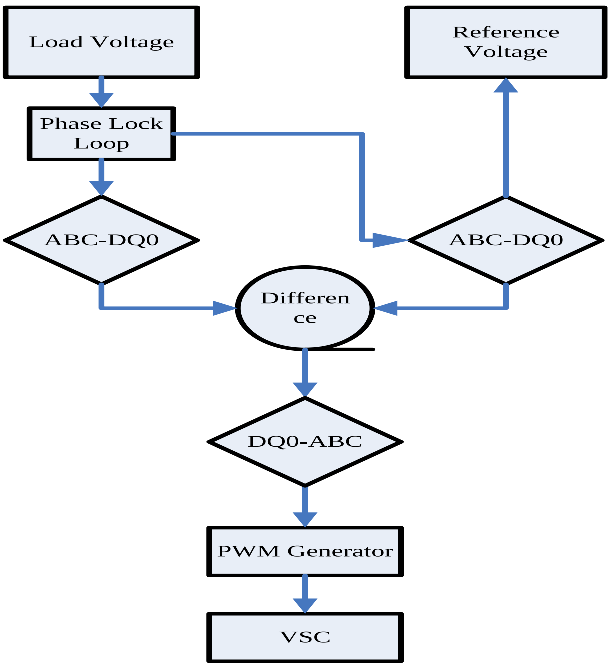


**Figure 4.1: DQ0 Control Scheme flow chart**

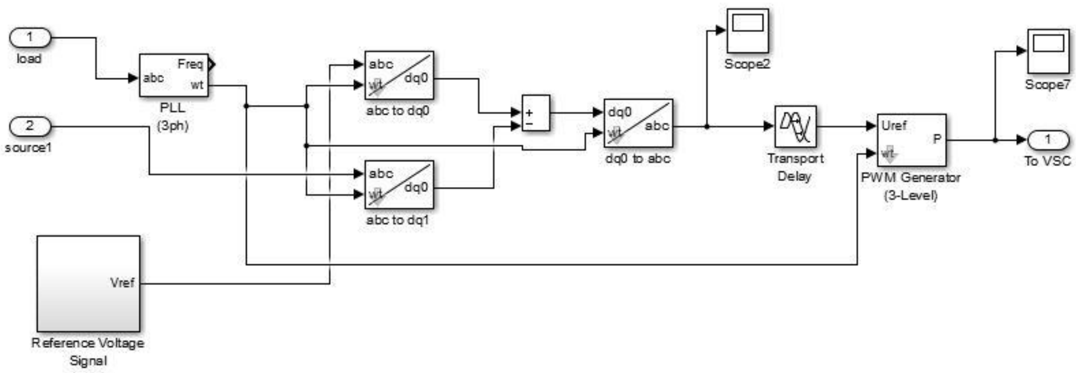


**Figure 4.2: Parks Transformation Detection Scheme**

## 4.2.Fuzzy Logic Controller:

Fuzzy set theory was first introduced by Lotfi Zadeh, a professor at the university of California Berkley and Mamdani was the first one to use fuzzy algorithms to the control system. The objective of the control scheme is to acquire an AC waveform that has low total harmonics distortion and good dynamic characteristics against supply and load characteristics. The complexity of the power system in increasing day by day and more and more power semiconductor switching custom power devices are incorporated into the grid. This make the system non-linear, complicated and difficult to model mathematically. The PWM schemes can perform well for linear load but when the nonlinear loads are there the voltage waveform tends to get distorted. Fuzzy Logic (FL) is a problem-solving control system methodology that lends itself to implementation in systems ranging from simple, small, embedded microcontroller to large, networked, multi-channel PC or workstation based data acquisition and control systems [12].

The PI controller is a generally used control scheme that is used for DVR. The PI controller is designed for a system performing in a very limited area. The parameters of the PI Controller are fixed and when the system parameters are changed the PI fixed parameters need to be changed accordingly for the controller to perform efficiently. So, generally designing the PI controller, prior information of the converter and some trials are needed to design the parameters. PI controller is a perfect example of traditional control systems which are based on mathematical models and any change in the parameters require that proper modelling of the system is done again[6], [11], [13]. In traditional control systems, the system response is usually defined by one or more differential equations. Fuzzy Logic comes in handy when such accurate modelling of the system is not possible like in the case of non-linear loads for the DVR. It offers a modest method to come to a sure conclusion founded upon unclear, uncertain, vague or missing input data[13].

With growing sophistication of modern technologies, the demand for the FL controller has risen. The complexities of the system have encouraged the use of more empirical approach systems because for many applications the mathematical models may not exist or the cost of the required digital technology may be too much. Fuzzy Logic Controller also gives an added extra layer of intelligence to the existing traditional controller systems. The Fuzzy Logic model is empirically based, relying on an operator's experience rather than their technical understanding of the system. The fuzzy controller designer must define what information/data flows into the system (control/input variable), how the information/data is processed (control strategy and decision) and what information/data flows out of the system (solution/output variable. Fuzzy Logic offers several unique features that make it a particularly excellent choice for many control problems [11], [13]–[16].

The fuzzy logic controller is used as a substitute for the conventional PI controller. The three-phase source voltages are transformed into *d* and *q* coordinate. The references values for $V_d$ and $V_q$ are compared with these transformed values and voltage errors are obtained. These errors are processed by two FL controllers evaluating 49 linguistic rules. Resulting outputs are retransformed into three-phase domain and compared with a carrier signal to generate PWM inverter signals. The proposed DVR has the capability of both balanced and unbalanced voltage sag compensation.

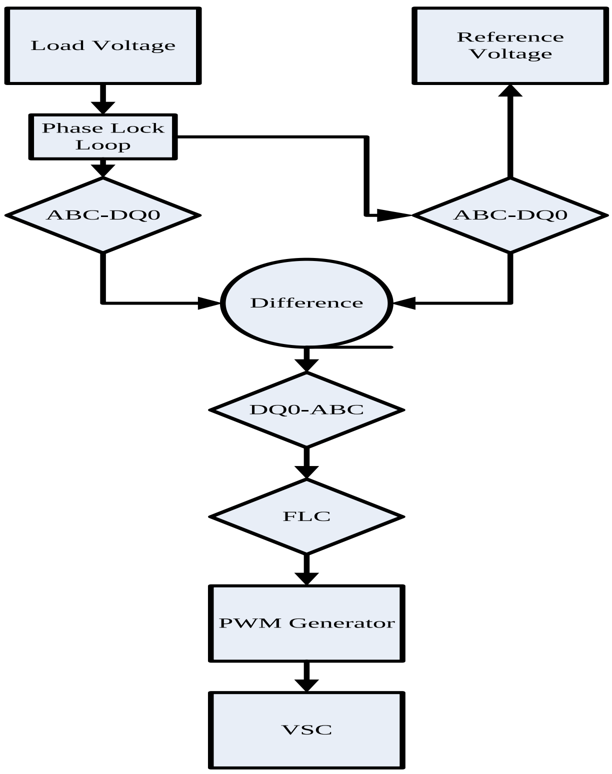


**Figure 4.3: Flow diagram of FLC Controller**

Fuzzy Logic Controller has two inputs measured at every sample time, which are labelled as error and error rate one output named actuating signal for each phase. The error is the subtraction between the injected voltage and the reference voltage while error rate gives the derivation of the error. The output of the fuzzy logic controller governs the voltage situation and directly instructs the switching process. There are three Stages involved in a fuzzy logic system which are fuzzification, decision making and de-fuzzification [17]–[20], [20]

### 4.2.1. Fuzzification

Every control set has its own set of language variable that it operated in and the first unit transforms the input variables of non-fuzzy nature into a fuzzy set (linguistic). Fuzzy logic

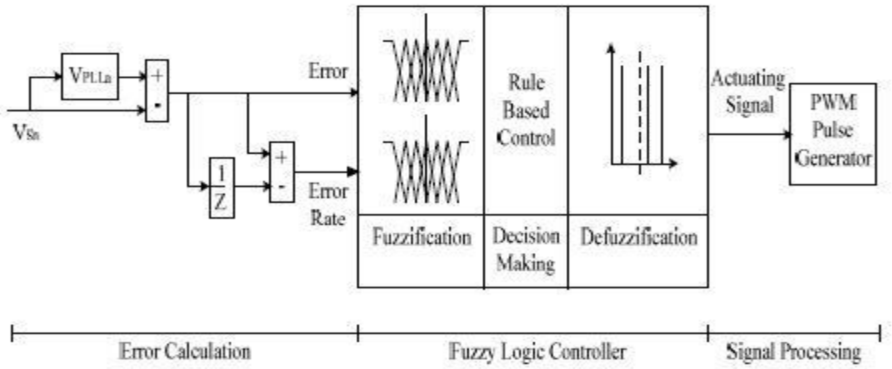


**Figure 4.4: FLC logic [19]**

controller only understands these fuzzy linguistic sets of clearly defined boundaries. The two inputs of the fuzzy logic controller are the error and the error rate. The linguistic variables that represent these inputs in this fuzzy logic controller system are Large negative (LN), medium negative (MN), Small negative (SN), zero (Z), small positive (SP), medium positive (MP) and the large positive (LP) characterized by memberships. The membership function in the fuzzy logic sets are a set of curves that define how each point in the input space is mapped to a membership value between 0 and 1. The most common type of membership functions are trapezoidal, bell shaped, triangular and constant functions. Three to seven curves are usually appropriate to cover the required range of an input value. The input membership functions are uniformly distributed over the input space. With this distributed scheme, the transition from one state to the next is not abrupt rather it’s a gradual change. The membership functions are usually overlapped which is more desirable for the fact that more isolated membership function will result in poorly defined operation and the output.

**Table 4.1: The weights of the input membership functions**

| Input | Error | Error Rate | Function |
|---|---|---|---|
| LN | -1.5 -1.5 -0.6 -0.4 | -0.5 -0.5 -0.2 -0.13 | Trapezoidal |
| MN | -0.6 -0.4 -.2 | -0.2 -0.13 -0.065 | Triangular |
| SN | -0.4 -0.2 0 | -0.13 -0.065 0 | Triangular |
| Z | -0.2 0 0.2 | -0.065 0 0.065 | Triangular |
| SP | 0 0.2 0.4 | 0 0.065 0.13 | Triangular |
| MP | 0.2 0.4 0.6 | 0.065 0.13 0.2 | Triangular |
| LP | 0.4 0.6 1.5 1.5 | 0.13 0.2 0.5 0.5 | Trapezoidal |

### 4.2.2. Decision Making

There are two methods in the fuzzy logic set where this fuzzy inference process is realized. one is the Mamdani's and the other is the Takgi-Sugeno method. The change between the two approaches is in the output membership functions. The Takagi-Sugeno output membership functions are linear or constant. It is a more compact and computationally efficient representation than a Mamdani System. Few number of fuzzy rules are needed in this method to express a highly non-linear functional relation. It also provides a higher performance and precision to the non-linear dynamic systems under various operating conditions. The determination of the output control signal is done in an inference engine with a rule base having if-then rules as

If Error is A, error rate is B: then output y=C.

Where A and B are the linguistic values of the error fuzzy sets of error and error rate, y is the output. The if-then rules connect the input to the output and thus define the fuzzy inference system (FIS). The decision table for if-then rules for the fuzzy logic control is given n 4.2. The Input of the FLC is associated with 7 membership functions, so the fuzzy system consists of 49 rules. These rules guide the operation of the FLC for optimum control action and each rule expresses an operating condition in the system. The design and efficiency of the FLC system depends highly on the experience and the technical knowledge of the designer about the behavior of the system. All rules are considered in parallel and correct use of these rules improve the system performance.

**Table 4.2: Fuzzy controller Control Rules**

| **E/ΔE** | **NL** | **NM** | **NS** | **Z** | **PS** | **PM** | **PL** |
|---|---|---|---|---|---|---|---|
| **NL** | PL | PL | PM | PM | PS | PS | Z |
| **NM** | PL | PL | PM | PM | PS | Z | NS |
| **NS** | PM | PM | PM | PS | Z | NS | NM |
| **Z** | PM | PS | PS | Z | NS | NM | NM |
| **PS** | PS | PS | Z | NS | NS | NM | NM |
| **PM** | PS | Z | NS | NM | NM | NM | NL |
| **PL** | Z | NS | NS | NM | NM | NL | NL |

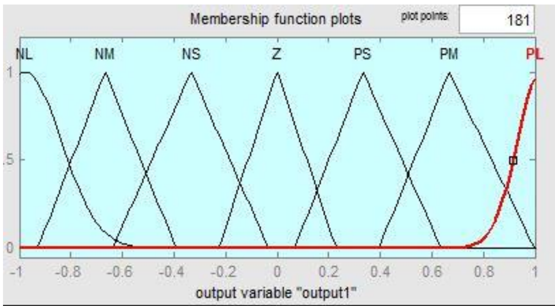


**Figure 4.5: Output member ship functions**

The system performance can be improved with increase number of rules in terms of accuracy but the complexity of the control system increases. Large amount of experiment shows that the distribution of the membership functions of input and output has different effect on the system performance. If the same distribution for all the membership functions is chosen, the optimal result cannot be obtained.

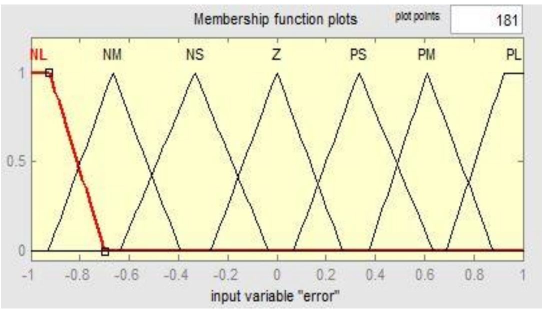


**Figure 4.6: Input membership functions**

### 4.2.3. De-Fuzzification

De-fuzzification is the inverse of the fuzzification process as the controller output is converted into a quantifiable result in crisp logic. It maps the fuzzy set to the crisp set. De-fuzzification is interpreting the membership degrees of the fuzzy sets into a specific decision or real value. The method used in this study for de-fuzzification is the centroid method.

