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IMPLEMENTATION OF DYNAMIC VOLTAGE RESTORER (DVR) FOR POWER QUALITY ENHANCEMENT IN POWER DISTRIBUTION SYSTEM

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SCHOOL OF RESEARCH AND POSTGRADUATE STUDIES
FACULTY OF ELECTRICAL AND COMPUTER ENGINEERING

IMPLEMENTATION OF DYNAMIC VOLTAGE RESTORER (DVR)
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DISTRIBUTION SYSTEM

CASE STUDY ON BAHIR DAR POWER DISTRIBUTION SYSTEM

BY
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BAHIR DAR, ETHIOPIA

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SYSTEM

CASE STUDY ON BAHIR DAR POWER DISTRIBUTION SYSTEM

By

Mulu Gebrelibanos Gebremariam

A thesis submitted to the school of Research and Graduate Studies of Bahir Dar
Institute of Technology, BDU in partial fulfillment of the requirements for the
degree of MASTER OF SCIENCE IN Power Systems Engineering in the
faculty of ELECTRICAL AND COMPUTER ENGINEERING

Advisor: Dr.-Ing. Belachew Bantyriga

Bahir Dar, Ethiopia

October, 2017

DECLARATION

I, the undersigned, declare that the thesis comprises my own work. In compliance with internationally accepted practices, I have acknowledged and refereed all materials used in this work. I understand that non-adherence to the principles of academic honesty and integrity, misrepresentation/fabrication of any idea/data/fact/source will constitute sufficient ground for disciplinary action by the University and can also evoke penal action from the sources which have not been properly cited or acknowledged.

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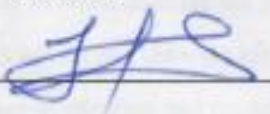
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LIST OF ACRONYMS AND SYMBOLS

DVR	Dynamic Voltage Restorer
DSS	Distribution Substation
DT	Distribution Transformer
PCC	Point of Common Coupling
PLL	Phase Locked Loop
PWM	Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
RMS	Root Mean Square
SCO	Short Circuit Operation
VSI	Voltage Source Inverter
THD	Total Harmonic Distortion
IGBT	Insulated Gate Bipolar Transistor
FFT	Fast Fourier Transform
ASD	Adjustable Speed Drive
D-STATCOM	Distribution Static Compensator
FACTS	Flexible AC Transmission System
GTO	Gate Turn-Off Thyristor
IEEE	Institute of Electrical and Electronics Engineers
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistor
PLC	Programmable Logic Controllers
PQ	Power Quality
pu	Per-Unit
SLGF	Single-Line to Ground Fault
SSTS	Solid State Transfer Switch
STATCOM	Static Synchronous Compensator
UPFC	Unified Power Flow Controller
UPS	Uninterruptible Power Supply

Symbols

C_{DC}	DC link capacitor
C_f	Filter capacitance
D	Maximum single-phase voltage sag to be compensated
D_r	Switch duty ratio
f_n	Nominal frequency
f_s	Switching frequency
I_{fault}	Short circuit current
I_{load}	Load current
L_f	Filter inductance
V_{inj}	Injection voltage
V_L	Load voltage
$V_{Lprefault}$	Pre-fault load voltage
V_r	Rated rms voltage of the primary feeder
V_{rs}	Rated supply voltage
V_s	Source voltage
Z_{line}	Line impedance
Z_s	Source impedance

ABSTRACT

Power quality is one of major concerns in the present era. It has become important, with the introduction of sophisticated devices, whose performance is very sensitive to the quality of power supply. Power quality problem is an occurrence developed as a nonstandard voltage, current or frequency that results in a failure of end user equipment. One of the major power quality problems on the power distribution network is the voltage sag. To solve this problem, the Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks was used. Dynamic Voltage Restorer (DVR) is a series connected power electronic based device that can quickly mitigate voltage sags in the system and restore the load voltage to the pre-fault value. Its appeal includes lower cost, smaller size, and its fast dynamic response to the disturbance. This thesis describes the effectiveness of using the dynamic voltage restorer (DVR) in order to mitigate voltage sags in low voltage distribution systems. Carefully chosen three case studies have been realized to verify the operation and performance of the designed system in practical power distribution system in MATLAB/Simulink program. In case (1) Single phase line to ground fault was generated and sag of 50% with 9° phase shift and 80% with 33.6° phase shift on phase A and Phase C was observed respectively. The simulated DVR was found to be capable of compensating for the missing voltages effectively by generating 0.492 pu for phase A & 0.495 pu for phase C. In case (2) the dynamic performance was tested with a three-phase symmetrical short circuit fault which resulted a 60% balanced voltage sag with phase shift of -41.4° on phase A, -45° on phase B and -48° on phase C. The DVR succeeded to protect the load from a 100 ms and 0.6 pu voltage sag by generating 0.708 pu voltage for each phase. In case (3) Simulation of multi stage fault generation block of two stages was carried out. In stage one three phase to ground fault was applied and on all Phases 35% reduction with phase shift of -41.4° was observed. While in stage two single-phase to ground fault was applied to Phase C and 30% with phase shift of -30.6° and 50% with phase shift of 16.2° reduction is observed on Phase B and Phase C respectively. Results of simulation showed that, the DVR was able to produce the required voltage component rapidly in each of the stages and helped to maintain a balanced and constant load voltage at 1 pu.

Keywords: Dynamic Voltage Restorer, Voltage Sag and Power Quality

Chapter 1 : Introduction

1.1 Background

In power distribution system it is important to remove any system faults so that the rest of the power distribution service is not interrupted or damaged. When a fault occurs somewhere in a power distribution system, the voltage is affected throughout the power system. Among various power quality problems, the majority of events are associated with voltage sags and they often cause serious power interruptions [1]. A voltage sag condition implies that the voltage on one or more phases drops below the specified tolerance for a short period of time. The causes of voltage sags are associated with faults within the power distribution system. Users located a close distance to the fault experience voltage sags much greater in magnitude and duration than users located farther away [2]. Often all users who are served by the power distribution system have power interruptions during a fault because of the effects of a voltage sag produced in the system by the fault.

It had been observed that in modern industrial devices most of devices are based on electronic devices such as programmable logic controllers and electronic drives [6]. The power electronic devices are very sensitive to disturbances and become less tolerant to power quality problems such as voltage sags, swells and harmonics in the entire problems associated with voltage dips is considered as one of the most severe disturbances to the industrial equipment. As far as industrial and commercial customers are concerned, several recent studies agree on the statement that voltage sags must be regarded as one of the most important concerns in power quality. This statement is particularly true for industrial facilities, where even short duration voltage sags are often responsible for much more long-lasting production downtimes and consequent large lost revenue [4].

Voltage dips (sags) are generally caused by faults occurring in the customers' installations on in the public distribution system. They are unpredictable, largely random events. The annular frequency varies greatly depending on the type of the supply systems and on the point of observation. Moreover, the distribution over the year can be very irregular.

There are several solutions currently available that will provide ride-through capability to critical loads under voltage sag conditions. Developed in the early 1990's, a Dynamic Voltage Restorer, with its excellent dynamic capabilities, when installed between the supply and a critical load feeder, can compensate for voltage sags, restoring line voltage to its nominal value within a few milliseconds and hence avoiding any power disruption to that load [10].

1.2 Motivation

The operation of most of the loads depend greatly on the voltage level at which the power is being supplied to them. But in the power system there are many power quality problems like deviations in the voltage due to sudden switching operations, faults etc. Voltage sag is the most common power quality related problem among the industrial, commercial and household consumers of electricity. Such voltage sag has a major impact on the performance of the microprocessor based sensitive loads. In order to maintain the voltage at a standard level there is a need to apply some device to the system. DVR is cost effective device, which is capable of addressing the above voltage sag problem effectively.

1.3 Objectives

1.3.1 General Objective

The objective of this research is to develop a novel voltage control mechanism using a custom power device called dynamic voltage restorer (DVR) that can compensate for voltage sag conditions in practical electric power distribution system.

1.3.2 Specific Objective

In this thesis a dynamic voltage restorer is designed and implemented in selected feeder of the distribution network which feeds relatively more sensitive loads and has significant voltage sag problem. The following are specific objectives of the thesis:

- To develop a model of the selected distribution substation (DSS) in the distribution network which is highly affected by voltage sag and,
- To design and model the dynamic voltage restorer,
- To study and analyze the behavior of the designed dynamic voltage restorer in reducing the voltage sag.

1.4 Problem Statement

One of the major problems observed in distribution system in recent days is Power Quality. Today most of the people are using the sophisticated electrical equipment based on semiconductor device, these equipment pollute the power quality. Power distribution systems, ideally, should provide their customers with an uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency however, in practice, power systems, especially the distribution systems, have numerous nonlinear loads, and is continuously under some system events such as usual (e.g. motor starting, overloading) and unusual (e.g. faults) which significantly affect the quality of power supplies. As a result of the nonlinear loads and system events, the purity of the waveform of supplies is lost. Such power quality problems cause sensitive equipment to fail, shutdown and create a large current unbalance. These effects can incur a lot of expensive from the customer and cause equipment damage. Thus it has been very important to improve the quality of power which is very severe for the customers as it can cause malfunctioning of several sensitive electronic equipments. One of the major power quality problems observed in the power distribution system is the voltage sag.

Electronic devices function properly as long as the voltage (or driving force) of the electricity feeding the device stays within a consistent range. Voltage sag is not a complete interruption of power; it is a temporary drop below 90 percent of the nominal voltage level. Most voltage sags do not go below 50 percent of the nominal voltage. Voltage sags are the most significant power quality (PQ) problem and they can be a significant problem for large commercial customers as well.

To solve this problem, custom power devices are used. One of those devices is the Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks. Its appeal includes lower cost, smaller size, and its fast dynamic response to the disturbance.

1.5 Expected Outcomes and Significance of the Thesis

1.5.1 Expected Outcomes

The expected outcome of this thesis are to develop model for a specific feeder which is highly affected by voltage sag problem from the distribution network and develop model for dynamic voltage restorer (DVR) for the enhancement of power quality in the concerned feeder. The effectiveness of the DVR in solving the power quality problem is to be proved through simulations, model development and analysis by using MATLAB/SIMULINK software.

1.5.2 Significance of the Thesis

Power quality is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance or life expectancy. All electrical devices are prone to failure when exposed to one or more power quality problems. The electrical device might be an electric motor, a transformer, a generator, a computer, a printer, communication equipment, or a household appliance. All of these devices and others react adversely to power quality issues depending on the severity of problems. Therefore by solving the power quality problems a healthy system can be created and all the linear & nonlinear devices that are connected to the system function properly and will have longer life.

1.6 Scope of the Work

It is observed that power quality is major area of concern for power engineers now days. Different types of custom power devices are proposed to improve the power quality and to maintain voltage profile at the desired point. Industrial loads such as induction motor drive and other nonlinear loads cause fluctuations and degrade the power quality. In order to improve the quality of power, one of the custom power devices which is dynamic voltage restorer (DVR) was used. The simulations were implemented by using Matlab/Simulink simulation software. The effectiveness of DVR was established for practical power distribution network with different sensitive loads under various operating conditions. As a limitation all the analysis and modeling of the components on this thesis have no practical implementation they all were done by using Matlab/Simulink simulation software.

1.7 Methodology

❖ Power Distribution System Description and Modeling

Within the scope of this study, Bahir dar city power distribution system which is supplying the electrical power required by the city was handled as a practical case study. Within the distribution network many power quality problems are observed. Among the power quality problems voltage sags are the most severe and common of the power distribution system.

The feeder which has significant voltage sag problem and feeds relatively more sensitive loads in the power distribution system was identified and a model was developed by collecting the following data from the appropriate organization:

- System voltage and major component ratings.
- Major medium-voltage cable lengths, sizes, and construction.
- Approximate number and ratings of all loads.

MATLAB/SIMULINK model of the distribution substation which suffers from a serious voltage sag problem was developed and the voltage sag mitigation technique was implemented on this specific low voltage system.

❖ How to Tackle the Problem?

Developed in the early 1990's, a Dynamic Voltage Restorer, with its excellent dynamic capabilities, when installed between the supply and a critical load feeder, can compensate for voltage sags, restoring line voltage to its nominal value within a few milliseconds and hence avoiding any power disruption to that load. This device employs solid-state power electronic switches in a pulse-width modulated (PWM) inverter structure. It injects a set of three-phase AC output voltages in series and synchronism with the distribution feeder voltages. The amplitude and phase angle of the injected voltages are variable and are controlled by a control system [8].

❖ Why DVR?

There are numerous reasons why DVR is preferred over other devices [11]:

1. DVR is less expensive compared to the UPS.
2. UPS also needs high level of maintenance because it has problem of battery leak and have to be replace as often as five years.
3. DVR has a relatively higher energy capacity and costs less compared to SMES device.
4. DVR is smaller in size and costs less compared to DSTATCOM.
5. DVR is power efficient device compared to the UPS.

For the modeling of distribution substation system of Ghion feeder MATLAB/SIMULINK simulation tool was used. To enhance the performance of distribution system and ensure quality power, DVR was connected to the distribution system. DVR was designed using MATLAB Simulink. Figure 1.1 shows the flowchart for the methodology.

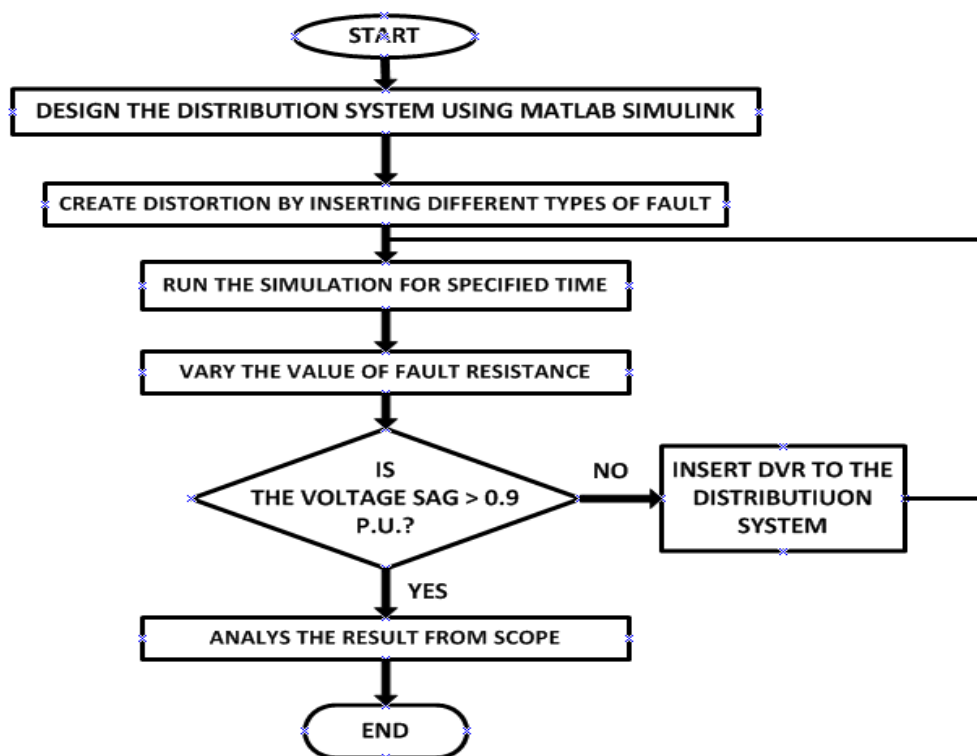


Figure 1.1: Flowchart for the methodology

1.8 Outline of the thesis

The thesis consists of the following chapters:

Chapter 1: is an introductory part giving a highlight on background of the study. The introduction part discusses about the background, statement of the problem, objectives, significance and scope of the thesis and methodology.

Chapter 2: Gives an overview of power quality issues, which are relevant for the design and control of a dynamic voltage restorer with focus on voltage sags. Presents a literature survey on the work accomplished on the area of design of custom power devices specifically the dynamic voltage restorer. This chapter reviews previous works on several issues such as modeling approaches, design features, control schemes and the possibilities in improving the restoring capability of the device.

Chapter 3: Gives an overview of the dynamic voltage restorer, a brief theoretical review on the main components of the custom power device, the control mechanism, the location of a DVR and the main system and converter topologies suited for a DVR.

Chapter 4: Presents a description and modeling of the system chosen for case study and design and modeling of the individual components of the dynamic voltage restorer. The models are implemented in the MATLAB/Simulink simulation software environment for simulation.

Chapter 5: In the first part it describes a methodology for voltage sag generation using Matlab/Simulink. It includes fault simulations for generation of different types of voltage sag using MATLAB/Simulink. In the second part, the performance and effectiveness of the proposed solution for voltage sag mitigation (the developed model of dynamic voltage restorer) is tested with different case studies. Its performance against different single and three phase fault scenarios has been evaluated.

Chapter 6: Summarizes and concludes on the obtained results and sketches the perspectives and future work regarding the dynamic voltage restorer.

Chapter 2 : Power Quality, Custom Power Devices and Voltage Sag

2.1. Power Quality

2.1.1. Definition of Power Quality

Power quality has different meanings to different people. The definition of power quality given in the IEEE dictionary originates in IEEE standard 1100: *“Power quality is the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment.”*

However, as is stated by Heydt (1998) and Bollen (1999), there is no single definition of the term “power quality”. For example, Heydt (1998) gives the following description: *“Power quality is the provision of voltages and system design so that the user of electric power can utilise electric energy from the distribution system successfully, without interference or interruption.”* The next explanation is provided by Bollen (1999): *“Power quality is the combination of voltage quality and current quality. Thus power quality is concerned with deviations of voltage and/or current from the ideal.”* On the other hand, power quality problems are described by Morán (1999) in the following way: *“A power quality problem exists if any voltage, current or frequency deviation results in a failure or in bad operation of the customer’s equipment. The quality of the power supply consists basically of two elements, the supply reliability and the voltage quality.”* Based on the previous descriptions it can be concluded that the concept “power quality” involves two parties: the supplier of the electricity and the user. The “power quality” can then be regarded as a measure of purity of the energy which is transferred from the supplier to the user.

Current quality is concerned with deviations of the current from the ideal. The ideal current is a single-frequency sine wave of constant frequency and magnitude. An additional requirement is that this sine wave is in phase with the supply voltage. Thus where voltage quality has to do with what the utility delivers to the consumer, current quality is concerned with what the consumer takes from the utility. Voltage and current are strongly related and if either voltage or current deviates from the ideal it is hard for the other to be ideal. Voltage quality is concerned with deviations of the voltage from the ideal. The ideal voltage is a single-frequency sine wave of constant frequency and constant magnitude. The term voltage quality can be interpreted as the quality of the product delivered by the utility to the customers. Power quality problem is defined as any power problem manifested in voltage, current or frequency deviations that result in failure or mal-operation of customer equipment.

The power supply system can only control the quality of the voltage; it has no control over the currents that particular loads might draw. Therefore, the standards in the power quality area are devoted to maintaining the supply voltage within certain limits. Any significant deviation in the waveform magnitude, frequency or purity is a potential power quality problem. Of course, there is always a close relationship between voltage and current in any practical power system. Although the generators may provide a near-perfect sine-wave voltage, the current passing through the impedance of the system can cause a variety of disturbances to the voltage [14]. Power quality is often considered as a combination of voltage and current quality. In most of the cases, it is considered that the network operator is responsible for voltage quality at the point of connection while the customer's load often influences the current quality at the point of connection [21]. Power quality disturbances can be summarized as follows: [12]

❖ Transients:

- Impulsive transients: Sudden, non-power frequency change in the steady state condition of the voltage, current or both.
- Oscillatory transients: Voltage or current whose instantaneous value changes polarity rapidly.

❖ Short duration voltage variations:

- Sag: 0.1 ~ 0.9 pu; 0.5 cycles to one minute; caused by system faults, energization of heavy loads and starting of large motors.
- Swell: 1.1 ~ 1.8 pu; 0.5 cycles to one minute; caused by system fault conditions.
- Interruption: Less than 0.1 pu; not exceeding one minute; caused by power system faults, equipment failures and control malfunctions.

❖ Long duration voltage variations:

- RMS deviation longer than one minute; voltage, current, frequency.
- Types: overvoltage, under voltage.

❖ Voltage imbalances:

- Percentage maximum deviation from the average of three-phase voltages or currents.

❖ Waveform distortions: DC offset harmonics, notching, noise.

❖ Power frequency variations:

- Deviations of the power system fundamental frequency from its specified nominal value.
- Depends on: load characteristics, response of generation control system to load.

❖ Voltage fluctuations:

- Systematic variations of the voltage envelop or series of random voltage changes.
- Not normally exceed 0.9 to 1.13 pu.

Power electronic based devices provide protection for industry and commercial customers from power quality problems basically sags, swells, harmonics, interruption and unbalance voltages that are shown in Figure 2.1.

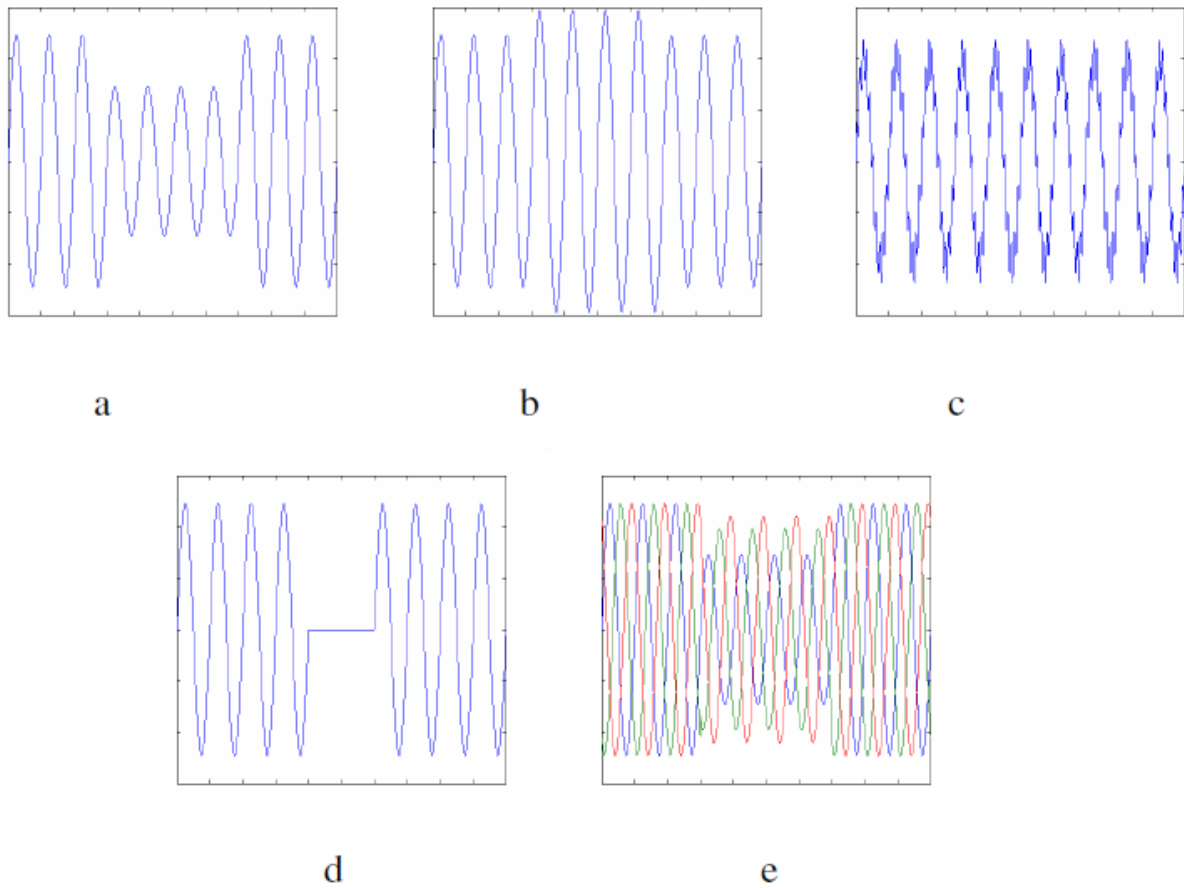


Figure 2.1: Waveforms of (a) Voltage Sag, (b) Swell, (c) Harmonic, (d) Outage and (e) Unbalance

2.1.2. Sources of Poor Power Quality

The nonlinear characteristics of various office and industrial equipment connected to the power grid could cause electrical disturbances leading to poor power quality. These electrical disturbances could destroy certain sensitive equipment connected to the grid or in some cases could cause them to malfunction. There is virtually no piece of office or industrial equipment that does not depend on electricity in some form or other. Among the office equipment are computers, fax machines, copiers, printers, and telephones etc. Computers have dominated the work place while the others in modern days have microprocessors. All this electronic equipment when connected to the power system can actually generate electrical disturbances, which can adversely affect other equipment within the power network. The main sources of poor power quality are listed as follows [3]:

- Adjustable –speed drives
- Switching Power supplies
- Arc furnaces
- Electronic Fluorescent lamp ballasts
- Lightning Strike
- L-G fault
- Non- linear load
- Starting of large motors
- Power electronic devices

Although all disturbances mentioned above are of concern in the power quality context, there is no doubt that the most problematic issue is the occurrence of faults, which is the most exploited topic in this thesis work. System faults can produce voltage variations at different points of the system with different magnitudes and time scales, depending on how far the analyzed point is from the fault location, the fault clearing procedure, and system impedances.

The large majority of faults on a utility system are single phase-to-ground temporary faults. Nevertheless, most of the three-phase breakers and reclosers on utility distribution system work on all three phases in order to prevent single phasing of three-phase loads such as large three-phase motors. It can thus be said that the single-phase fault will have the same effect downstream to the fault as a three-phase fault after the actuation of the protection scheme.

