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DEPARTMENT OF ELECTRICAL ENGINEERING

CERTIFICATE

This is to certify that this dissertation entitled **POWER QUALITY IMPROVEMENT BY DYNAMIC VOLTAGE RESTORER** is an authentic report of the project done by **NUMA MALHOTRA** in the partial fulfillment of the requirement for the award of the degree of Master of Technology in Power systems by the Delhi Technological University during the year 2012-13.

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Surely it is Almighty’s grace to get things done fruitfully.

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ABSTRACT

Power quality is one of the major concerns in the present era. It has become important, especially, with the introduction of sophisticated devices, as their performance is very sensitive to the quality of power supply. Power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in inefficient performance of end use equipments. The major problems related with power quality are the voltage sags, swells and harmonics.

To solve power quality problems, custom power devices are used. One such device is the Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks. The Dynamic Voltage Restorer (DVR) provides an advanced and economical solution for both voltage sag and swell problems. Its appeal includes lower cost, smaller size, and its fast dynamic response to the disturbance. Voltage sags and swells are an important power quality problem and the dynamic voltage restorer is an effective device to mitigate them.

To improve the performance of the distribution system and to improve the load voltage profile DVRs are used. The output voltage can be regulated using two schemes viz. open loop voltage control and closed loop voltage control. In open loop scheme the load voltage is maintained according to the reference voltage set but it is distorted. Load voltage is shown to be improved if the closed loop voltage control scheme is used. Furthermore, the closed loop voltage control scheme permits a closer tracking of the reference load voltage. In this work the open loop voltage control and closed loop voltage control schemes are simulated and the performance both the schemes are compared.

Dynamic voltage restorer is then controlled by using two control strategies, one is control of DVR using self generated PWM technique and other is control of DVR using SRF (synchronous reference frame) method. In first method controlling is done by analyzing the load side voltage and thus setting parameters of DVR to maintain the load voltage but this strategy could not work for variable load. Whereas, in SRF control method load voltage can be maintained under variable load conditions also. In this work both PWM technique and SRF method are used for DVR control. The analysis is done using MATLAB / SIMULINK and results obtained from both the methods.

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LIST OF ABBREVIATIONS

APF	Active Power Filters
DVR	Dynamic Voltage Restorer
FACTS	Flexible AC Transmission Systems
GTO	Gate Turn-Off thyristors
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistors
IPAC	In-phase Advanced Compensation
kV	Kilo volt
ms	Milli second
MVA	Megavolt ampere
MVAR	Mega volt amps reactive
MW	Megawatt
p.u.	Per unit
PCC	Point of common coupling
PWM	Pulse Width Modulation
RMS	Root mean square
VSC	Voltage Source Converter
SRF	Synchronous reference frame
IDVR	Interline dynamic voltage restorer
mH	Milli Henery
BESS	Battery Energy Storage Systems
DSTSTCOM	Distribution static synchronous compensators
DSC	Distribution Series Capacitors

SA	Surge Arresters
SMES	Super conducting Magnetic Energy Systems
SETC	Static Electronic Tap Changers
SSTS	Solid-State Transfer Switches
SSFCL	Solid State Fault Current Limiter
SVC	Static Var Compensator
TSC	Thyristor Switched Capacitors
UPS	Uninterruptible Power Supplies
MOSFET	Metal Oxide Semiconductor Field Effect Transistors
GTO	Gate Turn-Off thyristors
IGCT	Integrated Gate Commutated Thyristors

CHAPTER 1 INTRODUCTION

- *Introduction*
- *Power Quality*
- *Power Quality Problems*
- *Implications of PQ*
- *Benefits of PQ Improvement*
- *Custom Power Devices*
- *Objective and Scope of the Thesis*
- *Outline of the Thesis*

CHAPTER 1

INTRODUCTION

INTRODUCTION

Modern day power systems are complicated networks with hundreds of generating stations and load centers being interconnected through power transmission lines. As shown in Fig 1.1, an electric power system contains a generating plant, a transmission system, a sub transmission system and a distribution system.

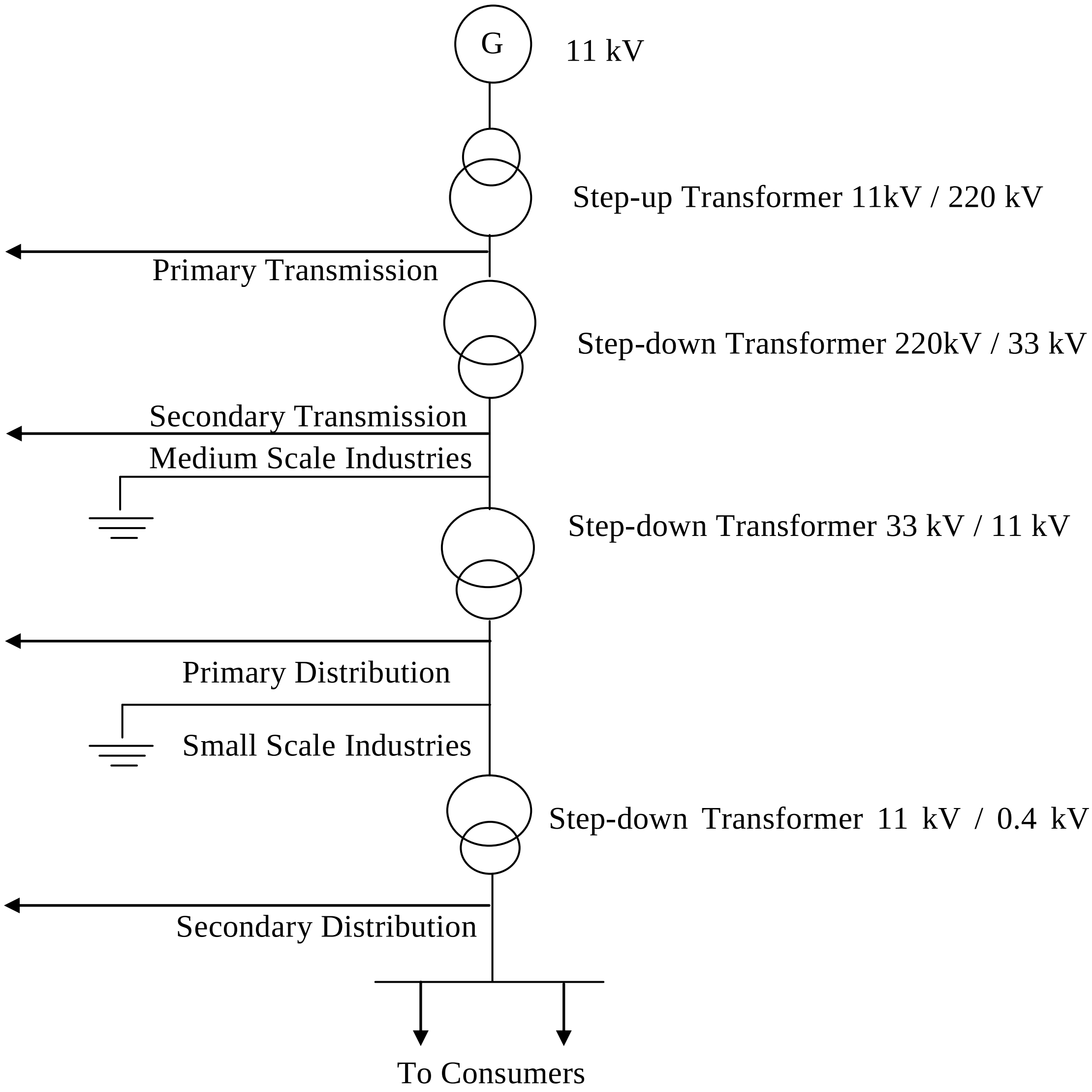


Fig: 1.1: Single Line Diagram of Power System

Many of these generating stations are remotely located. Hence the electric power generated at any such station has to be transmitted over a long distance to load centers. It can therefore be seen that there are various stages between the point of power generation to the stage when electric power is delivered to the end users. The correct operation of all components of a power system is absolutely critical for a reliable power delivery. The issues related to the power transmission are maintenance of power apparatus and system, the stability of the system operation, the operation of power distribution system, faults etc.

1.2 POWER QUALITY

Interest in Power Quality has been explicitly seen in Electrical Power Engineering since last few decades. Power quality may be defined as any power problems manifested in voltage, current or frequency deviations that results in failure or mis–operation or in-efficient operation of customers equipment. Both electric utilities and end users of electrical power are becoming increasingly concerned about the quality of electric power. Power quality is an umbrella concept for multitude of individual types of power system disturbances. The issues that fall under this umbrella are not necessarily new. What is new is that engineers are now attempting to deal with these issues with a systems approach rather than as individual problems. One important and noticeable change seen is that the quality of electricity supplied is now subject to legislation which considers it to be no different from other goods and services.