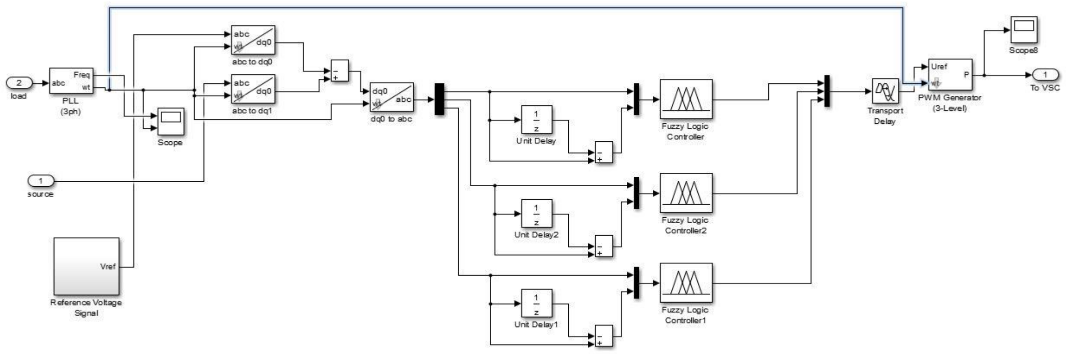


**Figure 4.7: FLC model in MATLAB**

In this Study, the FL controller is added to the existing dq0 transformation control scheme to make the compensation process more efficient. The output of the dq0-abc converter block is fed to the DEMUX where it is broken down into its constituent three signals and each signal acts an input for the FL controller. One input is the error and the second input is its derivative called error rate. All the FL controllers are equipped with same set of rules and their output is then fed into a MUX to transform the signal into one three phase signal used for the pulses generation in the PWM generator.

## 4.2.4. Signal Processing

The output of the LFC is then fed into a PWM generator which then creates the gate voltage signals for the IGBTs of the VSC according to the output of the FL controller.

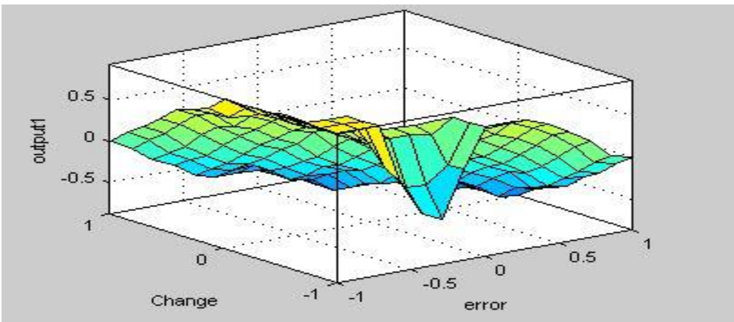


**Figure 4.8: Surface View of FLC**

According to IEEE Standard 519-1992, the objective of the current limit is to limit the maximum individual frequency voltage harmonic to 3% of the fundamental and the voltage THD to 5% for the system without a major parallel resonance at one of the injected harmonic frequency (IEEE Std. 519, 1992). The simulation results should meet the IEEE recommended standard limits

## 4.3. Conclusion

This chapter introduces us to the concept of the control system of the DVR and why it's of certain significance. The detection scheme of DQ0 is discussed and then an added controller of Fuzzy logic is introduced into the system. The concept and designing of the fuzzy logic controller is described in detail.

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# Chapter 5

# Simulation Results & Discussion

## 5.1.Simulation

In this simulation study, it is aimed to have the following attributes for load voltages:

- rms voltage recovery greater than 90% of nominal value
- The maximum individual frequency voltage harmonic to 3% of the fundamental value and the voltage THD to 5% for the system
- Load current THD as low as possible for voltage harmonic sensitive applications
- Losses of designed DVR lower than 1% of the nominal rating

## 5.2.Test System

Test System is modeled in MATLAB/Simulink environment. In this Test system, a programmable voltage source is used to generate the 15-kV signal which is then fed to a step-up transformer. The Step-up transformer steps up the voltage from 15 kV to 115 kV. a three phase RLC branch is used to implement the transmission line characteristics. At the End of the transmission line there is a step-up transformer hat brings the voltage down to 11 kV. This Transformer is connected in the primary distribution system whose primary voltage is 11 kV. Another Step-down transformer is connected at the load end which transforms the voltage to 380 V to which the load is rated to operate on.

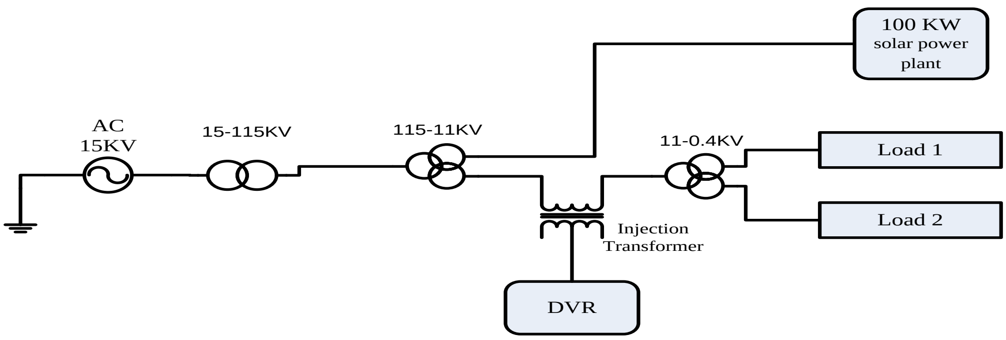


**Figure 5.1: DVR Test System**

### 5.2.1. Solar Power Plant[1]

A 100-kW PV array is connected to a 11-kV grid via a DC-DC boost converter and a three-phase three-level Voltage Source Converter (VSC). Maximum Power Point Tracking (MPPT) is implemented in the boost converter by means of a Simulink® model using the 'Perturb & Observe' technique.

The average model contains the following components.

- **PV array** delivering a maximum of 100 kW at 1000 W/m^2 sun irradiance.
- **DC-DC boost converter** (orange blocks)
- **3-level 3-phase VSC** (blue blocks).
- **100-kVA 260V/11 kV three-phase coupling transformer**.
- **Utility grid**

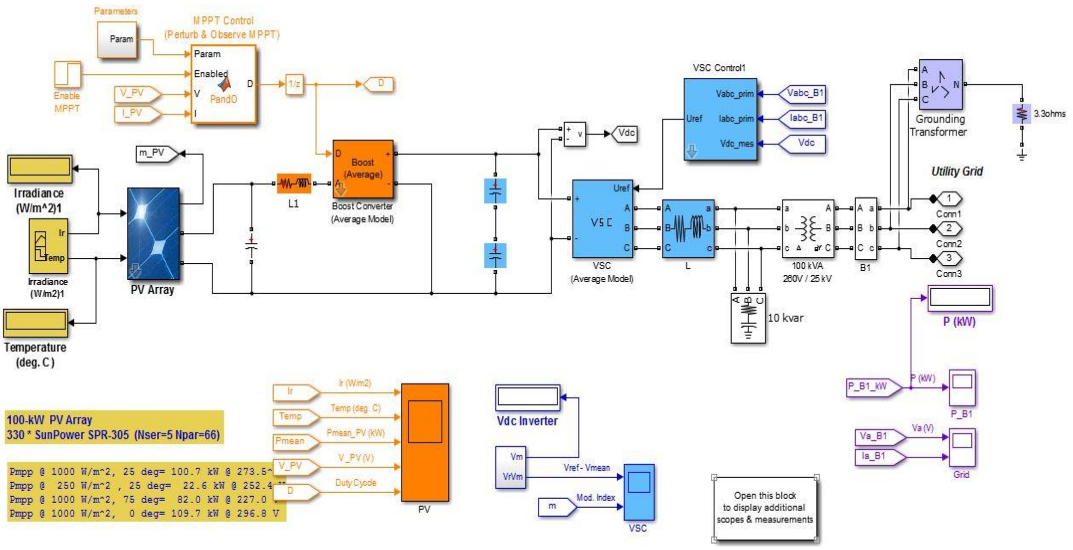


**Figure 5.2: 100-kW PV array in MATLAB**

The 'Perturb and Observe' MPPT algorithm is implemented in the MPPT Control MATLAB® Function block. The 100-kW PV array consists of 66 strings of 5 series-connected 305.2-W modules connected in parallel (66*5*305.2 W= 100.7 kW).

The PV array block has two inputs that allow you varying sun irradiance (input 1 in W/m^2) and temperature (input 2 in deg. C). The irradiance and temperature profiles are defined by a Signal Builder block which is connected to the PV array inputs.

## 5.3.Single line to ground Faults

This is the most common occurring faults in the power system in which one of the three phase experiences a fault and a voltage sag is caused[2], [3]. In this research, the Single-phase fault causes voltage sag of 30% in an 11-kV network. Fig 14 shows the voltage profile after the voltage sag of 30 is introduced in Phase A from 0.1 to 0.3 of the simulation time. The Two dynamic voltage restorers are installed in the system and their performance in compensating the voltage sag is analyzed.

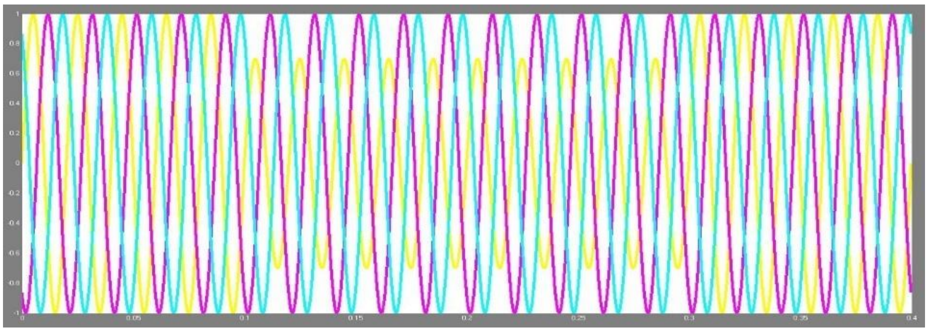

**Figure 5.3: Single Phase 30% Voltage Sag**

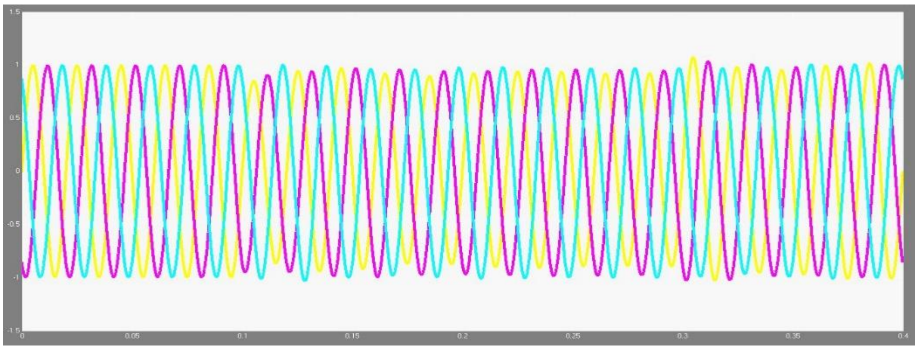

**Figure 5.4: load Voltage after DQ0 DVR injection**

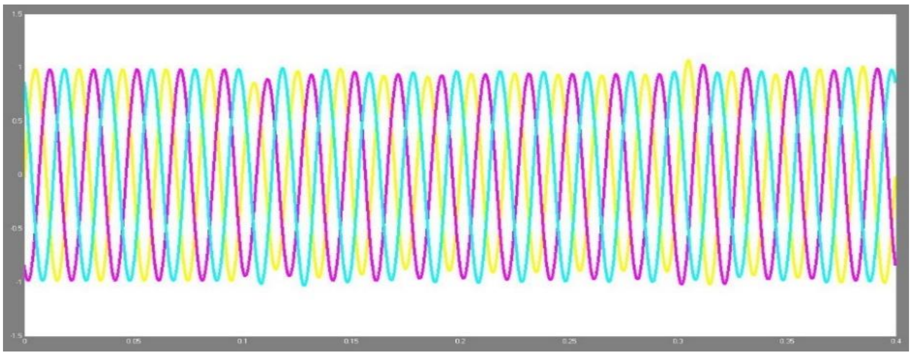

**Figure 5.5: Load Voltage after FLC DVR compensation**

Figure 5.3 shows the load voltage after the installation of the DQ0 based DVR. The DVR can mitigate the voltage sag caused by the single line to ground fault and restores the load voltage to 93% of the load voltage. Initially, the supply voltage is at the rated level so the power flow from the DVR to the grid are none as there is no voltage injection but as soon as the fault is introduced in the system that causes a voltage sag, the fuzzy controlled PWM converter starts producing the missing voltage to compensate for the voltage sag. Figure 5.4 represents the load voltage after using the FLC based DVR for compensation and it also helps restore the load voltage back to its normal voltage level but not entirely. The load voltage after experiencing 30% Voltage sag caused by SLG is restored back up to 96% of the reference voltage. Although, it is observed there is some voltage generated by the DVR in the standby mode and is injected which is due to the non-linear behavior of the DVR. Other Phases, B and C, remain unaffected by the voltage sag because the transformers eliminate the zero sequence components from the system. The THD analysis of both load Voltages demonstrate that both DVR operate in range of the IEEE Standards i.e. the injected harmonics are less than 5%. The DQ0 based DVR injects 4.3% harmonics and the FLC DVR causes only 3.7 % harmonics in the power system.

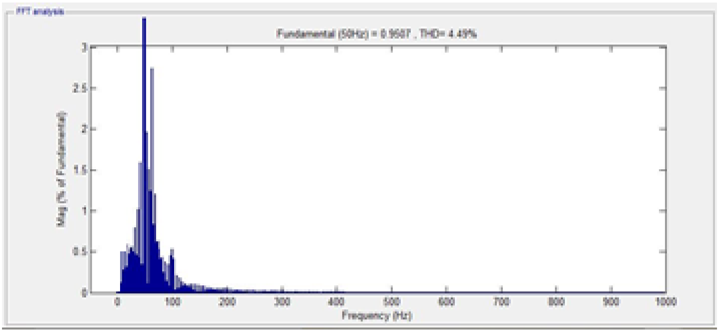


**Figure 5.6: DQ0 DVR FFT analysis for single phase voltage sag**

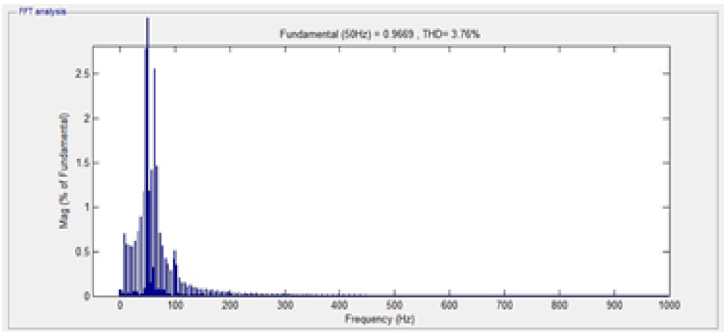


**Figure 5.7: FLC DVR FFT analysis for single phase voltage sag**

## 5.4.Double Phase Faults:

The analysis of Double line to ground faults shows that the DQ0 DVR restores the voltage up to 93% of the reference voltage as can be seen in figure 5.9 and the FLC DVR is able to improve the voltage profile up to 95% of the reference voltage seen from figure 5.10 thus performing better than the DQ0 based DVR. The FFT analysis shows that the THD levels are also under the allowed limit by the IEEE standards. DQO DVR injecting 3.81% while the FLC DVR injecting only 3.05% harmonics.