Operating the circuit breakers and reclosers only on the faulted phase is a usual practice if the feeder serves only single-phase loads.

2.1.3. Need of Power Quality

Now a day's Improvement of Power quality has become a major area of concern in electrical power system. Increased sensitive and sophisticated loads results nonstandard voltage, current and frequency and reduce quality of power. This nonstandard power results failure of the loads connected to the distribution systems. Thus it has been very important to improve the quality of power which is very severe for the industrial and commercial customers as it can cause malfunctioning of several sensitive electronic equipments. Voltage quality is the major problem which is very severe for the sensitive electronic equipment. The main reasons for concern with power quality (PQ) are as following [9]:

- End user devices become more sensitive to PQ due to many microprocessor and microcontroller based controls and power electronic devices, are more sensitive to power quality variations than that equipment used in the past.
- Power electronics equipment used for enhancing system stability, operation and efficiency. They are major source of bad PQ and are vulnerable to bad PQ as well.
- End users have an increased awareness of power quality issues. Utility customers are becoming better informed about such issues as interruptions, sags, and switching transients and are challenging the utilities to improve the quality of power delivered.
- Complex interconnection of systems, most of the networks are interconnected these days, which results in more severe consequences if any one component fails.
- Complexity of industrial processes: the re-startup is very costly.
- Large computer systems in many businesses facilities
- Deregulation of the power industry
- Continuous development of high performance equipment: Such equipment is more susceptible to power disturbances.

The users demand higher power quality to use more sensitive loads to automate processes and improve quality. Some basic criterions for power quality are constant rms value, constant frequency, symmetrical three-phases, pure sinusoidal wave shape and limited THD. These values should be kept between limits determined by standards if the power quality level is considered to be high. Power quality covers several types of problems of electrical supply

and power system disturbances. The cost of power interruptions and disturbances can be quite high as a result of the important processes controlled and maintained by the sensitive devices.

2.2. Custom Power Devices

2.2.1. Introduction to Custom Power Devices

The concept of custom power was introduced by N.G.Hingorani [6]. The term custom power means the use of power electronics controllers for distribution systems. The custom power increases the quality and reliability of the power that is delivered to the customers. Customers are increasingly demanding quality in the power supplied by the electric company. Custom power is a strategy, which is designed primarily to meet the requirements of industrial and commercial customer. The concept of custom power is to use of power electronic or static controllers in the medium voltage distribution system aiming to supply reliable and high quality power to sensitive users. Power electronic valves are the basis of those custom power devices such as the static transfer switch, active filters and converter based devices.

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

- No (or rare) power interruptions
- Magnitude and duration of voltage reductions within specified limits.
- Magnitude and duration of over voltages within specified limits.
- Low harmonic voltage.
- Low phase unbalance.

2.2.2. Types of Custom Power Devices

There are many types of Custom Power devices. Some of these devices are Active Power Filters (APF), Surge Arresters (SA), Battery Energy Storage Systems (BESS), Solid State Fault Current Limiter (SSFCL), Solid-State Transfer Switches (SSTS), Static VAR Compensator (SVC), Dynamic Voltage Restorer (DVR), Distribution Static synchronous Compensators (DSTATCOM) and Uninterruptible Power Supplies (UPS), Unified power quality conditioner (UPQC). Custom power devices can be classified into two major categories [12]. One is network configuring type and the other is compensating type. The network reconfiguration devices are used for current limiting, current breaking and current transferring devices. The following devices are mainly used for network reconfiguration:

- SSCL (Solid State Current Limiter)
- SSCB (Solid State Circuit Breaker)
- SSTs (Solid State Transfer Switch)

SSCL, SSCB, and SSTs are the most representative in this category. SSCL is a GTO based device that inserts an inductor in series with the power system and limits the fault current and once the fault is cleared the inductor is removed from the circuit. SSCB acts as a protection device. It isolates the faulty circuit from the power system. SSTs transfers rapidly the load from the faulted line to an alternative line to protect a sensitive load. Due to the use of GTO or thyristors in these devices, they are therefore called “solid state” devices.

The compensating type custom power devices can increase the availability of sensitive loads in the system and supply reliable power. These Custom power devices are typically building on the distribution system to provide higher power quality and most economical solution. High power solid-state switches insulated gate bipolar transistor (IGBT) and gate turn-off thyristor (GTO) with controlled turn- off capability are used to achieve high power quality. They perform rapid response and provide continuous and dynamic control in real time processes. They are mainly used in voltage sag mitigation, protection and control of sensitive loads, reactive power and voltage regulation and harmonic elimination applications. The custom power devices used for compensation are [14]:

- Distribution Static Compensator (DSTATCOM)
- Dynamic Voltage Restorer (DVR)
- Unified Power Quality Conditioner (UPQC)

DSTATCOM is connected in shunt with the power system while DVR is a series connected device that injects a rapid series voltage to compensate the supply voltage. UPQC is the combination of DSTATCOM and DVR. It injects series voltage and shunt currents to the system [22].

Any device that depends on a volatile memory chip for information storage is potentially at risk from power quality events. Many processes in industry depend on automated microprocessor control systems. Solutions to the power quality problems encountered with this type of devices that are known as sensitive equipment [16]. These devices are usually installed in the low voltage system (< 1 kV) and types are listed below:

- Programmable Logic Controllers (PLC)
- Computers
- fax machines, copiers, and printers
- Electromechanical Relays and Motor Contactors
- Adjustable Speed Drives (ASD)

They often consist of protection for the control system alone, the actual process not being sensitive to the more common disturbances.

2.3. Voltage Sag

2.3.1. Introduction to Voltage Sag

A voltage sag is a momentary decrease in rms ac voltage (0.1-0.9 p.u. of the nominal voltage), at the power frequency, of duration from cycles to a few seconds. Most voltage sags are caused by remote faults, such as single line- to-ground fault, double line to ground fault and three phase fault on the power distribution system.

Different power quality surveys done by researchers identify voltage sags as the most serious power quality problem for industrial customers. Voltage sag can cause serious problem to sensitive loads that use voltage sensitive components such as adjustable speed drives, process control equipment, programmable logic controllers, robotics, and computers. Malfunctioning or failure of this equipment can cause by voltage sags leading to work or production stops with significant associated cost [17].

In the conventional method to assess these effects, voltage sags are characterized by its magnitude and duration. The magnitude is defined as the percentage of the remaining voltage during the sag and the duration is defined as the time between the sag commencement and clearing. However, balanced and unbalanced faults not only cause a drop in the voltage magnitude but also cause change in the phase angle of the voltage. Therefore, power–electronics converter that use phase angle information for their firing instants may be affected by the phase angle jump [19], [21]. In order to find any solutions for voltage sag problems due to faults, it is necessary to identify characteristics of magnitude, duration and phase angle variations.

2.3.2. Voltage Sag Characteristics

Voltage sag is defined as a decrease in rms voltage at the power frequency for durations of 0.5 cycles to 1 minute. This definition specifies two important parameters for voltage sag: the rms voltage and duration. The standard also notes that to give a numerical value to sag, the recommended usage is sag 70%, which means that the voltage is reduced down to 70% of the normal value, thus a remaining voltage of 30%. Sag magnitude is defined as the remaining voltage during the event. The power systems faults not only cause a drop in voltage magnitude but also cause change in the phase-angle of the voltage. The parameters used to characterize voltage sag are magnitude, duration and phase angle jump.

- **Voltage Sag Magnitude**

The magnitude of voltage sag can determine in a number of ways. The most common approach to obtain the sag magnitude is to use rms voltage. There are other alternatives, e.g. fundamental rms voltage and peak voltage. Hence the magnitude of the sag is considered as the residual voltage or remaining voltage during the event. In the case of a three-phase system, voltage sag can also be characterized by the minimum RMS-voltage during the sag. If the sag is symmetrical i.e. equally deep in all three phases, the lowest remaining voltage in any of the phases can be used to characterize the sag. If the sag is unsymmetrical, i.e. the sag is not equally deep in all three phases; the phase with the lowest remaining voltage is used to characterize the sag [24].

The magnitude of voltage sags at a certain point in the system depends mainly on the type and the resistance of the fault, the distance to the fault and the system configuration.

- **Voltage Sag Duration**

The duration of voltage sag is mainly determined by the fault-clearing time. The duration of voltage sag is the amount of time during which the voltage magnitude is below threshold is typically chosen as 90% of the nominal voltage magnitude. For measurements in the three-phases systems the three rms voltages have to be considered to determine duration of the sag. The voltage sag starts when at least one of the rms voltages drops below the sag-starting threshold. The sag ends when all three voltages have recovered above the sag-ending threshold [24].

▪ Phase Angle Jump

To obtain the phase-angle jump of measured sag, the phase-angle of the voltage during the sag must be compared with the phase-angle of the voltage before the sag. The phase-angle of the voltage can be obtained from the voltage zero crossing or from the phase of the fundamental component of the voltage. The complex fundamental voltage can be obtained by doing a Fourier transform on the signal. This enables the use of Fast-Fourier Transform (FFT) algorithms [24].

2.3.3. Voltage Sag Types

The different types of faults increase the severity of balanced and unbalanced voltage sags. If the phase voltages during the sag have unequal magnitudes or phase relationship other than 120, the sag is considered to be unbalanced. The fault type, transformer connection and equipment influence the characteristics of voltage sag in each phase of a three-phase system. The voltage sags experienced by three- phase loads can be classified into seven types denoted as A, B, C, D, E, F and G [26].

Type A is balanced sag and the other types are unsymmetrical sags. Figure 2.2 shows the phasor diagrams of voltage sag types.

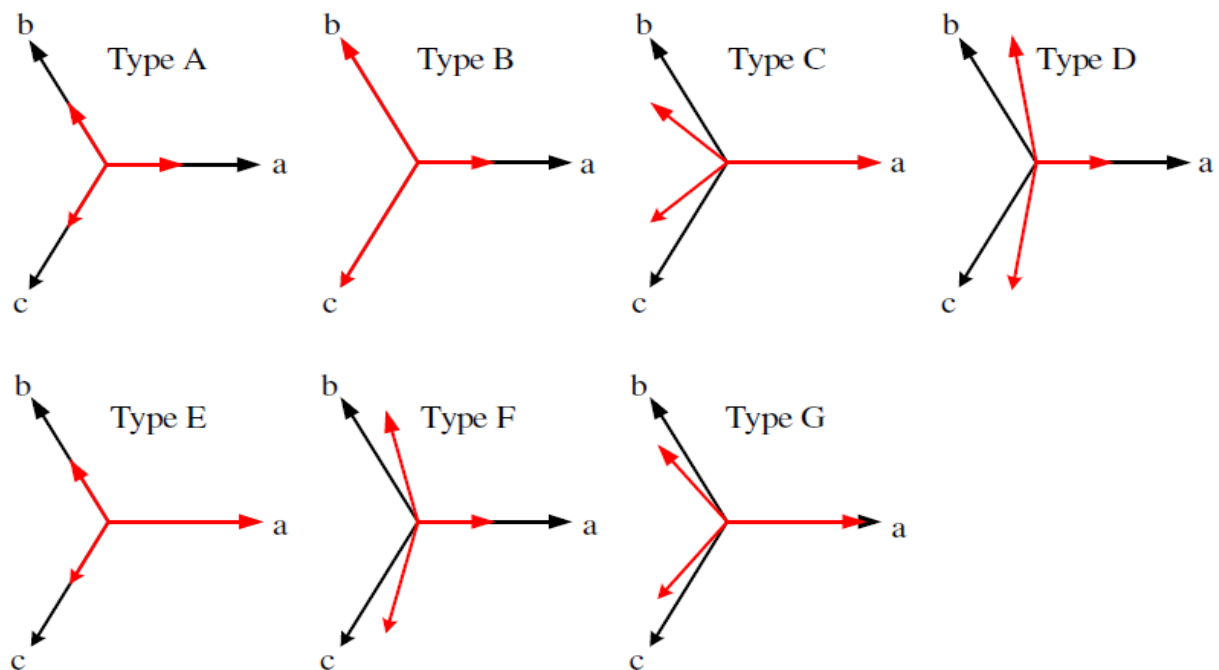


Figure 2.2: The phasor diagrams of voltage sag types

Type A sag generally occurs on the end user devices. It is rarely occurred in the distribution systems. The power requirement is the same for each of the three phase devices.

Type B and D are the sags of single-line faults and they are the most common types in the distribution systems, it has an occurrence percent of 70% among all sags. In Type B sag, the system is solidly grounded so the non-faulted phases are kept healthy. In Type D sag, the system is grounded through the impedance. The no faulted phases experience voltage change because the zero sequence differs from positive and negative impedance of the system.

Type C and E are the sags of double-line faults. These voltage sags have an occurrence of percentage of 20% among all types of sags that happen in distribution systems. Type C and E sags have common properties except for the angle between the sagged phases.

Type F and G are the sags of double-line ground faults. The worst case scenario for this type of sag is that the system is grounded through impedance. In that condition, the zero sequence voltage drops is increased drastically, so it is expected to have voltage change in non-faulted phases. The voltage changes in non-faulted phases occur because the zero sequence voltage drop increases effectively.

2.4. General Solutions to Sag Mitigation

Voltage magnitude, waveform and frequency determine the quality of power supply. Several measures may be taken by the utility, end user and equipment manufacturer to reduce the number and severity of voltage sags caused by faults. The realization of a good system design and using correct protective devices can be insufficient to reduce the existence of voltage sags. The methods to mitigate the voltage sags by end user can be summarized by as follows: [12]

- Modifying the overall system to decrease the number of voltage sags
- Re-designing the loads firmly to voltage sags
- Choosing proper connection type of the transformer
- Using power electronic based custom devices if the voltage sag is major problem for a number of sensitive loads, using a DVR is more economic and effective solution because it will succeed the voltage sag mitigation lower energy ratings than the D-STATCOM or UPS.

The methods to mitigate the voltage sags by the utility can be summarized as follows: [16]

- Fault prevention activities include tree trimming, adding line arresters, insulator washing.
- Insulation on utility lines cannot be expected to withstand all lightning strokes.
- Any line that shows a high susceptibility of lightning, induced faults should be investigated.
- On transmission lines shielding effectiveness and tower footing resistance should be considered carefully.
- Fault clearing practices may include adding line reclosers, eliminating fast tripping, adding loop schemes and modifying feeder designs.

2.5. Literature Review

Power quality is a comprehensive term that squeezes all features related with amplitude, phase and frequency of the voltage and current waveforms existing in a power circuit. Poor power quality may result from transient conditions accumulate in the power circuit or from the non-linear loads.

Power distribution systems ought to deliver their customers with an associate degree uninterrupted flow of energy with smooth sinusoidal voltage at the contracted magnitude level and frequency, but the distribution systems, have several nonlinear loads, which significantly affect the quality of power supplies [1-4].

The concept of custom power was introduced by N.G.Hingorani [6]. The term custom power means the utilization of power electronic controllers for distribution systems. The custom power devices will increases the quality and reliability of the power that is delivered to the customers. Customers are increasingly demanding more exigent quality in the power supplied by the electrical company.

IEEE Standard 1100-1992 (IEEE Emerald Book) defines voltage sag as “an rms reduction in the AC voltage, at the power frequency, for durations from a half-cycle to a few seconds”. Note: The IEC terminology for sag is dip. They may be accompanied with phase jumps. If the voltage is reduced to zero, the disturbance is said to be a momentary outage or micro interruption. The most obvious way to characterize voltage sag is in terms of the reduced

voltage rms, duration and probably accompanied phase jump. Voltage dips (sags) are generally caused by faults occurring in the customers' installations on in the public distribution system. They are unpredictable, largely random events. The annular frequency varies greatly depending on the type of the supply systems and on the point of observation. Moreover, the distribution over the year can be very irregular [9].

Voltage sags are often generated by starting of large loads, such as motors, transformer energizing, equipment faults, transmission and distribution system faults. Faults on the distribution and transmission systems can be caused by numerous sources such as lightning strikes, conductors blowing together in a storm, contact with objects (e.g. tree branches, animals, etc.) or vandalism [12]. Most of these faults (70-80%) are temporary in nature; they are self-clearing within a few milliseconds. The fault that does not clear will cause a protective device/s (e.g. fuse, circuit breaker, or recloser) to operate to interrupt current to that part of the system in the affected area.

B.Sharath Kumar and MD. Yaseen, [11] presents the analysis and control of a dynamic voltage restorer (DVR) and a unified power flow controller (UPFC) for the compensation of voltage sag/swell. A Unified Power Flow Controller (UPFC) is an electrical device for providing fast-acting reactive power compensation on voltage electricity networks. Dynamic Voltage Restorer (DVR) is a custom power device used in power distribution networks to protect consumers from sudden sags and swells in grid voltage. Voltage sag/swell is one of the most important power quality problems challenging the utility industry. The DVR provides three-phase controllable voltage source, whose voltage vector (magnitude and angle) adds to the source voltage during sag event, to restore the load voltage to pre-sag conditions. The DVR is designed for protecting the whole plant with loads in the range of some MVA. The DVR can restore the load voltage within few milliseconds. The modeling of dynamic voltage restorer and UPFC is carried out component wise and their performances are analyzed using MATLAB software.

Afshin LASHKAR ARA and Seyed Ali NABAVI NIAKI, [12] describes the power electronic devices and technical review in various power engineering levels. In energy transmission systems, effective equipments on power control are generally known as Flexible AC Transmission System (FACTS). In addition, the power electronics-based equipment, which are called power conditioners are use to solve power quality problems. Since the topologies of these equipments are similar to those used in FACTS equipment, power

conditioners are also called Distribution FACTS (DFACTS). The principal operating modes and applications whichever one of equipment in transmission and distribution system (such as STATCOM, SSSC, UPFC, DSTATCOM, DVR and UPQC) are discussed and compared.

G.O. Suvire and P.E. Mercado, [16] presents that causes of a poor power quality are harmonic currents, poor power factor, supply voltage variations, etc. Voltage sag/swell, momentary interruption, under/over voltages, noise and harmonics are the most common power quality issues. A new connection for a unified power quality conditioner (UPQC) to improve the power quality of two feeders in a distribution system is proposed. It illustrates how UPQC can improve the quality of power by mitigating all these PQ disturbances.

Risha Dastagir and Mariam Asif, [13] describes the effectiveness of using dynamic voltage restorer (DVR) in order to mitigate voltage sags and swells in low voltage distribution systems. Dynamic Voltage Restorer can provide the most cost effective solution to mitigate voltage sags and swells that is required by customer. The Dynamic Voltage Restorer (DVR) is a rapid, flexible and resourceful solution to power quality problems.

Anita Pakharia and Manoj Gupta, [14] presents the comprehensive reviews of various articles, the advantages and disadvantages of each possible configuration and control techniques pertaining to DVR. The compensation strategies and controllers have been presented in literature, aiming at fast response, accurate compensation and low costs. The review helps the researchers to select the optimum control strategy and power circuit configuration for DVR applications. This will also very helpful in finalizing the method of analysis and recommendations relating to the power quality problems.

Deepa Patil, [15] Illustrates for improving power quality as a cost effective solution and for the protection of sensitive loads from voltage disturbances a dynamic voltage restorer (DVR) has great significance. Dynamic voltage restorers are mostly utilized to deal with voltage sag and swells in distribution systems. In this paper, a Dynamic voltage restorer and review of proposed control strategies applied in Dynamic voltage restorers are discussed.

Chapter 3 : The Dynamic Voltage Restorer

Power quality issues and resulting problems are consequences of the increasing use of solid state switching devices, nonlinear and power electronically switched loads, electronic type loads. The advent and wide spread of high power semiconductor switches at utilization, distribution and transmission lines have non sinusoidal currents. Power quality problems can cause system equipment mal function, computer data loss and memory mal function of the sensitive equipment such as computer, programmable logic devices [PLC] controls, and protection and relaying equipment [1].

Power quality in the distribution system can be improved by using a custom power device the dynamic voltage restorer – DVR. The DVR has been developed by Westinghouse for advance distribution. The DVR is able to inject a set of three single-phase voltages of an appropriate magnitude and duration in series with the supply voltage in synchronism through injection transformer to restore the power quality. The DVR is a series conditioner based on a pulse width modulated voltage source inverter. Voltage sags caused by unsymmetrical line-to-line, line to ground, double-line-to-ground and symmetrical three phase faults is affects the sensitive loads, the DVR injects the independent voltages to restore and maintained sensitive load voltage to its nominal value.

Dynamic Voltage Restorer is series connected voltage source converter based compensator which has been designed to protect sensitive equipment like Programmable Logic Controllers (PLCs), adjustable speed drives, computers etc from voltage sag. Its main function is to monitor the load voltage waveform constantly by injecting missing voltage in case of sag. To obtain above function a reference voltage waveform has to be created which is similar in magnitude and phase angle to that of supply voltage. During any abnormality of voltage waveform it can be detected by comparing the reference and the actual waveform of the voltage. As it is series connected device so it cannot mitigate voltage interruptions. The first DVR was installed for rug manufacturing industry in North Carolina. Another was used in Australia for large dairy food processing plant [4] [5] [6].

The DVR functions by injecting three single phase AC voltages in series with the three phase incoming network voltages during sag, compensating the difference between faulty and nominal voltages. All three phases of the injected voltages are of controllable amplitude and phase. Figure 3.1 shows block diagram of dynamic voltage restorer.

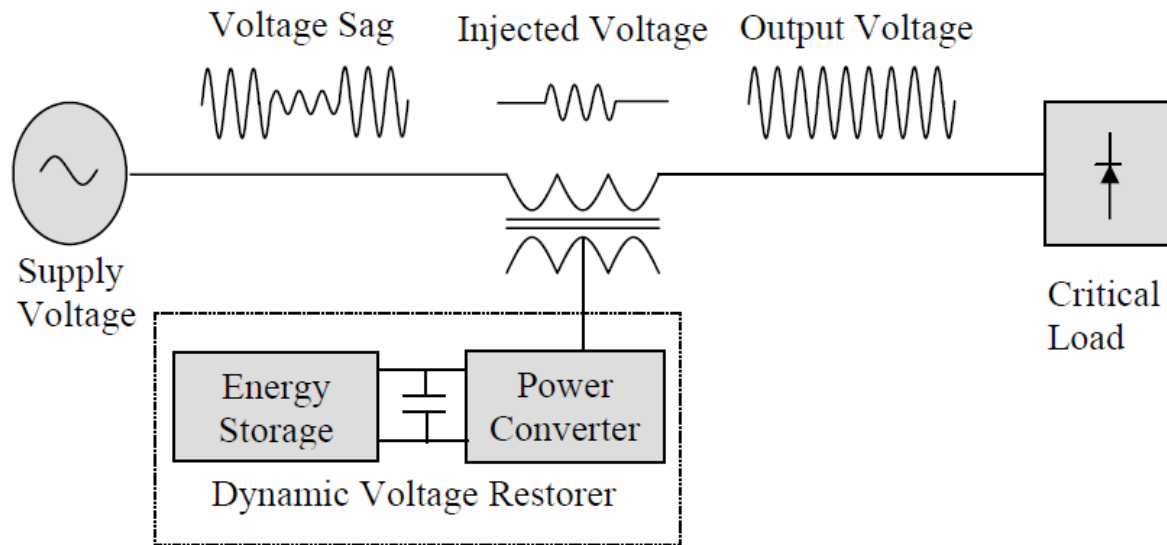


Figure 3.1: The block diagram of the DVR

At the heart of the DVR are three phase voltage source inverter/s: a solid state power electronics device which converts DC to AC. By fast switching a DC source, the DVR is able to synthesize an AC waveform. The DVR constantly monitors incoming supply voltage and compares it with a reference voltage. In the event of a disturbance it injects three phase AC output voltages of compensatory amplitude, phase and harmonic content. This ensures that the voltage seen by the load is of the desired magnitude, preventing unnecessary process interruptions.

The primary side of the DVR injection transformer is sized to carry full line current. The primary voltage rating is the maximum voltage that the DVR can inject into the line for a given application. The secondary voltage is controlled by voltage source inverter connected to the DC link. The bridge outputs are filtered before being applied to the injection transformer by the harmonic filter and are independently controllable to allow each phase to be compensated individually.

3.1. Operating Principles

Among the voltage transients (sags, flickers, interruption, harmonics...), the voltage sags are the most severe disturbance. The users may improve end-use devices or use protection devices to reduce the number of voltage sags. But overall solution to mitigate the voltage sags and recovering the load voltage to the pre-fault value is using a Dynamic Voltage Restorer (DVR). It is a solid state DC to AC switching power electronic converter that injects three single-phase AC voltages in series between the feeder and sensitive load [7]. Using a DVR is more reliable and quick solution to maintain with a clean supply of electricity for customers. The DVR is connected in the utility primary distribution feeder as shown in Figure 3.2. This location of DVR will mitigate the certain group of customer by faults on the adjacent feeder [8].