The main concern of consumers of electricity is the reliability and quality of power. Just a few decades ago, momentary power outages, sags, swells, surges had relatively little effect on most industrial processes. Today, manufacturing systems, sensitive telemetry, and precision electronic equipment can be disturbed, halted, or even damaged by voltage sag of two or three electrical cycles Short-lived sags may not cause much harm other than cause a slight flickering of lights; temporary sag is bound to have a greater impact on the industrial customers. If the sags exceed two to three cycles, then manufacturing systems making use of sensitive electronic equipments are likely to be affected leading to major problems. It ultimately leads to wastage of resources (both material and human) as well as financial losses.

The increasing competition in the market and the declining profits has made it pertinent for the industries to realize the significance of high-power quality. This is possible only by ensuring that uninterrupted flow of power is maintained at proper voltage levels. Electric utilities are looking for solutions to ensure high quality power supply to their customers.

The ideal power supply to a low voltage customer is 240 / 415 V at 50 Hz with a sinusoidal wave shape. The electricity supplier through his local network cannot keep the supply exactly at the ideal due to a range of disturbances outside its control and attempts to maintain its voltage within specified ranges. Power Quality problems arise when these ranges are exceeded and this can occur in three ways a) Frequency events: change of the supply frequency outside of the normal range, b) Voltage events: change of the voltage amplitude outside its normal range (may occur for very short periods or be sustained) and c) Waveform events: distortion of the voltage waveform outside the normal range.

1.3 POWER QUALITY PROBLEMS

The causes of power quality problems are very complex and difficult to detect. There are many ways in which the lack of quality power affects customers. While power disturbances occur on all electrical systems, the sensitivity of today's sophisticated electronic devices makes them more susceptible to the quality of power supply. For some sensitive devices, a momentary disturbance can cause scrambled data, interrupted communications, a frozen mouse, system crashes and equipment failure etc. A power voltage spike can damage valuable components. Power Quality problems encompass a wide range of disturbances as given below.

- **Voltage transients**: They are temporary, undesirable voltages that appear on the power supply line. Transients are high over-voltage disturbances (up to 20kV) that last for a very short time. The transients mainly came from capacitive switching operations, transformer energisation etc. Impulsive transients do not travel very far from their point of entry but it can give rise to oscillatory transient, which can lead to transient overvoltage and consequent damage to the power line insulators.
- **Voltage dip**: A voltage dip (also known as voltage sag) is used to refer to short-term reduction in voltage for half a second to one second. Voltage sag is the sudden decrease of the voltage to about 10-90% of the supply voltage. This is caused due to the sudden increase of load across that particular feeder. Voltage dips can cause tripping of sensitive loads and the cost associated with short duration voltage dips can in some cases justify the insertion of power electronic equipment to compensate for the poor power quality. It can cause loss of production since voltage sag can trip a motor cause its controller to malfunction. Voltage sags can occur at any instant of time, with amplitudes ranging from10 – 90%. In the case of a sag the termination of process is sudden, but normal operation can be resumed after normal voltage is restored.
- **Voltage swell**: Voltage swell is defined as an increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min. voltage swell is the sudden increase of voltage to about more than 110% amplitude of the supply voltage. This is caused due to the sudden reduction of the load across that particular feeder. Even it can put stress on loads. A temporary interruption lasting a few seconds can cause a loss of production. The impact of long duration voltage variations is greater than those of short duration variations. Some of the causes of voltage sag are rural location remote from power source, unbalanced load on a three phase system, switching of heavy loads, long distance from a distribution transformer with interposed loads, unreliable grid systems and equipments not suitable for local supply.
- **Voltage 'spikes', 'impulses' or 'surges':** These are terms used to describe a very brief increases in voltage value. Some of the causes are lightening, arc welding, switching on heavy or reactive equipments such as motors, transformers, motor drives or electric grade switching etc. They have very adverse effects like damage of electronic equipment, corruption of data, system failure or rejection of work through process

interaction etc. Methods of preventing voltage spikes are good earthing, chokes or ferrites, transient voltage surge suppressors

- **Harmonics**: In India the fundamental frequency of the AC electric power distribution system is 50 Hz. A harmonic frequency is any sinusoidal frequency, which is a multiple of the fundamental frequency. Harmonic frequencies can be even or odd multiples of the sinusoidal fundamental frequency. This can cause waveform distortions. Unwanted harmonic currents flowing through the distribution network can causes needless losses. Harmonics can also cause malfunctioning of equipments.
- **Flickers**: This is defined as, visual irritation and introduction of many harmonic components in the supply power and their associated ill effects. Voltage flickers are caused by arc discharge lamps, arc furnaces, starting of large motors, arc welding machines etc. Voltage flickers are frequent variations in voltage in the range of 3 to 15 times per second. It can badly affect the human health and can also reduce the life span of electronic equipment etc.

The power quality problems are summarized in Table 1.1.

1.4 IMPLICATIONS OF POOR POWER QUALITY

Some of the implications of poor power quality are:

- Increase in line & equipment current leading to additional ohmic loses
- Increase in line & equipment current leading to blocked capacity and/or increased capital investment.
- Increased losses leading to higher operating temperatures and consequent reduction in life of equipment.
- Premature failure of equipment due to increased electrical and thermal stresses.
- Malfunction of equipment
- Poor quality of production
- Unplanned outages leading to loss of production.[2]

1.5 BENEFITS OF POWER QUALITY IMPROVEMENT

- Reduction in line & equipment currents and losses and hence lower energy bills.
- Release of blocked capacity and consequent avoided cost of capital investment
- Improvement in power factor and avoided penalty for low power factor or incentive for high power factor.
- Reduction in maximum demand and reduction in demand charges.
- Tax benefits such as accelerated depreciation benefits for installation of power conditioning energy saving devices.
- Improvement in voltage profile and consequent efficient operation of power equipment.
- Reduction in harmonic distortion and consequent reduction in copper loss, core loss and stray loss.

- Prevention of malfunction of equipment and avoided loss of production.[2]

Table 1.1 Various Power Quality Problems

Problems	Effects	Methods of Characterization	Causes
Transients	Impulsive	Peak magnitude, rise time and duration	Lightning strike, transformer energization, capacitor switching
	Oscillatory	Peak magnitude, frequency components	Line or capacitor or load switching
Short duration voltage variation	Sag	Magnitude, duration	Ferroresonant transformers, single line to ground faults
	Swell	Magnitude, duration	Ferroresonant transformers, single line to ground faults
	Interruption	Duration	Temporary (self clearing) faults
	Overvoltage	Magnitude, duration	Switching off loads, capacitor energization
	Sustained interruptions	Duration	Faults
Voltage imbalance		Symmetrical components	Single phase loads, single phasing condition
Waveform distortion	Harmonics	THD, harmonic spectrum	Adjustable speed drives and other nonlinear loads
	Notching	THD, harmonic spectrum	Power electronic converters
	DC offset	Volts, amps	Geo-magnetic disturbance, half wave rectification
Voltage flicker		Frequency of occurrence, modulating frequency	Arc furnace, arc lamps

1.6 CUSTOM POWER DEVICES

There are two approaches to the mitigation of power quality problems. The solution to the power quality can be done from customer side or from utility side. One approach is to ensure that the process equipment is less sensitive to disturbances, allowing it to ride-through the disturbances. The other approach is to install a custom power device to suppress or counteract the disturbances.

Many custom power system devices are commercially available in the market today such as, active power filters (APF), battery energy storage systems (BESS), distribution static synchronous compensators (DSTATCOM), distribution series capacitors (DSC), dynamic voltage restorer (DVR), power factor controller (PFC), surge arresters (SA), super conducting magnetic energy storage systems (SMES), static electronic tap changers (SETC), solid-state transfer switches (SSTS), solid-state circuit breaker (SSCB), static var compensator (SVC), thyristor switched capacitors (TSC) and uninterruptible power supplies (UPS). Focusing on the compensation the effective and economic measures for power quality solutions, the number of devices can be narrowed down

Lightening and Surge Arresters

Arresters are designed for lightening protection of transformers, but are not sufficiently voltage limiting for protecting sensitive electronic control circuits from voltage surges.

Active Power Filters

Series active power filters must operate in conjunction with shunt passive filters in order to compensate load current harmonics. Shunt active power filters operate as a controllable current source and series active power filters operates as a controllable voltage source. Both schemes are implemented preferable with voltage source PWM inverters, with a dc bus having a reactive element such as a capacitor.

Thyristor Based Static Switches

The static switch is a versatile device for switching a new element into the circuit when the voltage support is needed. It has a dynamic response time of about one cycle. To correct quickly for voltage spikes, sags or interruptions, the static switch can used to switch one or more of devices such as capacitor, filter, alternate power line, energy storage systems etc. The static switch can be used in the alternate power line applications.

Energy Storage Systems

Storage systems can be used to protect sensitive equipments from shutdowns caused by voltage sags or momentary interruptions. These are usually DC storage systems such as UPS, batteries, superconducting magnet energy storage (SMES), storage capacitors or even fly wheels driving DC generators .The output of these devices can be supplied to the system through an inverter on a momentary basis by a fast acting electronic switch. Enough energy is fed to the system to compensate for the energy that would be lost by the voltage sag or interruption.