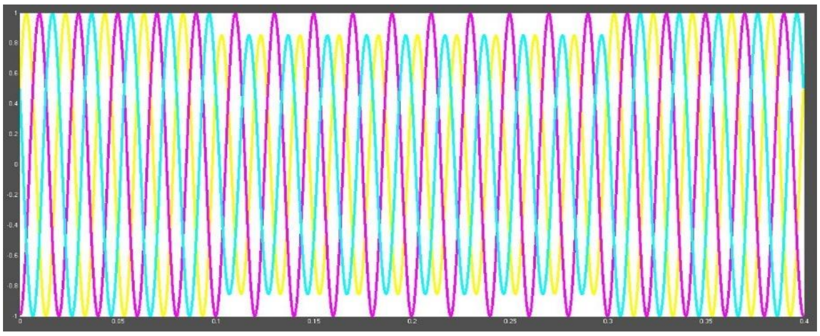

**Figure 5.8: voltage sag after double line to ground fault**

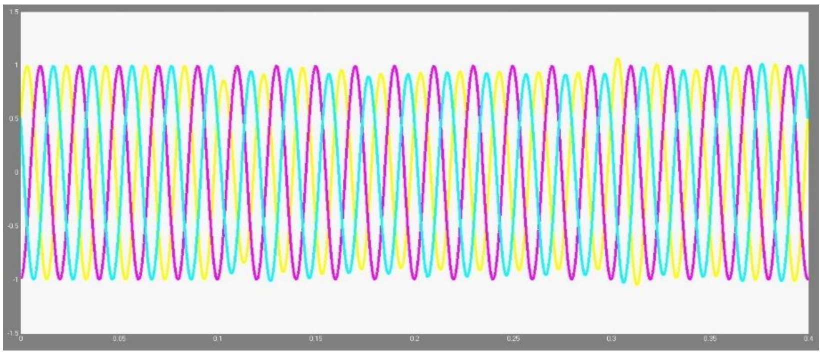

**Figure 5.9: Load Voltage after DQ0 DVR compensation**

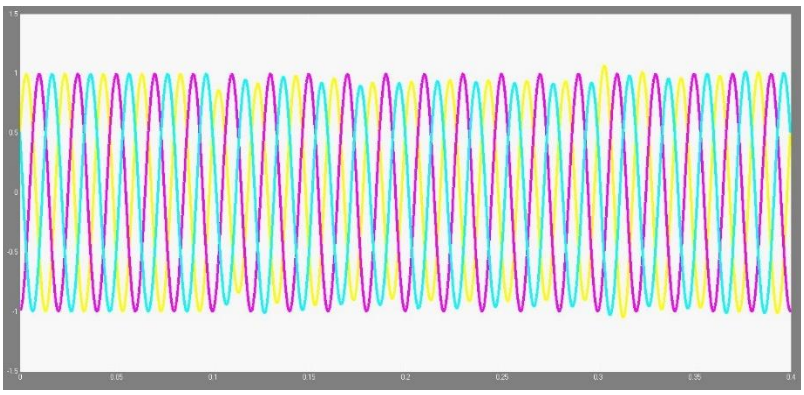

**Figure 5.10: FLC DVR for double phase voltage sag**

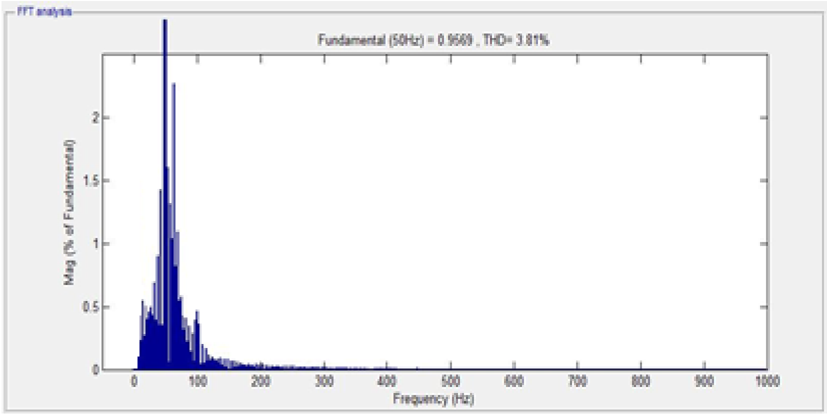


**Figure 5.11: DQ0 DVR FFT analysis for double phase voltage sag**

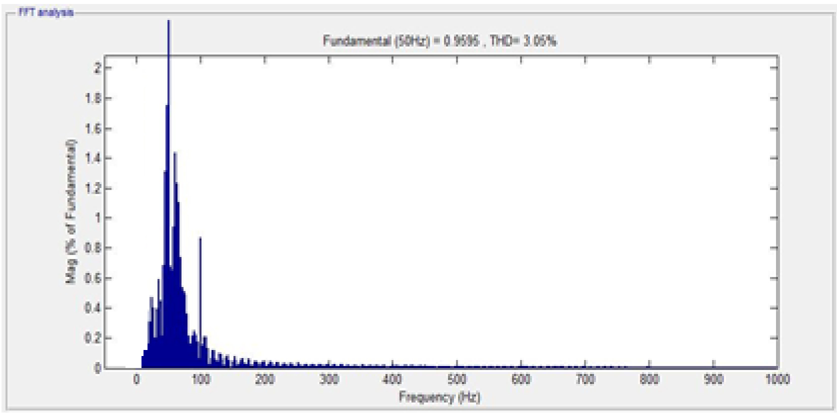


**Figure 5.12: FLC DVR FFT analysis for double phase voltage sag**

## 5.5.Three Phase Faults:

The three Phase to ground fault causes a symmetrical voltage sag of 30% in the load voltage for 200 milliseconds. The DVR inject the compensating voltage signal into the power system at PCC and try to restore the voltage back to its normal voltage. It can be seen from the figure 5.14 that the DQO based DVR was successful in compensating the voltage signal up to 91% of the load voltage while the figure 5.15 shows that FLC DVR once again performed better that its competitor in restoring the voltage up to 94% of the reference voltage. The FFT analysis also goes in favor of the FLC controlled DVR as it injects only 4.13% Harmonics to the 4.30 % injected by the DQ0 based DVR.

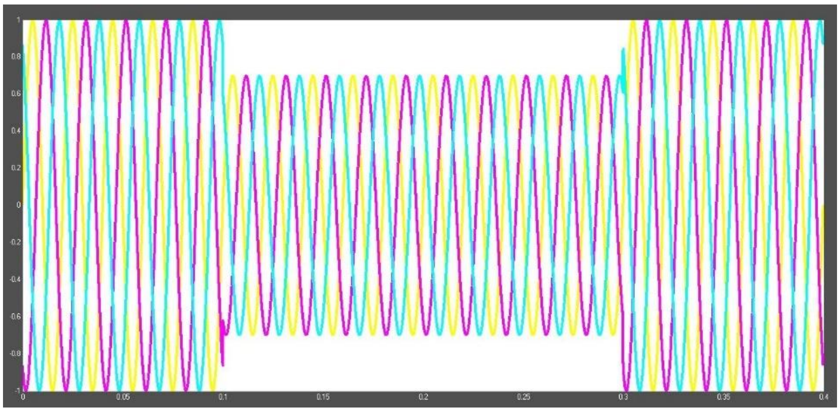

**Figure 5.13: 30% Voltage Sag Three Phase fault**

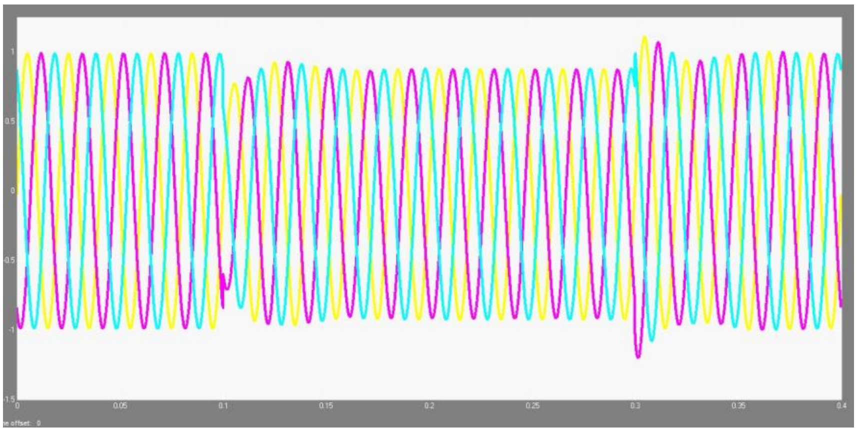

**Figure 5.14: Load Voltage after DQ0 DVR Injection**

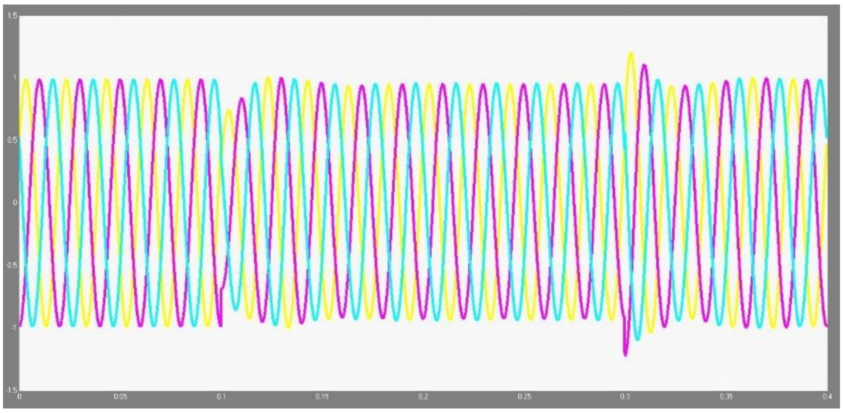

**Figure 5.15: Load Voltage after FLC DVR compensation**

## 5.6.Total Harmonics Distortion Analysis (THD)

**Table 5.1: THD Analysis of DQ0 & FLC DVR**

| | **Source voltage THD (%)** | **DQ0 DVR THD (%)** | **Fuzzy Logic Controlled DVR THD (%)** |
|---|---|---|---|
| | $V_s$ | $V_{load}$ | $V_{load}$ |
| **SLG** | 11.97 | 4.30 | 3.76 |
| **DLG** | 7.31 | 3.81 | 3.05 |
| **Three Phase Fault** | 12.98 | 4.30 | 4.13 |

## 5.7.LOAD Voltage Compensated level

**Table 5.2 Load: Voltage levels after Compensation in per unit**

| | **DQ0 DVR** | | **FLC DVR** | |
|---|---|---|---|---|
| | **Load Voltage before compensation (pu)** | **Load Voltage After compensation (pu)** | **Load Voltage before compensation (pu)** | **Load Voltage After compensation (pu)** |
| **SLG** | 0.98 | 0.93 | 0.98 | 0.96 |
| **DLG** | 0.98 | 0.93 | 0.98 | 0.95 |
| **Three Phase Fault** | 0.98 | 0.91 | 0.98 | 0.94 |

The fuzzy logic controlled DVR & DQ0 based DVR were been developed in this thesis to response quickly (less than 2 ms) and obtain a good dynamic performance. The control method does not require a complex computer algorithm. The elimination of transformations, multiplications and divisions makes the FLC control system simple and more reliable. The controller has obtained high performance with relatively low sampling time and switching frequency. A phase locked loop (PLL) has satisfactorily tracked the source voltage and generated reference signal for PWM modulation without experiencing a disturbance. The control system has not dealt with the compensation of zero sequence voltages because the faults have occurred in medium voltage system and the shunt transformers connected in delta have eliminated these voltage components.

The LC filter unit has eliminated the dominant harmonics of the inverter output voltage and kept the total harmonic distortion of the load side below the standard limits. The even harmonics can become visible in the load side due to small negative sequence components and natural unbalances in the system. The proper meetings of the LC filter and control algorithm have improved the power quality of PWM inverter output without disregarding duration and magnitude of the sags. It is appropriate before choosing the rating of DVR components to determine a proper compensation strategy. The control algorithm based on in-phase injection method has been employed in the thesis. This method has ensured the minimum injected voltage magnitude and reduced active power injection especially for high power factor loads.

Both DVR have shown the ability to mitigate the voltage sags at the PCC. DVRs have stayed in standby mode until the sag magnitude exceed the its limit. The small voltage drop on the sensitive load can be seen during standby mode because DVR uses series based topology and is composed of non-linear semiconductor switching devices. The voltage injection has been allowed until the source voltage reached its pre-fault level.

The carefully chosen three case studies have been realized to verify the operation and performance of the designed system in MATLAB/Simulink program. The voltage sags have been generated by performing controlled short circuits in the grid. It is concluded that the proposed DVR has successfully mitigated the long duration balanced and unbalanced voltage sags and perfectly restored the critical load voltage to nearly 1 pu. In all simulated cases, the fundamental values (50 Hz) of load voltages have been kept higher than 91% of nominal and THD of load voltages have been kept less than 5% of nominal. The results have verified the efficiency, flexibility and transient response capability of the developed control strategy. The designed DVR has provided a regulated and sinusoidal voltage across the sensitive load. The nearly perfect sinusoidal output voltages have resulted in improvements in the current and power quality of the sensitive load.

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# Chapter 6

# Conclusion

The proposed DVR rated for 20 kVA has been assumed to be in medium voltage distribution network level and it can mitigate three-phase sags up to 30% of the nominal voltage. The studied DVR is based on voltage source inverter (VSI). Pulse width modulation (PWM) technique with switching frequency 2 kHz has been employed in VSI. The DVR has been designed with special importance at the control of PWM inverter. The quick response and high performance have been proposed in the thesis. The traditional control techniques have been analyzed and it has been deduced that they have three main drawbacks: slow transient response, necessity of complex mathematical modeling of the system and requirement of the transformation process.

The proposed system has shown that a high efficiency and reliability can be reached theoretically. The IGBT based VSI technology and dynamic performance capability of fuzzy controlled DVR have improved the quality of critical load quantities by preventing the sags and losses. The suitable settings of DVR parameters have successfully dealt with the various levels and types of voltage sags. The system has eliminated the voltage harmonics and reduced the transient time when switching to the standby mode or the injection mode. The system has successfully met IEEE 519 harmonic standard under all fault conditions.

The DVR is considered the best cost-effective solution against the voltage sags. However, DVR has two main drawbacks which are the need of an energy storage device that could be quickly operated and existence of harmonics in the system during the fault period. Some studies have proposed to reduce the drawbacks and cost of DVR and improve the response of it. The new researches to reduce the cost and improve the response of DVR are the addition of DC/DC converter for minimizing the energy storage device, transformer-less DVR and absence of energy storage device. The application of voltage tolerance compensation method for injection strategy and three-level converter to minimize the harmonic content are other interesting alternatives. The DVR is considered a new class of power electronic based equipment for electric power systems. The simulation results of fuzzy controlled DVR are encouraging future research in the fuzzy controller applications.