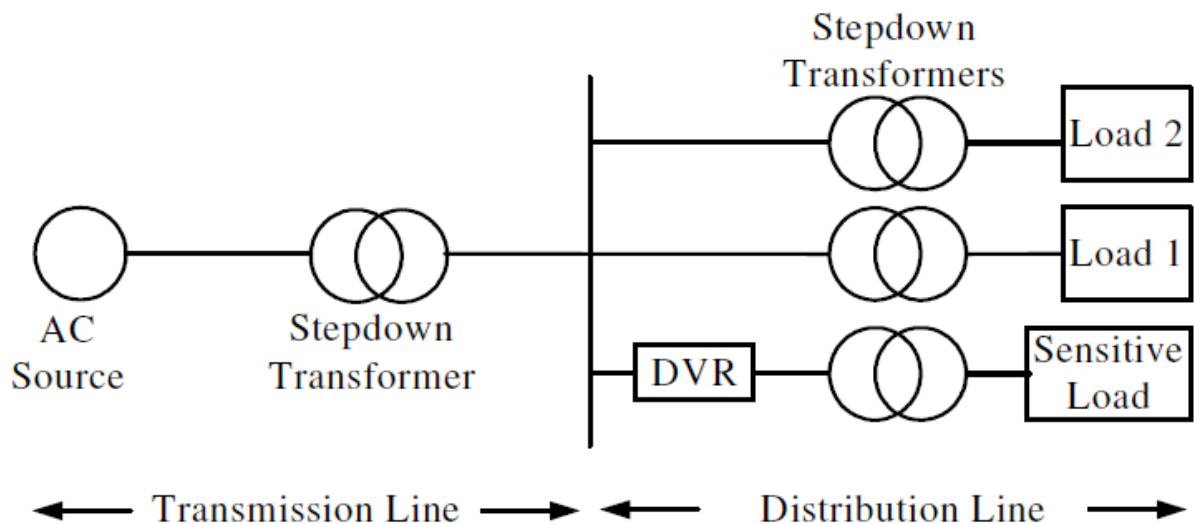


Figure 3.2: DVR inserted into distribution network

The energy storage unit is common voltage source for PWM inverter and it is composed of DC capacitor bank. The PWM inverter unit produces required missing voltage by evaluating the control unit signals and this compensating voltage is inserted to the system by injection transformer.

The basic operation principle of DVR is measuring the missing voltage by using control unit and injecting the dynamically controlled missing voltage in series to the line and providing the load voltage unchanged during sag [12].

Generally, the operation of the DVR can be categorized into three operation mode: protection mode, standby mode (during steady state) and injection mode (during sag).

3.1.1. Protection Mode

The DVR will be isolated from the system if the system parameters exceed the predetermined limits primarily current on load side. The main reason for isolation is protecting the DVR from the overcurrent in the load side due to short circuit on the load or large inrush currents. The control system detects faults or abnormal conditions and manages bypass (transfer) switches to remove the DVR from system thus preventing it from damages as shown in Figure 3.3.

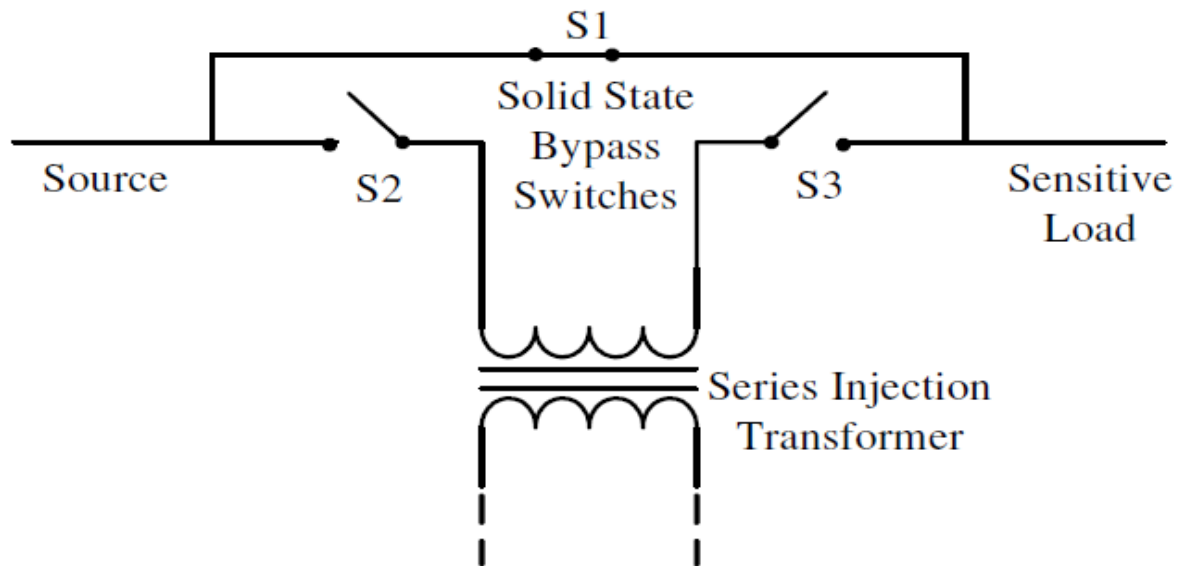


Figure 3.3: Scheme of the protection mode

During the overcurrent period, S1 will be closed; S2 and S3 will be opened so there will be another path for current to flow. By removing the DVR from system at fault condition, the effects of additional disturbances that can be caused by the DVR are prevented onto the system.

3.1.2. Standby Mode

In standby mode (normal steady state conditions), the DVR may either go into short circuit operation or inject small voltage to compensate the voltage drop on transformer reactance or losses. Short circuit operation of DVR is generally preferred solution in steady state because the small voltage drops do not disturb the load requirements. The solid-state bypass switches

are used to perform short circuit operation and they are placed between the inverter and secondary (low side) of series injection transformer as shown in Figure 3.4.

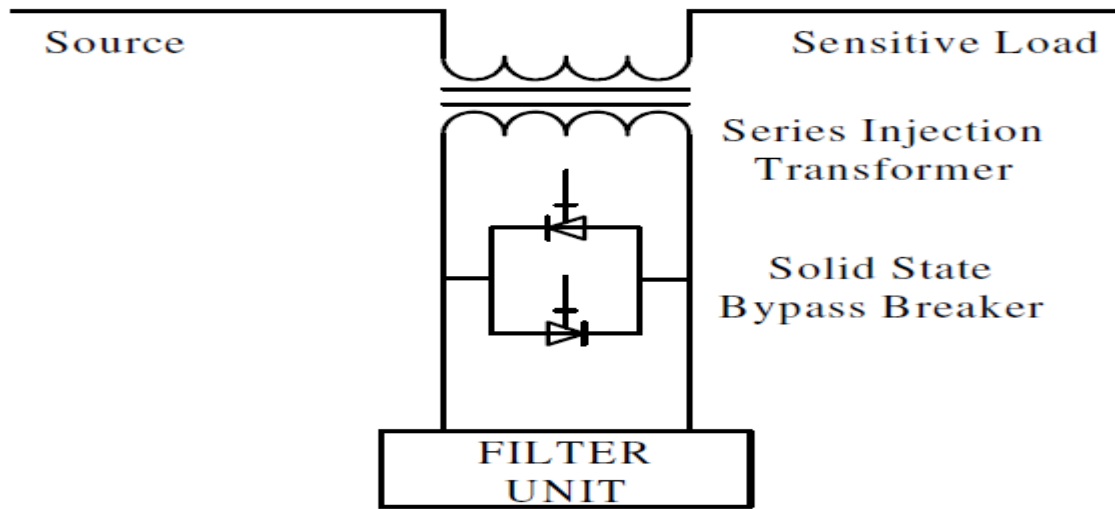


Figure 3.4: Scheme of the standby mode

If the distribution circuit is weak there is need to inject small compensation voltage to operate correctly. During short circuit operation, the injected voltages and magnetic fluxes are virtually zero thereby full load current pass through the primary. The DVR will be most of the time in normal mode operation. During standby mode normal operation), the short circuit impedance of the injection transformer determines the voltage drop across the DVR.

3.1.3. Injection Mode

The primary function of Dynamic Voltage Restorer is compensating voltage disturbances on distribution system. To achieve compensation, three single-phase ac voltages are injected in series with required magnitude, phase and wave shape.

Three single-phase injection transformers are used to inject the missing voltage to the system at the load bus. To integrate the injection transformer correctly into the DVR, the MVA rating, the primary winding voltage and current ratings, the turn-ratio and the short-circuit impedance values of transformers are required.

As an overview the following main design criteria influence the rating and the performance of the DVR [5]:

- Maximum MVA-load and power factor,
- Maximum 1 phase and 3 phase voltage sags to be compensated,
- Maximum duration of 3 phase voltage sag,
- Maximum allowed voltage drop across DVR under steady-state conditions,
- Short circuit impedance of the injection transformers,

3.2. Basic DVR Components

Dynamic voltage restorer is a series connected device designed to maintain a constant RMS voltage across a sensitive load [12]. The structure of DVR is shown in Figure 3.5. The general configuration of the DVR consists of the following equipment:

- Voltage Source Inverter (VSI)
- Injection Transformer
- Harmonic Filter
- Energy Storage Unit
- Control System

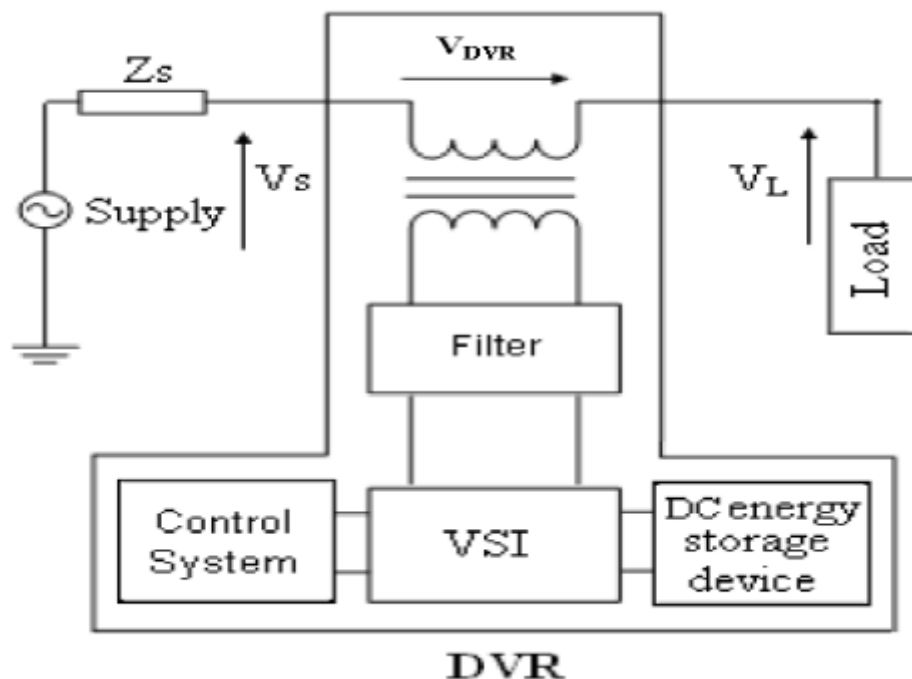


Figure 3.5: Dynamic Voltage Restorer (DVR) general configuration

3.2.1. Voltage Source Inverter (VSI)

The Voltage Source Inverter (VSI) or simply the inverter converts the dc voltage from the energy storage unit to a controllable three phase ac voltage. The inverter switches are normally fired using a sinusoidal Pulse Width Modulation (PWM) scheme. Since the vast majority of voltage sags seen on utility systems are unbalanced, the VSI will often operate with unbalanced switching functions for the three phases, and must therefore treat each phase independently.

Pulse width modulated voltage source inverters are commonly used converters for this type of application. Applying a VSI to compensate for a missing voltage requires an injection transformer and a line filter to damp generated switching harmonics. Additionally, losses should be minimized, because the DVR conducts the load current continuously and a fast response is important to avoid a deterioration of the load voltage. The critical factors when choosing a converter for a DVR application are [9]:

- Switching frequency
- Generation of switching harmonics
- Ripple current in the converter
- Power losses caused by the switching and conduction
- Dynamic response
- DVR impedance

In general useful topologies are those where active power easily can be transferred from a simple DC voltage circuit to the DVR converter. A full bridge converter is also a good choice for DVR converters, by unipolar switching the first harmonic appear at the twice the switching frequency.

3.2.2. Injection Transformer

The injected voltages are introduced into the distribution system through an injection transformer connected in series with the distribution feeder. It is known that in order to guarantee the maximum reliability and effectiveness of this restoration scheme, good selection of the injected transformer is a prerequisite. In order to carefully select a suitable injection transformer the following issues should carefully be addressed [17]:

- 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

The ac electrical energy is converted from one ac voltage level to another ac voltage level at the same frequency by transformers. The sketch of an ideal single-phase transformer is shown in Figure 3.6.

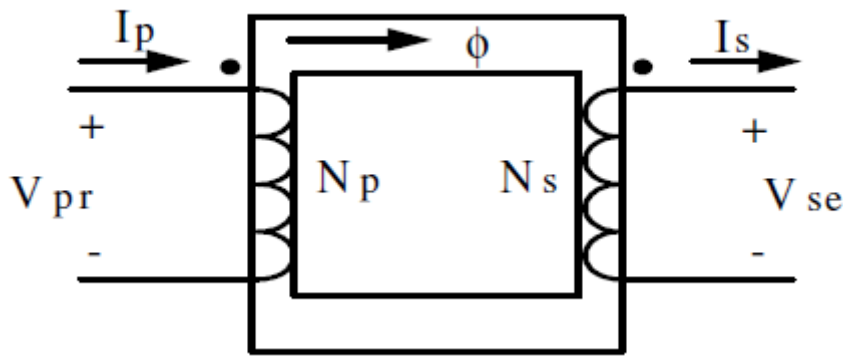


Figure 3.6: Sketch of an ideal transformer

The magnetic flux presents a connection between the primary and secondary coils. The basic relationship between the parameters is shown in equation 3.1:

$$\frac{V_{pr}}{V_{se}} = \frac{I_s}{I_p} = \frac{N_p}{N_s} = m \quad (3.1)$$

V_{pr} is the voltage produced on the primary side; V_{se} is the voltage produced on the secondary side; N_p is the turn of wire on its primary; N_s is the turn of wire on its secondary respectively; m is the turn-ratio of the transformer.

It has been recognized that in order to guarantee the maximum reliability and effectiveness of this restoration scheme, judicious selection of the injection transformer is a prerequisite. To integrate the injection transformer correctly into the DVR the MVA rating, the short circuit impedance, the primary winding voltage and current ratings, the turn-ratio and winding parameters of the injection transformer should be carefully calculated [27].

❖ MVA Rating

The MVA rating is determined by using power calculation equation by considering safety margin denoted as K_s . V_{pr} is the primary voltage of the injection transformer and I_{pr} is the current rating of injection transformer.

$$P = K_s V_{pr} I_{pr} \quad (3.2)$$

The correct value of safety margin will include the instantaneous voltage and current values during switching period in system design. The injection transformer should be designed to keep at least the twice the normal steady state flux to avoid from the saturation.

❖ The Primary Winding Voltage and Current Ratings

The primary side voltage rating of series injection transformer is related with the maximum voltage sag depth, filtering unit and voltage sag characteristics. The rating of the injection transformer can be calculated by using Equation (3.3).

$$V_{inj} = DV_r \quad (3.3)$$

$$V_s = (1 - D)V_r \quad (3.4)$$

V_r is the rated rms voltage of the primary feeder; D is the maximum single phase voltage sag to be compensated ($D < 1$); V_{inj} is the injection voltage.

The sources of voltage sags are typically lighting strikes or short circuit faults. The faults can cause the phase and amplitude shift of the supply voltage. The voltage injection strategies are described in section 3.4. These strategies will restore the voltage and determine the magnitude of the voltage rating on the primary side.

The filtering system of DVR is another parameter that determines the voltage ratings. The filtering system can be placed either on the line side (high voltage side) or inverter side (low voltage side). The inverter side filtering system will eliminate the high order harmonics from the inverter and thus transformer current rating can be neglected. In line side filtering system the high order harmonic currents will penetrate through injection transformer and they will carry harmonic voltages.

The primary side current rating is primarily determined by the rated capacity of the sensitive load because the inverter side filtering system will not allow the high order harmonics to penetrate through the injection transformer. The more calculations are required for line side filtering scheme because the high order harmonics generated by the inverter will change the current carrying capability of the inverter.

❖ Turn-Ratio

The turn-ratio determines the secondary voltage and current ratings. By taking into account the available switching devices (proper current carrying capability, blocking voltage and cost) and DC link capacitor, the optimum secondary parameters are determined. In practice, the turn-ratio is adjusted until finding available switching devices with minimum cost of storage device.

❖ Short Circuit Impedance

The system generally operates in steady state conditions but the characteristic of the system in the short circuit or abnormal conditions must be known. The fault current, design of filtering system and the voltage drop on transformer are related with short circuit impedance value. The shorter the electrical distance between the DVR and the fault, the closer is the characteristics of the voltage sensed at the DVR to that at the fault location.

The simplified equivalent circuit of DVR when inverter side filtering is applied is shown in Figure 3.7.

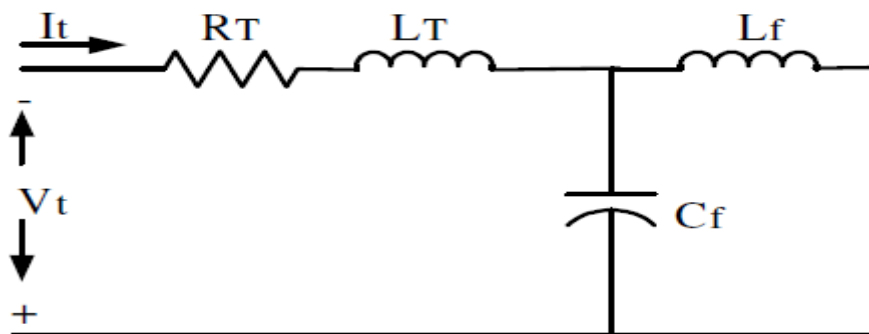


Figure 3.7: Equivalent circuit of DVR with inverter side filter

V_t is the specified voltage drop value across the injection transformer during the normal operating conditions of the system; R_T is the short circuit resistance value; X_T is the short circuit reactance value; C_f is the filter capacitance value; X_f is the filter reactance value.

$$R_T = R_{ps} + m^2 R_{ss} \quad (3.5)$$

$$L_T = L_{ps} + m^2 L_{ss} \quad (3.6)$$

R_{ps} is the resistance of primary side coils; R_{ss} is the resistance of secondary side coils; L_{ps} is the leakage inductance in the primary side; L_{ss} is the leakage inductance in secondary side and m is the turn ratio.

The voltage drop across the injection transformer during standby mode must be less than specified value. To satisfy this condition, the short circuit impedance should be as shown in equation 3.7 [21]:

$$\sqrt{R_T^2 + \omega^2 (L_T L_f / (1 - \omega^2 L_f C_f))^2} < (V_t / I_t) \quad (3.7)$$

Under normal conditions the short circuit impedance of injection transformer determines the voltage drop across the DVR. This impedance must be low and must have an impact on the fault current through the voltage source PWM inverter on secondary side caused by a short circuit at load side.

3.2.3. Harmonic Filter

The semiconductor switching devices are used in wide variety of industrial loads. The non-linear characteristics of semiconductor devices cause distorted waveforms associated with harmonics. To overcome this problem and providing clean electrical supply filter unit is used. The filter unit eliminates the dominant harmonics produced by inverter circuit. The inverter side filtering and line side filtering are basic types of filtering scheme [23].

The inverter side filtering scheme has the advantage of being closer to the harmonic source thus high order harmonic currents are prevented to penetrate into the series injection transformer but this scheme has the disadvantages of causing voltage drop and phase angle shift in the fundamental component of the inverter output. In the line side filtering system harmonic currents penetrate into the series injection transformer but the voltage drops and phase shift problems do not disturb the system [27].

As the unique values of the parameters of the LC filter cannot be specified based on the total harmonic of the capacitor voltage alone an additional criterion based on the minimum

reactive power of the LC filter is used to specify these parameters [31]. In this thesis, the inverter side filtering is preferred for harmonic elimination, so it will be analyzed deeply.

❖ Inverter Side Filter

The inverter side filter is closer to the harmonic source and low voltage side thus it prevents the harmonic currents to penetrate into the series injection transformers [33]. The equivalent circuit of single-phase PWM inverter with inverter side filtering scheme is shown in Figure 3.8.

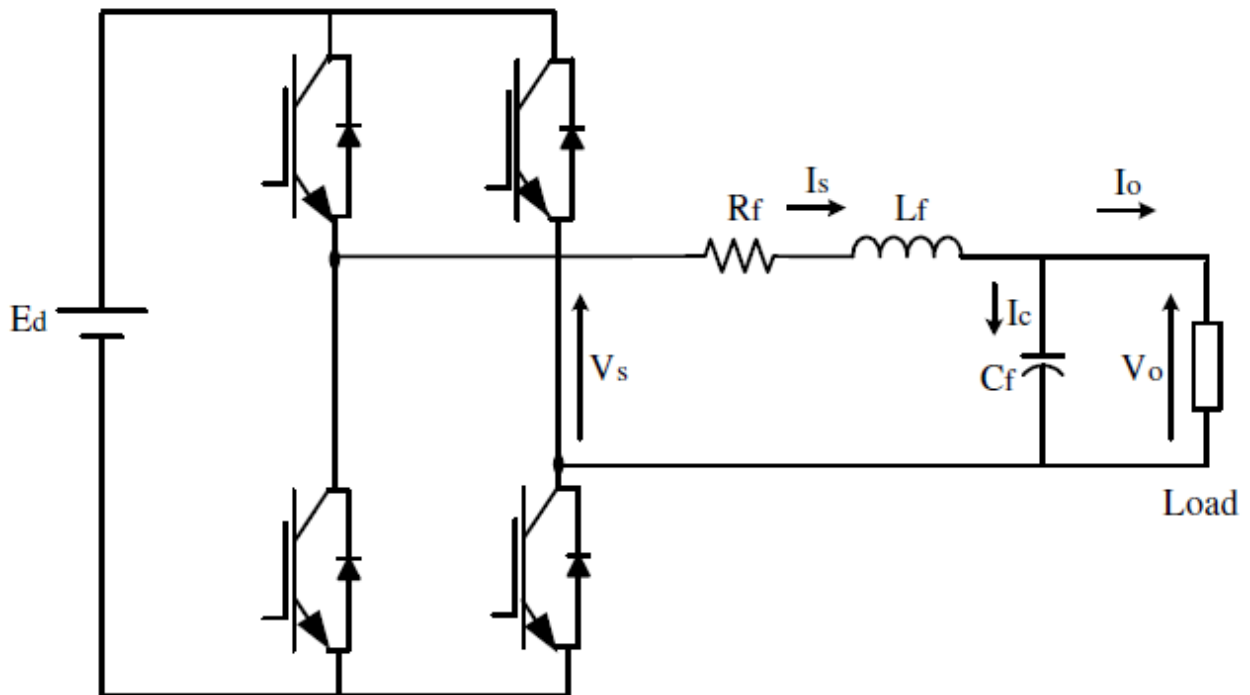


Figure 3.8: Equivalent circuit for inverter side filter

Where:

Ed is the nominal dc source voltage,

Rf is the filter resistance,

Lf is the filter inductance,

Cf is the filter capacitance,

Vo is the load voltage.

Vs is the output voltage of the PWM inverter,

Is is the source current,

Ic is the capacitor current,

Io is the load current and

In this analysis, the followings are assumed:

- The dc source voltage E_d is ripple free and constant.
- The inverter switching devices are assumed as ideal switches.
- The equivalent series resistance of the filter capacitor is neglected.
- The load is a linear load.

Based on the Figure 3.8, the output voltage equation of the inverter can be written as:

$$V_s = V_0 + R_f I_s + L_f \frac{dI_s}{dt} \quad (3.8)$$

The design procedure of the LC filter can be divided into three steps by considering the assumptions. The following equations are obtained through comprehensive analysis of derived formulas. The deeper analysis about the derivation of formulas can be obtained from the reference papers [21], [27], [29].

Calculation of modulation index: Based on the dc source voltage E_d and nominal load voltage V_0 , the modulation index is calculated.

$$k = \sqrt{2} \frac{V_0}{E_d} \quad (3.9)$$

Because the voltage drop across the filter inductor cannot be determined before the parameters of the filters are specified, this voltage drop can be assumed to be negligible. The rms value of the output voltage of the inverter can be assumed equal to the rms value of the load voltage ($V_s \approx V_0$). The result is used to calculate the factor K by using Equation (3.10).

$$K = \left[\frac{k^2 - \frac{15}{4}k^4 + \frac{64}{5\pi}k^5 - \frac{5}{4}k^6}{1440} \right]^{1/2} \quad (3.10)$$

Calculation of the inductance of the filter: Equation (4.11) calculates the optimum value of the filter inductance.

$$L_f = \frac{V_0}{I_0 f_s} \left\{ K \frac{E_d}{V_{0,av}} \left[1 + 4\pi^2 \left(\frac{f_r}{f_s} \right)^2 K \frac{E_d}{V_{0,av}} \right] \right\}^{1/2} \quad (3.11)$$

f_s is the switching frequency; $V_{0,av}$ is the total harmonic of the load voltage; f_r is the fundamental output frequency.

Calculation of the capacitance of the filter: Equation (3.12) calculates the filter capacitance.

$$C_f = K \frac{E_d}{L_f f_s^2 V_{0,av}} \quad (3.12)$$

The LC filter attenuates the harmonics by providing a shunt path for the harmonic current and series impedance for the harmonic voltages.

3.2.4. Energy Storage Unit

The DC energy storage device provides the real-power requirements of the DVR during compensation. Various storage technologies have been proposed including flywheel energy storage, superconducting magnetic energy storage (SMES) and super capacitors. These have the advantage of fast response [25], [28].

3.2.5. Control System

The basic functions of a controller in a DVR are the detection of voltage sag events in the system; computation of the correcting voltage, generation of trigger pulses to the sinusoidal PWM based DC-AC inverter, correction of any anomalies in the series voltage injection and termination of the trigger pulses when the event has passed.

A control strategy for voltage sags with phase jump should be considered, to be able to compensate the particular type of sag into the pre sag voltage effectively. The control strategy highly depends on the type of the load connected. Some loads are very sensitive to phase jump and the load should be protected from them.