Distribution static synchronous compensators (DSTATCOM)

This is a shunt connected device that has the same structure as that of a STATCOM. This can perform load compensation, i.e., power factor correction, harmonic filtering, load balancing etc. when connected at the load terminals. It can also perform voltage regulation when connected to a distribution bus, in this mode it can hold the bus voltage constant against any unbalance or distortion in the distribution system. However the DSTATCOM must be able to inject an unbalanced and harmonically distorted current to eliminate unbalance or distortions in the load current or the supply voltage.

Dynamic Voltage Restorer (DVR)

DVRs are a class of custom power devices for providing reliable distribution power quality. They employ a series of voltage boost technology using solid state switches for compensating voltage sags/swells. Dynamic Voltage Restorer is a series-connected device, which corrects the voltage disturbances and restore the load voltage in case of a voltage dip. The topology is illustrated in Fig 1.2. The DVR applications are mainly for sensitive loads that may be drastically affected by fluctuations in system voltage.

Even though the DVR is commercially available today, but still it is not so much in use and several areas regarding its design and control are at the basic research level. The design of a DVR varies from size of the voltage, power and current rating. The DVR is a series connected device and one of the drawbacks with series connected devices is the difficulties to protect the device during short circuits and avoid interference with the existing protection equipment.

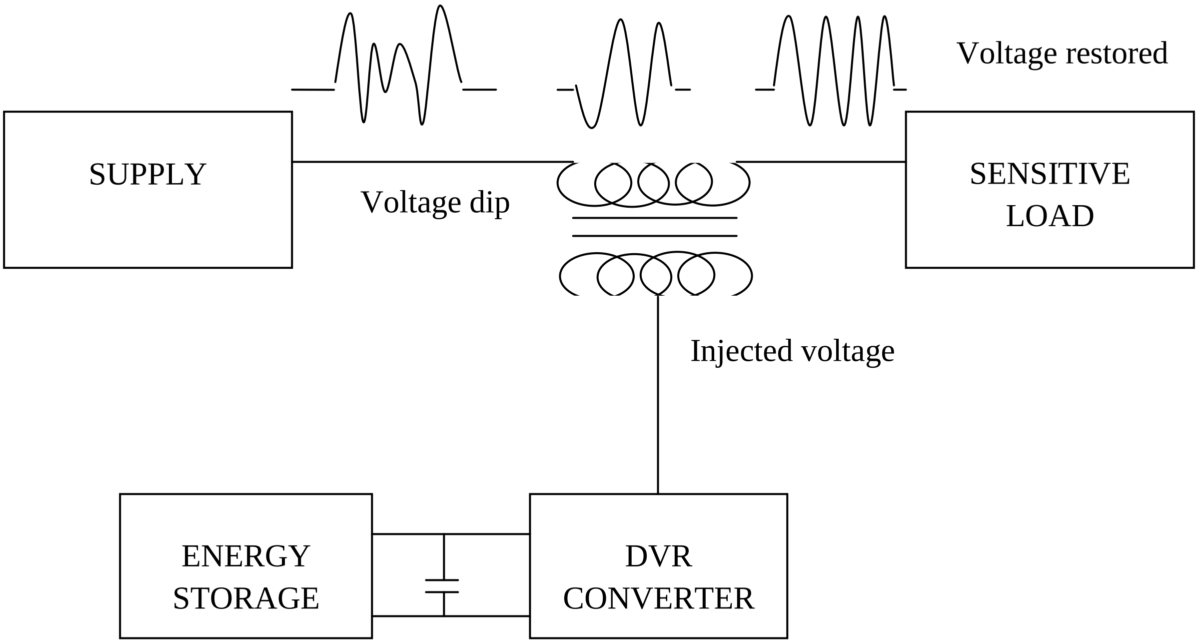


Fig 1.2: DVR Restores the Load Voltage

1.7 OBJECTIVE AND SCOPE OF THE THESIS

Based upon the extensive review of literature the major objectives and the scope of the thesis are outlined below:

- To study the configuration, working and operating modes of Dynamic voltage restorer (DVR) and to study different voltage injection methods.
- To regulate the load voltage of a distribution system with DVR using open loop voltage control and closed loop voltage control.
- Comparison of different methods for controlling DVR.
- Study the performance and working of interline dynamic voltage restorer (IDVR).

1.8 OUTLINE OF THE THESIS

A chapter wise summary of the work done in this thesis is described below:

- **Chapter 1:** describes the introduction of the thesis highlighting the present scenario of power quality and its importance and solution to its problems with a brief introduction of DVR.
- **Chapter 2:** presents an exhaustive review of literature for giving the recent developments in DVR for enhancing (i) the power flow in the system, (ii) improving system stability (iii) controlling the actual transmitted power, at defined transmission voltage etc.
- **Chapter 3:** describes the Dynamic voltage restorer (DVR), its configuration, its working, operating modes, model and voltage injection methods.
- **Chapter 4:** presents the open and closed loop voltage control blocks regulating the load voltage and their results are compared.
- **Chapter 5**: describes the controlling of DVR using self generated PWM technique and synchronous reference frame (SRF) theory. The compensations of sag, swell and harmonics in supply voltage using the reduced rating DVR are simulated using MATLAB with its Simulink power system block set (PSB) toolboxes and the control schemes are compared.
- **Chapter 6**: presents the brief introduction about inter line dynamic voltage restorer (IDVR), its configuration and principle of operation.
- **Chapter 7**: presents the concluding remarks, a brief review of the investigations carried out in this thesis and suggestions for future work are highlighted.

A detailed list of references is included in the present thesis.

CHAPTER 2 *LITERATURE REVIEW*

CHAPTER 2

LITERATURE REVIEW

This chapter presents a comprehensive review of the development in the area of dynamic voltage restorer (DVR) for improving the power system performance. The emphasis has been given on the recent advances that have taken place in various fields of DVR performance. Recent advances in the field of DVR are also highlighted.

Results of world's first Dynamic Voltage Restorer (DVR) was installed on the major US utility system to protect a critical customer plant load from power system voltage disturbances ushers in a new era of power quality problem solution on the utility side of the revenue billing meter. It was verified by N.H. Woodley, L. Morgan and A. Sundaram, on a 12.47-kV system by building a prototype DVR and installing it on the utility side of weaving company where it provides protection from disturbances coming from the utility distribution system that serves the plant.[1-3]

Norbert EDOMAH in 20th International Conference on Electricity Distribution presented a paper in which he has surveyed the 15 multi-national companies in southwest Nigeria to ascertain the causes and effects of poor power quality on electrical equipment and its economic implications. The survey revealed that 9 out of 15 of those companies loose an average of 5 variable speed (AC) drives every year owing to poor power quality. It also revealed that the most common disturbances faced are voltage sag and swell. He has also explained some of the predominant power disturbance parameters, their sources and causes, the effect they have on electrical equipment, and their cost/economic implications. Thus he has given some practical solutions and methods of addressing poor power quality issue. [4-6]

Anita Pakharia and Manoj Gupta also M.Sharanya, B.Basavaraja and M.Sasikala presented comprehensive reviews on power quality over its various articles with solutions to it. In which they have mentioned the most popular methods of sag and swell compensation is Dynamic Voltage Restorer (DVR), which is used in both low voltage and medium voltage applications. They have explained the advantages and disadvantages of each possible configuration and control techniques pertaining to DVR. They found DVR to be most suitable due to its fast response, accurate compensation and low costs. There review helps the researchers to select the optimum control strategy and power circuit configuration for DVR applications. [7-9]

Mahinda Vilathgamuwa, A. A. D. Ranjith Perera, and S. S. Choi has also examined the performance of dynamic voltage restorer (DVR). They have shown through simulation that the open-loop control strategy used for the DVR to regulate load voltage can produce poorly damped response due to the presence of the switching harmonic filter in the restorer. Damping is shown to be improved if the multi loop controller is used. Furthermore, the new control scheme permits a closer tracking of the reference load voltage under varied load conditions. [10, 11]

Voltage Quality Improvement Using DVR has been simulated by Chellali BENACHAIBA and Brahim FERDI. They have discussed DVR principles and voltage restoration methods at the point of common coupling (PCC). Simulation results presented helps in understanding the performances of DVR in load voltage compensation. [12-14]

John Godsk Nielsen and Frede Blaabjerg has given a detailed comparison on System Topologies for Dynamic Voltage Restorer. They have described four different system topologies for dynamic voltage restorers (DVRs) and thus analyzed and tested, with particular focus on the methods used to acquire the necessary energy during voltage sag. Comparisons are made between two topologies that can be realized with a minimum amount of energy storage, with energy taken from the grid during the voltage sag, and two topologies that take energy from stored energy devices during the voltage sag. Hence, they have concluded that DVR show that the no-energy storage concept is feasible, but an improved performance can be achieved for certain voltage sags using stored energy topologies. Thus their results of this comparison rank the no-storage topology with a passive shunt converter on the load side first, followed by the stored energy topology with a constant dc-link voltage. [15, 16]