## Future recommendations

The suggestions for future researches on this topic should be pointed out which are given below:

- The developed control strategy and designed DVR should be tested by connecting the DVR into a real network where the efficiency and accuracy of the proposed system can be better evaluated.
- The efficiency and performance comparison of fuzzy controlled DVR with, neural network and PI controller based DVR.
- Modeling and verifying the proposed control system using PSCAD/EMTDC simulation program.
- The detailed study for the effect of transient characteristics of the system, voltage unbalance, voltage harmonics and various load types on the performance of DVR.
- Application of proposed control algorithm to other kinds of series type voltage compensators such as series active filters, static synchronous series compensators and bootstrap variable inductances.
- Mitigation of zero sequence components from the sensitive load side by improving the proposed control scheme if the transformer is not delta connected.

By performing the suggestions for future researches on this topic, the DVR technology can be rapidly and efficiently developed and employed.

c

# Acknowledgement

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In the end love and gratitude for my dear family, on whose unconditional love, support and encouragement, I have relied throughout my studies.

# Advances in the Control & Energy Storage systems for Dynamic Voltage Restorer (DVR): An Overview

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## Abstract:

Dynamic Voltage Restorer (DVR) is a series connected power electronic devices that is used in the distribution system of medium voltage (MV-DVR) as well as Low voltage (LV-DVR) levels for the compensation of the voltage sags/swells caused by the different faults within the power system. This study gives a comprehensive overview of the advances in the field of the Dynamic voltage restorer's energy storage techniques as well as the development in the control systems techniques for the DVR. The effectiveness of these control schemes in comparison to other control schemes has also been discussed.

**Keywords:**

Dynamic Voltage Restorer (DVR), Compensation voltage, DVR Control Systems, DC Energy storage, Fuzzy Logic controller.

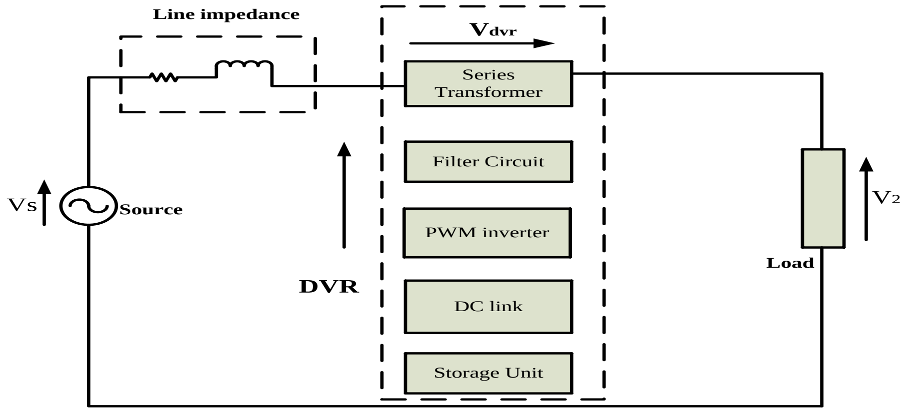
## 1. Dynamic Voltage Restorer (DVR):

Power Quality is one of the most significant characteristics of the modern power systems and to ensure that the power in a system is maintained at a standard level power electronics based custom power devices are widely connected in the modern power systems. The use of sophisticated sensitive digital devices in residential, commercial and industrial sectors is on a rise in recent years and raised the issue of continual service of superior quality power to avoid any damage to the equipment leading to economic loss for the consumer. The Dynamic voltage restorer (DVR) is a custom power device that is generally installed in series with a distribution system between the voltage source and the critical load feeder at the PCC to protect from the voltage fluctuations in the network. It is the utmost cost-effective answer to voltage profile problems whether it be sags, swells or interruptions. Additional properties that include line voltage harmonics compensation, fault current limitations and reduction of transients in voltage make DVR a more attractive Custom power device to use. A pulse width modulated voltage source inverter, that generates or absorbs real or reactive power independently is used in DVR, a series conditioner device.[1] The DVR with the lead acid battery is an engaging method to deliver admirable dynamic voltage compensation ability, This DVR also holds the edge of being economical when compared to shunt connected devices. Whenever the System experiences voltage sag/swell, voltage unbalance and voltage harmonics, the DVR can keep the load voltage at a standard amplitude and phase at the point of common coupling. The DVR can generate or absorb independently controllable real and reactive power at the load side. The DVR is made up of solid state DC to AC Switching power converter that ensures that the distribution line voltages maintain their standard voltage by injecting or absorbing independently controllable real or reactive power into the grid though PCC. The DVR operation does not depend upon the type of the fault of any kind of activity happening in the system and performs its operation if that the entire system stays coupled to the supply grid.[2]

### 1.1. Basic Components of DVR:

A conventional DVR system mainly comprises of two major parts. Frist is the power circuit and second is the control unit. Basic components of DVR consists of the following[2][3][4]:

- Energy Storage device
- Series injection Transformer
- Voltage Source Converter
- Passive filter
- Control system




*16 Block Diagram of Dynamic Voltage Restorer*

### 1.2. Operation of DVR:

The Two mode of operations of DVR are standby mode and the second is called Boost Mode. The DVR is not supplying any compensation signal and the network is bypassing the DVR during Standby. In the injection mode, the $V_{DVR}$>0, which means that the DVR is providing a compensation signal to the network through the injection transformer

### 1.3. Voltage Injection Modes:

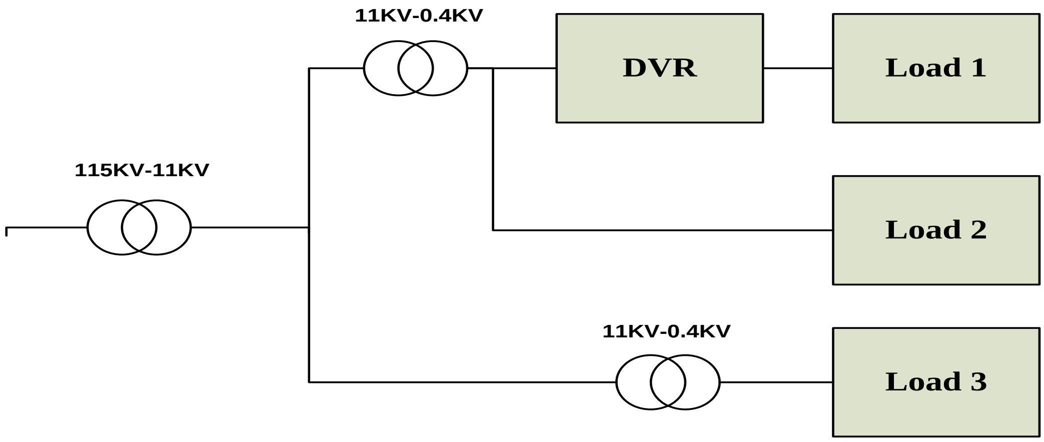
A Dynamic Voltage Restorer can inject the compensating signal in four different method[5]

- Pre-sag compensation
- In phase compensation
- In phase advanced Compensation
- Voltage tolerance method with minimum energy injection

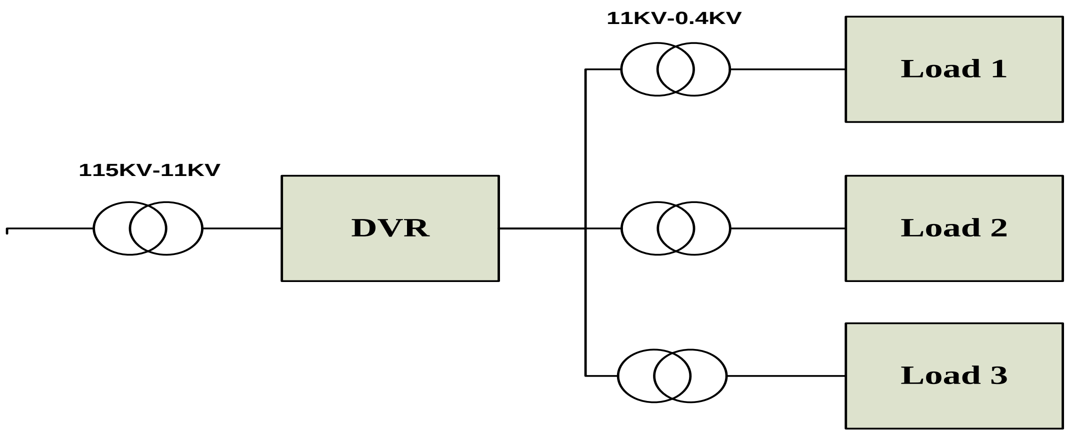
There has been a lot of development in the field of Dynamic voltage restorer in recent years and further studies are being performed to enhance the operation and efficiency of the Dynamic voltage restorer. Globally the market of DVR is expanding owing to excellent manufacturing capabilities, latest research and the realization of its importance in the power system. Dynamic voltage restorer can be designed and implemented at different voltage level with in the distribution system. It can be installed near to the sensitive load on low voltage distribution system and also in the medium voltage distribution network that allows it to protect a wide range of loads and part of the distribution network. Of course, the DVR installed at the medium voltage distribution network will be higher in ratings then the DVR used at low voltage network. Using DVR at low voltage network requires greater number of DVRs for protection of individual loads whereas only a few DVRs at Medium voltage distribution network can protect a large number of loads[6]. There are two major areas in DVR that are under focus these days. The Energy storage that is being used to generate the compensation signal and the Control System of the DVR. With both having huge potential for further innovation and improvement. Both the energy storage and the control system are discussed in light of recent studies related to DVR in the next sections

## 2. Energy Source for the DVR:

The energy source is a basic component of the DVR arrangement as it is the source of the compensation signal which is then injected into the power system to stabilize or regulate the Voltage levels. The voltage necessary can be acquired in two basic ways. First is from the grid to which the DVR is connected. An arrangement of rectifiers in series with the DVR can provide the DC voltage that is required for compensation signal generation and second is by using an independent voltage source. Different topologies are used for the energy sources for the DVR systems which are given below.




*17 DVR installed at Low level voltage Network*




*18 DVR installed at Elevated Level Voltage Network*

- Auxiliary Supply
  - Variable DC link Voltage
  - Constant DC link Voltage
- Line Connected Shunt Converter
  - Load Side Connected
  - Source Side Connected

## 2.1. Auxiliary Supply

If the system that the DVR is connected to is weak then this topology is preferred to increase the performance. There are two topologies when using auxiliary supply, variable DC link Voltage or DC link Voltage.

### 2.1.1. Variable DC link Voltage:

In this topology, a low rating DC link is used that incorporates a capacitor. This deals with the short-term voltage sags because its capacitor decays exponentially and it cannot handle long time sags. The energy stored in the capacitor is given by the following equation.

$$E_{st} = \frac{1}{2} C_{DC} V^2{}_{DC} \quad (1)$$

$$P_{Series} = \left(1 - \frac{V_{pcc}}{V_{rs}}\right) P_{load} \quad (2)$$

In the above equations, the DC link voltage is represented by $V_{DC}$ and the $C_{DC}$ is the capacitor capacitance. $V_{PCC}$ gives the sag voltage at the point of common coupling whereas $V_{rs}$ is the Source voltage. $P_{series}$ and $P_{load}$ are the powers handled by the series converter and the load respectively.

### 2.1.2. Constant DC Link Voltage

This topology is used for a better performance through continuous supply of constant voltage. the energy is provided through a high-energy storage to the small rated DC link that helps in ensuring that the DC link voltage is kept constant. The complexity of this topology increases though. If the DVR is connected to the strong grid, the remaining voltage can be used to provide the required power to the system through line connected Shunt converter & DVR.

## 2.2. Line Connected Shunt Converter

### 2.2.1. Supply Side Connected Converter:

In this topology, the DC link capacitor is charged through the shunt converter which is connected to the supply side, an uncontrollable DC link voltage. The DC link voltage is effected during the compensation of the voltage sags and its voltage will drop according to the equation below

$$V_{DC} = \sqrt{6} V_s = \sqrt{6} V_{pcc} \quad (3)$$

$$P_{shunt} = P_{series} = 3\left(1 - \frac{V_{pcc}}{V_{rs}}\right) P_{load}) \quad (4)$$

$$I_{shunt} = \frac{\left(1 - {V_{pcc}}/{V_{rs}}\right)}{{V_{pcc}}/{V_{rs}}} I_{load} \quad (5)$$

The power handled by the shunt converter is equivalent to the voltage difference between the supply voltage and the load voltage.

### 2.2.2. Load Side Connected Converter

In this topology, the shunt converter used to charge the DC link is connected on the load side which means that the load voltage will provide the energy required to compensate its missing part. The DC link voltage remains constant as its being provided from the corrected constant load voltage. however, the currents drawn by the shunt converter on the load side will be distorted in nature and its will seriously degrade the power quality of the load voltage.

$$V_{DC} = \sqrt{6} V_L \quad (6)$$

$$P_{shunt} = P_{series} = \frac{\left(1 - {V_{pcc}}/{V_{rs}}\right)}{{V_{pcc}}/{V_{rs}}} P_{load} \quad (7)$$

If the line connected Shunt converter is used to power the DC link for the VSC then the DC charging Circuit will be needed that will have two tasks to perform

- Keep the Energy Source Charged after a sag compensation

- Maintain the DC link Voltage at the nominal DC link Voltage

The Problem with energy Storage systems are their costs. Large Energy Storage systems cost too much to be incorporated for systems like DVR. The size of the energy storage effects the performance limitation of dealing with longer voltage interruptions. Therefore, we see most of the proposed solutions are realized through a shunt converter fed from the line itself. The DC voltage source can also be any kind of energy storage devices like batteries or flywheels or also be an autonomous generation source such as PV and fuel cells equipped with storage devices for better performance. Photovoltaic based DVR have been presented in literature in which the PV Arrays are used as a source of energy for compensation signal generation. DC-DC converter arrangement is required to control DC link voltage due to the varying nature of solar power [7]. The series injection transformer is provided for the injection of series voltages during sags, swells and is configured into parallel connection through switches when the system is experiencing a power outage. The PV cell output voltage depends on photocurrent that mainly is derived by the load current but it also depends upon the solar irradiation level throughout the process. The PV cell output voltage is given by the following equation.