A phase jump could be initiated by certain voltage sags with phase jump, or by the DVR itself to reduce the power drain or maximize the load voltage at severe sags. In both cases a phase jump may be undesirable for the load and may initiate transient currents in capacitors, transformers and motors, etc. The operation of line commutated converters may also be disturbed by a sudden change in the phasor of the load voltage.

The dqo transformation or Park's transformation based control system [32], [33] is used to control the DVR. The dqo method gives the sag depth and phase shift information with start and end times. The quantities are expressed as the instantaneous space vectors. Firstly it converts the voltage from a-b-c reference frame to d-q-o reference. Figure 4.9 illustrates a flow chart of the feed forward dqo transformation for voltage sag detection. The detection is carried out in each of the three phases.

The control is based on the comparison of a voltage reference and the measured terminal voltage (V_a, V_b, V_c). The voltage sags is detected when the supply drops below 90% of the reference value. The error signal is used as a modulation signal that allows generating a commutation pattern for the power switches (IGBT's) constituting the voltage source inverter. The commutation pattern is generated by means of the sinusoidal pulse width modulation technique (SPWM); voltages are controlled through the modulation.

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & 1 \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (3.13)$$

Above equation 3.13 defines the transformation from three phase system a, b, c to dqo stationary frame. In this transformation, phase A is aligned to the d axis that is in quadrature with the q-axis. The theta (θ) is defined by the angle between phases A to the d-axis.

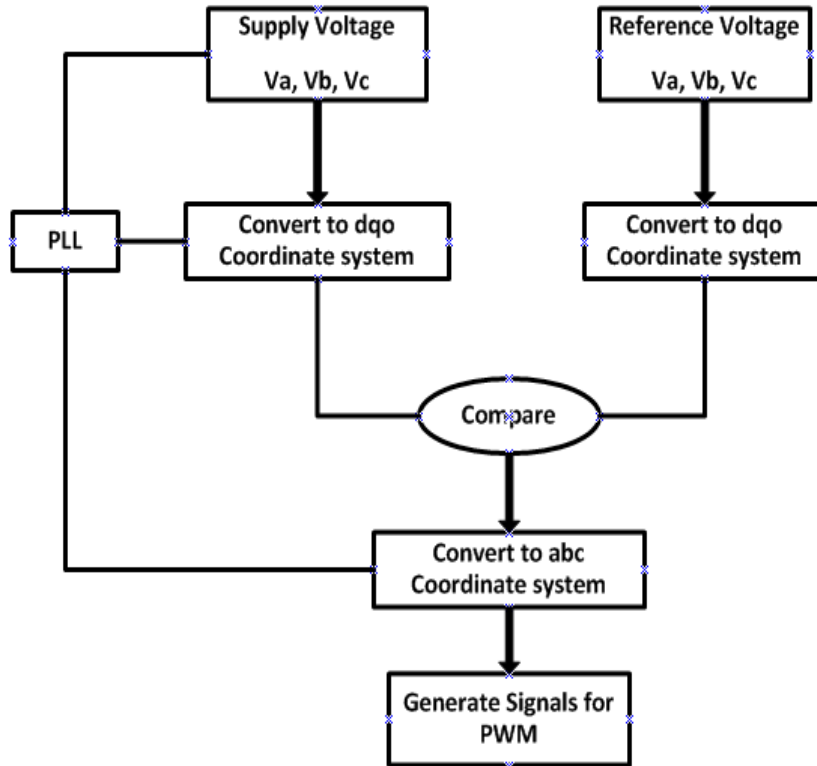


Figure 3.9: Flow chart of feed forward control technique for DVR based on dqo transformation

The PLL circuit is used to generate a synchronizing frequency at which the transformation block should operate. Practically, the capability of injection voltage by DVR system is 50% of nominal voltage. This allows DVRs to successfully provide protection against sags to 50% for durations of up to 0.1 seconds. Furthermore, most voltage sags rarely reach less than 50% [17] [18].

3.3. Compensation Strategies

Three basic compensation strategies for a DVR can be stated as [15]:

- **Method 1:** Pre-sag compensation; the supply voltage is continuously monitored and the load voltage is compensated to the pre-sag condition. The method gives nearly undisturbed load voltage, but can often exhaust the rating of the DVR.
- **Method 2:** In-phase compensation; the generated DVR voltage is always in phase with the measured supply voltage regardless of the load current and pre-sag voltage.

- **Method 3:** Energy optimal compensation; to fully utilize the energy storage, information about the load current is used to minimize the depletion of the energy storage.

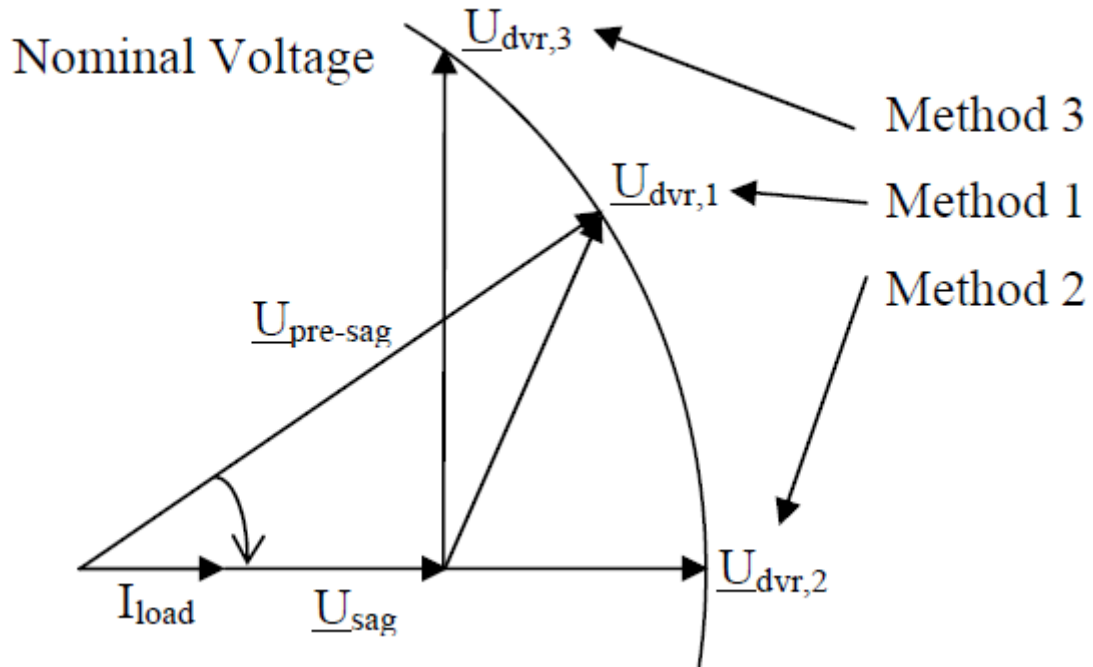


Figure 3.10: Compensation Strategies for DVR

The discussed three methods are illustrated in Figure 3.10 and by studying Figure 3.10 it appears like the energy storage can be reduced applying the DVR voltage perpendicular to the load current, but the load current will change phase according to the new load voltage applied to it and energy will be drawn from DVR.

3.4. Location of DVR

The DVRs intended location is either at the MV distribution level or at the LV-level close to a LV customer. This section discusses the different perspectives with the two alternatives.

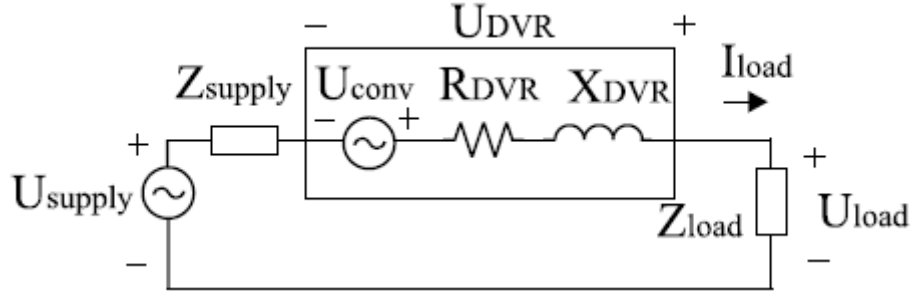


Figure 3.11: Single-phase simplified model of the DVR.

A simplified model of the DVR is illustrated in Figure 3.11 and can help to evaluate the best location of a DVR. The DVR can be represented as an ideal voltage source (U_{conv}) with an inserted reactive element (X_{DVR}), which mainly represents the reactive elements in the injection transformers and line filters, and an inserted resistive element (R_{DVR}), which represents the losses in the DVR. The size of the inserted impedance is closely related to the DVR voltage rating (U_{DVR}) and the DVR power rating (S_{DVR}) according to:

$$X_{DVR} = \frac{(U_{DVR})^2}{S_{DVR}} u_{DVR,X} \quad (3.14)$$

$$R_{DVR} = \frac{(U_{DVR})^2}{S_{DVR}} u_{DVR,R} \quad (3.15)$$

$$Z_{DVR} = \frac{(U_{DVR})^2}{S_{DVR}} u_{DVR,Z} \quad (3.16)$$

$$u_{DVR,Z} = u_{DVR,R} + j u_{DVR,X} \quad (3.17)$$

$u_{DVR,Z}$ depends on the type of transformer used, the line-filter, losses in the VSC etc. A DVR with high injection capability (high U_{DVR}) and the ability only to protect a small load (low S_{DVR}) has large equivalent DVR impedance (Z_{DVR}).

Going from a LV-level DVR to a higher voltage level DVR the pu value of the reactance ($u_{DVR,X}$) tends to increase, and the pu value resistance ($u_{DVR,R}$) tends to decrease.

A high resistive part increases the energy, which should be dissipated from the DVR and the costs associated with the losses. High total inserted DVR impedance increases the potential load voltage distortion and load voltage fluctuations if the load is non-linear and/or has a fluctuating load behavior.

3.4.1. The DVR applied to the MV-level

Connected to the MV-level, the DVR protects a large consumer or a group of consumers. The insertion of a DVR in the medium voltage distribution system is illustrated in Figure 3.12. Inserting a large DVR at the MV-level will only increase the supply impedance for a LV load slightly. Assuming an infinite bus bar at the 50 kV level, the impedance for a LV load consists of the summation of impedances from the 50/15 kV transformer, cables and overhead lines at the 15 kV level, the 15/0.38 kV distribution transformer and finally LV cables to the LV load. The impedance and the increase in impedance by inserting a DVR can be expressed as:

$$Z_{supply,before} = Z_{50/15} + Z_{line,15} + Z_{15/0.38} + Z_{line,0.38} \quad (3.18)$$

$$Z_{supply,after} = Z_{supply,before} + Z_{DVR} \quad (3.19)$$

$$Z_{increase,\%} = \frac{Z_{DVR}}{Z_{supply,before}} * 100\% \quad (3.20)$$

For a LV load the dominating impedance is most likely the LV line impedance ($Z_{line,0.38}$) and the impedance of the distribution transformer ($Z_{15/0.38}$). Protecting a large MV load close to the DVR, the increase in impedance experienced by the load can be significant. Inserting one high rated DVR at the MV-level has certain advantages:

- The increased impedance inserted with a DVR seen by a LV load can be relative small if a large DVR is placed at the MV-level.
- The costs per MVA to protect are expected to be lower if one large central DVR is located at the medium voltage level instead of decentralized low voltage units.

Some of the disadvantages can be summarized to:

- Protecting a large load may require a medium voltage DVR otherwise the losses in the DVR will be too high.
- During ground faults in the MV system the phase to ground voltages can increase with $\sqrt{3}$, and a higher isolation level of the injection transformers must be ensured.
- A part of the DVR rating may be utilized on loads, which do not require a supreme voltage quality.

- The DVR is connected to a voltage level, which requires a high isolation level and the short circuit level is high.

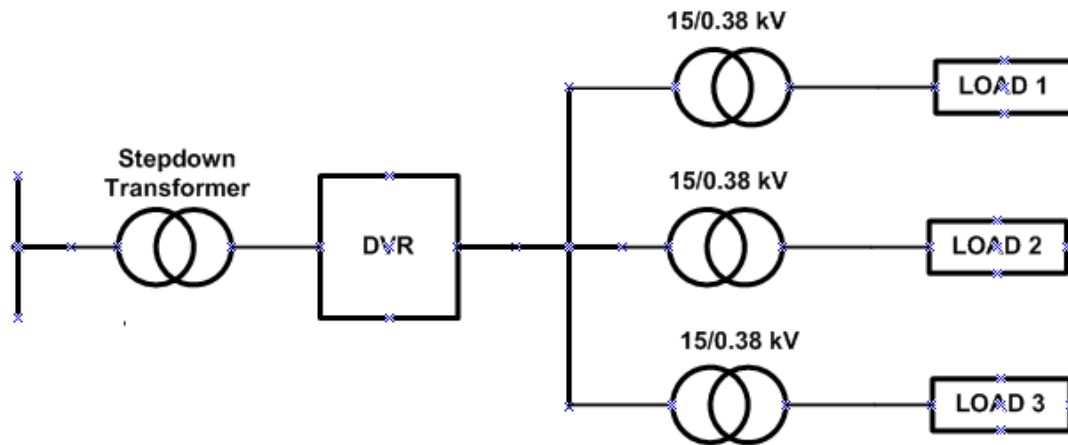


Figure 3.12: DVR located at the medium voltage distribution system.

3.4.2. The DVR applied at the LV-level

The insertion of a DVR at the low voltage four-wire 380 V level is illustrated in Figure 3.13. The increase in impedance by insertion of a small rated DVR can be significant for the load to be protected from voltage sags. Thereby, the percent change in the impedance ($Z_{increase,\%}$) in (3.20) can be increased by several hundred percent. Inserting a DVR at LV-level has certain advantages:

- The DVR can be targeted more specifically at voltage sag sensitive loads.
- A majority of electric customers have only access to the LV-level and the DVR can both be placed by the customer at the customer domain or by the utility at the utility domain.
- The short-circuit level is significantly decreased by the distribution transformer and the DVR is easier to protect.

And the disadvantages with a LV solution are:

- The impedance increase after the insertion of the DVR for the protected load can be large, which may influence the site short circuit level and protection.

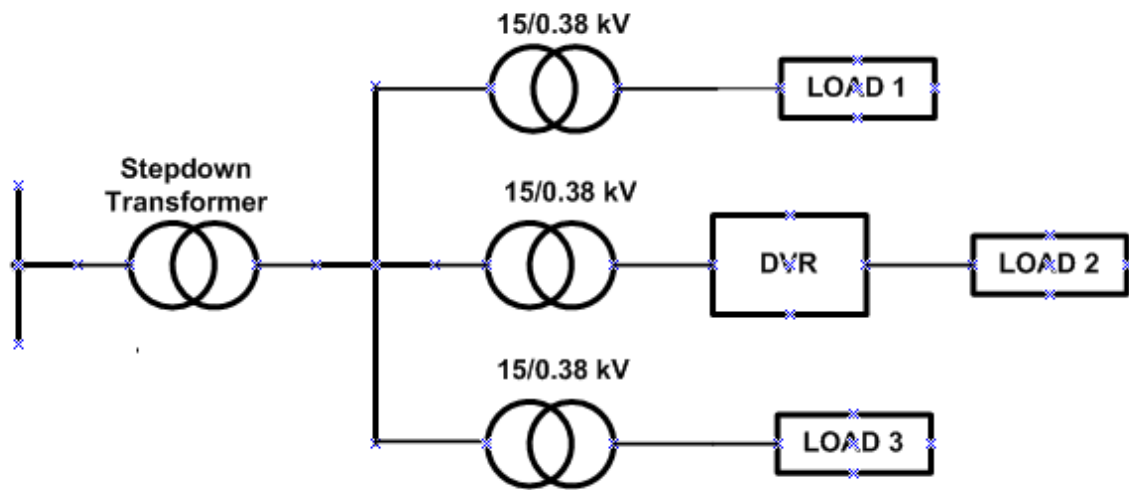


Figure 3.13: DVR located at the low voltage distribution system.

Chapter 4 : System Design and DVR Modeling

4.1. General

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. Simulink includes a comprehensive block library of sinks, sources, linear and non-linear components and connectors. Simulink provides a graphical user interface (GUI) for building models as block diagrams. You can easily build models from scratch or take an existing model and add to it. You have instant access to all the analysis tools in MATLAB, so you can take the results and analyze and visualize them.

The Power System Block set is designed to provide a modern design tool that allows scientists and engineers to rapidly and easily build models that simulate power systems. After you define a model, you can simulate it, using a choice of integration methods, either from the Simulink menus or by entering commands in the MATLAB Command Window. Using scopes and other display blocks, you can see the simulation results while the simulation is running. You can change many parameters and see what happens for "what if" exploration.

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

4.2. System Description and Modeling

Within the scope of this study, the Bahirdar power distribution system will be handled as a practical case study from the Ethiopian electric utility company. The power distribution system in the city includes two power substations, which give power to Bahirdar city that is Bahirdar substation I and Bahirdar substation II. According to the data gathered in July 2017 from the Ethiopian electric utility north west region in Bahirdar, Bahirdar substation I has a total of four 15 kV outgoing feeders namely Gambi, Sematat, Boiler and Hamusite with a total installed capacity of 43,345 kVA while Bahirdar substation II has a total of seven 15 kV outgoing feeders namely Papyrus, Ghion, Bata, AirForce, Industry, Tis Abay and Adet with total installed capacity of 77,185 kVA. The whole distribution system assumed to have a minimum power factor of 0.85. The equipment in the substation includes transformers, bus bars, circuit breakers, lightning arrester, CT and PT for measurement and protection, Isolators and switchgear.

The feeder data showing the name of feeder, length of feeder, number of transformers, total capacity of transformers and maximum loading are shown in appendix - 1. The Tis Abay feeder has least installed capacity of 2070 kVA while the Bata feeder has highest installed capacity of 17,400 kVA as shown in the appendix.

From the available total 11 feeders originating from both substations the Ghion feeder is chosen as practical case study due to the reason that this feeder is highly characterized by a frequent faults which are the main causes of power quality problems specifically the voltage sag. This feeder originates from Bahirdar power substation II extending up to a length of 20.05 kilometers and having a total number of 53 distribution transformers with total installed capacity of 14,620 kVA. The name and rating of each distribution transformer, the total load connected to each transformer alongside the power factor of each load of the Ghion feeder is given in appendix 2.

From the discussion done on section 3.4 of chapter three it was found that from the comparison of the two possible locations of the dynamic voltage restorer the placement of the component in the low voltage distribution system has superior advantages than the placement on the medium voltage area. Therefore the simulation of the designed dynamic voltage restorer is done on selected distribution substation on the specified feeder.

4.3. Modeling the Distribution Substation

For the modeling of distribution substation system of Ghion feeder and proposed DVR components MATLAB/SIMULINK simulation tool was used. The criteria for choosing the distribution substation on which the dynamic voltage restorer (DVR) should be installed is depending on the total installed capacity and sensitivity of the connected loads to the concerned power quality problem which is the voltage sag. But the Ethiopian electric utility was unable to provide data concerning to the type of loads that are fed by each DSS. This has brought a difficulty in choosing the distribution substation depending on the sensitivity of the connected loads. Due to this the second criteria was not used but according to the first criteria Ghion Line T-021 with the largest installed capacity is selected. The installed total load of the distribution transformers in the vicinity is also a deciding factor for the selection of the distribution substation. Referring to appendix-2 and the load flow analysis done on the Ghion feeder using DIGSILENT which is an advanced integrated and interactive software package dedicated to the analysis of transmission, distribution, and industrial electrical power systems; on distribution substations Ghion Line T-018, Ghion Line T-024 and Ghion Line T-026 the installed total load capacity is slightly higher than the ratings of each DT, i.e. the DTs are overloaded. This overloading on each of the transformers contributes to the creation of voltage sag on the selected distribution substation Ghion Line T-021. This is due to the reason that in addition to faults which are the major causes of voltage sag in a power system overloading of adjacent feeder also generates voltage sag on the neighboring feeder. Due to the above mentioned reasons the distribution substation Ghion Line T-021 on the Ghion feeder was found to be the best candidate and is chosen for simulation. The result of the load flow analysis is shown in figure 4.1.

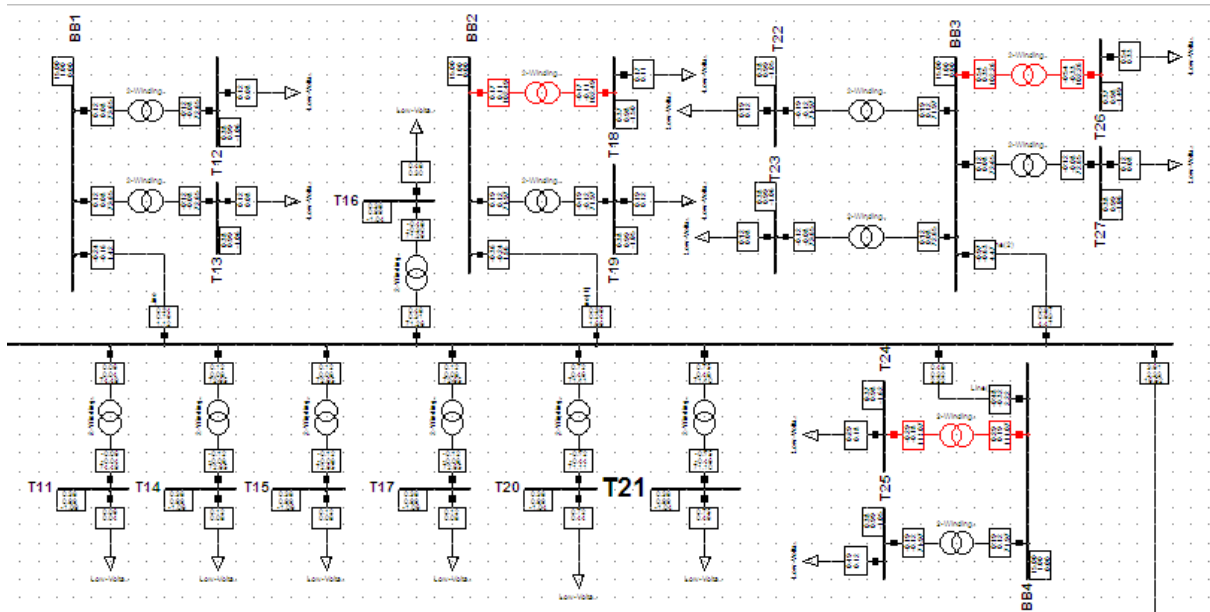


Figure 4.1: Result of Load Flow Analysis

MATLAB/SIMULINK model of the chosen distribution substation is shown in figure 4.2 .It is composed by a 15 kV, 50Hz, source feeding distribution network through the three winding transformer 15kV/380V connected in delta/wye, to a load which has a total capacity of 1250 kVA at 0.85 power factor. To ensure a quality power specifically to maintain a good voltage profile the Dynamic Voltage Restorer is installed in series. To disturb the system different types of fault is applied at the high voltage side of the distribution transformer at different fault resistance values for some specified time duration.

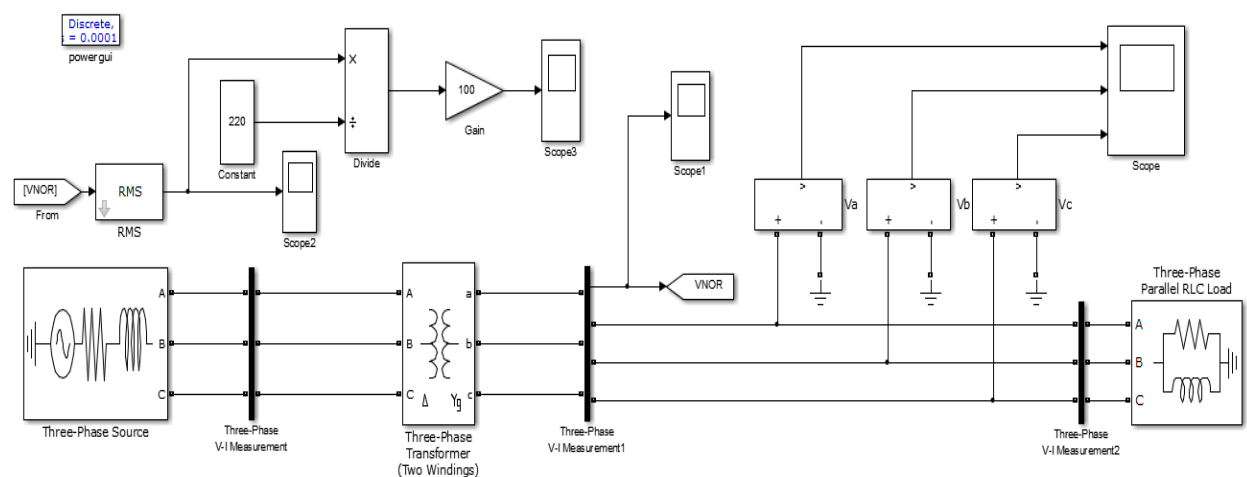


Figure 4.2: Matlab/Simulink diagram of Ghion Line T-021

4.4. Modeling the DVR

The ratings of DVR components should be selected properly to ensure fast and reliable response. Referring to Figure 4.5 in chapter four, there are four main elements, which deserve consideration in the design of a DVR.

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

4.4.1. Voltage Source Inverter

The DVR uses voltage controlled three single-phase full bridge PWM inverters to control and maintain the desired compensating output voltage. Three of single-phase inverters are fed by DC source and can switch at a high frequency to mitigate the voltage sags from system. The DC voltage source is an external source supplying DC voltage to the inverter for AC voltage generation. The inverter side LC filters block high frequency harmonics caused by DC to AC conversion to reduce distortion in the output.