Woo-Hyun Kim and Chul-Woo Park has worked on the reliability of DVR in a 3-phase phase-controlled rectifier. Their work investigated the relationship between the response time of DVR (Dynamic Voltage Restorer) and the possible compensation range for voltage dips by the DVR system which protects the 3-phase phase-controlled rectifier from said dips. As a result, the permissible range of voltage dip can be found in a 3-phase phase-controlled rectifier when the DVR compensates for voltage dip. The range of voltage dip can be compensated according to the DVR's response time, thus DVR response time can be determined. Therefore, the use of excessively fast equipment can be avoided, improving the stability of the overall system. [17, 18]

Antonio Moreno-Munoz, Daniel Oterino, Miguel Gonzalez, Fernando A. Olivencia and Juan J. Gonzalez-de-la-Rosa presented a voltage dip analysis in which they have worked with dynamic voltage restorer (DVR) which is a Static Series Compensator (SSC) suitable for protecting industrial plant against voltage dip. They have presented comparative analysis of three compensation techniques of DVR that is in-phase compensation method, pre-dip compensation method (called too voltage difference compensation), and phase advance compensation method. [19-22]

Dynamic Voltage Restorer (DVR) is a custom power device that is used to compensate voltage sag. The DVR generally consists of voltage source inverter (VSI), injection transformers, passive filters and energy storage (battery). The efficiency of the DVR depends on the efficiency of the control technique involved in switching the inverters. Agileswari Ramasamy, Vigna Kumaran Ramachandaramurthy, Rengan Krishna Iyer and Liew Zhan Liu have used new switching technique. The inverters are switched using Space Vector Pulse Width Modulation pulses (SVPWM) to maximize the usage of DC link voltage. They have used DSP board TMS320F2812. The implementation of the control using TMS320F2812 is tested using a 3kVA lab prototype and thus simulated. [23-25]

John Godsk Nielsen, Michael Newman, Hans Nielsen, and Frede Blaabjerg have given a cost effective solution for the protection of sensitive loads from voltage sags. Implementations of the DVR have been proposed at both a low voltage (LV) level, as well as a medium voltage (MV) level; and give an opportunity to protect high power sensitive loads from voltage sags. They have performed a practical test whose results obtained on a medium voltage (10 kV) level using a DVR at a Distribution test facility in Kyndby, Denmark. The DVR was designed to protect a 400-kVA load from 0.5-p.u. maximum voltage sag. The reported DVR verifies the use of a combined feed-forward and feed-back technique of the controller and it obtains both good transient and steady state responses. The effect of the DVR on the system is simulated under both faulted and nonfaulted system states, for a variety of linear and nonlinear loads. Variable duration voltage sags were created using a controllable LV breaker fed by a 630 kVA Distribution transformer placed upstream of the sensitive load. The fault currents in excess of 12 kA were designed and created to obtain the required voltage sags. It is concluded the DVR works well in all operating conditions.[26-28]

The compensation strategy of the dynamic voltage restorer (DVR) has significant impact on the compensation result. Sun Zhe, Guo ChunLin, Xu YongHai, Xiao XiangNing, Liu Yingying and Tao Shun has presented a new analysis method which is based on pre-sag load voltage. The new method choosen by them takes the pre-sag load voltage phasor as the reference phasor and put the centre of the limit compensation voltage circle at the terminal of the system voltage phasor. It not only has definite physical concept but also is convenient to determine the compensation range. More importantly, it could be applied to unbalanced load. Using this new method, the minimum energy compensation strategy was realized through the simulation when unbalanced voltage sag happened in the case of the unbalanced load. The conditions for zero active power compensation were also analyzed by them which could prolong the compensation time of DVR. The simulation result presented by them shows the correctness of the theoretical analysis. [29-33]

Vijayan Immanue and Gurunath Yankanchi presents the development of a novel waveform synthesis technique for effective voltage sag compensation for multilevel inverter based Dynamic Voltage Restorer (DVR). An effective control algorithm for calculation of reference compensating voltages based on PQR power theory together with Space Vector Modulation (SVM) technique which is implemented using a three-level Diode Clamped Voltage Source Inverter (VSI) configuration. Their simulation results show that the proposed scheme for voltage sag compensation is seamless with negligible THD. [34-36]

Bingsen Wang, Giri Venkataramanan and Mahesh Illindala has also used the dynamic voltage restorer (DVR) as a means of series compensation for mitigating the effect of voltage sags. With the use of the cascaded multilevel type of power converter topology they have designed a closed loop regulator to maintain the load voltage within acceptable levels in a DVR using transformer coupled H-bridge converters, and thus simulated the system. [37-39]

Modelling and Simulation of Dynamic Voltage Restorer for Power Quality Improvement has been done by H.Lakshmi, T. Swapna, Rosli Omar, Nasrudin Abd Rahim, Marizan Sulaiman, Shazly A. Mohammed, Abdel-Moamen, B. Hasanin, B.vijayalakshmi, P. Jayaprakash, Bhim

Singh, D. P. Kothari, Ambrish Chandra and Kamal-Al-Haddad. They all have used the dynamic voltage restorer (DVR) to regulate the voltage at the load terminals under various power quality problems like sag, swell, harmonics, unbalance etc., in supply voltage. They have discussed the control of the compensation voltages in DVR based on dqo algorithm. It first analyzes the power circuit of a DVR system in order to come up with appropriate control limitations and control targets for the compensation voltage control. Thus as we know, DVR is a power electronic based device that 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 can restore the load voltage within few milliseconds. They have used, different voltage injection schemes for dynamic voltage restorers (DVRs) ,and are analyzed with particular focus on the methods used to minimize the rating of the voltage source converter (VSC) used in DVR. [40- 42]

CHAPTER 3 *DYNAMIC VOLTAGE RESTORER*

- *Introduction*
- *Basic Configuration of DVR*
- *DVR Structures*
- *DVR Model*
- *Series compensator Characteristics*
- *System Topologies for DVR*
- *Operating Modes Of DVR*
- *DVR Rating*
- *Voltage Injection Methods of DVR*
- *Conclusion*

CHAPTER 3

DYNAMIC VOLTAGE RESTORER

INTRODUCTION

A power electronic converter based series compensator that can protect critical loads from all supply side disturbances other than outages is called a dynamic voltage restorer (DVR). It is the most efficient and effective modern custom power device used in power distribution networks. DVR is a recently proposed series connected solid state device that injects voltage into the system in order to regulate the load side voltage. By inserting a voltage of required magnitude and frequency, the series compensator can restore the load side voltage to the desired amplitude and waveform even when the source voltage is unbalanced or distorted. Among the power quality problems (sags, swells, harmonics…) voltage sags are the most severe disturbances. DVR is normally installed in a distribution system between the supply and the critical load feeder at the point of common coupling (PCC) as shown in Fig: 3.1. Without the presence of the DVR, the occurrence of voltage disturbance will trip the sensitive load causing a loss of production.

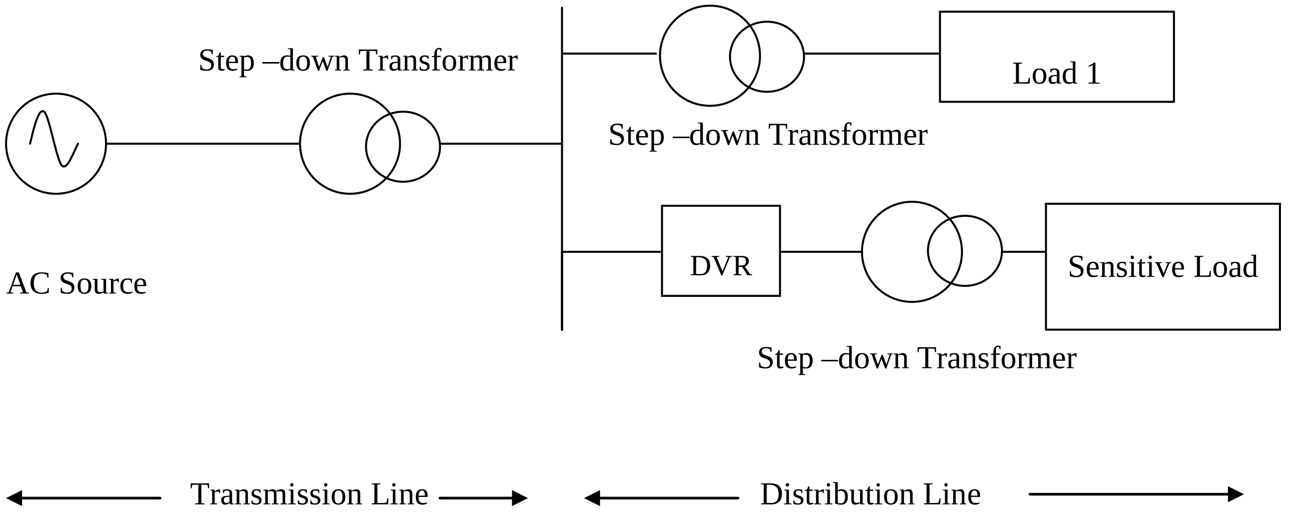


Fig 3.1 Location of DVR

The DVR is capable of generating or absorbing independently controllable real and reactive power at its AC output terminal. DVR is made up of a solid state dc to ac switching power converter that 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 thereby allowing control of the real and reactive power exchange between the DVR and the distribution system. The dc input terminal of a DVR is connected to an energy source or an energy storage device of appropriate capacity for real power exchange. The reactive power exchanged between the DVR and the distribution system is internally generated by the DVR without ac passive reactive components, but it is however to be mentioned that the rating of a DVR is not unlimited. Thus DVR can only supply partial power to the load during very large variations (sags or swells) in the source voltage.