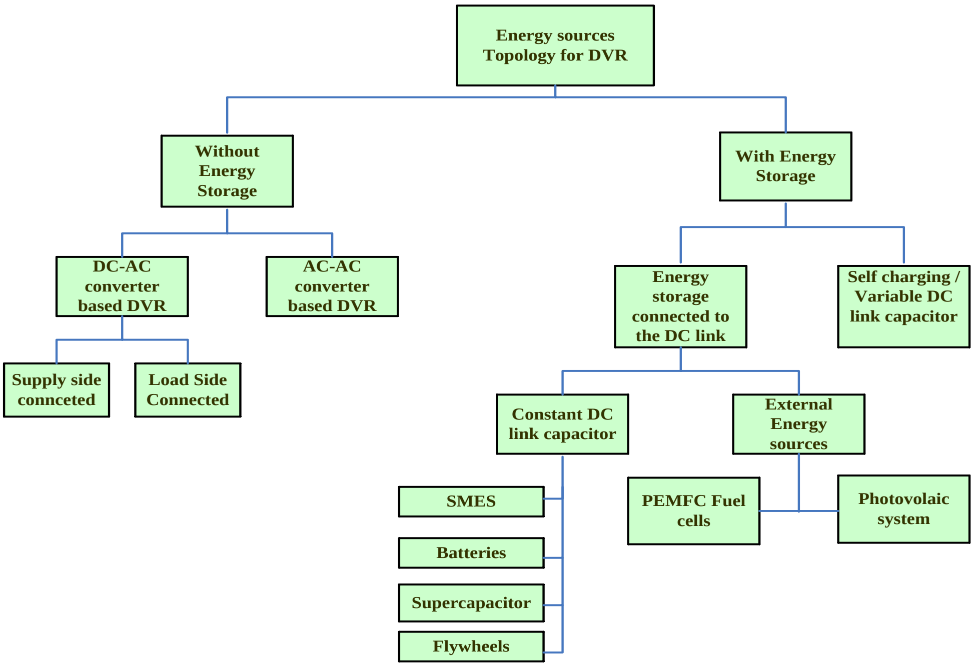
$$V_o = \frac{AkT_c}{e} \ln(\frac{I_{ph} + I_0 - I_c}{I_0}) - R_s I_c \qquad (8)$$

Where e= charge of an electron, k= Boltzmann constant, $I_{ph}$= photo current, $I_0$= reverse saturation current, $I_C$= cell output current, $R_S$= internal resistance of PV cell, Tc= Solar cell operating temperature Studies have shown that PV based arrays can be used instead of a capacitor bank or battery bank for the generation of compensation signal for DVR during daytime and through the energy stored in the reserve batteries during the daytime through PV arrays [7][8]. On the other hand, there are drawbacks of using the PV as a source of energy in DVR due to intermittent nature of the sunlight but [9] deals with one such drawback and introduces the maximum power point tracking(MPPT) through fuzzy based Perturb & Observe (P&O) algorithm that eradicates the disadvantage of original PV-DVR and helps in optimizing the PV-DVR application and conserving the total energy use. This way the PV-DVR can act as the sole source if the Maximum demand can be met by the PV during the day by cutting off the Grid supply. In sunny days, it can save up to 12.6KWh of energy for a residential or small industrial customer. There are two factors that affect the Operation temperature of the PV cell, first is the solar irradiation level and second is the ambient temperature of the environment where the solar cell is functional. CTV and CTI are the temperature coefficients that are used to represent the effect of the change in the solar radiation levels and the ambient temperatures

$$C_{TV} = 1 + \beta_T (T_a - T_x) \qquad (9)$$

$$C_{TI} = 1 + \frac{\gamma_T}{S_c} (T_a - T_x) \qquad (10)$$

Where $\beta_T$ = 0.004 and is the slope of the coefficient CTV and $\gamma_T$ = 0.006, is a constant that represents the variation in temperature because of change in solar radiation. $T_a$ Represents the ambient temperature of the cell and $T_x$ represent the ambient temperature of the atmosphere. The PB based DVR with low DC-DC boost converter equipped with fuzzy logic controller based P&O MPPT Algorithm, when applied with minimum energy injection technique at low voltage distribution system for residence or small industrial load has shown to save up to 2900$ per year in panel tariff costs[10].The use of interleaved high step up DC-DC converters instead of low boost DC-DC converters further enhances the performance of the PV based DVR [11] The Advantages that interleaved high step up DC-DC converters hold over low boost converters is that they are ran at high ratios which cause high voltage and current stress on switch. The voltage gain is higher as compared to other converters and the current is ripple free.




The grid integrated PV systems can also be integrated with the DVR systems and incorporated in such a way that the same PV systems that are supplying Grid with energy act as the source of energy for DVR to generate compensation signal. Generally the PV systems and the DVR systems each uses separate converters but [12] proposes PV and DVR integration in such a way that only one converter is required for the operation of grid connected PV and DVR system, thus reducing the switch count by 25% than conventional system and also allows the DVR to use the active power generated by the PV systems to fight the deep voltage sags more efficiently thus increasing the DVRs operating range. The proposed Configuration is useful for low to medium power load with sensitive devices and considerable onsite PV generation capacity. The Proposed configuration uses six port output converters in which three ports are assigned to the converters connection to the grid while other six are for the DVR converter. PV isn't the only non-conventional source of energy used in DVR application. Proton exchange membrane Fuel cell (PEMFC) Stack through a DC-DC boost converter that boosts up the output voltage of fuel cell to fulfill the DC requirements for the voltage source converter has also been used in literature [13]. The output voltage of the PEMFC is low but it is converted to higher levels through the boost converters. One of the advantages it has over the use of PV-DVR is the slight greenhouse gas emission and a reliable efficient system operation.[14] Uses the AC-DC-AC topology where the DC voltage is made available via a transformer from the grid via a rectifier for the DVR required energy for compensation voltage, filter, phase angle regulator, tap changing transformer and Quadrature booster using a distinct procedure that entire process is performed by a lone entity. This topology is preferred when the system is experiencing deep voltage sags. DVR based on energy storage device are not suitable for the compensation deep sags i.e. <0.5 p.u. The Shunt converter based DVR can produce voltage signal of any range by appropriate choice of the firing angles. The theoretical range on attainable load voltage is given by the following relation

$$V_l = \frac{V_{t1}}{\sqrt{1 - a_1^2}} \tag{11}$$

And the DVR voltage Equation is given by

$$V_{DVR} = a_1 * \frac{V_s}{Cos\emptyset} \tag{12}$$

The phase angle is regulated through the Phase Angle regulator (PAR) but when DVR is padding through the PAR it results in a voltage drop. This scheme allows the DVR to deal with voltage sags problems in power systems with deep and frequent voltage sag problems. Studies have shown almost a 50 % improvement on the weakest bus of the system.[15] discusses a self-supported DVR where a large DC capacitor is used for the compensation signal generation. The reactive power needed for compensation is generated entirely by the PWM converters but the exchange of active power is done through storage elements as large capacitors.

The Shunt converter topology doesn’t use any energy storage devices rather small DC link capacitors but the energy is extracted from the grid itself. This is done through supply side connected converters and load side connected converters. DVR compensates the voltage by providing real and reactive power to the load, if the real power is needed to be transferred then there must be a source of power which in this case is grid itself. [16] focuses on the use of DC link which is split between low voltage capacitors. These capacitors are charged through the power from the grid using shunt converters. Next the unidirectional full bridge DC-DC converters are used that provide voltage for the CMI based Full bridge inverters. This proposed scheme implements the HF transform based isolation for medium level voltage application. As this is a higher voltage application, several DC-DC converters are stacked together to split the DC-link between several low-voltage capacitors. HF transformer is preferred to line frequency transformer because of its low weight, small size and its ability to evade any kind of overload in the startup transient. In[17], a comparison of these shunt converter topologies and a constant DC voltage source is presented. The first topology with supply side connected rectifier, the DC capacitor kept discharging until the sag ended so the size of the DC capacitor matters a lot in this topology. In the load side connected rectifier, the DC link capacitor supplies the power to the load and the DC link voltage drops to half of the load voltage and stays constant until the sag is cleared while the DVR topology with a DC voltage source compensated voltage without any interruption in the load voltage.

# 3. Control System:

A DVR needs a control unit that can detect the presence of voltage sags in the system, then proceed to compensate that voltage sag by calculating the voltage difference, generating the reference voltage signal for PWM generator to trigger the VSC. One of the simplest efficient control of DVR is done using PI controller which is a feedback controller and uses the sum of the error and the integral of that value for control. Literature study has revealed huge amount of work done in which PI controller have been used for the DVR control purposes [18][19][20]. Many low voltage applications of DVR have used Parks transformation alone for the control purposes [21][22][23]. Park's transformation is also called direct quadrature zero transformation, in brief DQO transformation, in which a DQ0 controller is used for power quality improvement in the low voltage distribution network but mostly for complex and higher end voltage application require a more efficient control system. Only the parks transformation is used for the error voltage detection and compensating voltage signal generation. The DVR uses three single phases of the injection transformer and the low pass filters can be installed at both the higher voltage side and the lower voltage side of the injection transformer. It is possible to install the LC filter at either side but installing at the high voltage side has a few major disadvantages. The high order harmonics current that is produced due to the switching of the VSC will penetrate through the injection transformer and carry with it the harmonic voltages into the system that are being fed to the critical load.[24] . also suggests that this controller might also be used to change the VSC into rectifier mode to charge the capacitors in the DC energy link in the nonappearance of the voltage interruptions. In this technique, the detected and the reference voltages are transformed from three phases to DQ0 frames by the use of following relation which makes the computation process easier and for ease the zero sequence components is overlooked.

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \quad (13)$$

The measured and reference voltage values are compared in DQ0 frames and then the error signal is converted back to the three phases by using the inverse transform and the error signal is used for the generation of PWM signal.

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) & 1 \\ \cos(\omega t - \frac{2\pi}{3}) & -\sin(\omega t - \frac{2\pi}{3}) & 1 \\ \cos(\omega t + \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} \quad (14)$$

The sag/swell conditions introduced in the system are dealt with this scheme and kept the voltage at 1 p.u for the whole duration. As mentioned earlier that parks transformation based DVR are best for low voltage applications but with the increase in the complexity of the system, these techniques are often coupled with PI and Fuzzy logic controllers in various arrangements to get a more efficient performance. One such study is done in [25] where the focus is upon making the DVR operation more Efficient. An arrangement of discrete PWM based modulation, DQ0 Transformation and PI controller is used which resulted in minimum DVR's ratings and better performance in dealing with voltage sags, swells and Phase Angle Jumps. The DQ0 transformation makes analysis of three phase system much simpler and the PI controller helps in eliminating the error between the generated output and the required output. The Proposed DVR had a better performance in mitigation of the voltage sags and swells by injecting less amount of active power then the classical DVR that was using a 6kV battery source. In case of a 0.5 p.u voltage sag the Proposed DVR injected a 0.15 p.u voltage to compensate for the loss of the voltage signal whereas the classical DVR only managed to compensate up to 0.8 p.u when using a 6kV battery source.

These PI controllers operations are then evaluated against common voltage sag indices described as *Voltage Total Harmonic Distortion (THDV), Detroit Edison Sag Score (SS), Voltage Sag Lost Energy Index (VSLEI) and Phase Unbalance Rate* to assess their performance while minimizing the voltage distortion, voltage phase unbalance and sag lost energy [26] [27]. The robustness of the controller can be put to test by introducing a three-phase diode rectifier, a nonlinear load in parallel with the sensitive load. The system becomes more harmonic distorted but still the THDV percentages are within the limits of the IEEE Standard 519-1992 for all the cases under study.

Often the Voltage sags experienced by the system are due to the due to inrush current during transformer energization in addition to a three-phase fault in the distribution system [10]. An interesting point that the DVR equivalent circuit is composed precisely the identical as the series active power filter. Therefore, the DVR can also be used as an active power filter with fast and smooth transient responses without adding any additional requirements [28]. Choosing the control technique for DVR is highly affected by the percentage of load distortion. Low value of distortion allows the use of simple techniques such as PI controllers. The higher the load distortion, more complex the control operation is needed for efficient performance such as Fuzzy controller, adaptive PI controllers. The problem with the PI control is that it's a linear control scheme and is non-flexible to the dynamism of the Power system i.e. the gain values that are used in case of a PI controller ($K_P$ and $K_I$) are robust and cannot adjust themselves according to the changing power system parameters which results in a bad dynamic response for the system. This is due to the fact the rise and fall of the error is not considered when making the decision and only the instantaneous error voltage is determined.

Literature put forward a comprehensive comparison between the PI controllers and the more complex Fuzzy logic controllers. Fuzzy logic controllers (FLC) can perform efficiently where the PI controller struggles with system parameters. Fuzzy logic controller is the utmost effective operations of fuzzy set theory that uses a set of linguistic variables rather than numerical variables

Fuzzy logic implementation depends upon the human capability of understanding the system and its responses to the quality control rules. FLC is found to be more efficient and robust for voltage sag/swell mitigation with a better voltage compensation and THD reduction[29] [30]. The shortcoming of the PIC controller have been discussed earlier but it has been dealt with in a way in [31] ,that compares the control schemes of DVR with a Proportional Integral (PI) controller to the DVR with a Fuzzy logic controller. But the Fuzzy logic controller here is sued for the purposes of calculating the gain parameters of the PI controller. Thus, this is called Fuzzy PI controller (FPI). The PI controller has a control scheme that is incapable to react to abrupt changes in the error signal whereas the Fuzzy logic PI controller, based on Mamdani's system, is formed to express appropriate sensitivity for every operating point. FPI has two inputs, one is the difference between the rms voltage and the source or reference voltage and the other is the derivative of error. The value of constants proportional gain $K_P$ and the integral gain $K_I$ are changed according to these error signal (**$\varepsilon$**) and the rate of error (**$\Delta\varepsilon$**). On simulating the two control schemes the FPI scheme shows a better voltage regulation and THD result of 4.45% then the PI controlled DVR that showed a THD of 8.89%. Now these two controllers can be used with each other in such an arrangement that they complement each other with fuzzy logic controller helping in overcoming the issues inherent with the PI controller. Addition of a Fuzzy logic controller with a PI controller helps in overcoming these shortcomings. It also holds advantage over using the fuzzy logic controller only as the use of PI controller helps in achieving faster response as compared to the conventional Fuzzy controller. linguistic If-then rules determine the values of the Output $K_P$ and $K_I$ which are adjusted for the PI controller to help with the efficient dynamic response. The Fuzzy PI controllers did show a better voltage regulation and harmonic performance then either PI and Fuzzy logic controller alone[32][33] [34]. Many other techniques have been used to overcome the drawback of the PI controller. One such scheme is the real coded genetic algorithm (GA) optimized PI controllers. This scheme is compared against the FL controller in [35], and validated against $H^{\infty}$ controller based medium voltage (MV) level DVR. The real code GA optimizes the PI controller parameter for three different type of fault conditions and sag magnitudes but the performance of FL controllers was noticed to me more efficient and superior to real coded GA PI controller. The performance of the real coded GA PI controller is improved when the converter operation point is unchanged. The same scenario was found in case of THD in the system with PI controller gains that are fixed being the least effective in reducing the THD levels and the FL controller showing effective performance in reducing the THD levels in the system. Another advantage of using the FL controller is that it reduces the tracking error and transient overshoot of the PWM[36][37]. Fuzzy Logic DVR is effective in handling both balanced and unbalanced voltage sags and swells with sufficient efficiency and accuracy to compensate any deviation from the supply line voltage.[38] Simulates the FLC DVR, employing Fourier Transform technique for detection and quantification of voltage disturbances, for the protection of industrial induction motor loads from voltage sags and swell.