The missing voltage is generated by accurately controlling the switches in the inverter. VSIs based on IGBT devices generate the injection voltages to compensate for the voltage sag. The PWM inverter is the most important part of the DVR. MATLAB/Simulink model of the single-phase PWM inverter is shown in Figure 4.3.

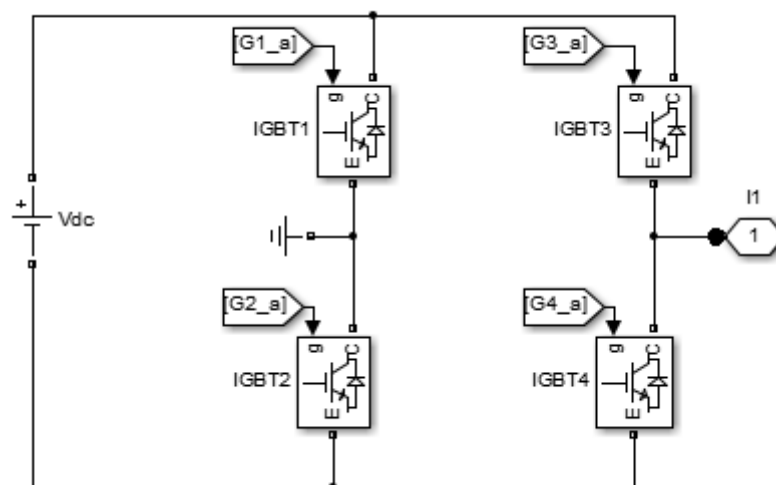


Figure 4.3: MATLAB/Simulink model of the single-phase inverter

4.4.2. Injection Transformer

The injection transformer connects the DVR to the distribution network as shown in Figure 4.4. They transform and couple the injected compensating voltages generated by the VSI to the incoming supply voltage. The ratings of injection transformers are related with the depth of voltage sag, supply current and capacity of DC link.

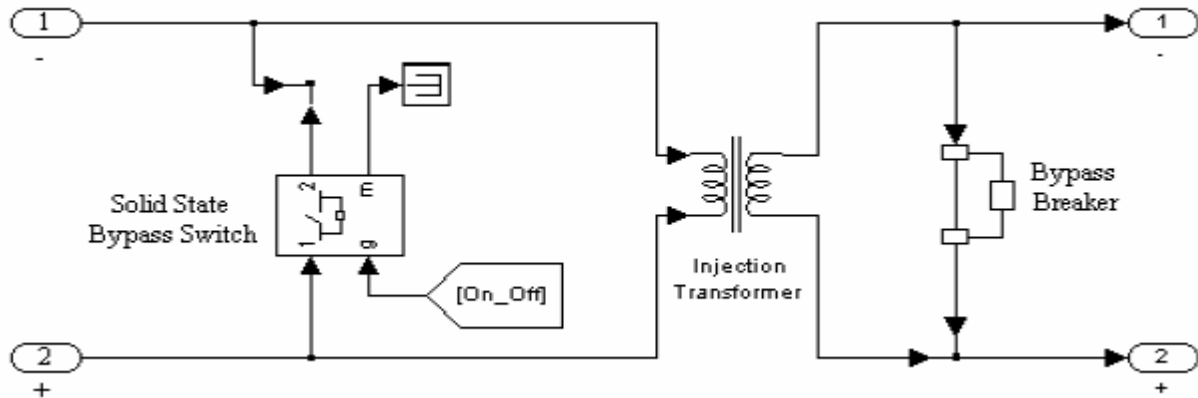


Figure 4.4: Single-phase circuit of injection transformer

❖ Voltage Rating Of Primary Winding

To be cost-effective, partial boosting is often considered when designing a DVR. In other words, in selecting the injection transformer, the determination of its expected maximum voltage output is of special significance, both economically and technically. And hence the ratings of the injection transformer are calculated when the system is arranged to perform the worst-case (i.e. three-phase to ground fault with deepest voltage sag magnitude and the longest duration). In this case, the primary side voltage of the single-phase injection transformer is calculated by equation (4.3). In this study, $D = 0.5$ pu and $V_r = 220$ Vrms. The theoretical calculation according to the formula results 110 Vrms. The voltage on filter capacitor at maximum sag (0.5) determines the secondary side voltage, which is 110 Vrms.

❖ Current Rating Of Primary Side

The injection transformer is connected in series with the sensitive load which is to be protected by the DVR. Thus the current rating of the injection transformer is primarily determined by the rated capacity of the sensitive load. This results the current rating of the primary side to be 1.9 KA. And hence in this thesis, 3 single-phase transformers 209 kVA and 110/110V (rms) ratings are used.

4.4.3. LC Filter

The DVR system model is non-linear owing to the presence of power semiconductor switches in the inverter switches. To provide high quality waveforms, an output filter consisting of inductors and capacitors minimizes the modulation components generated by the inverter modules, which otherwise would be imposed on the utility system [35]. Filter circuit allows some signal frequencies to pass while limiting others.

The DVR generally should not actively produce any harmonics but during the sag period, the DVR tends to generate harmonics. In this thesis, inverter side filtering method is preferred to keep the harmonic voltage content generated by PWM inverter to the permissible level. This scheme is closer to harmonic voltages with low magnitudes.

The ratings of the inductance (L) and capacitance (C) are related with the maximum injection limit of the DVR. The design procedure of the LC filter is shown in the section 3.2.3.

If the dc source voltage varies widely during the operation, the worst value of the dc voltage that results in the higher value of the output voltage harmonic should be used in this design.

Based on the design procedure, the modulation index k is calculated from Equation (3.9) and the factor K is calculated from Equation (3.10). The theoretical calculations result in:

$$k = 1.56, K = 0.095.$$

By substituting the obtained values into Equation (3.11) and (3.12), the filter parameters are calculated as:

$$L = 6.9 \text{ mH}, C = 2.78 \text{ } \mu\text{F}.$$

The obtained closed form expressions of the inductance and capacitance of the LC filter eliminate the time consuming conventional Fourier series method. The obtained L and C value are effective in reducing the harmonics to the permissible level.

4.4.4. Control system

Figure 4.5 shows the control unit of DVR based on parks transformation. Parks transformation is another name for dqo transformation that stands for direct-quadrature-zero transformation. It is a mathematical transformation used to simplify the analysis related to three-phase circuit in electrical engineering. This technique can be applied to reduce the three ac quantities to two DC quantities. It makes the calculation and simulation much simpler. It is seen from figure 5.4 that the supply voltage and the reference voltage are transformed from abc coordinate to dqo coordinate with the help of Abc_to_dqo transformation block. The dqo signal of both supply voltage and reference voltage splits using the demux block. The direct (d) and quadrature (q) value of the supply signal are compared with those of the reference signal. The resultant d and q is then sent to the dqo_to_abc transformation block with the help of mux block. The dqo_to_abc transformation block converts the resultant dqo coordinate to abc coordinate and thus the signal for generation of pulse is generated. The output of the block is then sent to the VSC with harmonic filter unit. Discrete 3-phase PLL block generates an output signal whose phase is related to the phase of the input signal.

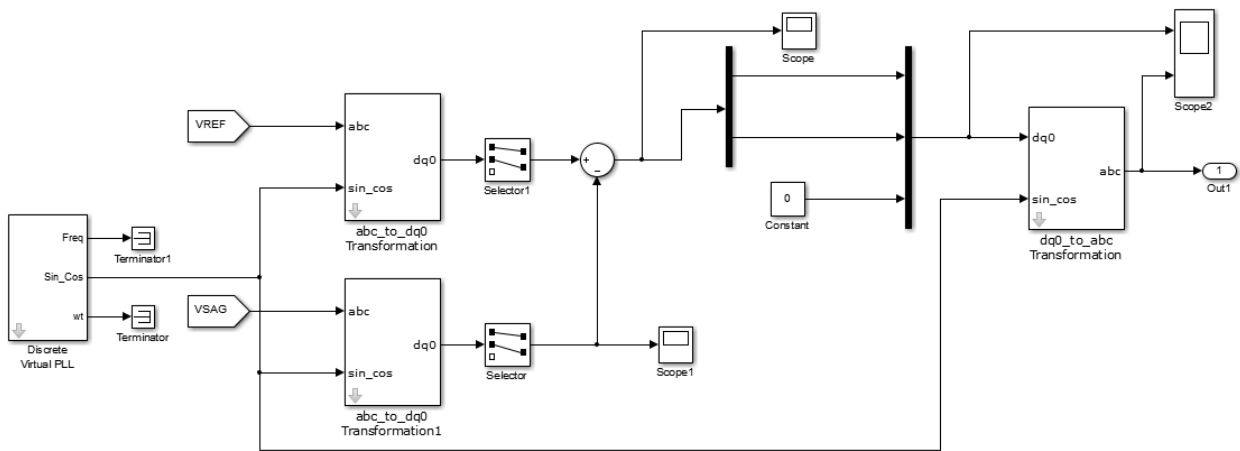


Figure 4.5: DVR control unit using Park's transformation

Chapter 5 : Result and Discussion

5.1. Challenges in Computer Simulation

At the beginning, several factors that make simulation of power electronic systems very challenging should be stated [29]:

- Solid-state switches including diodes, thyristor, GTO's and metal oxide semiconductor field effect transistors (MOSFET) present extreme nonlinearity during their transitions from one state to the other. The simulation program ought to be able to represent this switching of states in an appropriate manner.
- The simulation may take long time, the time constants, or in other words the response time of various parts within the system may differ by several orders of magnitude.
- Accurate models are not always available. This is especially true for semiconductor devices (even for simple diodes) but is also the case for magnetic components such as inductors and transformers.
- The controller in block diagram that may be analog and/or digital needs to be modeled along with the power converters.
- Even if only steady state waveforms are of interest, the simulation time is usually long due to unknown values of the initial circuit states at the start of the simulation.

The challenges listed above dictate that the objective of the simulation is carefully evaluated. In general, it is not desirable to simulate all aspects of the system in detail. The reason is that the simulation time may be very long and the output at the end of the simulation may be overwhelming, thus obscuring the phenomena of interest, in this aspect, the best simulation is the simplest possible simulation that meets the immediate object.

The performance criterion of proposed DVR operation is compensation of load voltages with a fast dynamic response according to the voltage injection strategy with harmonic content within the limits defined by the system requirements [11].

To observe the effects of the possible faults within the distribution system and the performance of DVR against these faults, voltage sag due to power system faults such as single-phase-to-ground and three-phase-to-ground were created in the distribution substation model developed in chapter five. This section describes a methodology for voltage sag generation using Matlab/Simulink. It includes fault simulations for generation of different types of voltage sag using MATLAB/Simulink.

5.2. Distribution Substation Fault Simulink Model

The location of fault is essentially random and the magnitude and phase angle jump of the voltage sag highly depends on the distance between the location of the fault and the place at which the voltage sag is measured. The shorter the distance the higher is the magnitude and phase angle jump of the voltage sag. And hence in order to account for the worst case scenario the location of the fault was chosen to be at the high voltage side of the distribution transformer. In this section, the voltage sags are generated by switching on impedance to the ground or other phases on the PCC at desired time and size.

The distribution substation Fault Model shown in figure 6.1 consists of 15 KV 50 Hz three phase source block feeding through a 15KV/380V 1250 KVA delta/wye distribution transformer to a 1250 KVA resistive inductive load with power factor of 0.85 which is the Simulink model developed in chapter five and a fault block located at the source feeder line (high voltage side of the distribution transformer) to simulate various types of line faults and a multistage fault block to simulate multistage fault. This distribution substation fault model is capable of simulating various line faults including L-G, L-L-G, L-L, and three phase and multistage faults.

To observe the effects of the possible faults within the distribution system and the performance of DVR against these faults, two types of fault was chosen. The first one is the single line to ground fault (SLGF) and this is due to the reason that the frequency of occurrence of this type fault is higher than all the other types. The second type of fault chosen for the simulation is the three phase to ground fault (3- ϕ LGF) due to its high severity than any other type of fault. These were the two extreme cases that the performance of the DVR has been tested against. All other remaining cases were found to be in between this two extremes and the DVR had given an effective response to the extreme cases.

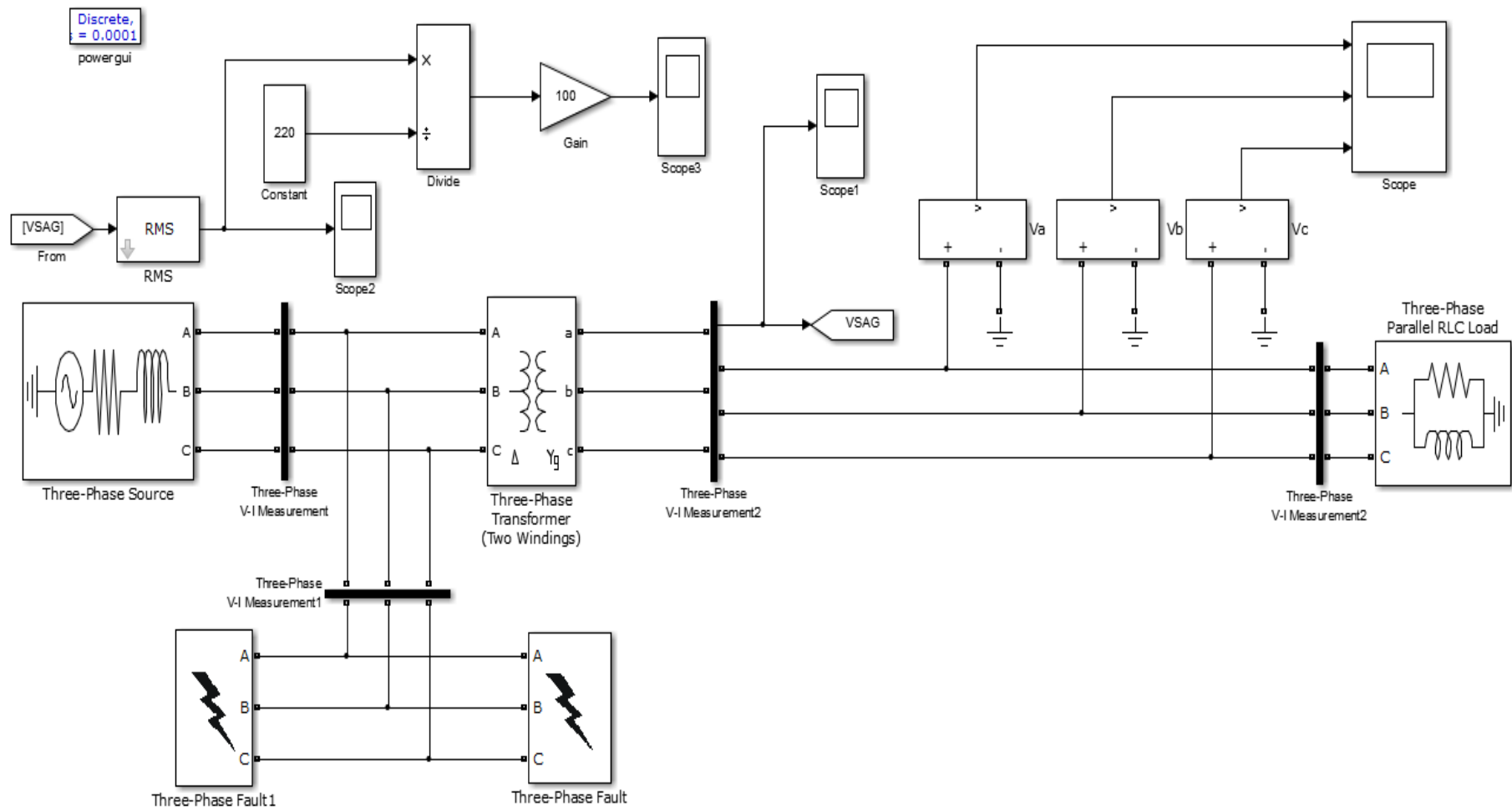


Figure 5.1: Distribution Substation Fault Model

Using the Signal rms block the rms value of voltage can be obtained and the scope is used to observe the simulation results.

5.3. Generation of different voltage sag

The balanced or unbalanced voltage sags are caused mainly by faults on the transmission or distribution system and by sudden load increases on adjacent feeders. Balanced voltage sags mainly originate from three-phase faults. Unbalanced voltage sags are caused by either single-phase to ground fault or two-phase fault or the combinations of these faults.

Before showing the restoring function of the proposed DVR and its performance, the system is disturbed by applying different types of faults in order to generate different types of voltage sags under the following case studies.

5.3.1. Simulation of a single fault

5.3.1.1. Case 1: Single-phase to ground fault (Phase A faulted)

It's known that the frequency of occurrence of single line to ground fault is higher relative to the other types of faults. This is the reason why this type of fault is considered first. The SLGF occurs on phase A resulting in 48 % decrease on Phase A and 20% decrease on Phase C from nominal value during the period 0.06 - 0.16 s for a duration of 0.1 s While phase B i.e. voltage of green phase remains unaffected. The rms value of voltage sag and corresponding instantaneous voltage sag waveforms from simulation results without presence of DVR are shown in Figure 5.2 and Figure 5.3 respectively. Figure 5.4 shows the percentage reduction of the post sag wave forms from the nominal RMS value.

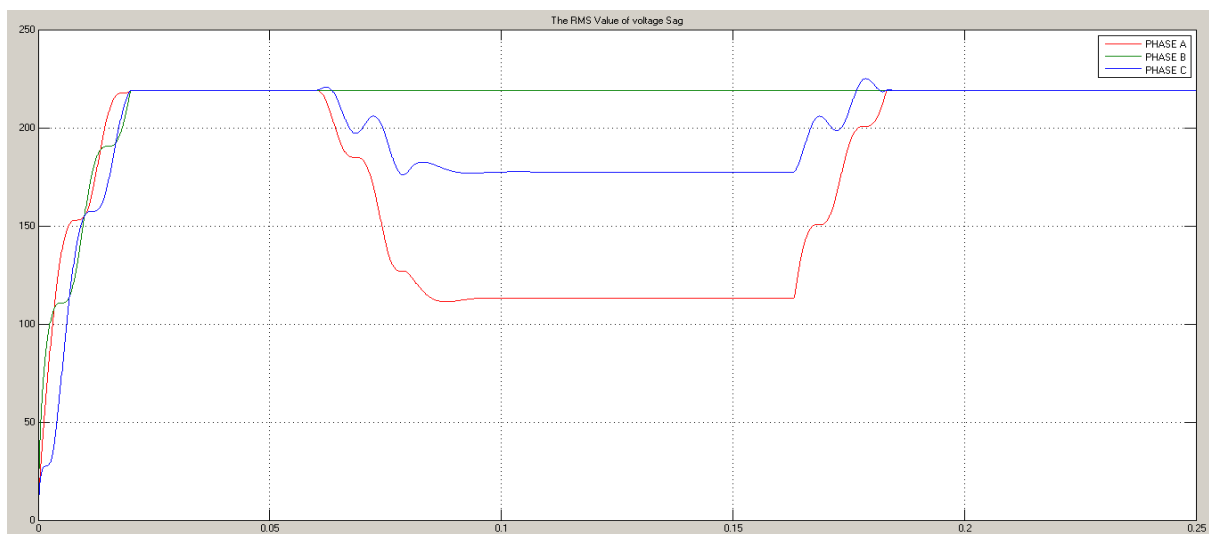


Figure 5.2: The rms value of voltage sag without compensator (Case #1)

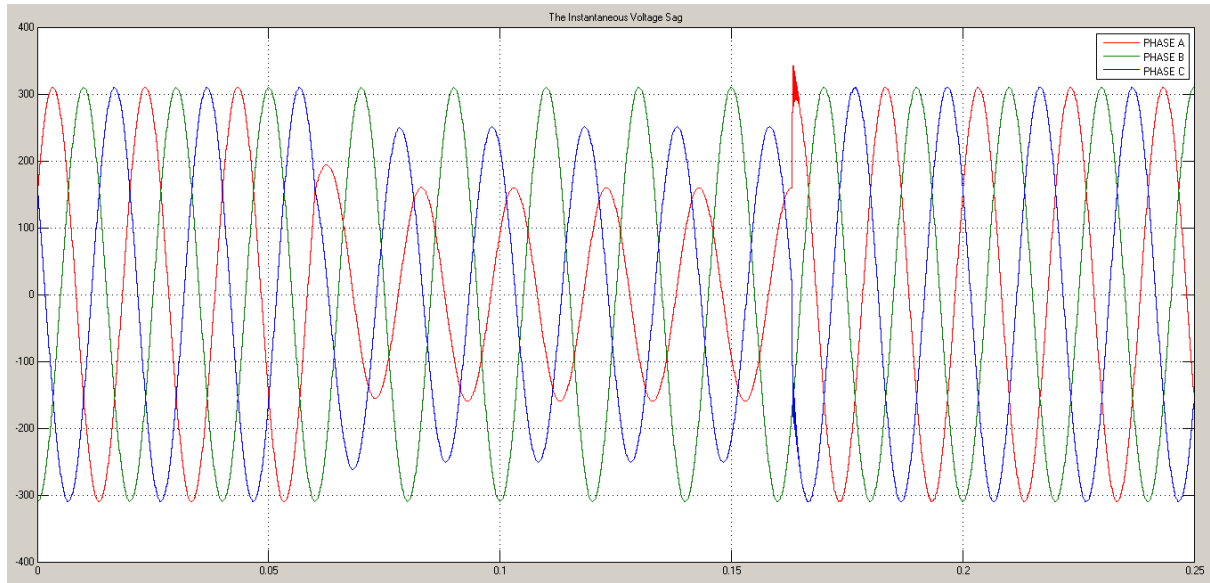


Figure 5.3: The instantaneous voltage sag without compensator (Case #1)

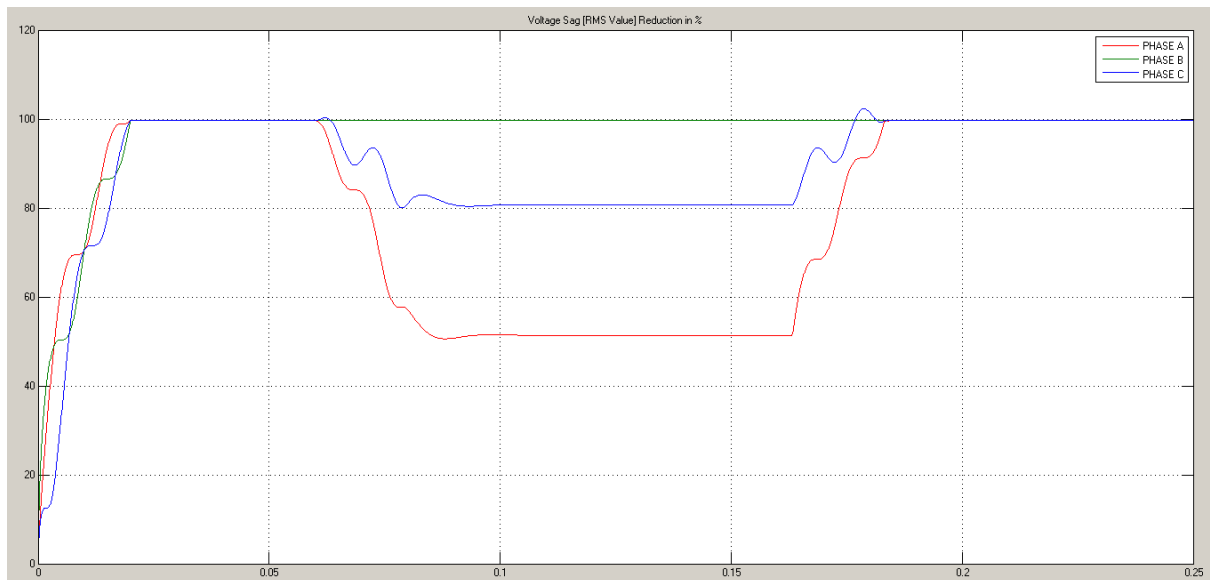


Figure 5.4: Percentage Reduction of the post sag voltage wave forms from nominal RMS value (Case #1)

5.3.1.2. Case 2: Three-phase to ground fault

By applying three phase to ground fault with the same value of fault resistance to all the phases, phase A, phase B and phase C source voltages of each individual phase is decreased to 60% from their nominal values during the period 0.06 - 0.16 s for a duration of 0.1 s. The rms value and instantaneous Post-Sag Phase to ground Voltage Waveforms of the simulation result are shown in Figure 5.5 and Figure 5.6 respectively. Figure 5.7 shows the percentage reduction of the post sag wave forms from the nominal RMS value.