3.2 BASIC CONFIGURATION OF DVR

The schematic diagram of DVR is given in Fig 3.2. A DVR comprises of [6]

- An Injection transformer
- Filter
- Converter
- DC link and energy storage
- A Control and Protection system

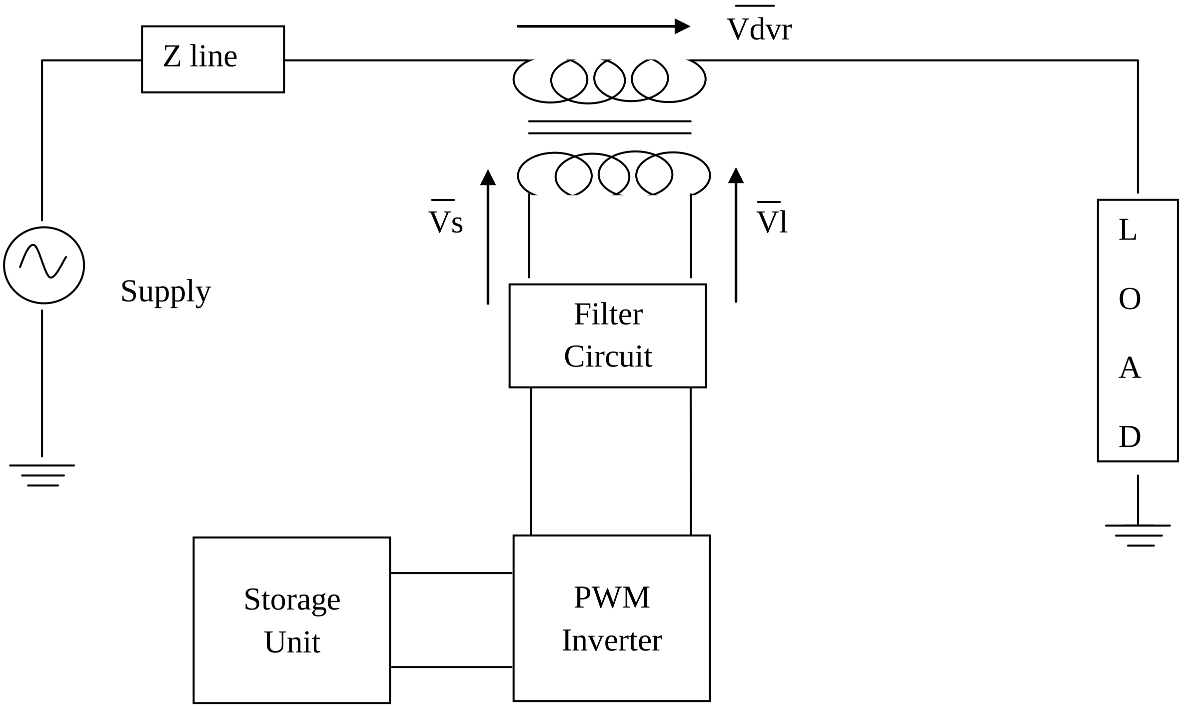


Fig. 3.2: Schematic Diagram of DVR

3.2.1 Injection/ Booster transformer

In DVR applications the DVR is equipped with injection transformers. It is a specially designed transformer that attempts to limit the coupling of noise and transient energy from the primary side to the secondary side. It perform two main functions that firstly it connects the DVR to the distribution network via the HV-windings and transforms and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage and secondly it serves the purpose of isolating the load from the system (VSC and control mechanism).

The transformers not only reduce the voltage requirement of the inverters but also provide isolation between the inverters. This prevents the dc storage capacitor from being shorted through switches in different inverters.

3.2.2 Harmonic Filter

The capacitor filter is connected across the secondary of the transformer. This prevents switching frequency harmonics from entering the system. The direct connection of PWM (VSI) to the transformer primary results in losses in the transformer. The high frequency flux variation causes significant increase in transformer iron losses.

3.2.3 Converter

The converter is most likely a Voltage Source Converter (VSC) which Pulse Width modulates (PWM) the DC from the DC-link/storage to AC-voltages injected into the system. A VSC is a power electronic system consists of a storage device and switching devices, which can generate a sinusoidal voltage at any required frequency, magnitude, and phase angle. In the DVR application, the VSC is used to temporarily replace the supply voltage or to generate the part of the supply voltage which is missing.

There are mainly four types of switching devices

- Metal Oxide Semiconductor Field Effect Transistors (MOSFET)
- Gate Turn-Off thyristors (GTO)
- Insulated Gate Bipolar Transistors (IGBT)
- Integrated Gate Commutated Thyristors (IGCT)

Each type has its own benefits and drawbacks. The IGCT is a recent compact device with enhanced performance and reliability that allows building VSC with very large power ratings. The DVR can compensate dips which are beyond the capability of the past DVRs using conventional devices with the use of IGCT, because of its highly sophisticated converter design. The purpose of storage devices is to supply the necessary energy to the VSC via a dc link for the generation of injected voltages.

3.2.4 DC Link and Energy Storage

A DC-link voltage is used by the VSC to synthesize an ac voltage into the grid. As during majority of voltage disturbances (dip) active power injection is necessary to restore the supply voltages. The dc charging circuit has two main tasks.

- The first task is to charge the energy source after a sag compensation event.
- The second task is to maintain dc link voltage at the nominal dc link voltage.

3.2.5 Control and Protection System

The control mechanism of the general configuration typically consists of hardware with programmable logic. All protective functions of the DVR should be implemented in the software. Differential current protection of the transformer, or short circuit current on the customer load side are only two examples of many protection functions possibility.

3.3 DVR STRUCTURES

There are two different structures of the DVR, namely

- Rectifier supported DVR
- DC capacitor supported DVR

3.3.1 Rectifier Supported DVR

As shown in Fig 3.3, in DVR without battery energy storage system the dc bus of the VSI is supplied from the feeder through a rectifier. Therefore the DVR can absorb real power from the feeder through the dc bus.

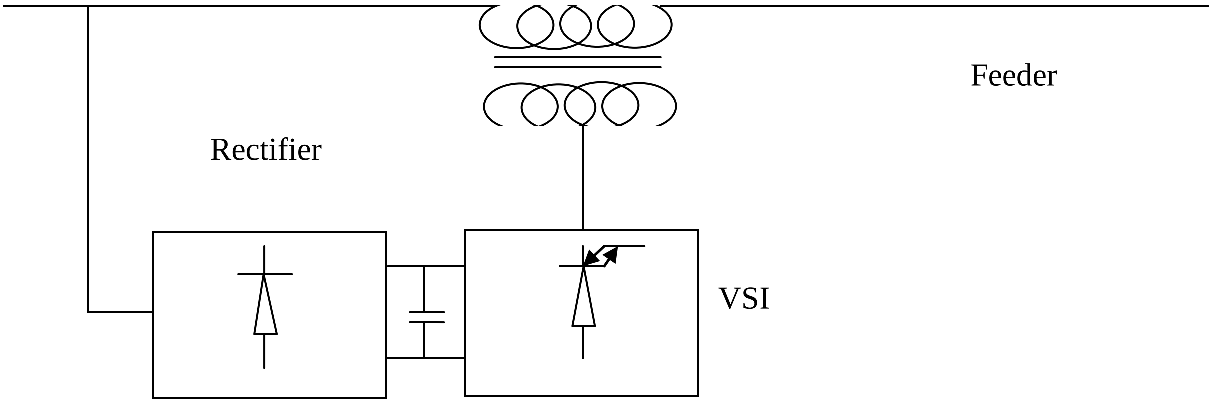


Fig: 3.3 Rectifier supported DVR

In this case, the reverse power flow may damage the rectifier unit. We must therefore always ensure that the phase angle of the desired load bus voltage is less than that of the terminal voltage.

3.3.2 DC Capacitor Supported DVR

In this the DVR is supplied by a dc storage capacitor, as shown in Fig 3.4. Therefore the DVR in this structure operates in the mode in which it will have no real power exchange with the ac system in the steady state.