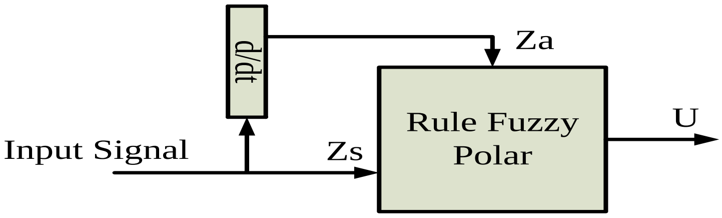
Usually the zero sequence components effect the voltage sag extremely in a system with a grounded neutral and are blocked by using the wye-delta connected blocking transformer that is placed in between the Supply and DVR. Zero sequence blocking is used so that the sensitive load is protected from the zero-sequence current and voltages. The use of the injection transformer or the Zero sequence blocking transformer increases the cost of the DVR system considerably but one study introduces the concept of the fuzzy polar controller for the voltage sag and harmonic compensation in low voltage distribution system[39] .The fuzzy polar controllers helps in minimizing the membership function for fuzzy logic and also will not require the use of blocking transformer thus making the cost of the DVR less expensive. There is no transformer connected between the load and the distribution system for zero sequence isolation. There are three basic parameters of Fuzzy polar controller. Derivative multiplier ($A_S$), the angle membership function (α) and the radius membership function ($D_R$). The operational values of the polar coordinates are given by

$$p(k) = [Z_S(k).A_S Z_A(k)] \tag{15}$$

$$D(k) = \sqrt{\left[Z_S(k)^2 + \left(A_S Z_A(k)\right)^2\right]} \tag{16}$$

$$\theta(k) = \tan^{-1}(\frac{A_S Z_A(k)}{Z_S(k)}) \tag{17}$$

Where $Z_s$ is the input signal and $Z_a$ is the derivative of the input signal. D(k)is the magnitude and θ(k) is the angle.

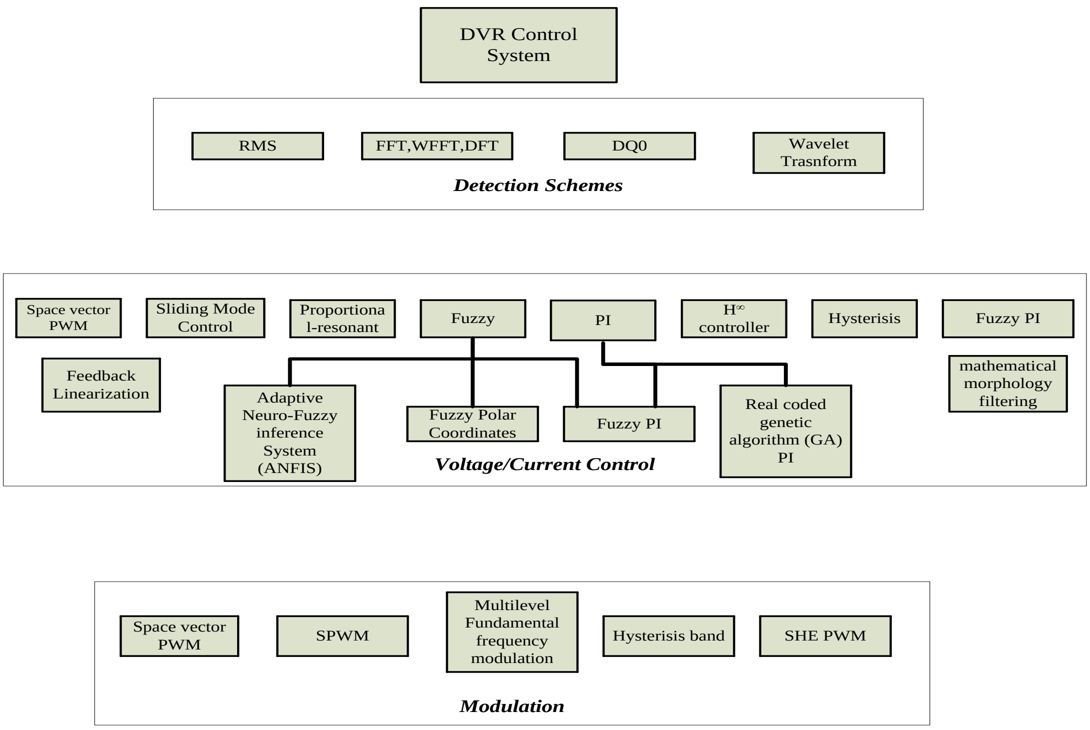



*19 Fuzzy polar Controller*

This DVR using Fuzzy polar controller can compensate voltage sup to 99.02% and compensate for the voltage harmonics from 10.22% to 0.66% without the use of the blocking transformer under different fault conditions. As mentioned earlier Fuzzy Logic controller utilization depends largely on the intuition of the experts who design the membership function and define the rule base system. The Effectiveness of the System then depends upon the Knowledge of the programmer or Expert in this case of how well the said expert understand the systems responses. If the Parameters of FLC controllers are need to be changed it can only be done with trial and error method because there is no scientific optimization methodology inbuilt with the fuzzy inference system[40]. An Adaptive Neuro-Fuzzy inference System (ANFIS) is introduced in [41] which optimizes a regular fuzzy controller that has two inputs and one outputs with seven membership functions into an optimized fuzzy logic controller with one input ,one output with only three membership functions . It is reported in the literature that ANFIS is a hybrid Neuro-Fuzzy technique that combines the capabilities of neural network to fuzzy inference systems and can be used to model nonlinear functions, identify nonlinear components and predict a chaotic time series. It consists of five layered structure where each layer can act as a membership function that are used in general fuzzy logic. The membership functions were adjusted based on hybrid learning algorithm. This helps in implementing a DVR that has the same effectiveness level as any Fuzzy logic system but with only one input, one output with less membership functions and is very cost effective in its implementation.[6] Discusses about the calculation of voltage sags and the DVR at different voltage levels of distribution. DVR at low voltage level and Medium Voltage Levels are discussed and the calculation for the inserted impedance in the circuit is calculated.[42] Introduces a new control technique that can deal with the balanced and the unbalanced voltage sags by means of different compensation techniques. In case of balanced voltage sags, the phase advancement compensation method is used and in case of unbalanced sags, the in-phase compensation technique is used. This permits the discrete control of each of the phases and the active power injection during balanced and unbalanced voltage sags and swells can be limited. The error signal is fed to the control block which then decides whether the sag or swell experienced by the system is balanced or unbalanced in nature. If it is unbalanced in nature the control block uses the in-phase compensation voltage signal and if the two times of the single-phase error is larger than 95% of the addition of the other two phase's error voltage then it is a balanced sag/swell and the phase advance compensation voltage signal is used. On simulating the system and introducing both balanced and unbalanced voltage sags at different time periods it was noticed that the DVR compensated according to the compensation strategy devised. It compensated various levels of voltage sags and swells using a combination of in phase and phase advance compensation technique for balanced and unbalanced faults. The multilevel inverters as they are becoming an attractive option because of their higher power capability, reduce electromagnetic interference, better harmonic performance and lower commutation losses. This is further supported by [43] which introduces the multilevel inverter in the distribution system that helps in dealing with high voltage applications and multifunctional control system is introduced that with the help of P+ Resonant controllers and the charge regulators protects the DVR protected load voltage when the cause of disturbance is in the parallel feeders. The capability of the DVR depends upon the switching frequency of the PWM and the control strategy that is applied in the DVR. The P+ Resonant compensator used in this is expressed by

$$G_R(s) = K_p + \frac{2K_I w_{cut} S}{s^2 + 2w_{cut}S + w_0^2} \tag{18}$$

Where $K_p$ and $K_I$ are the gains constants and $w_{cut}$ is, the compensator cut off frequency which in this case is 1 rad/s. This more realistic compensator has a gain of 40db which is enough for eliminating the voltage tracking error. The flux charge model is used to restore the PCC voltage and to protect the DVR components from the fault current by making the DVR feel like it is a variable inductance in series with the distribution feeder. A test system with 22kV voltage source, 100 W RLC load and 415V distribution side voltage was introduced with a sudden 10MW load and it results in a voltage sag in the system. The performances of both, the six pulse inverter and the three phase fifteen level inverter was studied and found that the multi-level inverter performed considerably better in ensuring voltage levels at the critical load side and the grid side as well and the performance of the P+ resonant controller ensure better THD profile for the overall system as compared to many switching devices.[44] Uses the c to deliver fast transient responses minus added loop compensation. It comprises of evaluation of the output voltage and the tolerance limits around the reference voltage in between which no switching occurs and when there is a difference between the output voltage and any of the limits, the DVR operates and the difference is eliminated to keep the output voltage in the acceptable limits. The error signal is fed to the hysteresis voltage control block which acts as a pulse generator for the inverter. The Error signal detection technique is based on DQ0 transformation as discussed in earlier references but the error signal in this case is not fed to the PWM generator, rather to the hysteresis voltage control block that acts as a pulse generator for the considered inverter, the Hysteresis voltage control model is shown in the figure below The Use of DVR in micro grids is also being studied and considered as an alternative for the power quality solution in [45]. Compensation voltage detection is performed through the DQ0 transformation method and combined with mathematical morphology filtering algorithm that is used in Digital signal processing the 1 MVA DVR is used in micro grid with a 7.5 kV 3 phase voltage source and constant impedance loads. The Voltage sag of 50%, phase shift of 40 degree is introduced into the system and the DVR effectively operates and compensates the load voltage. Coming to the cost effectiveness of the DVR. Few researchers have suggested to remove the injection transformer from the DVR circuitry and have gone on to introduce new strategies to make up for the DVR operation without a transformer. Removing the bulky & expensive transformer will not only reduce the cost but also reduce the complexity from operation and maintenance point of view. The voltage loss, phase shift and harmonic loss due to the injection transformer will be eliminated. After each sag restoration cycle the transformer suffers from DC magnetic flux bias in the core that exceeds the transformer nominal limit. This irregularity introduces overcurrent and overheating which in turn reduces the life of the transformer and avoiding this saturation requires adding to the cross sectional area of the transformer core[46] one solution to overcome this problem is by controlling the compensation voltage which is the cause of this saturation. This is done by shutting off the reference voltages while the current exceeds a certain limit. Two methods to deal with flux linkage control are discussed in [46] which deal with controlling the compensation signal . First method multiplies the compensation signal by half during the first fundamental cycle after the sag is detected. Second method detects whether the flux will exceed the maximum limit or not at the detection moment. If the flux is going to cross the limit then form factor is introduced to limit the compensation signal. [47] Addresses the transformer less DVR and the issues that arise with the removal of the injection transformer. The two key issues are lack of voltage boost and isolation. Voltage boost problem is somewhat addressed by using cascaded inverter and the isolation problem is dealt with by introducing a separate DC-link for each of the single-phase inverters which will avoid the short circuit between the phases and DC-link. This proposed DVR performed satisfactorily in restoring the voltage to its reference value and doing it at a relative low cost without the injection transformer. The Space vector PWM technique which is an advanced, computation intensive technique as the control algorithm for the generation of controlling pulses of the dynamic voltage restorer for its better digital realization, utilization of the DC bus, simplicity and response is used in[48].A typical model of three phase PWM shows eight switching states and the output of the inverter is based upon these eight switching voltage space vectors. Both balanced and unbalanced fault conditions were simulated and voltage sags were introduced and the SVPWM DVR performed very well in restoring the Voltage back to its normal value in the circuit. The number of DVRs installed in the power system also impacts the overall power quality improvement costs. Few researchers have focused their efforts in coming up with algorithms and techniques to find the optimal DVR placement in the grid and the size of the DVR ratings. Different multi-objective optimization problems are formulated for analyzing the optimal placement and sizing problem for the DVR and other FACT devices such as Simulated Annealing for optimal placement of static VAR compensators [61]Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) have been used by different researchers separately and also combined to optimize the process parameters involved in FACT devices costs and optimal placement objective functions [62][63][64].




*20 Techniques Used in Different Stages of DVR*[49]–[60]

In[65] firefly algorithm(FA) is proposed for this particular problem . a multi objective optimization function is formulated that is a weighted sum of individual objectives that deals with minimization of Voltage harmonic distortion, power flow limits, minimization of voltage deviation, minimization of total cost investment, bus voltage limits and the DVR capacity limits. This FA algorithm has been proven to be more successful and efficient then GA and PSO individually for continuous problems[66]. The proposed DVR placement method was tested by placing three DVRs in the test system and the results obtained from FA algorithm were compared with those obtained by GA and PSO algorithm which further proved the efficiency advantage of FA over GA and PSO.

# 4. Conclusion:

The Dynamic Voltage Restorer has emerged as one of the most significant solution for the power quality problems in the recent years. An overview of the Schemes that are in use in the DVR and the recent development of these schemes has been presented in this paper considering various researches. The development of the control system techniques keeps on improving through years and there is still room for current schemes to be improved upon. Some of the Schemes that were introduced with earlier DVRs are still being used in the DVR operation with new improvements being consistently made into them. The Energy Storage techniques are covered in this overview will remain to dominate the DVR performance but it has been developed that innovative technologies should be introduced to bring the cost of the energy storage for DVR down from their current levels.

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# Voltage profile improvement using DQ0 and Fuzzy logic controller based Dynamic Voltage Restorer with low DC voltage supply in Medium level distribution system

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Higher penetration of nonlinear devices installed in the power system at various levels is introducing complexities and power quality issues. Dynamic Voltage Restorer (DVR) is a custom power device that is used in modern times as a voltage stabilizer. This study uses the DVR, based on DQ0 based compensation scheme and a fuzzy logic based DVR, in medium level voltage distribution system where it protects the 11kV distribution network and the subsequent sensitive devices connected at low voltage network from voltage sag caused by diverse types of faults in the power system. Application of DVR in medium and high voltage distribution network is limited by the requirement for large capacity energy storage for DVR. In this study, a DC low voltage source of only 200 V is utilized with the help of a step-up injection transformer. Both DQ0 based DVR & Fuzzy Logic Controller (FLC) based DVR are modelled and simulated in a test system in MATLAB/ Simulink environment, that ensures the effectiveness and reliability during power systems faults causing voltage sags. FLC based DVR performed more effectively in compensating Voltage sags and caused less harmonic distortion in the system. Modelling of the two DVRs and the test system are described in detail in this study

**Keywords:** Parks transformation, Fuzzy logic, Power Quality, Dynamic Voltage Restorer, medium level distribution system

## 1. Introduction:

The use of sophisticated sensitive electronic equipment in industrial, residential and commercial sectors is on a rise in recent years and raised the issue of continual service of excellent quality power to avoid any damage to the equipment leading to economic loss for the consumer. Dip in power quality results in low grade operation or in some cases total malfunctioning of the system which is highly undesirable. The first sign that the quality of power is affected is when the voltage waveform diverges from the sinusoidal waveform or there is a change in amplitude from a standard level that the power source must provide to the utility and this disturbance from the normal operation can be of few milliseconds up to hours. Now this disturbance in the system can be the result of a problem anywhere in the entire system, it can be from the power generation side or the transmission system and major substations, it can be from the distribution system that incorporates distribution transformers, primary and secondary power lines and even these problems can be from the very equipment the power is being supplied to, for example the power electronics converters [1]. These power quality disturbances mainly occur in the commercial networks, industrial networks and the utility networks. The Dynamic voltage restorer (DVR) is a custom power device that is generally installed in series with a distribution system between the voltage source and the critical load feeder at the PCC to protect from the voltage fluctuations in the network. It is the utmost cost-effective answer to voltage profile problems whether it be sags, swells or interruptions. Additional properties that include line voltage harmonics compensation, fault current limitations and reduction of transients in voltage make DVR a more attractive Custom power device to use. This DVR also holds the edge of being economical when compared to shunt connected devices. Whenever the System experiences voltage sag/swell, voltage unbalance and voltage harmonics, the DVR can keep the load voltage at a standard amplitude and phase at the point of common coupling. The DVR can generate or absorb independently controllable real and reactive power at the load side. The DVR operation does not depend upon the type of the fault of any kind of activity happening in the system and performs its operation if that the entire system stays coupled to the supply grid.[2].