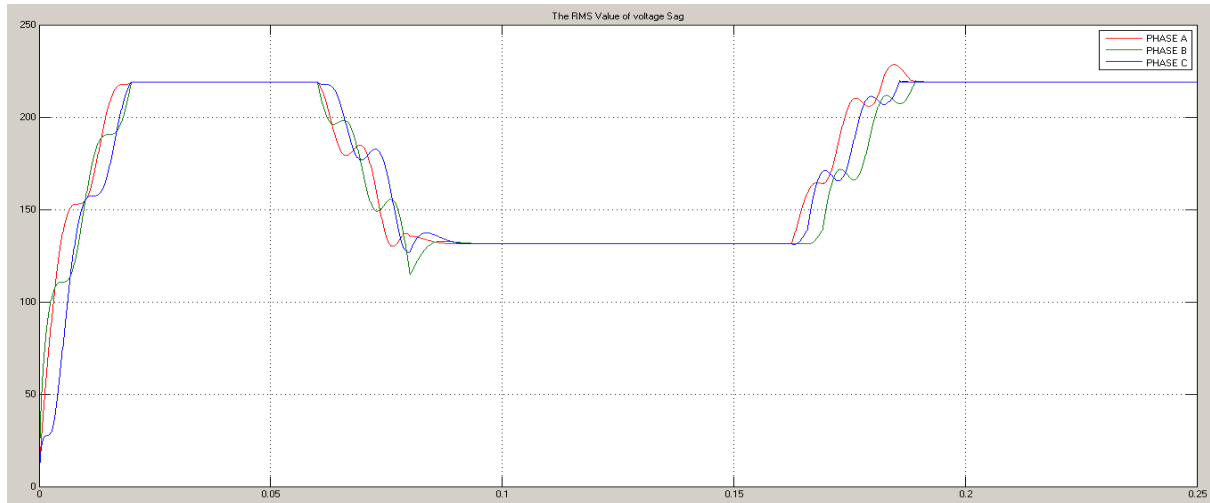


Figure 5.5: The rms value of voltage sag without compensator (Case #2)

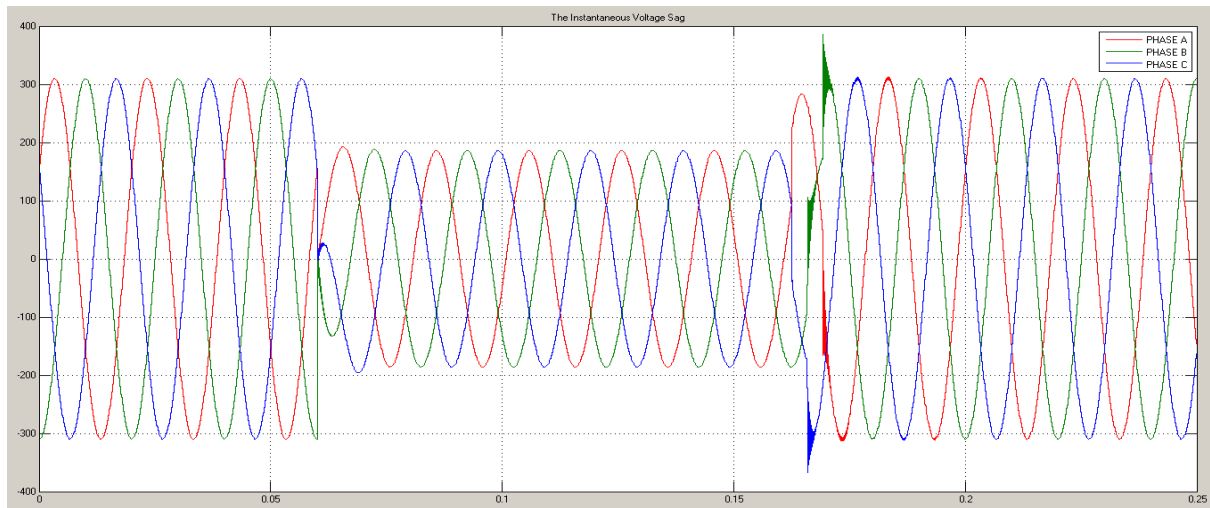


Figure 5.6: The instantaneous voltage sag without compensator (Case #2)

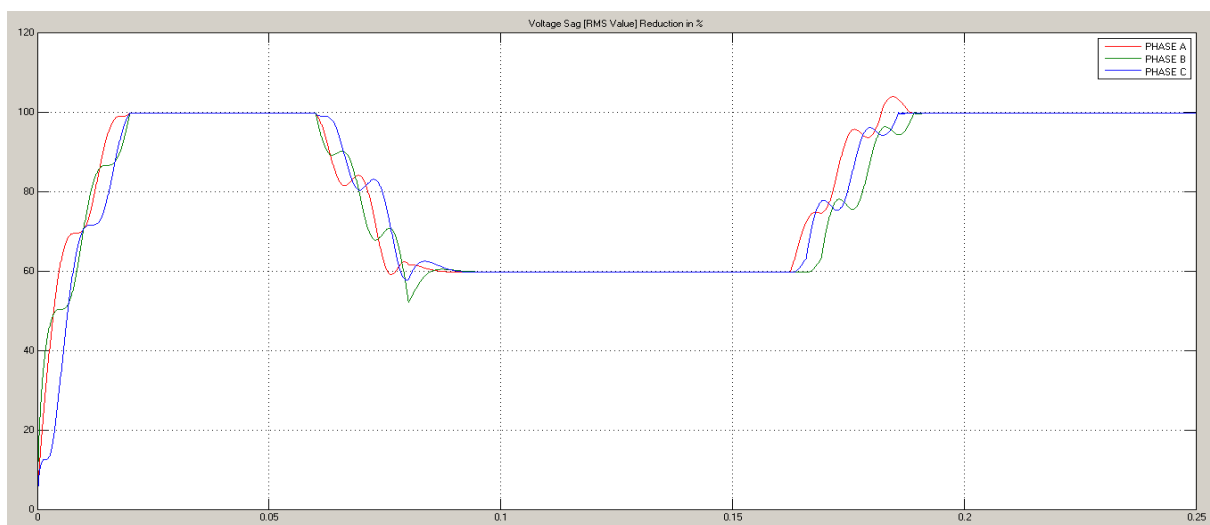


Figure 5.7: Percentage Reduction of the post sag voltage wave forms from nominal RMS value (Case #2)

5.3.2. Simulation of Multistage Faults

5.3.2.1. Case 3: Two Stage Fault Simulation

In Case #3 a multistage fault of type three-phase to ground and single-phase to ground was simulated. In stage one which stays for duration of 0.04s extending from 0.03s to 0.07s three phase to ground fault was applied to all the Phases. While in stage two which has duration of 0.08s ranging from 0.13s to 0.21s single-phase to ground fault was applied to Phase C. On all Phases 35% reduction from their nominal RMS values was observed in stage one while 30% and 50% reduction from the nominal RMS value is observed on Phase B and Phase C in stage two on the specified time ranges respectively while Phase A remained unchanged. The rms value of voltage sag and corresponding instantaneous voltage sag waveforms from simulation results without presence of DVR are shown in Figure 5.8 and Figure 5.9 respectively. Figure 5.10 shows the percentage reduction of the post sag wave forms from the nominal RMS value.

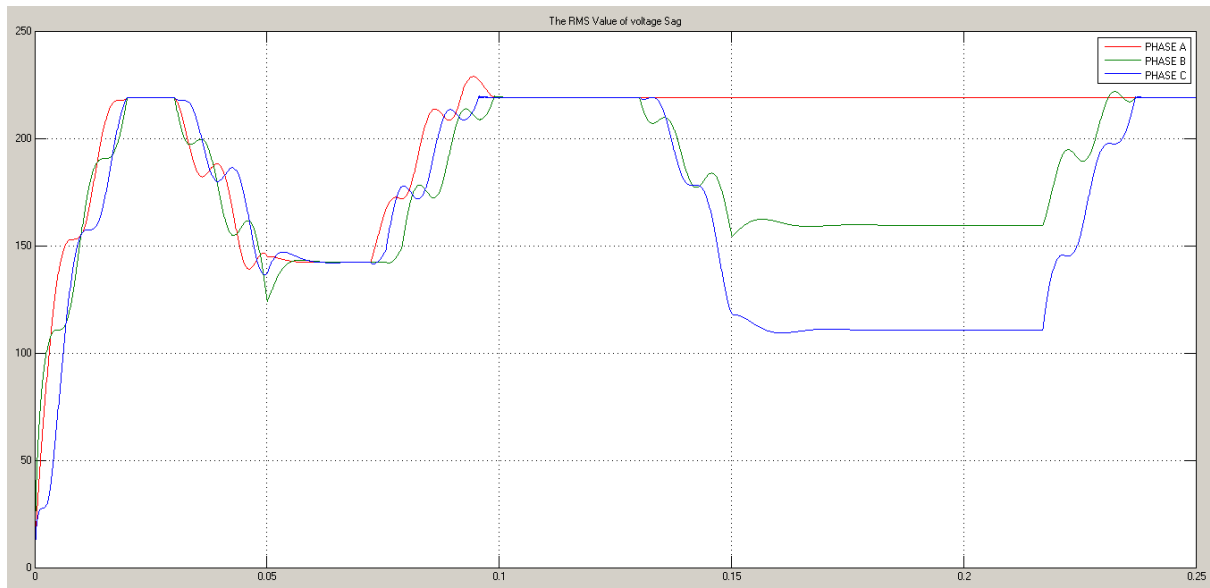


Figure 5.8: The rms value of voltage sag without compensator (Case #3)

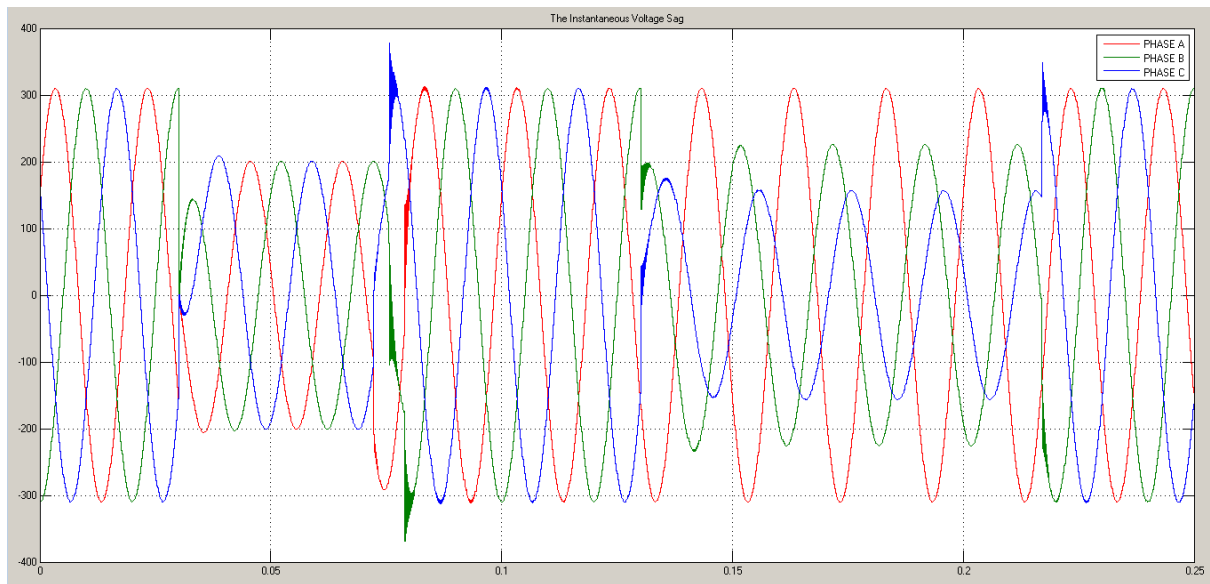


Figure 5.9: The instantaneous voltage sag without compensator (Case #3)

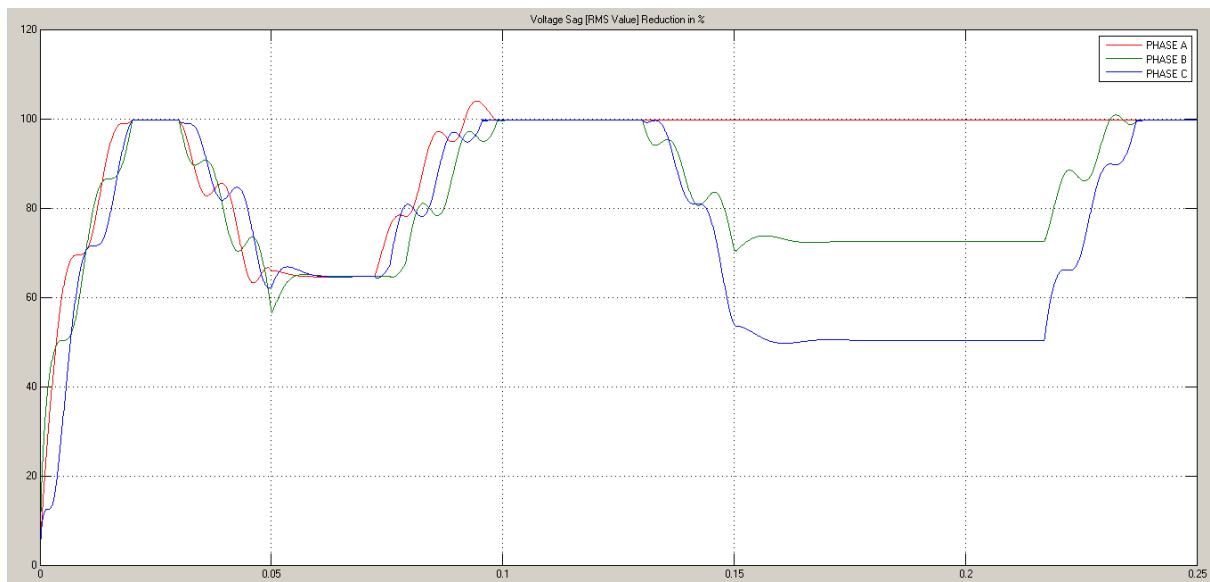


Figure 5.10: Percentage Reduction of the post sag voltage wave forms from nominal RMS value (Case #3)

Simulated fault cases are summarized in Table 5.1. In the simulated cases, voltage sag was generated by applying a fault through a controllable resistance between phases and ground.

Table 5.1: Simulated Fault Cases

CASE	FAULT TYPE	VOLTAGE SAG IN PERCENTAGE		
		PHASE A	PHASE B	PHASE C
Case #1	SLGF	52	100	80
Case #2	3- $\emptyset$ -LGF	60	60	60
Case #3	3- $\emptyset$ -LGF	65	65	65
Case #3	SLGF	100	70	50

5.4. Performance of DVR against Different Fault Cases

In this section, the performance and effectiveness of the proposed solution for voltage sag mitigation (the developed model of dynamic voltage restorer) was tested with different case studies which are developed in sections 5.3.

A proposed DVR built in MATLAB/Simulink and installed into the distribution substation system to protect a sensitive load in a distribution system is presented in Figure 5.11. The 15 kV (rms) source energizes the proposed system. The Ghion feeder is divided into 53 distribution substations with a radial configuration. The single line diagram of the feeder is given in appendix-3. Each of the distribution substations is connected to different loads which have a capacity listed in appendix-2. Among the available 53 distribution substations as per the reasons and situations discussed in section 5.3 in chapter five the Ghion Line T-021 DSS is selected as a case study. The performance of the dynamic voltage restorer is tested on this selected distribution substation. The sensitive load is rated at 1250 kVA at 85% power factor and receives power from the grid at 380 V.

The voltage sags were generated by switching on impedance to the ground at PCC by using the three phase fault block of MATLAB/Simulink. In this section the designed dynamic voltage restorer (DVR) was tested against its performance in mitigating all possible types of voltage sags that are generated in the previous section categorized into three cases.

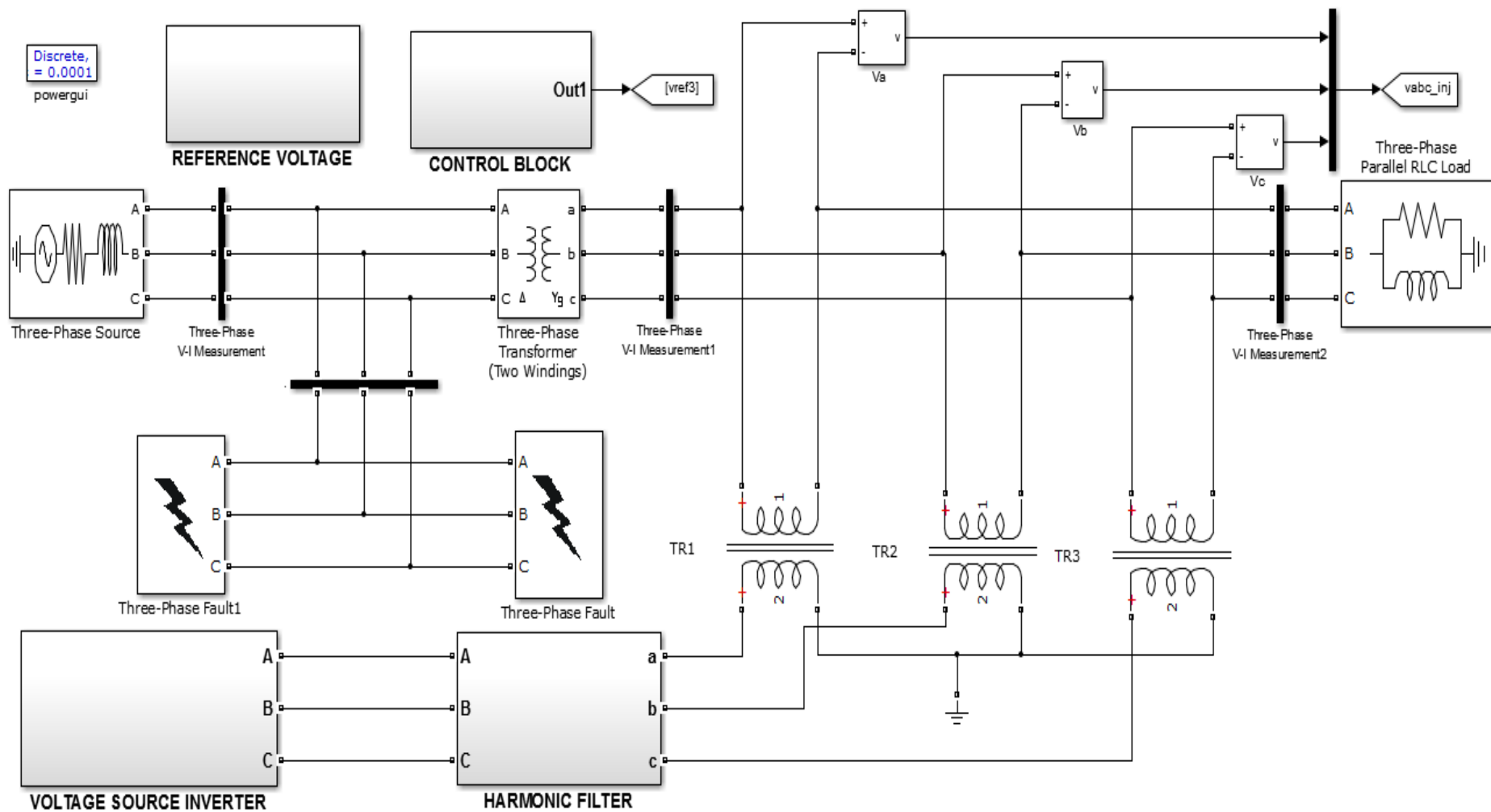
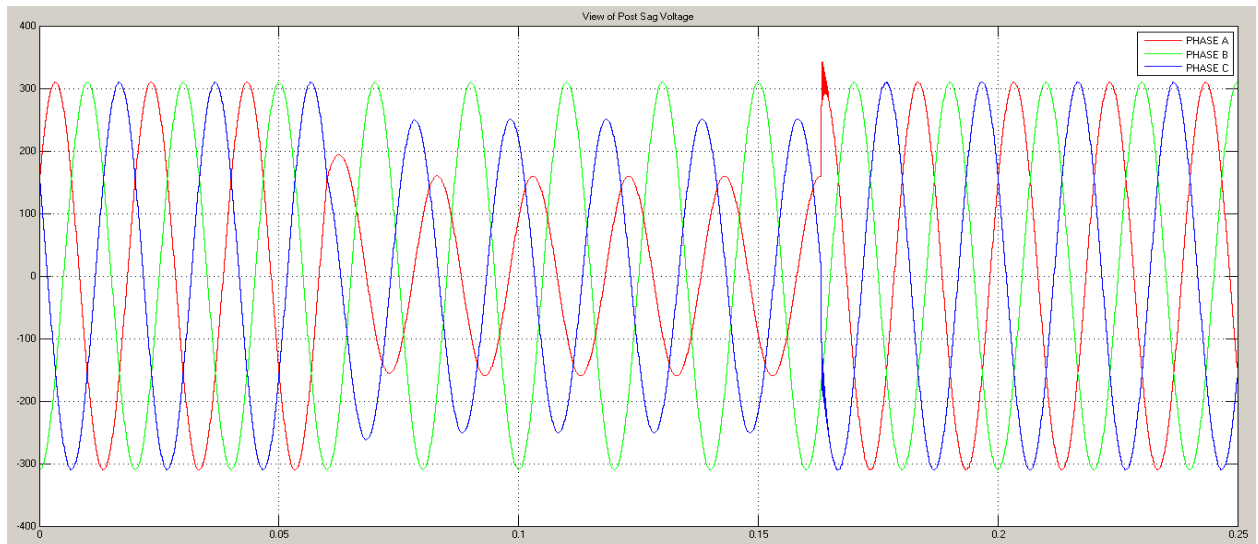


Figure 5.11: Matlab/Simulink Model of DVR installed into DSS

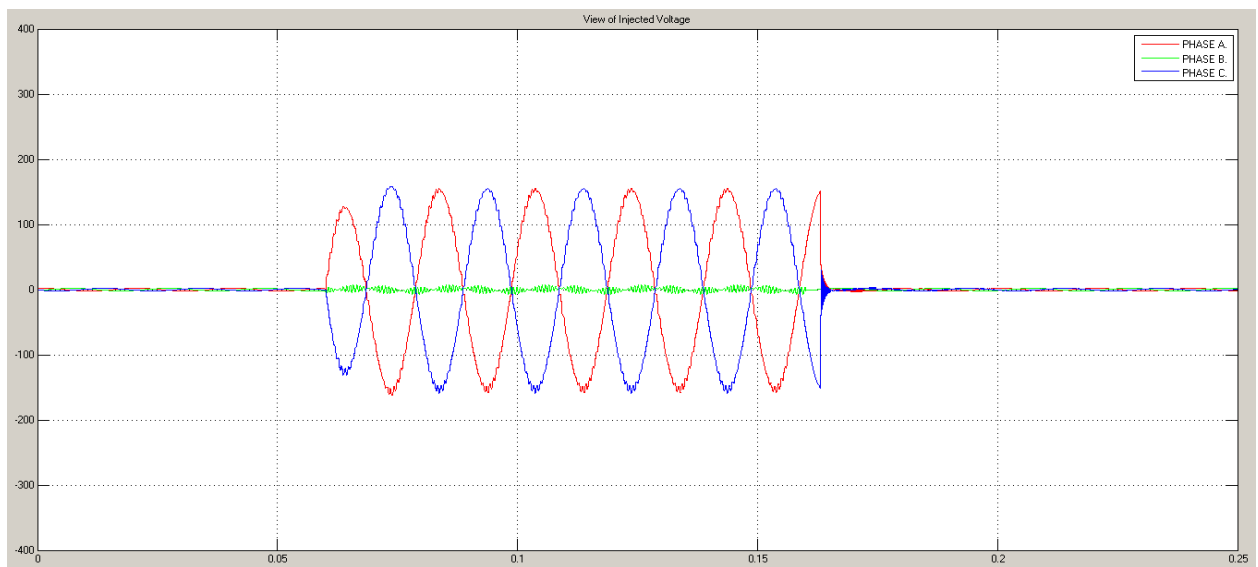
To show the restoring function (voltage sag mitigation performance) of the proposed DVR and protection of the connected loads, the system is tested for the following case studies which are developed in section 5.3 and 5.4.

5.4.1 Performance against case #1

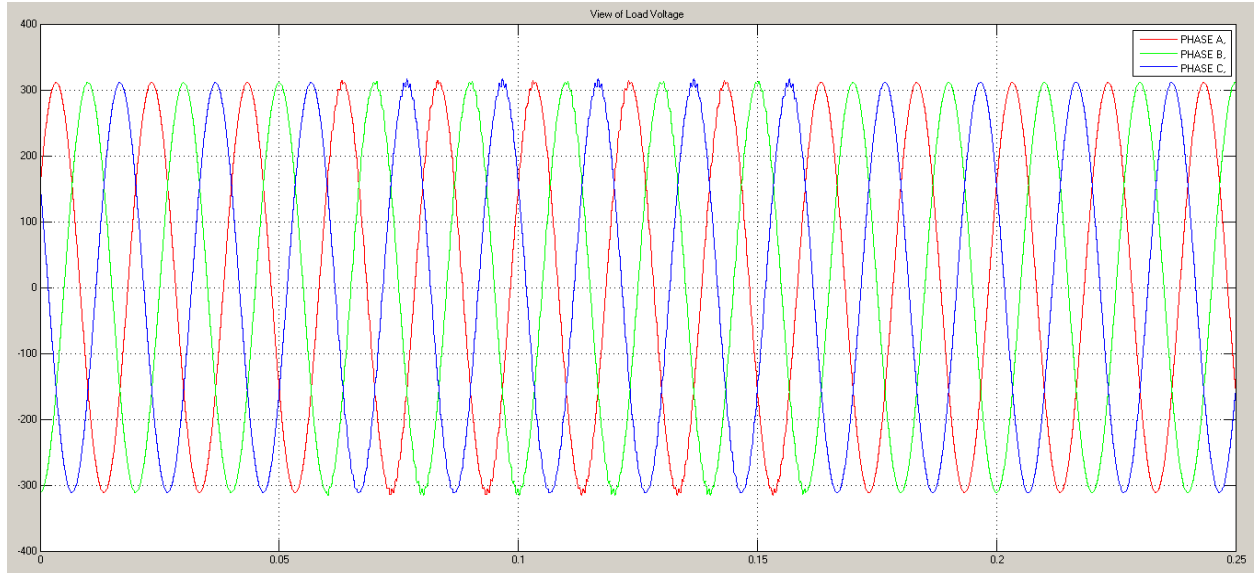
The SLGF occurs on phase A with proper fault resistance resulting in 48% decrease on Phase A and 20% decrease on Phase C from nominal RMS value. The instance at which fault applied is 0.06s and fault lasts till 0.16s for a duration of five cycles. Figure 5.12 shows the Post-Sag Phase to ground Voltage Waveforms, injected voltages by the dynamic voltage restorer and the restored load voltages at SLGF.