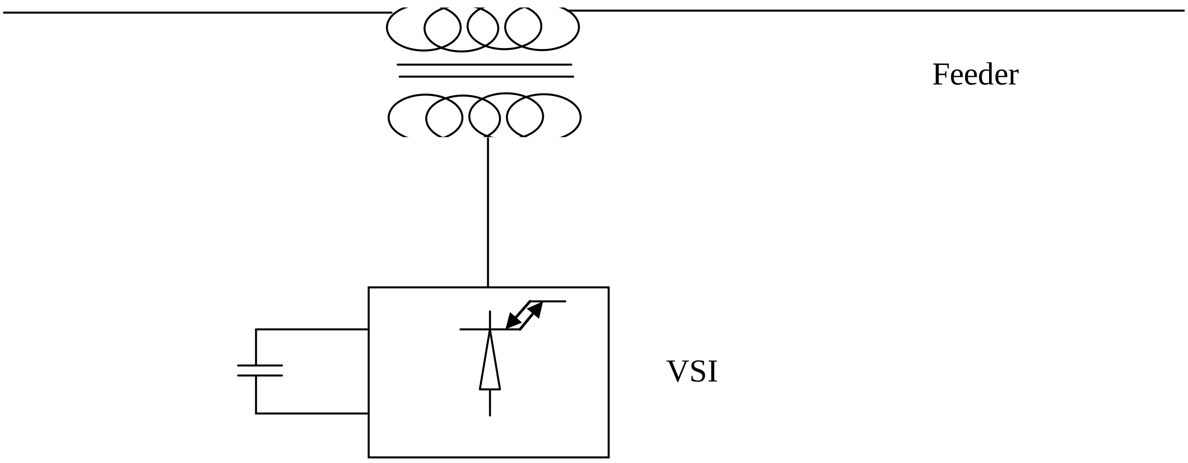


Fig 3.4 DC Capacitor supported DVR

3.4 DVR MODEL

Fig. 3.5 shows that the load voltage is regulated by the DVR through the injection voltage V_{dvr}. Assume that the load has an inductance L_l and resistance r_l and the DVR harmonic filter has an inductance of L_f , a resistance of r_f and a capacitance of C_f . The DVR injection transformer has a combined winding resistance of r_t , leakage inductance of L_t and turns ratio of 1 : n. [4]

The state–space equations (3.1)- (3.5) can be obtained from Fig 3.5

$$V_i = V_c + I_f r_f + L_f (dI_f / dt) \tag{3.1}$$

$$I_f = I_c + nI_l \tag{3.2}$$

$$I_c = C_f (dV_c / dt) \tag{3.3}$$

$$V_{dvr} = n (V_c - n (r_t I_l + L_t (dI_l / dt))) \tag{3.4}$$

$$V_2 = V_1 + V_{dvr} \tag{3.5}$$

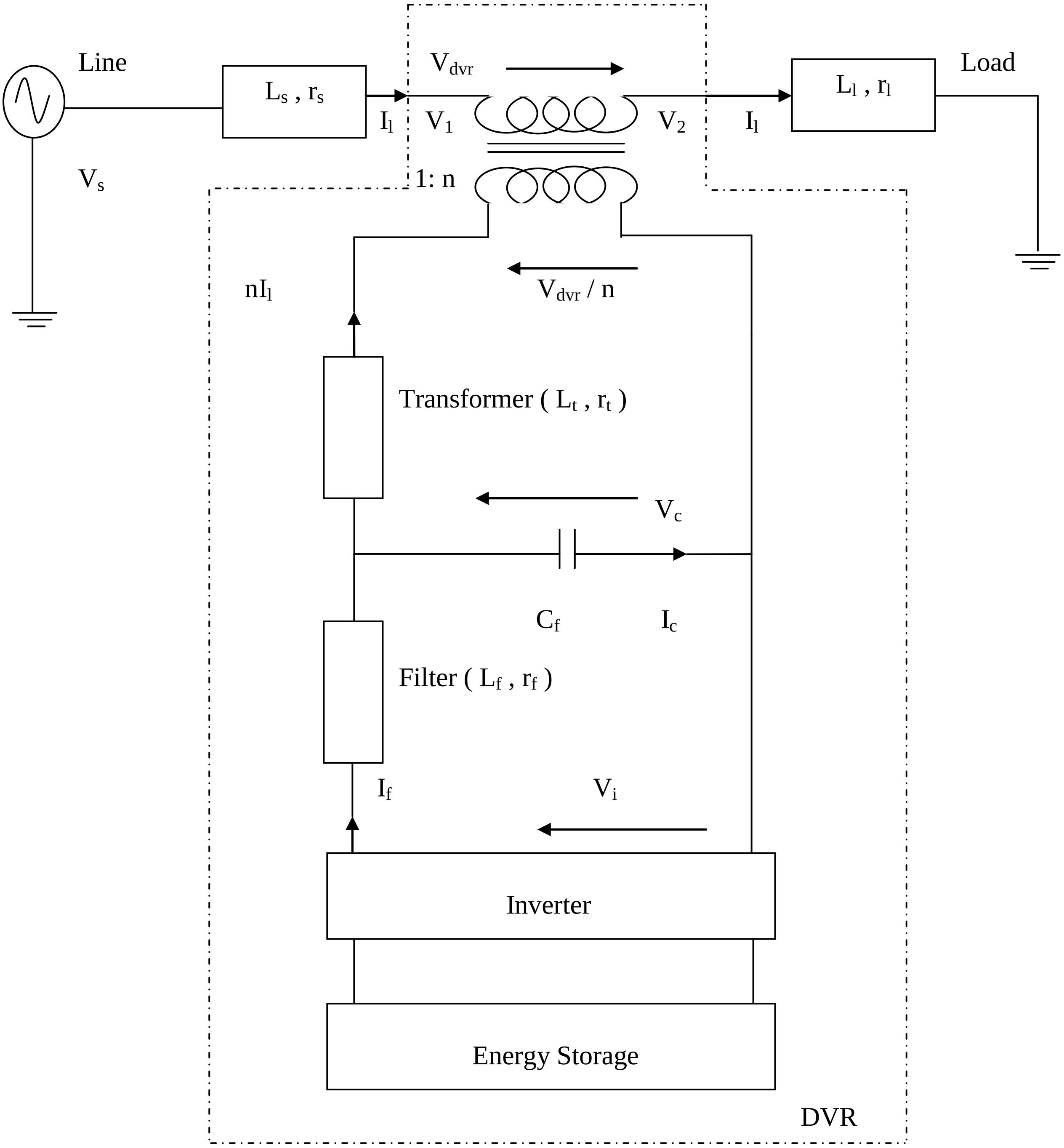


Fig 3.5 DVR connected to power system

These equations form the basis of the DVR model which will be used for the controller design in chapter 4.

3.5 SERIES COMPENSATOR CHARACTERISTICS

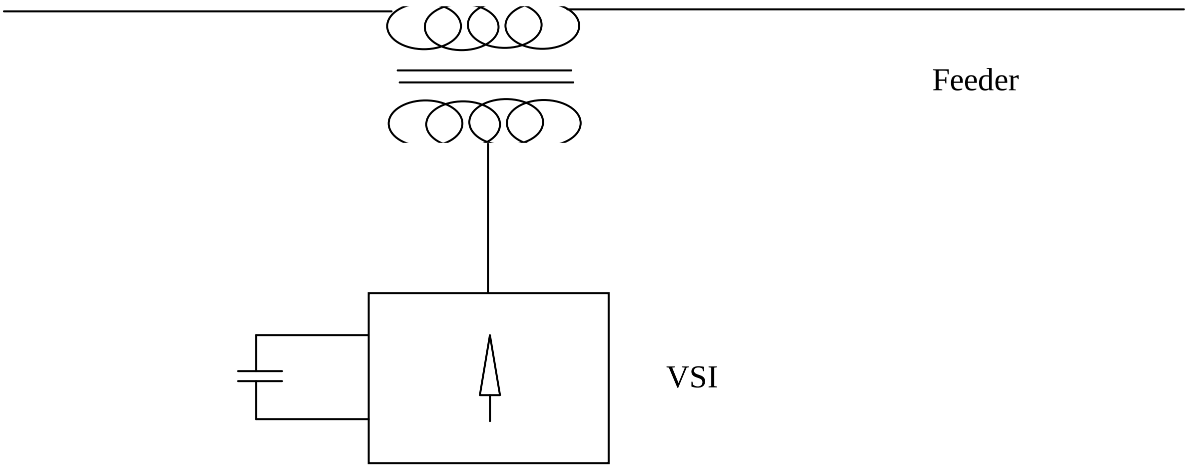


Fig 3.6 Self supported DVR

Considering the DVR structure with dc capacitor as shown in Fig 3.6. DVR can not only act as a voltage restorer but also as a voltage regulator. This implies that the DVR does not absorb or supply any real power in steady state.

On the basis of sinusoidal steady state analysis of a DVR connected to power system. In this analysis we assume that the magnitude of the source voltage is V pu and we want to regulate the magnitude of the load voltage to V pu by injecting a voltage from the series compensator that is DVR.

Condition 1: The DVR need not supply any real power in the steady state. This implies that the phase angle difference between DVR voltage phasor and the line current phasor must be $\pi/2$ in the steady state.

Under this condition the operation of DVR can be divided into three different cases depending upon the feeder and load impedances.