### 1.1. Basic Components of DVR:

The DVR installed in the power system can perform auxiliary tasks as well such as line voltage harmonics compensation, reduction of transients in voltages and fault current limitation.[3–5] The Basic arrangement of DVR comprises of

- Injection/Boost Transformer
- Sag/Swell Detection Algorithm
- Control System
- Voltage source Converter
- LC filter

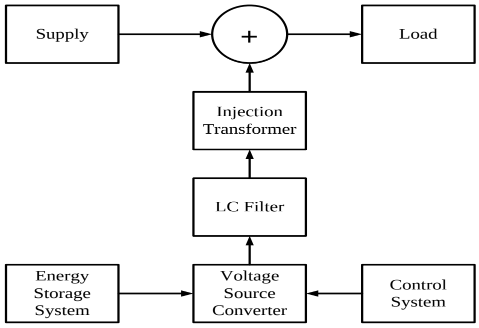


Fig 1 Dynamic Voltage Restorer Structure

1.1.1. Energy Storage Unit

The energy storage unit is the source that is used for generating compensation signal of load voltage during voltage sags, swells or interruptions. The reactive power, that is traded between the DVR and the distribution system, is produced internally by the DVR except for any ac passive reactive components, e.g. reactors or capacitors. The grid or an auxiliary energy storage device is utilized for the real power exchange with the distribution system[6]. Superconductive magnetic energy storage (SMES), batteries and capacitors are some of the option but mostly an electrolytic capacitor bank is used as the energy storage device in DVR applications, and grid itself can also be used by mean of rectifiers to be the provider of that required energy. The choice of the best topology and DVR ratings is associated with the supply of the remaining voltage, the outage cost and investment cost[7]. The auxiliary energy storage device can be a variable DC link capacitor or a constant voltage DC link capacitor. For the case where grid supplies energy, there are two types as well, supply side connected converter and load side connected converter. The selection of energy storage device topology depends upon the type of disturbances expected to be experienced by the system, the grid strength, the complexity of the system and the cost incurred by the system for the topology. The two components of the DVR structure that increase its cost are the injection transformer and the energy storage device. DVR can operate without the use of energy storage devices but the performance is affected when long duration voltage sags are experienced. Hence, most of the proposed DVR solutions in the literature are realized using shunt converter, fed from the line itself or an auxiliary supply. Each topology has its own strengths and weaknesses. Cost of energy storage unit depends upon the either size of capacity. The injection strategy determines the magnitude of the injected voltage. The different topologies available are

Auxiliary energy storage:

- Variable DC link Voltage capacitor
- Constant DC link voltage Capacitor

Energy Storage with Grid:

- Supply side connected converter
- Load side connected converter

1.1.2. Inverter Circuit

The inverter is used to convert the DC power into AC power. There are two basic types of inverters, Voltage source fed converter and current source fed converter [8].

1.1.2.1. Voltage Source Converter

A voltage source inverter (VSC) is fed through a rigid DC voltage supply. This supply has little impedance at the input. A VSC can produce a sinusoidal voltage at any required frequency, magnitude, and phase angle. The load current does not affect the output voltage of the VSC. Voltage source converters can, in some cases, provisionally substitute the supply voltage or just be used for generating the compensating signal of the missing voltage. The main type of switching devices that are used in VSC are the Gate Turn-Off thyristors (GTO), Metal Oxide Semiconductor Field Effect Transistors (MOSFET), Insulated Gate Bipolar Transistors (IGBT), and Integrated Gate Commutated Thyristors (IGCT). Individually, all types have their own set of advantages and disadvantages. Recently, IGCTs are being used in the VSCs to enhance the DVR performance and dependability at higher power ratings as compared to the other switching device based VSCs. IGCT Gives VSC a higher power rating through its improved performance and dependability. DVRs, Equipped with VSCs Having IGCT can compensate dips more severe than their predecessor DVRs. VSCs are broadly utilized in low and high-power applications like AC-DC converters, traction, UPS and bi-directional motor drives. The VSC is energized through a low impedance DC stiff Voltage supply and the output voltage does not depend on the current drawn by load. The technique called Pulse width modulation is used to produce gate pulses for the VSC to operate. The PWM converts the compensation voltage waveform into the gating signals used for VSC. The Advantage of using a PWM VSC is that it provides better performance in case of asymmetries and overcurrent during an unbalanced fault. The PWM uses fast switching speed of the power switches to improve the efficiency of the converter. Its simplicity in nature and a better response are added advantages.

1.1.3. Inverter side filter unit:

The problem with the semiconductor switching devices is their nonlinear characteristics which causes distorted waveforms associated with harmonics. Filters are used to eliminate these harmonics introduced by nonlinear switching devices in the inverter. The inverter side filter topology has the advantage of being close to the source of the harmonics and filters out the harmonics as well as stops the harmonics currents to infiltrate the series injection transformer. The drawback is the voltage drop that is caused by the inverter inductance on the inverter side and, a phase shift is experienced by the fundamental component of the inverter output. The output voltage of the inverter can be found using the following equation

$$V_s = V_o + R_f I_s + L_f \frac{dI_s}{dI_f} \quad (1)$$

Where Vs is the source voltage, $I_s$ is the source current and $R_f$ and $L_f$ represent the resistance and the reactance of the filter. The following equations are used for the calculation of LC filter parameters $L_f$ & $C_f$ , Where Vo is the output load voltage, $I_o$ output current ,$E_d$ is the DC supply voltage, $f_r$ is the system frequency and $f_s$ is the switching frequency as discussed in [9].

$$L_f = \left(\frac{V_o}{I_o f_s}\right)\sqrt{\{K\frac{E_d}{V_{o,av}}\left(1+4\pi^2\left(\frac{f_r}{f_s}\right)^2 K\frac{E_d}{V_{o,av}}\right)\}} \quad (2)$$

$$C_f = K\frac{E_d}{L_f {f_s}^2 V_{o,av}} \quad (3)$$

1.1.4. Injection/ Booster transformer:

The injection transformer is used to link the DVR to the distribution network via HV windings and inject the VSC produced AC voltage into grid voltage at same or another level at the same frequency to regulate the incoming supply voltage back to acceptable level after a disturbance in the power system causes the voltage levels to differ from the standard level. They also attempt to bound the coupling of the noise and transient energy from the primary side to the secondary side while isolating the load from the DVR system that has VSC and DC storage capacitor. The electrical parameters of the injection transformer must be selected carefully to guarantee all-out efficiency. Therefore, the short circuit impedance, MVA ratings, the turn ratio and winding parameters of the injection transformer calculations becomes integral to guarantee reliability and effectiveness. The relationship between the different parameters of the transformer is given by the following relation:

$$\frac{V_p}{V_s} = \frac{I_s}{I_p} = \frac{N_p}{N_s} = m \quad (4)$$

The Primary and secondary voltages are represented by $V_P$ and $V_S$ respectively, $I_S$ gives the secondary current and $I_P$ gives the primary current in the transformer. $N_p$ is the number of turns of wire on the primary side whereas $N_s$ gives the number of turns on the secondary side of the transformer. The factor m, in the above relation is called the turn-ratio of the transformer.

- *MVA Rating:*

$$P = K_s V_p I_p \quad (5)$$

- *Primary Winding Voltage & Current Ratings:*

$$V_{inj} = DV_r \quad (6)$$

$$V_s = (1-D)V_r \quad (7)$$

- *Short Circuit Impedance:*

$$R_k = R_{ps} + m^2 R_{ss}$$

$$L_k = L_{ps} + m^2 L_{ss} \quad (9)$$

Voltage drop across the transformer must be lower than the specified limit and it should meet the following condition

$$\sqrt{{R_k}^2 + w^2(L_k + L_f/(1-w^2 L_f C_f))^2} < \left({V_T}/{I_T}\right)$$

The per unit resistance and inductance values, for each winding, are defined as:

$$R_{(pu)} = \frac{R(\Omega)}{R_{base}} \quad (10)$$

$$L_{(pu)} = \frac{L(H)}{L_{base}} \quad (11)$$

The Base resistance and base inductance used for each winding are

$$R_{base} = \frac{(V_n)^2}{P_n}$$

$$L_{base} = \frac{R_{base}}{2\pi f_n}$$

1.1.5. DVR Location in the Power System

Dynamic Voltage restorers are modelled for low voltage(LV) operations (0.2-0.4kV) typically in the literature. They are designed to protect the designated sensitive load in the LV network close to the load hubs from the voltage disturbances. But DVRs can be more effective if they are modelled to operate in medium or high voltage distribution network so it can protect many loads connected to that distribution network. Of course, the ratings and the cost will be higher for the medium or high voltage DVR but so will be the effectiveness. The conventional method is that for medium level DVR operation the cost of the capacitor and the energy storage unit is increased as the energy storage device ratings are chosen according to the compensation voltage signal that they would be generating. So, for medium to elevated level voltage network DVR the Energy storage device usually have voltage ratings in many Kilo volts for effective operation. Only radial structure grid is considered for MV level Grid installation of DVR. This research paper uses the low voltage rating energy storage device with the use of a step-up transformer to compensate for the voltage sags faced by the medium level voltage distribution network. The DVR is installed at high voltage side of the network thus making sure that it protects many different sensitive loads from the voltage disturbances.

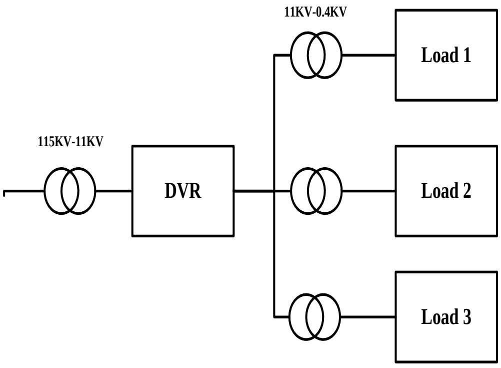


*Fig 2* Location of DVR in Medium Voltage Network

## 2. Methodology

### 2.1. Detection Scheme

The first step in the DVR operation is to detect whether the system is experiencing a voltage fluctuation or not and literature puts forward several detection schemes that have been used for the detection of voltage sags and swell in the voltage profile of the power system. Some of the schemes are rms, wavelet transform, FFT, WFFT and DFT[10–12]. Parks Transformation, also known as DQ0 transformation, is also one such scheme used for the detection of Voltage sags and swells in the system. DQ0 transformation is preferred due to its simple applicability and easiness of the process. In the DQ0 transformation the three-phase system is converted into D and Q equations where they can be easily operated on.

Once the sag detection is done the D and Q components are then converted back to the three phase abc system.

### 2.2. Control Schemes

The two control schemes discussed in this research paper are Parks transformation and Fuzzy logic controller.

#### 2.2.1. Parks Transformation

The control scheme involving the Parks transformation is simple the voltage sags and swell are detected through the DQ0 Transformation when both the source voltage and the defected load voltage are compared with each other and the correction voltage is computed. The correction signal is then forwarded to the PWM generator that is used to convert the compensating signal waveform into gate signals for the Voltage Source converter. The Voltage Source converter then operates according to the gate pulses and generates the compensating signal that is then injected into the power system through injection transformer.

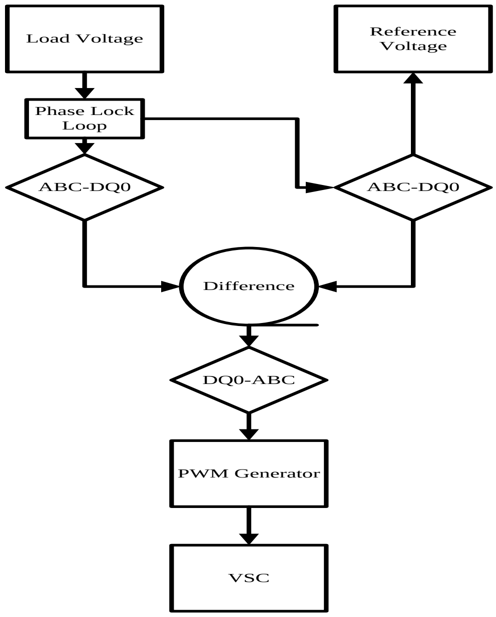


Fig 3 Parks Transformation control scheme

#### 2.2.2. Fuzzy Logic Controller (FLC)

The Fuzzy logic controller is used when the exact mathematical formulations of the system are not possible. Using FLC, the tracking error and transient overshoots of PWM are significantly controlled[13, 14]. The input of the FLC is the error signal that is the difference between the rms voltage and reference voltage and the second is rate of change of the error. The FLC is based on Mamdani's system. There are three phases in the operation of FLC. The first phase is called Fuzzification, second phase is rule execution, the third and final stage is de-fuzzification. In the first phase the crisp variables "error" and "rate of change of error" are transformed to fuzzy variables by means of triangular membership functions shown in figure. ε and Δε are separated into seven fuzzy subsets that are NL (Negative Large), NM (Negative Medium), NS (Negative small), Z (Zero), PS (Positive Small), PM (Positive Medium), PL (Positive Large). All the Variables are defined through membership functions and are shown in the figure below.