(a)



(b)



(c)

Figure 5.12: Simulation results for Case (#1): (a) - Post sag voltage, (b) - voltages injected by the DVR, (c) - voltage at load.

As seen from Figure 5.12 after sensing the post sag voltage drops, DVR starts operating to inject the missing voltage so that the load voltage is almost maintained constant. The controller of the DVR rapidly responds to disturbances to restore the pre fault (pre sag) load voltage effectively. Figures 5.13 and 5.14 shows the individual post sag, injected and compensated load voltages of phase A and phase C in a single view respectively. In Figure 5.13 the injected voltage is almost in phase with the post sag voltage with only 9° phase shift while in Figure 5.14 there is a higher phase jump of 33.6° between the post sag and injected voltages. This is due to the reason that the power system faults not only cause a drop in voltage magnitude but also cause change in the Phase angle of the voltage. Thus the applied single line-to-ground fault has brought a phase angle jump of 33.6° in addition to the 20% reduction in magnitude on Phase C where the phase angle of the pre sag load voltage of phase A was only affected slightly and hence the injected voltage seems in phase with the post sag voltage from the waveforms.

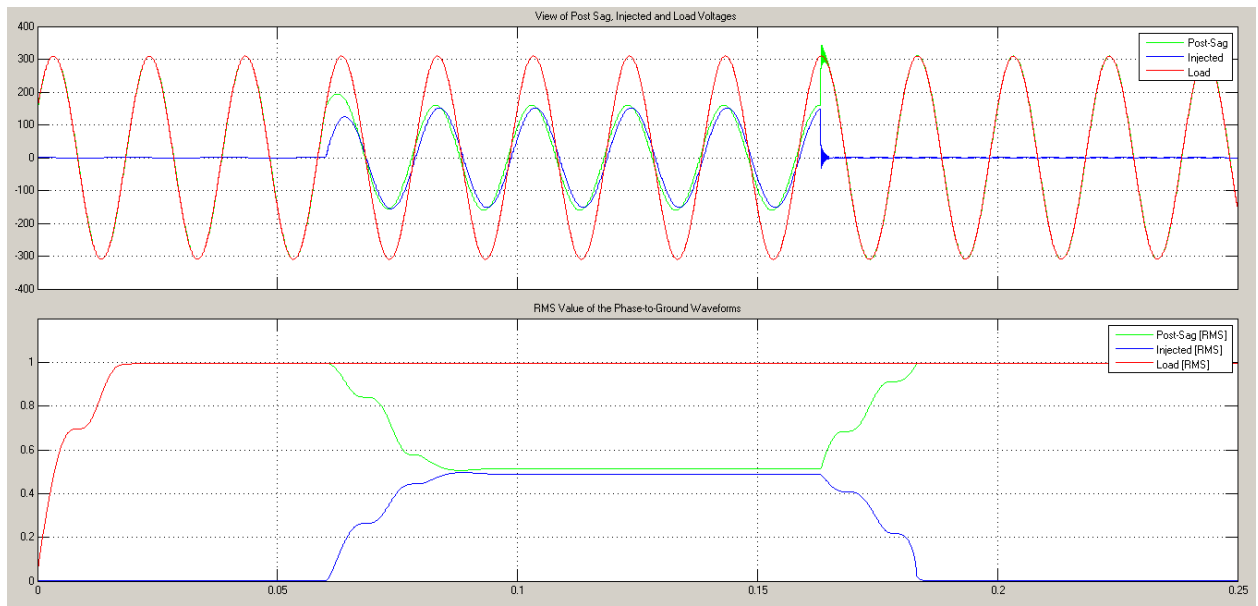


Figure 5.13: The Post sag, injected and load voltages of phase A (Case #1)

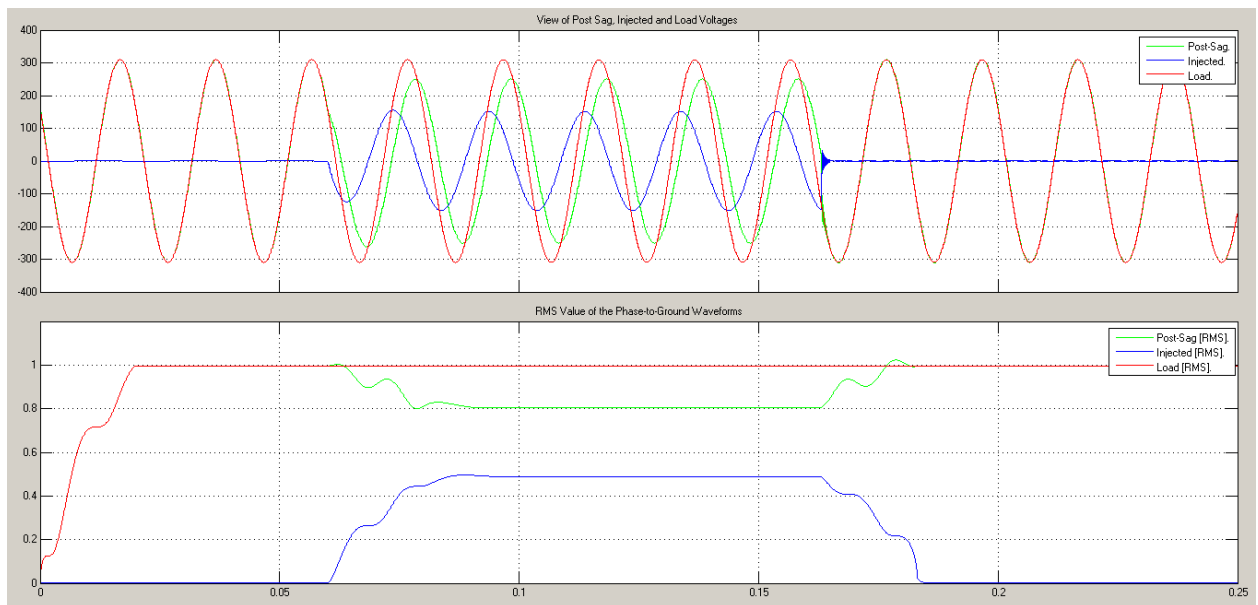


Figure 5.14: The Post sag, injected and load voltages of phase C (Case #1)

Table 5.2 summarizes the effects of source, injected and load voltages with and without DVR applied to the distribution substation.

Table 5.2: Voltage values (pu) and Phase angle (degree) with and without DVR (Case #1)

PHASE	Per Unit Value of fundamental Voltage (50 Hz)						ANGLE JUMP
	POST SAG		INJECTED		LOAD		
	Magnitude	Angle	Magnitude	Angle	Magnitude	Angle	
PHASE A	0.513	324	0.492	336.6	0.998	333	9
PHASE C	0.806	237.6	0.495	156.6	1.009	207	-33.6

Post sag is the measured phase supply voltage; Injected is the measured injection voltage and Load is the measured sensitive load voltage.

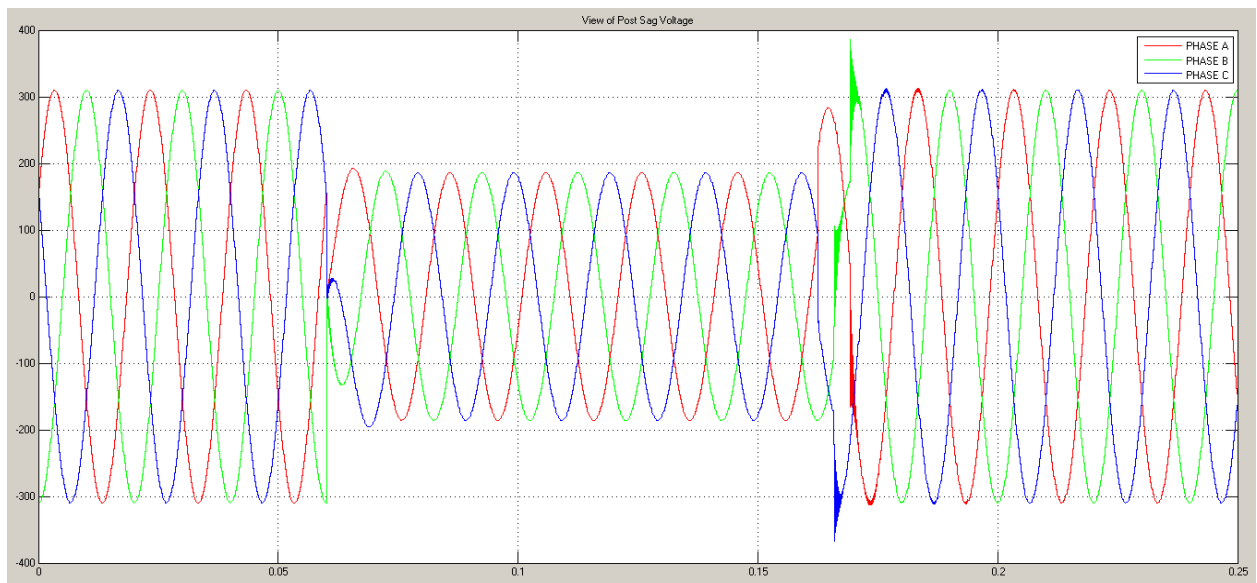
It is observed that the injected voltages effectively compensate the load voltage to the pre sag magnitude and phase angle. Phase B voltage is not affected by the fault because Δ/Y_n connected transformers remove the zero sequence components from the system.

The dqo transform based controller start to operate in case of voltage sag is detected. The control is based on the comparison of a voltage reference and the measured terminal voltage (V_a, V_b, V_c). The voltage sags is detected when the supply drops below 90% of the reference value. The error signal is used as a modulation signal that allows generating a commutation pattern for the power switches (IGBT's) constituting the voltage source inverter. The commutation pattern is generated by means of the sinusoidal pulse width modulation technique (SPWM); voltages are controlled through the modulation.

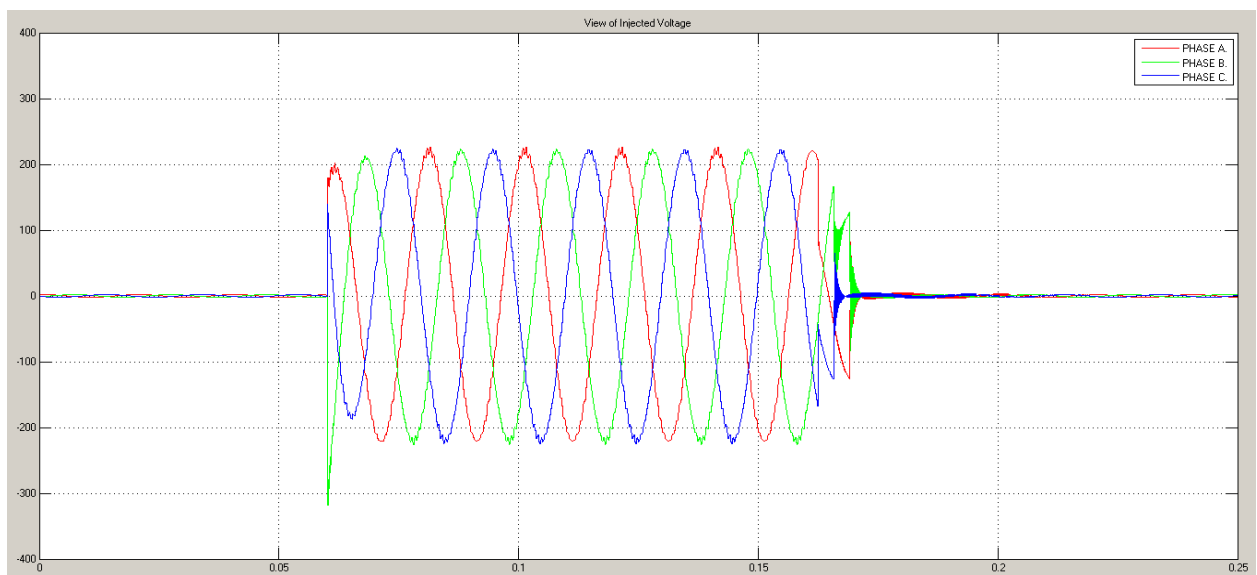
The dqo transform based controller applied to DVR enable the proposed system for providing a good power and voltage quality to the critical load.

5.4.2 Performance against case #2

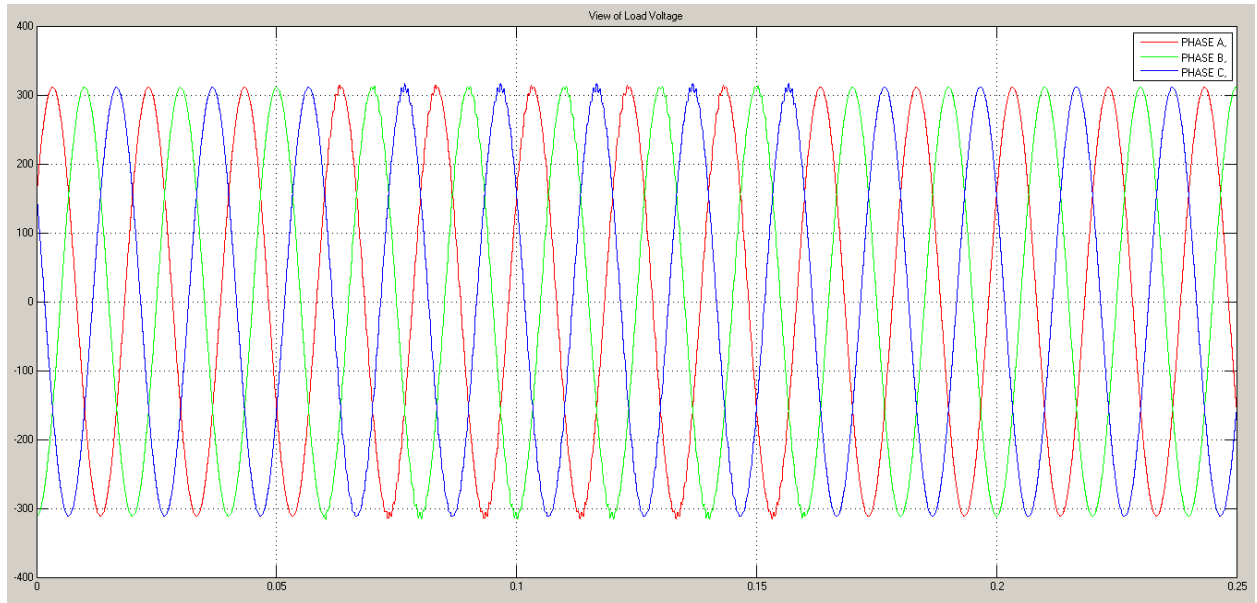
In case #2 simulation of three phase voltage sag is simulated by applying three phase to ground fault between all the phases with a proper fault resistance value and result of simulation showed that a 60% three-phase voltage sag has occurred at Phase A, Phase B and phase C as shown in Figure 5.15 (a). The voltage sag is initiated at 0.06s and it is kept until 0.16s, with total voltage sag duration of 0.1s. Figures 5.15 (b) and (c) show the voltage injected by the DVR and the corresponding load voltage with compensation respectively. As a result of DVR, the load voltage is kept at the required pre fault value.



(a)



(b)



(c)

Figure 5.15: Simulation results for Case (2): (a) - Post sag voltage, (b) - voltages injected by the DVR, (c) - voltage at load.

Figure 5.16 presents the simulation results for the system under simulation of case # 2 showing the instantaneous and RMS values of the post sag voltage, voltage generated by the DVR (injected voltage) and the compensated load voltage on a single view for phase A. As it can be seen from the figure the green line which is the post sag voltage waveform shows 60% voltage sag on the RMS value display due to the applied fault. From table 5.3 the applied fault not only reduced the magnitude but also introduced a phase angle jump of magnitude - 41.4° from the pre fault phase angle on phase A. The controller then takes the saged voltage and by comparing it with reference voltage an error signal is obtained; the one that needs to be injected into the system to restore the pre sag system voltage. The error signal is used as a modulation signal that allows generating a commutation pattern for the power switches (IGBT's) constituting the voltage source inverter. The commutation pattern is generated by means of the sinusoidal pulse width modulation technique (SPWM); voltages are controlled through the modulation. And hence by the control of the error signal the inverter produces the missing voltage at the required magnitude and phase angle which is represented by a blue color in figure 5.16. This missing voltage is then injected into the system by the help of injection transformer and the required pre sag voltage of the load is restored effectively as shown on the same figure by the red color. Thus as a result of DVR, the load voltage is kept almost constant at pre sag value throughout the simulation.

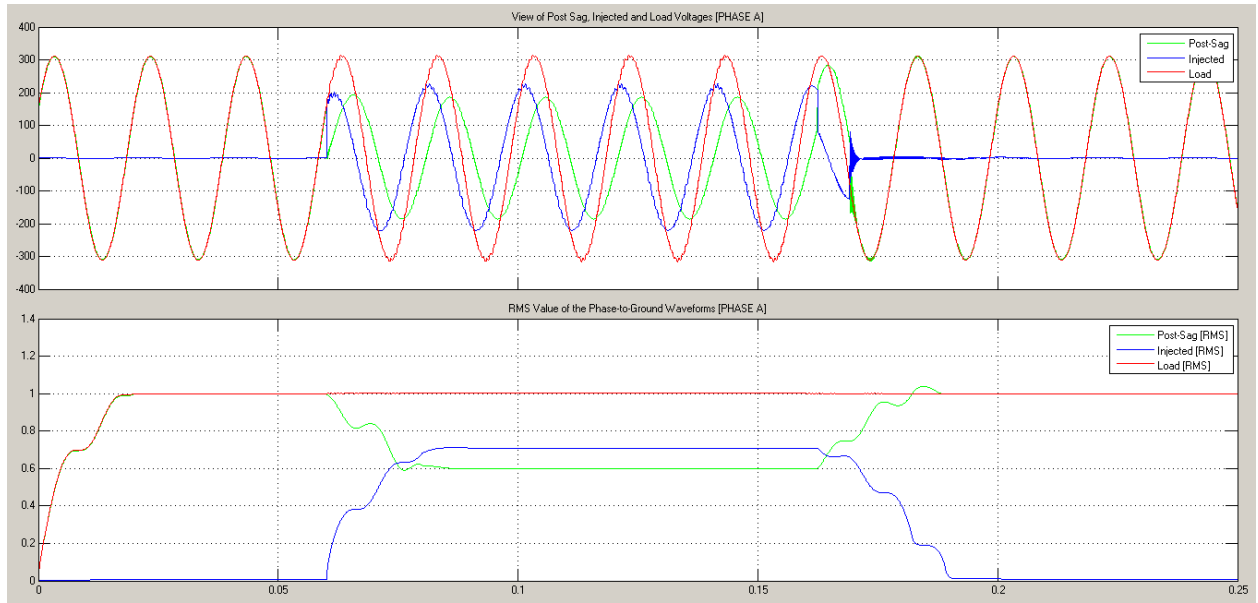


Figure 5.16: The Post sag, injected and load voltages of phase A (Case #2)

Similarly Figure 5.17 presents a single view of the post sag voltage, voltage generated by the DVR and the compensated load voltage for phase B. As it can be seen from the figure 60% voltage sag is observed on the green line which shows the post sag voltage phase to ground waveform for phase B. Once the voltage sag is generated the DVR acts increasing the load voltage amplitude by generating the missing voltage as per the controller shown by the blue color to restore the critical load voltage. The red color on figure 5.17 illustrates how quickly the DVR responses for sudden changes to keep the sensitive load voltages at reference value.

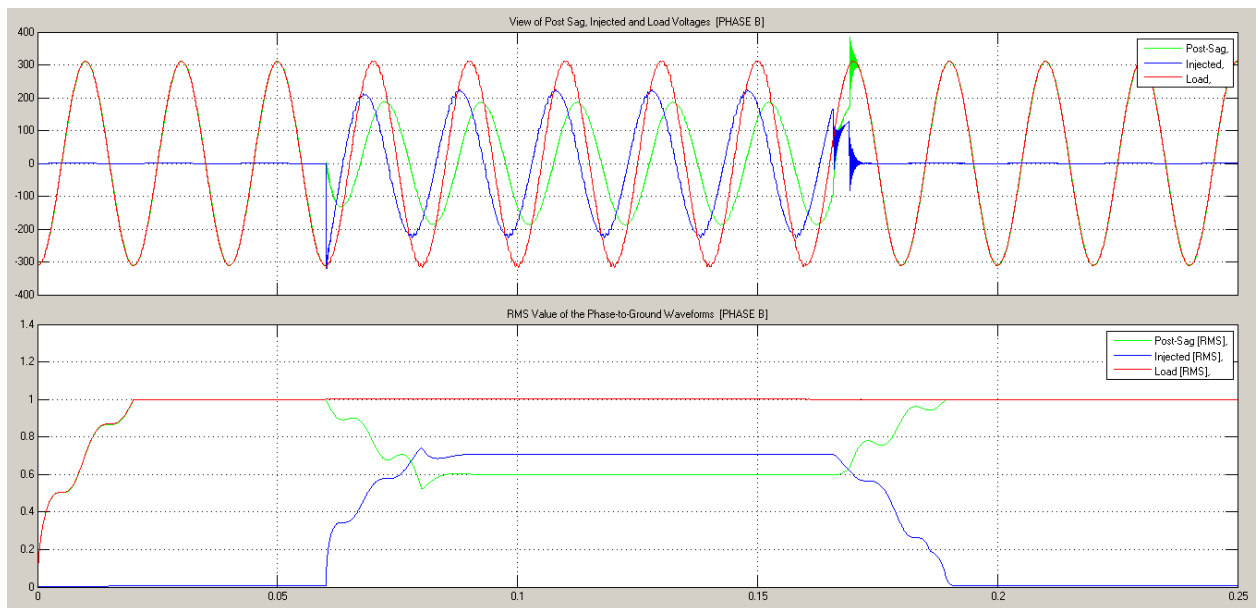


Figure 5.17: The Post sag, injected and load voltages of phase B (Case #2)

In Figure 5.18 which shows the three voltages (Post sag, injected and load) for Phase C a similar case can be observed. As it can be seen from the figure 60% voltage sag is observed on phase C due to the applied fault at the high voltage side of the distribution transformer. But this voltage sag is not only characterized by this percentage reduction in magnitude but also there is a considerable phase angle jump between the pre sag and post sag voltage waveforms of magnitude -48° as it can be seen from Figure 5.18 and table 5.3. Therefore to restore the pre sag voltage of the critical load at the required magnitude and phase angle the dynamic voltage restorer needs to take care of this phase angle jump. And hence the generated missing voltage to be injected into the system is found to have a magnitude of 0.708 pu at a phase angle of -3.6° . The generated injection voltage exactly compensates the sag because the controller exactly calculates the missing voltage. As a result the restored load voltage was found to have a magnitude of 1.008 pu at a phase angle of 27° .

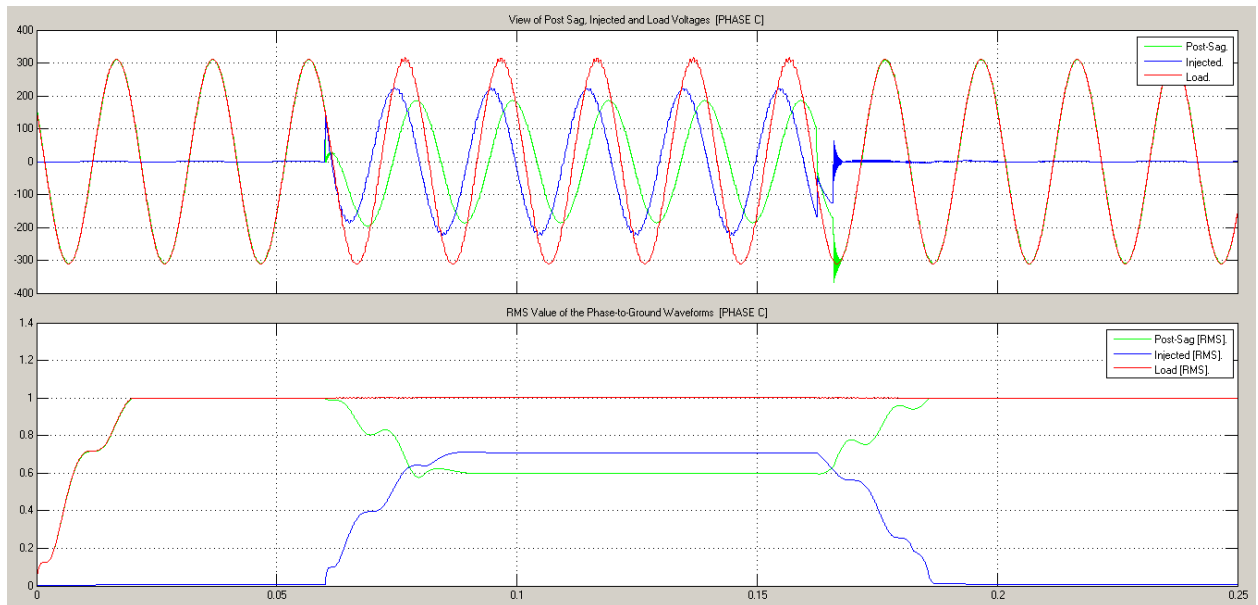


Figure 5.18: The Post sag, injected and load voltages of phase C (Case #2)

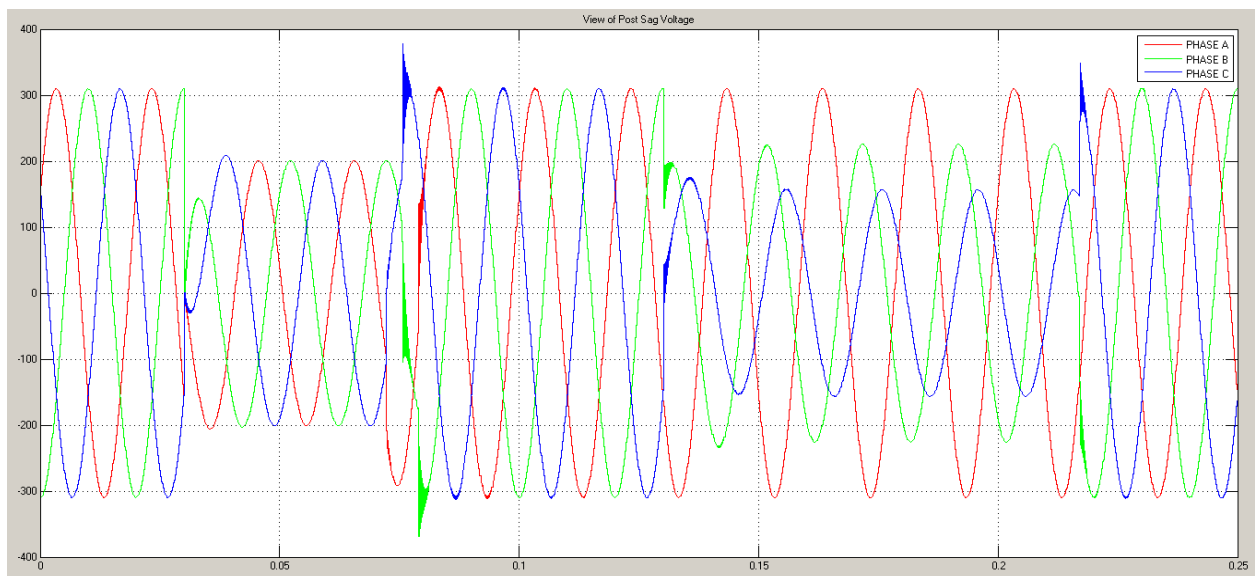
Table 5.3 summarizes the effects of source, injected and load voltages with and without DVR applied to the distribution substation for case (2). Referring to the table the applied fault has introduced a similar 0.598 pu voltage sag in all of the phases and a phase angle jump of magnitude -41.4° , -45° and -48° on phase A, B and C respectively. This is due to the reason that the type of fault is balanced three phase line to ground fault and hence it has introduced a balanced sag both in magnitude as well as phase angle on each of the three phases. The single-phase PWM inverters managed by the control system generate the three distinct series inverter output voltages to compensate the source voltages at the same sag level.