Case 1: When line resistance is negligible, i.e, R=0 , the phasor can be drawn as shown in Fig 3.7. The load and source voltage magnitudes can be equal when the DVR completely compensate for the reactive drop in the feeder. This will force the source and load voltages to be in phase.

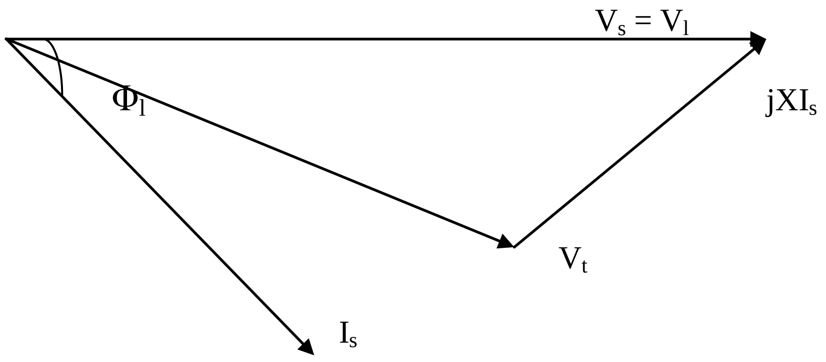


Fig 3.7: Phasor diagram for case-1

Case 2: When the load is resistive, i.e , $X_l = 0$, as shown in Fig 3.8. The magnitude of the source and load voltages will never be equal in this case unless the condition that the series compensator must not supply (or absorb) real power is relaxed.

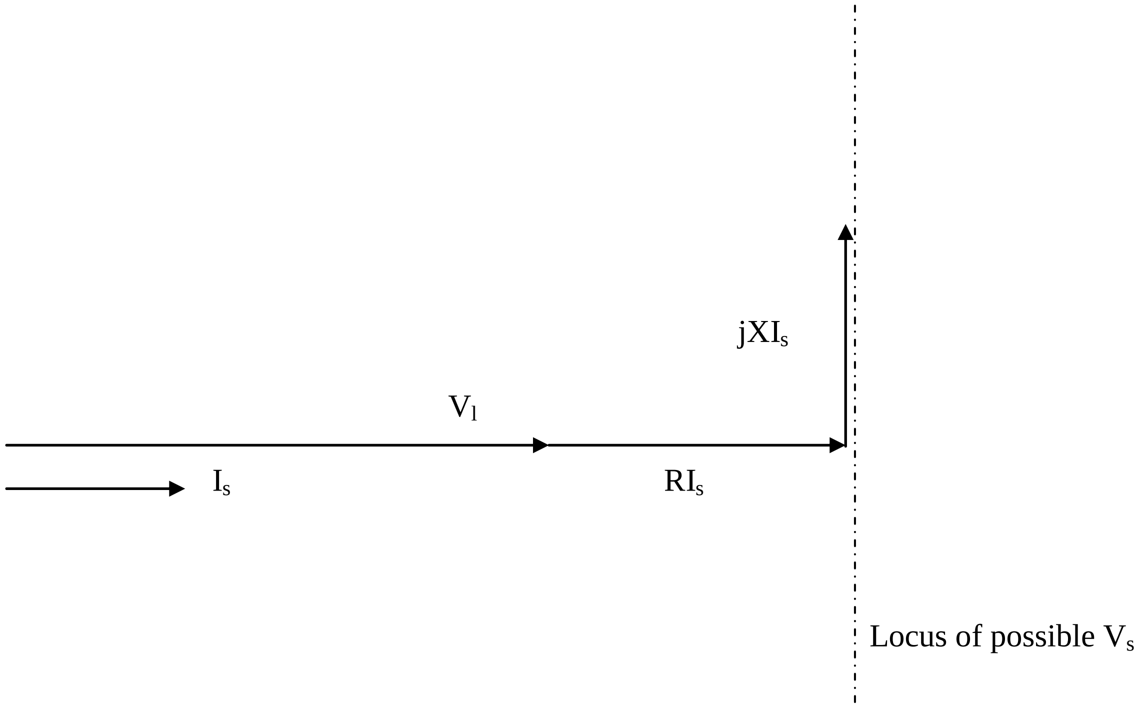


Fig 3.8 Phasor diagram for case 2

Case 3: It is the most general case in which the load current lags the load voltage and feeder resistance is not neglected. Let, the load voltage is fixed at V pu and the source voltage is allowed to vary. As shown in Fig 3.9 and 3.10 the locus of desirable V_s is the semicircle and it is desired to have the magnitudes of V_l and V_s to be equal.

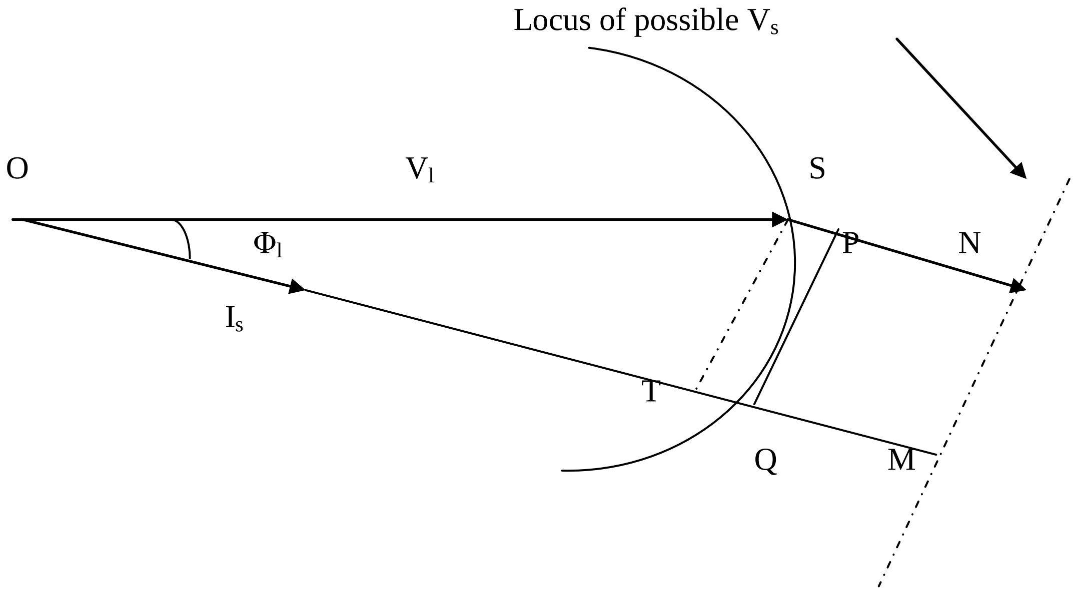


Fig 3.9 Phasor diagram of the limiting condition for case 3

Fig 3.9 shows the limiting behavior. Let the resistive drop (RI_s) in the feeder is greater than the length SP (as shown in Fig 3.9). Since the DVR must inject voltage in quadrature with the load current, it will not be possible to get the source voltage to be equal to V pu. Even though the source voltage can be fixed anywhere along the line NM, the maximum of $|V_l|/|V_s|$ is obtained when the source voltage is equal to OM. Let the magnitude of the source voltage (OM) is equal to 1 pu and the load voltage isv V pu. We then have the distance OT = $V\cos\Phi_l$ Hence the distance MT will be equal to 1- $V\cos\Phi_l$. Thus, $RI_s = 1-V\cos\Phi_l$.

If the RI_s drop is exactly equal to SP, the load and source voltages can be made equal by aligning the source voltage with the line current. Then the magnitude of the source voltage is equal to OQ.

Now, let the RI_s drop is less than the SP. DVR must then compensate the entire reactive drop in the feeder and should provide additional injection such that the magnitude of the source voltage becomes V pu. As shown in Fig 3.10 there are two possible intersection points with the semicircle one at A and other at B.