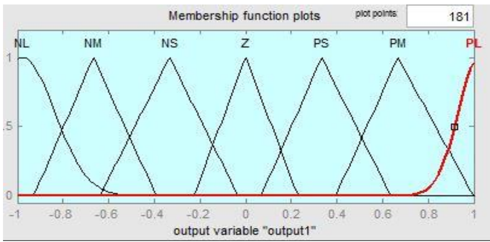


Fig 4 output member ship functions

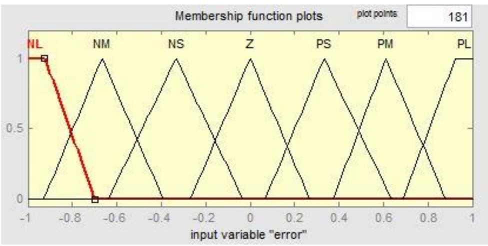


Fig 5 input membership

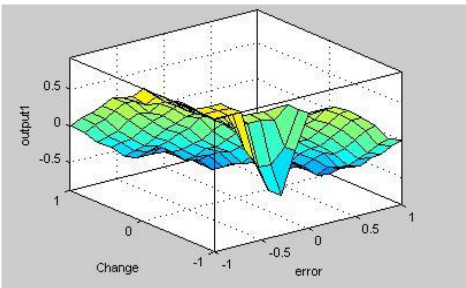


Fig 6 Surface View of FLC

The next stage is called rule execution in which an inference engine processes the inputs variables ε and Δε by executing a set of control rules that are articulated by means of the information of the DVR behavior. The control Rules are shown in tabular form in table 1. The next stage called De-fuzzification uses the centroid de-fuzzification process. This phase calculates the crisp value as the center of gravity of the membership function and the output variables are converted into crisp values[15–17].

Table 3 Fuzzy controller Control Rules

| E/ΔE | NL | NM | NS | Z | PS | PM | PL |
|---|---|---|---|---|---|---|---|
| NL | PL | PL | PM | PM | PS | PS | Z |
| NM | PL | PL | PM | PM | PS | Z | NS |
| NS | PM | PM | PM | PS | Z | NS | NM |
| Z | PM | PS | PS | Z | NS | NM | NM |
| PS | PS | PS | Z | NS | NS | NM | NM |
| PM | PS | Z | NS | NM | NM | NM | NL |
| PL | Z | NS | NS | NM | NM | NL | NL |

Table 4 Voltage disturbance characteristics defined by IEEE

| Disturbance Type | Typical Voltage Magnitude | Typical Duration |
|---|---|---|
| Sag | 0.1-0.9 pu | 0.5-30 cycles |
| Swell | 1.1-1.8 pu | 0.5-30 cycles |
| Flicker | 0-1% | Steady State |
| Interruption | <0.1pu | 0.5 cycles |
| Imbalance | 0.5-3% | Steady State |
| Harmonics | 5% | Steady State |

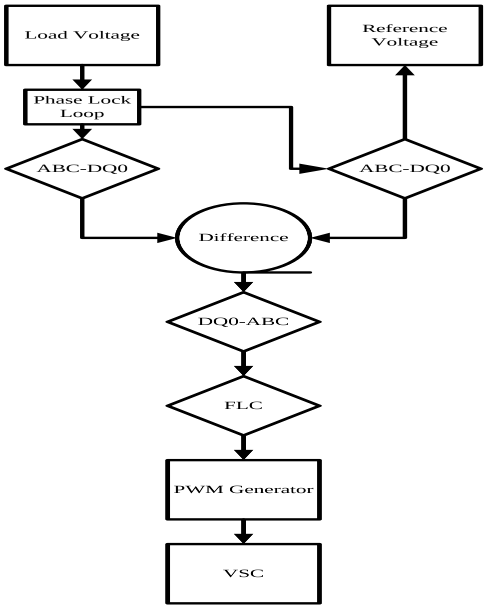


Fig 7 FLC Control Scheme

### 2.2.3. Performance Evaluators

The DVR must be able to compensate for the Voltage sags in the system as close to as possible to its rated voltage without introducing any phase shift and Considerable harmonic distortion. IEEE defines standards for compatibility of the equipment that are connected to the power network as well as the emissions from the equipment. The IEEE 519-1992 and IEEE 1159-1995 standards define the Harmonics injection level up to 5% in the steady state which modelled devices must follow to be according to the regulations. A Summary of the characteristic properties of the disturbances is given n table 4.

## 3. Simulation results and evaluation

### 3.1. Test System

The two DVRs i.e. DQ0 controlled and the FL controlled DVRs are tested in a section of a distribution system that has been modified to suit the requirement of this DVR system. The single phase, double phase and three phase Faults are introduced in the distribution network which causes voltage sags of diverse types and the two DVR performances are evaluated against each other in removing the voltage sags and swells.
Figure 11 represents the Test system for the specified DVRs. The distribution system is a medium voltage level system set to a voltage of 11kV. The DVR is installed in the 11kV distribution network where it protects the 11kV system and the loads that are fed through this 11kV distribution system from voltage sags and interruptions. The Modelled DVRs are capable of injecting voltages up to 30% of the reference voltage i.e. 2540 V. The load voltage is stepped

down to 380V through another step-down distribution transformer

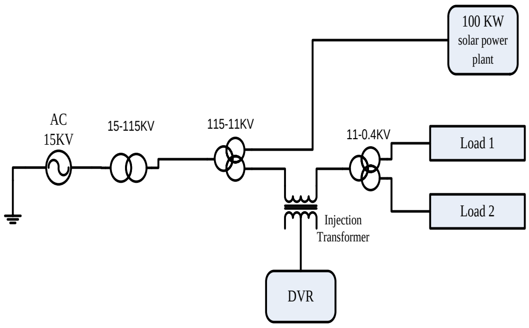


*Fig 8 Test System*

| | |
|---|---|
| Fundamental Frequency | 50 Hz |
| Sampling frequency | 20Khz |
| Supply Voltage(Ph-Ph) | 15 kV $V_{Ph-Ph}$ (Vrms) |
| MV Level Network Voltage (Ph-Ph) | 11 kV $V_{Ph-Ph}$ (Vrms) |
| Three Phase Injection Capability | 2540 V $V_{Ph-Ph}$ (Vrms) |
| Max Voltage injection (Single phase) | ≤ 30 % |
| DC Voltage Source | 200 V |
| Switching Frequency | 4350 Hz |
| Injection Transformer Nominal Power | 100MVA |
| Injection Transformer winding rating | 140-2540 $V_{Ph-Ph}$ (Vrms) |
| Load Transformer nominal power | 100kVA |
| Load Transformer windings rating | 11000-380 $V_{Ph-Ph}$ (Vrms) |

### 3.2. Single Phase Faults

This is the most common occurring faults in the power system, about 65-70% of faults, in which one of the three phase experiences a fault and a voltage sag is caused. In this research, the Single-phase fault causes voltage sag of 30% in an 11kV network. Fig 11 shows the voltage profile after the voltage sag of 30% is introduced in Phase A from 0.1 to 0.3 of the simulation time.

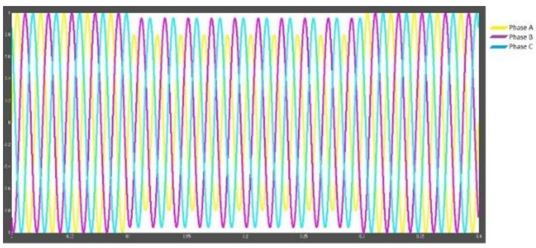

Fig 9 Single Phase 30% Voltage Sag

The Two dynamic voltage restorers are installed in the system and their performance in compensating the voltage sag is analyzed. Figure 12 shows the load voltage after the installation of the DQ0 based DVR. The DVR is able to mitigate the voltage sag caused by the single line to ground fault and restores the load voltage to 93% of the load voltage but it is seen that the other two phases experience distortion in their magnitudes level due to this DVR performances. The DQ0 technique falls behind when it comes to the unbalanced faults in the system. Figure 13 represents the load voltage after using the FLC based DVR for compensation and it also helps restore the load voltage back to its normal voltage level but not entirely. The load voltage after experiencing 30% Voltage sag caused by SLG is restored back up to 96% of the reference voltage. The THD analysis of both load Voltages demonstrate that both DVR operate in range of the IEEE Standards i.e. the injected harmonics are less than 5%. The DQ0 based DVR injects 4.3% harmonics and the FLC DVR causes only 3.7 % harmonics in the power system.

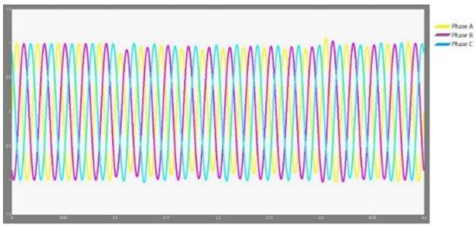

Fig 10 load Voltage after DQ0 DVR injection

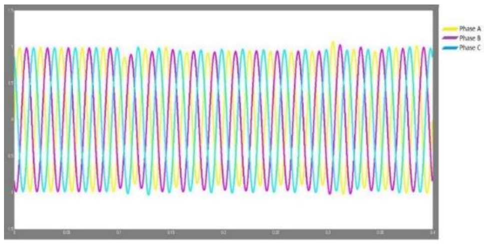

Fig 11 Load Voltage after FLC DVR compensation

### 3.3. Double Phase Faults:

Double line faults constitute about 15-20% of the faults experienced by the transmission system. These maybe due to a storm where two lines meet each other and the ground. The analysis of Double line to ground faults shows that the DQ0 DVR restores the voltage up to 93% of the reference voltage as can be seen in figure 15 and the FLC DVR is able to improve the voltage profile up to 95% of the reference voltage. Thus, performing better than the DQ0 based DVR. The FFT analysis shows that the THD levels are also under the allowed limit by the IEEE standards. DQO DVR injecting 3.81% while the FLC DVR injecting only 3.05% harmonics.

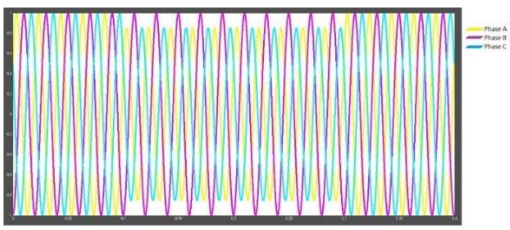

Fig 12 voltage sag after double line to ground fault

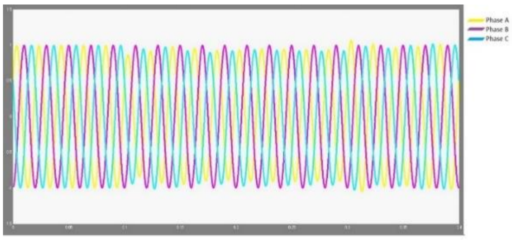

Fig 13 Load Voltage after DQ0 DVR compensation

3.4. Three Phase Faults:

The three phase faults can be the short-circuit among the three phases or the three phases being grounded. The three-phase fault causes a symmetrical voltage sag of 30% in the load voltage for 200 milliseconds. The DVR inject the compensating voltage signal into the power system at PCC and try to restore the voltage back to its normal voltage. It can be seen from the figure 17 that the DQO based DVR was successful in compensating the voltage signal up to 91% of the load voltage while the figure 18 shows that FLC DVR once again performed better that its competitor in restoring the voltage up to 94% of the reference voltage. The FFT analysis also goes in favor of the FLC controlled DVR as it injects only 4.13% Harmonics to the 4.30 % injected by the DQ0 based DVR.

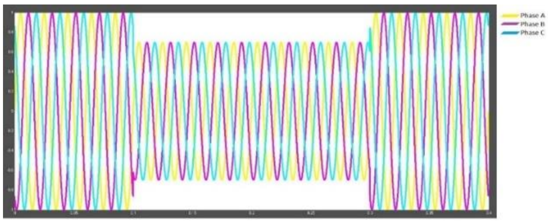

Fig 14 30% Voltage Sag Three Phase fault

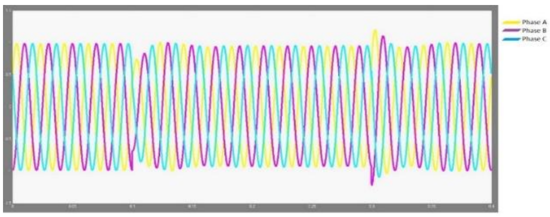

Fig 15 Load Voltage after DQ0 DVR Injection

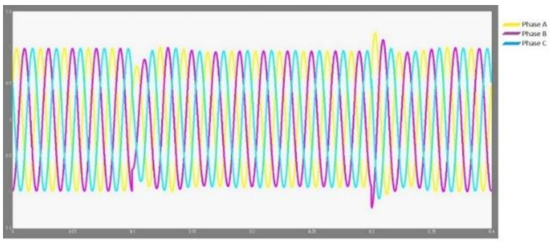

Fig 16 Load Voltage after FLC DVR compensation

Table 5 Total Harmonics Distortion Analysis (THD):

| | *Source voltage THD (%)* | *DQ0 DVR THD (%)* | *FLC DVR THD (%)* |
|---|---|---|---|
| | $V_s$ | $V_{load}$ | $V_{load}$ |
| *SLG* | 11.97 | 4.30 | 3.76 |
| *DLG* | 7.31 | 3.81 | 3.05 |
| *Three Phase Fault* | 12.98 | 4.30 | 4.13 |

Table 6 Load Voltage levels after Compensation in per unit

| | *DQ0 DVR* | | *FLC DVR* | |
|---|---|---|---|---|
| | *Vprefault (pu)* | *Vcompensated (pu)* | *(pu)* | *(pu)* |
| *SLG* | 0.98 | 0.93 | 0.98 | 0.96 |
| *DLG* | 0.98 | 0.93 | 0.98 | 0.95 |
| *Three Phase Fault* | 0.98 | 0.91 | 0.98 | 0.94 |

4. Conclusion:

Table 3 and 4 compare the performances of both DVRs and show that the FLC based DVR is better in terms of its effectiveness and performance based on the compensated voltage levels and in terms of the total harmonic distortion caused by each DVR. The FLC DVR compensates up to 96% of the reference voltage whereas the DQ0 DVR was only able to mitigate 93% in SLG voltage sag. Overall performance of FLC is better but the difference is not very much. The Main difference in performance is noted in the unbalanced faults where the DQ0 DVR struggles with the compensation signal generation but the FLC DVR performed effectively in dealing with both the balanced and unbalanced voltage sags. The success of the proposed DVRs with low voltage DC supply encourages the use of these DVRs into medium voltage level distribution system. The step-up transformer equipped DVRs managed to compensate most of the voltage sags, with FLC-DVR outperforming the DQ0-DVR in compensating the voltage sags as well as injection of lesser harmonics into the system. The advantage is due to the fact the FLC-DVR implies a more complex control scheme as compared to DQ0. This study has revealed that even DQ0-DVR are capable of compensating voltage sags up to rated voltages in high voltages. Though the distortion in the final voltage waveform due to DQ0 is more noticeable, The DQ0 scheme struggles with the unbalanced faults sags. The low voltage DC supply provided sufficient energy to compensate for the voltage sags through the step-up transformer. Usually, these higher voltage levels require much higher DC voltage source for compensation signal generation but by using the Step-up transformer, the rating of the DC voltage is set lower than usual and it reduces the cost of the DVR considerably. Placing the DVR in Medium voltage level distribution system gives the added advantage of protecting all the load connected in the downstream of the distribution system.


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