Table 5.3: Voltage values (pu) and Phase angle (degree) with and without DVR (Case #2)

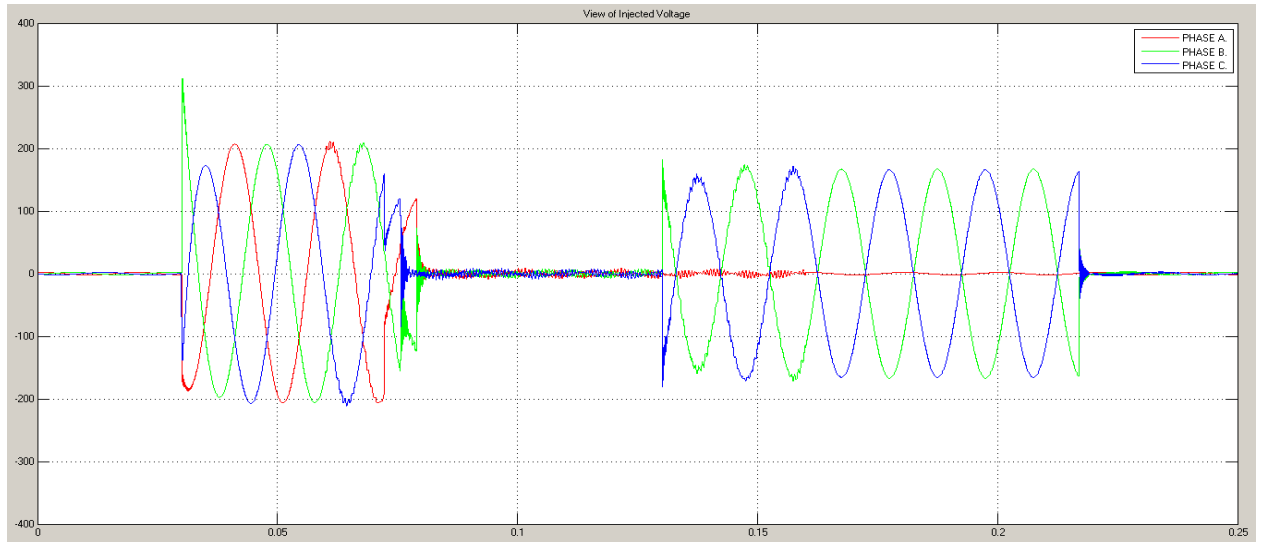
PHASE	Per Unit Value of fundamental Voltage (50 Hz)						ANGLE JUMP
	POST SAG		INJECTED		LOAD		
	Magnitude	Angle	Magnitude	Angle	Magnitude	Angle	
PHASE A	0.598	192.6	0.708	115.2	1.021	151.2	-41.4
PHASE B	0.598	313.2	0.708	235.6	0.968	268.2	-45
PHASE C	0.598	75.6	0.708	-3.6	1.008	27	-48

5.4.3 Performance against case #3

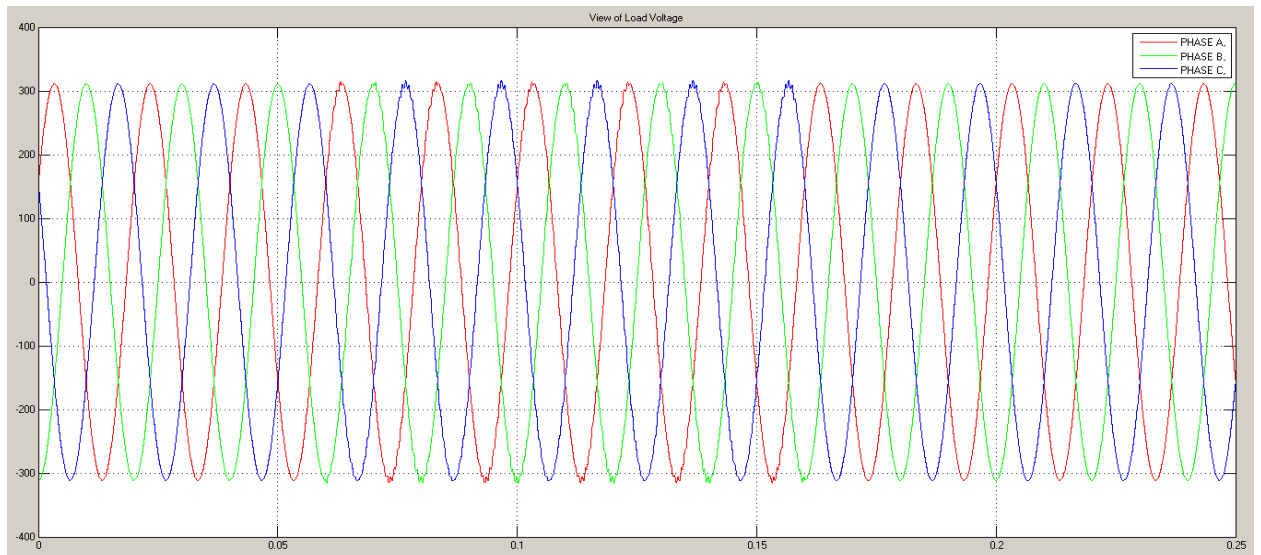
In Case #3 a multistage fault of type three-phase to ground and single-phase to ground was simulated. In stage one which stays for a duration of 0.04s extending from 0.03s to 0.07s three phase to ground fault was applied all the Phases. While in stage two which has duration of 0.08s ranging from 0.13s to 0.21s single-phase to ground fault was applied to Phase C. On all Phases 35% reduction from their nominal RMS values was observed in stage one while 30% and 50% reduction from the nominal RMS value is observed on Phase B and Phase C in stage two on the specified time ranges respectively. The Post-Sag Phase to ground Voltage Waveforms, the compensating voltage generated by DVR and the restored load voltage are shown in figure 5.19 (a), (b) and (c) respectively.



(a)



(b)



(c)

Figure 5.19: Simulation results for Case (3): (a) - Post sag voltage, (b) - voltages injected by the DVR, (c) - voltage at load.

Due to the applied three phase fault in the system to create balanced voltage sag in stage one all the three phases are affected both in magnitude as well as phase angle jump. While in stage two unbalanced voltage sag occurs due to single line to ground fault in the network and this produced reduction of rms value and phase angle jump in phases B and C where phase A remains unaffected. The post sag, compensating and load voltage of phase A, phase B and phase C for both stages are shown in Figure 5.20, 5.21 and 5.22 respectively. The DVR respond to the disturbance and inject the compensating voltage. After sag compensation, the load voltage regains its previous profile.

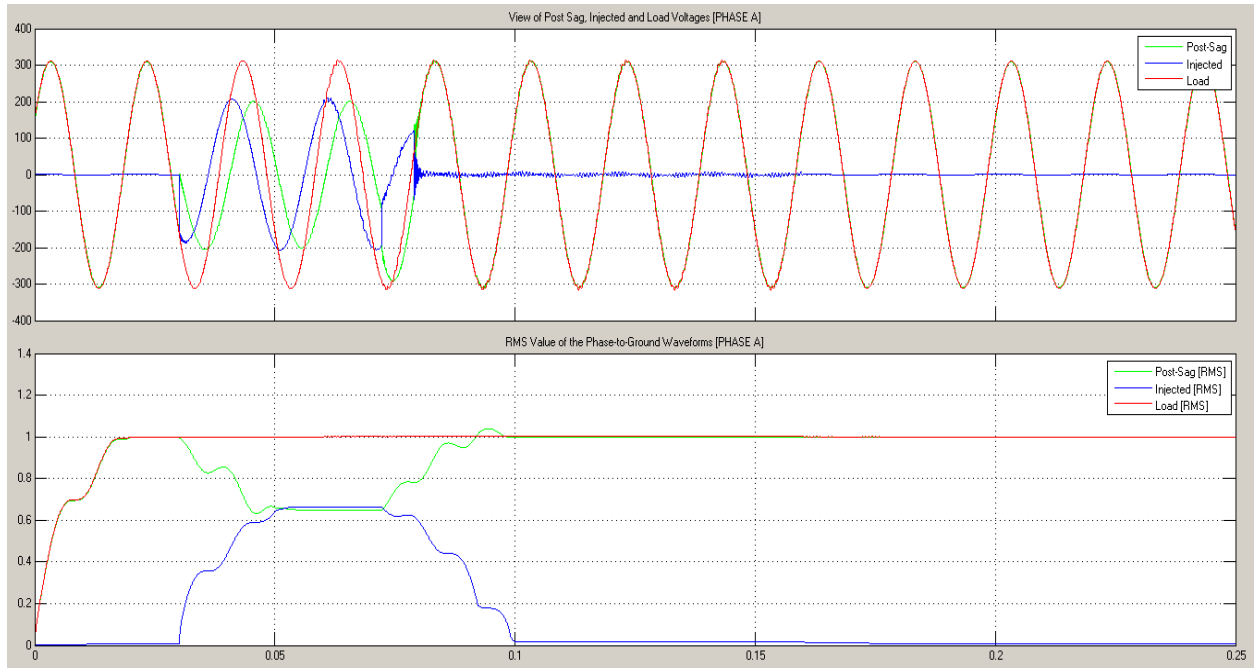


Figure 5.20: The Post sag, injected and load voltages of phase A (Case #3)

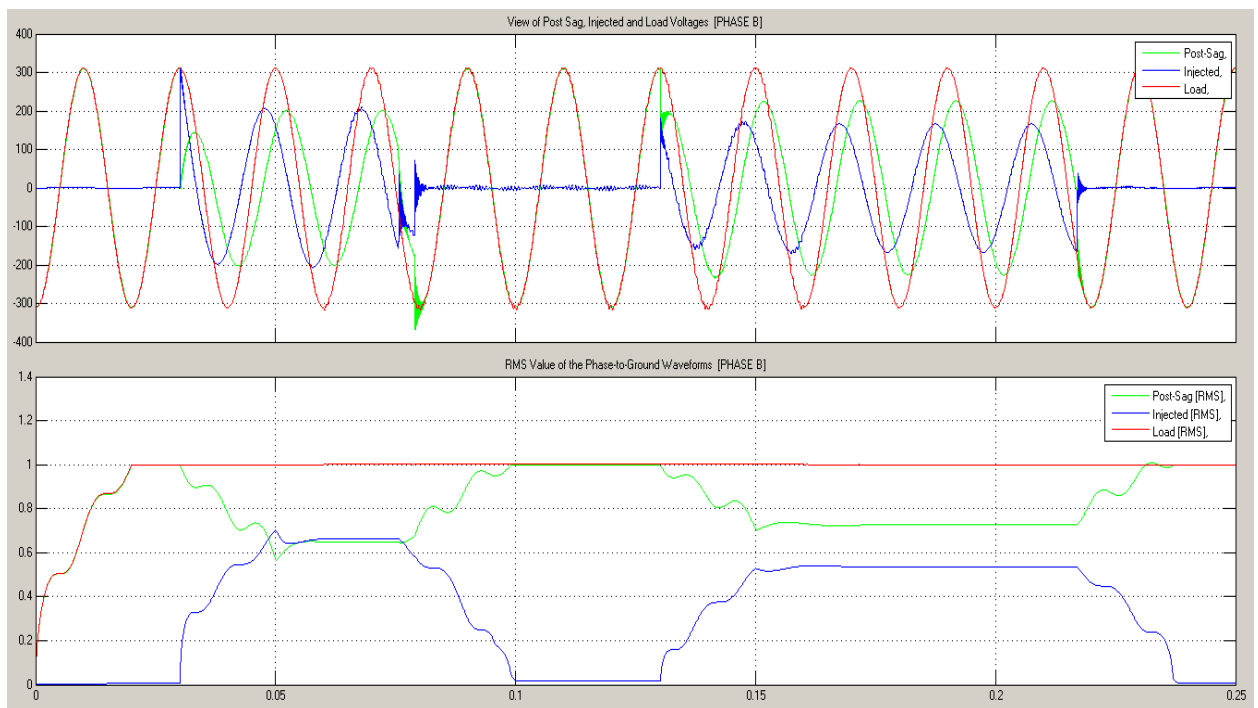


Figure 5.21: The Post sag, injected and load voltages of phase B (Case #3)

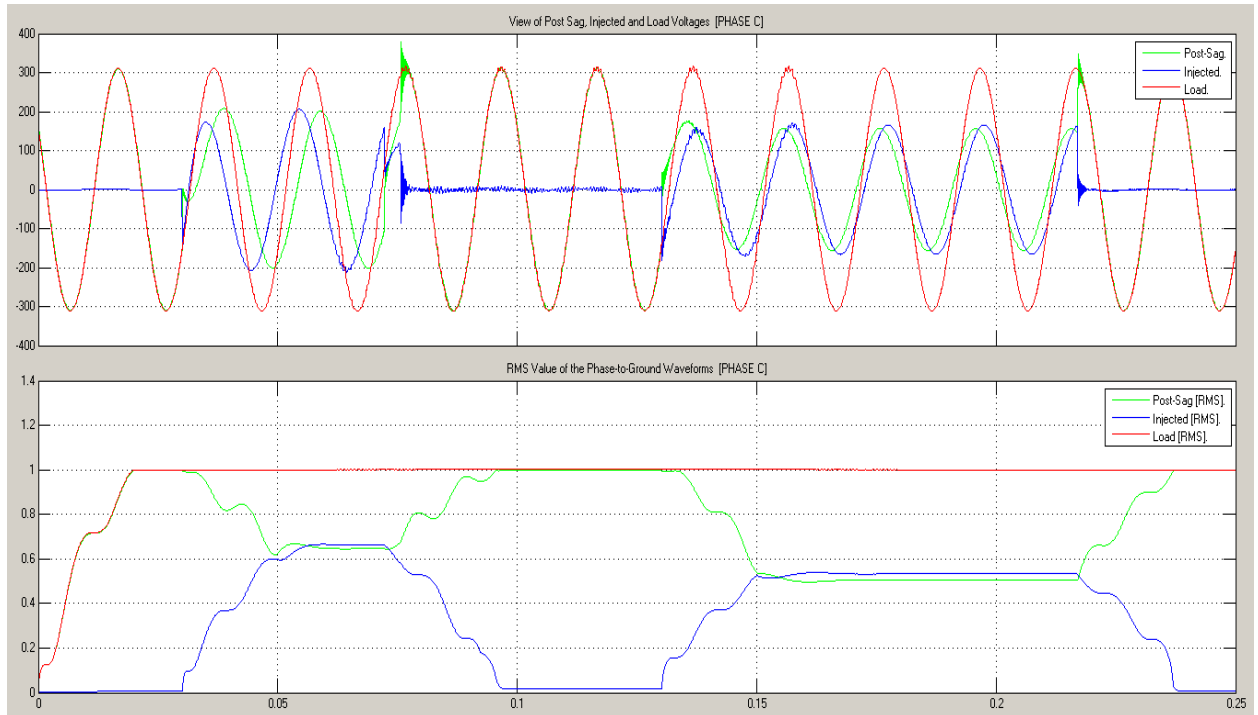


Figure 5.22: The Post sag, injected and load voltages of phase C (Case #3)

Table 5.4 summarizes the effects of source, injected and load voltages with and without DVR applied to the distribution substation due to the balanced and unbalanced faults in both the stages.

Table 5.4: Voltage values (pu) and Phase angle (degree) with and without DVR (Case #3)

STAGE	PHASE	Per Unit Value of fundamental Voltage (50 Hz)						ANGLE JUMP
		POST SAG		INJECTED		LOAD		
		Magnitude	Angle	Magnitude	Angle	Magnitude	Angle	
ONE	PHASE A	0.646	12.6	0.663	-70.2	0.982	-28	-41.4
	PHASE B	0.647	131.4	0.657	50.4	0.991	90	-41.4
	PHASE C	0.646	252	0.664	171	0.996	210.6	-41.4
TWO	PHASE B	0.725	127.8	0.536	37.8	0.901	97.2	-30.6
	PHASE C	0.503	194.4	0.533	226.8	1.046	210.6	16.2

Chapter 6 : Conclusion and Recommendation

6.1 Conclusion

This thesis is focused on one type of custom power device, which is referred to as a dynamic voltage restorer (DVR). The main characteristics of the device are that it is series connected to the supply, and it has the ability to inject controlled voltage into the grid to compensate for voltage sags. The proposed DVR has been assumed to be located in low voltage distribution network level and it can mitigate three-phase sags up to 50% of the nominal voltage. The studied DVR is based on forced commutated series connected voltage source inverter (VSI). The DVR has been designed with special importance at the control of PWM inverter. The parks transformation based control of DVR has been developed in this thesis to response quickly and obtain a good dynamic performance. The controller has obtained high performance with relatively low sampling time and switching frequency. The quick response and high performance have been obtained by directly processing the measured source voltages and employing the direct feed forward control algorithm. The three Phase discrete PLL has satisfactorily tracked the source voltage and generated synchronizing frequency for PWM modulation without experiencing a disturbance. The control system has not deal with the compensation of zero sequence voltages because the faults have occurred in medium voltage system and the transformer connected in delta have eliminated these voltage components. Simulation and testing of a DVR by inserting it in a practical power distribution system has been presented. First, a modeling of the chosen practical power distribution system components has been done using the MATLAB/Simulink simulation software. Generation of different types of faults which are considered to be the main causes of voltage sags was done using the simulation. The voltage sags have been generated by performing controlled short circuits in the grid. Carefully chosen three case studies have been realized to verify the operation and performance of the designed system in MATLAB/Simulink program. The dynamic performance of dynamic voltage restorer (DVR) was first tested with Single phase line to ground fault. When the waveforms of such a case are examined, it was observed that a controlled single-phase line-to-ground fault generated on phase-A causes a sag of 50% and 80% on phase A and Phase C respectively. The simulated DVR was found to be capable of compensating for the missing voltages effectively. From the simulation of the non-symmetrical fault the results have verified the efficiency, flexibility and transient response capability of the developed custom power device – the DVR. The designed DVR has provided a regulated and sinusoidal voltage across the sensitive load.

The performance of the dynamic voltage restorer was also tested against symmetrical faults. The dynamic performance was tested with a three-phase symmetrical short circuit fault which resulted a 60% balanced voltage sag in each of the three phases. The DVR succeeded to protect the load from a 100 ms and 0.6 pu voltage sag. Simulation has been carried out using a multi stage fault generation block of two stages. In stage one three phase to ground fault was applied to all the Phases from 0.03s to 0.07s. On all Phases 35% reduction from their nominal RMS values was observed. While in stage two single-phase to ground fault was applied to Phase C from 0.13s to 0.21s. In this stage 30% and 50% reduction from the nominal RMS value is observed on Phase B and Phase C respectively. Results of simulation showed that, the DVR was able to produce the required voltage component rapidly in each of the stages and helped to maintain a balanced and constant load voltage at 1 pu.

Based on the simulation carried out, it was found that a DVR can tackle voltage sags when protecting sensitive loads. The DVR handled both balanced and unbalanced situations without any difficulties and injected the appropriate voltage component to correct rapidly any disturbance in the supply voltage to keep the load voltage balanced and constant at the nominal value. The DVR is considered to be an efficient solution due to its relatively low cost and small size; also it has a fast dynamic response.

6.2 Recommendation

A series connected voltage controller like the DVR is expected to experience an increased attention in the future, because it can be an effective and relative inexpensive solution to stabilize the voltage compared to high power rated UPS systems. Therefore as suggestion for future researches 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. In addition to this other power quality problem that occurs in power system network has to be considered.

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Appendix-1: Bahir Dar City 15 kV Feeder Data

S.No.	Name of Feeder	Total Number of DT on Feeder	Total capacity of DT (kVA)	Total Length of Feeder (km)	Total installed load (kVA)
1	Gambi	27	6435	8.53	6120
2	Papyrus	49	16075	19.20	16075
3	Ghion	53	14130	20.05	14620
4	Sematat	61	15065	28.21	16245
5	Bata	80	17200	61.24	17400
6	AirForce	38	8170	23.57	8170
7	Industry	65	12005	32.60	12005
8	Boiler	9	15190	0.90	15190
9	Hamusite	49	5790	62.32	5790
10	Tis Abay	13	2070	19.27	2070
11	Adet	46	6845	23.6	6845

Appendix-2: Ghion Feeder MV Distribution Transformer List

S.No.	Name of Feeder	Name Of DT	Size of DT (kVA)	Installed Load (kVA)	Power Factor
1	Ghion	Ghion Line T-001	800	800	0.85
2	"	Ghion Line T-002	800	800	0.85
3	"	Ghion Line T-003	200	200	0.85
4	"	Ghion Line T-004	100	105	0.85
5	"	Ghion Line T-005	100	100	0.85
6	"	Ghion Line T-006	25	25	0.85
7	"	Ghion Line T-007	200	200	0.85
8	"	Ghion Line T-008	25	25	0.85
9	"	Ghion Line T-009	200	200	0.85
10	"	Ghion Line T-010	100	100	0.85
11	"	Ghion Line T-011	100	100	0.85
12	"	Ghion Line T-012	200	200	0.85
13	"	Ghion Line T-013	200	200	0.85
14	"	Ghion Line T-014	200	200	0.85
15	"	Ghion Line T-015	200	200	0.85
16	"	Ghion Line T-016	100	100	0.85
17	"	Ghion Line T-017	200	200	0.85
18	"	Ghion Line T-018	200	220	0.85
19	"	Ghion Line T-019	315	315	0.85
20	"	Ghion Line T-020	1200	1200	0.85
21	"	Ghion Line T-021	1250	1250	0.85
22	"	Ghion Line T-022	315	315	0.85
23	"	Ghion Line T-023	200	200	0.85
24	"	Ghion Line T-024	315	340	0.85
25	"	Ghion Line T-025	315	315	0.85
26	"	Ghion Line T-026	630	670	0.85
27	"	Ghion Line T-027	200	200	0.85
28	"	Ghion Line T-028	315	315	0.85

29	"	Ghion Line T-029	315	315	0.85
30	"	Ghion Line T-030	50	50	0.85
31	"	Ghion Line T-031	200	205	0.85
32	"	Ghion Line T-032	100	100	0.85
33	"	Ghion Line T-033	315	315	0.85
34	"	Ghion Line T-034	200	200	0.85
35	"	Ghion Line T-035	200	200	0.85
36	"	Ghion Line T-036	315	315	0.85
37	"	Ghion Line T-037	315	315	0.85
38	"	Ghion Line T-038	630	630	0.85
39	"	Ghion Line T-039	315	315	0.85
40	"	Ghion Line T-040	100	100	0.85
41	"	Ghion Line T-041	200	200	0.85
42	"	Ghion Line T-042	315	315	0.85
43	"	Ghion Line T-043	100	105	0.85
44	"	Ghion Line T-044	100	100	0.85
45	"	Ghion Line T-045	200	200	0.85
46	"	Ghion Line T-046	100	100	0.85
47	"	Ghion Line T-047	315	315	0.85
48	"	Ghion Line T-048	315	315	0.85
49	"	Ghion Line T-049	200	210	0.85
50	"	Ghion Line T-050	100	100	0.85
51	"	Ghion Line T-051	50	50	0.85
52	"	Ghion Line T-052	200	200	0.85
53	"	Ghion Line T-053	315	315	0.85

Appendix-3: Single Line Diagram of Ghion Feeder