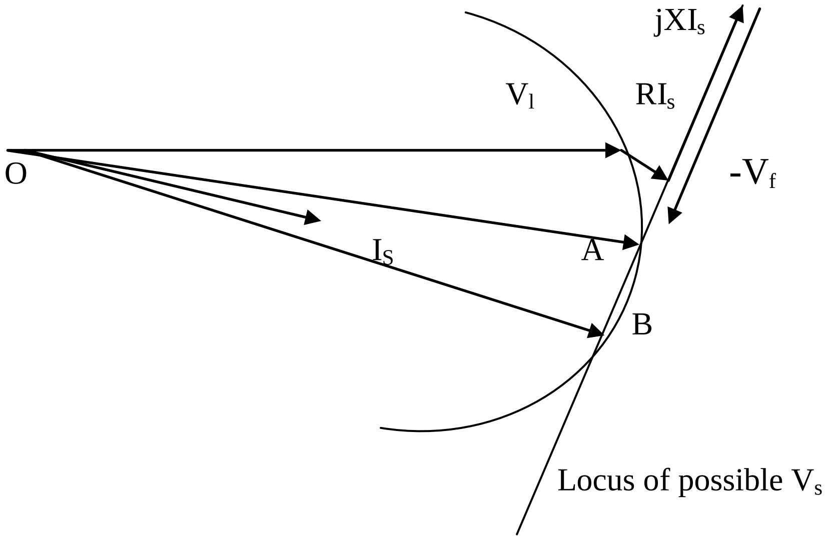


Fig 3.10: Phasor diagram showing multiple solutions for case 3

In the first case the source voltage will be along OA, while in the other case it will be along OB. OA is the best choice because as seen from the Fig 3.10 intersection at A requires much smaller voltage injection from the DVR.Therefore,

$$RI_s \leq 1 - V \cos \Phi_l \qquad (3.6)$$

$$I_s \leq (1 - V \cos \Phi_l) / R \qquad (3.7)$$

3.6 SYSTEM TOPOLOGIES FOR DVR

Conceptually, DVRs operate to maintain the load side voltage at its rated value. During voltage sag and swell, the DVR injects a voltage to restore the load side voltages. In this mode the DVR exchanges active and reactive power with the surrounding system. If active power is supplied to the load from the DVR, it needs a source for this energy. Two types of system are considered one using stored energy to supply the delivered power and the other having no significant internal energy storage. The stored energy can be delivered from different kinds of energy storage systems such as batteries, capacitors, flywheel, or super magnetic energy storage (SMES). For the no-storage topology, the DVR has essentially no internal energy storage capacity and instead energy is taken from the faulted grid supply during the sag.

3.6.1 Topologies with No Energy Storage

DVR topologies with no energy storage use the fact that a significant part of the supply voltage remains present during the sag, and this residual supply can be used to provide the boost energy required to maintain full load power at rated voltage. However, the approach has the disadvantage that the topologies draw more current from the line during the fault, and hence the upstream loads will see a higher voltage drop. On the other hand, a saving is obtained on the energy storage system, and the ability exists to compensate longer sags. In particular, where the DVR is connected to a strong grid, the necessary power to the load can be readily ensured by increasing the supply current to a shunt converter and injecting the missing voltage with the series converter.

Two basic topologies can be used, which are categorized here according to the location of the shunt converter.

System 1 Supply-Side-Connected Shunt Converter

Energy is taken from the incoming supply through a passive shunt converter connected to the supply side. The supply-side-connected passive converter has an uncontrollable dc-link voltage and the passive converter will charge the dc-link capacitor to the actual state of the supply voltage. The dc-link voltage is approximately equal to the peak phase-phase value of the supply voltage and, hence, during voltage sags the dc-link voltage drops proportionally to the sag voltage.

It should be noted that the power ratings of the two converters are not equal, since the power handled by the series converter is directly proportional to the missing voltage, while the maximum voltage and current loadings of the shunt converter do not occur simultaneously, because the current drawn by the shunt converter rises significantly during severe sags as its input voltage reduces. Hence, the ability to compensate for deep voltage sags will be limited

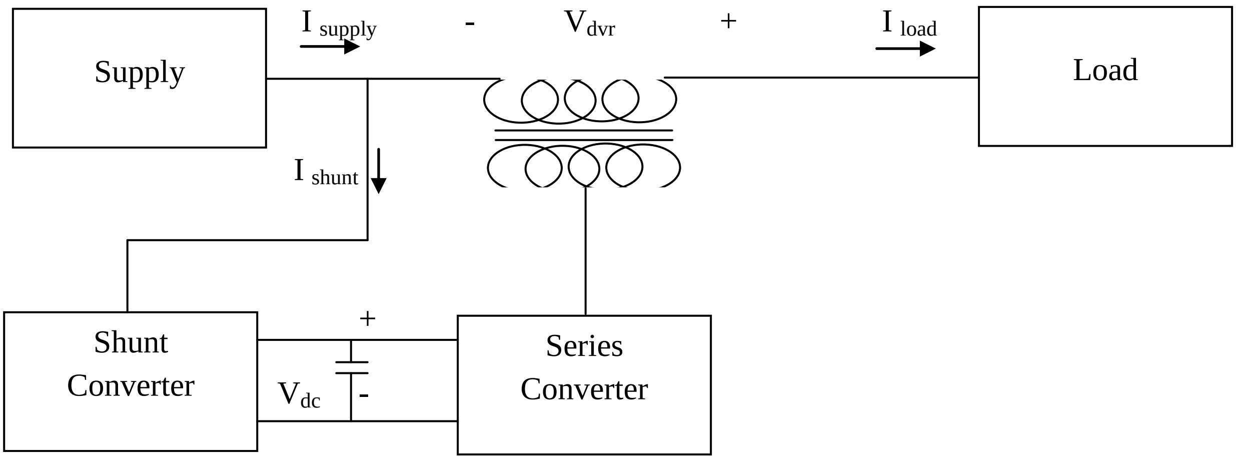


Fig 3.11: DVR with no energy storage and supply side connected converter

as the dc-link voltage in the topology follows the line voltage down and the voltage available for compensation becomes limited. Topology is as shown in Fig 3.11. The shunt current and DC-link voltage are poorly controllable and at non-symmetrical voltage dip the current drawn by the shunt converter will be very uneven distributed between the phases. The DC-link level is proportional to the voltage dip depth and at severe voltage dips the required voltage injection is high, but the DC-voltage can here be expected to be low In the case of a voltage dip the power is not absorbed by the shunt converter until the DC-link voltage have dropped below a certain dip dependent voltage.

System 2 Load-Side-Connected Shunt Converter

As shown in Fig 3.12, Energy is taken from the incoming supply through a passive shunt converter connected to the load side. With a load side connected shunt converter the input voltage to the shunt converter is controlled within the limits of the series converter, and the dc-link voltage can be held almost constant by injecting sufficient voltage. The power rating of the series converter is greater to that of the shunt converter. A DVR with a load side connected passive converter can basically keep the DC-link voltage almost constant, because the load voltage is controlled by the DVR itself. The voltage rating of the converters depends on the injected voltage capability and the restored load voltage level. A DVR with this circuit topology, seems to be a very effective solution, the DClink can be held relatively constant. In the case of non-symmetrical voltage dip the current can still be taken equally from each phase.

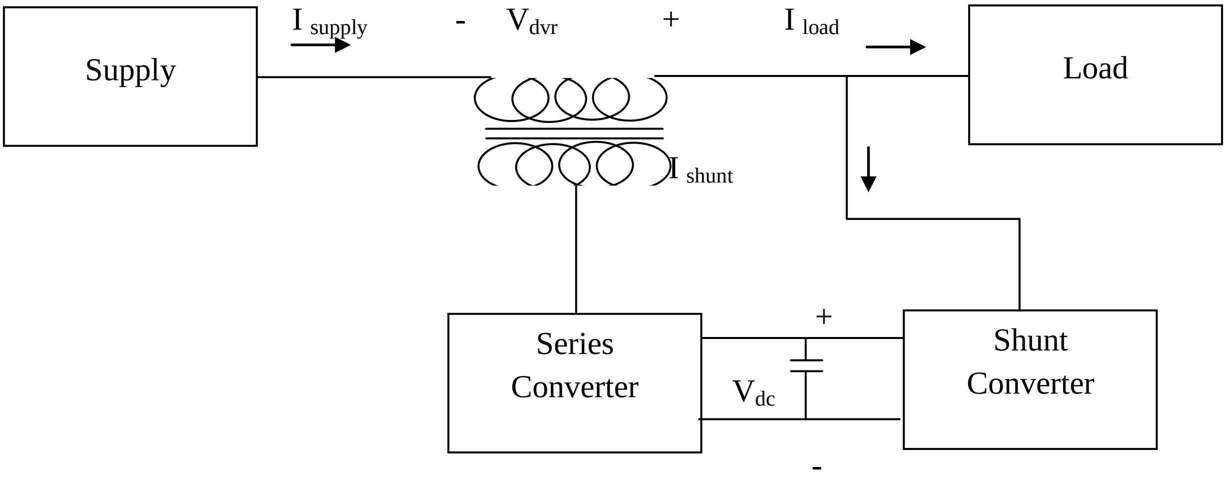


Fig 3.12 DVR with no energy storage and load side connected converter

This topology has the disadvantage of larger currents to be handled by the series converter. Also, the load can be disturbed by the nonlinear currents drawn by the passive shunt converter. However, a DVR using this circuit topology may be an efficient solution in terms of the shunt converter design because the dc-link voltage can be held constant.

3.6.2 Topologies with Energy Storage

Storing electrical energy is expensive, but for certain types of voltage sags the performance of the DVR can be improved and the strain on the grid connection is lower. Two methods are there and in both the current flow from the grid is unchanged during a voltage sag.

System 3 Variable DC-Link Voltages, Energy Stored in DC-Link Capacitors

Storing energy in the dc-link capacitors is a well-suited solution for DVRs. A simple topology can be operated with a variable dc-link voltage. The stored energy is proportional to the square of the rated dc-link voltage.

The voltage decays exponentially during a voltage sag compensation and as the dc-link voltage decays the ability to compensate severe sags deteriorates. Hence, the compensator using dc-link voltage stored energy can be used only down to a certain voltage level. As shown in Fig 3.13.

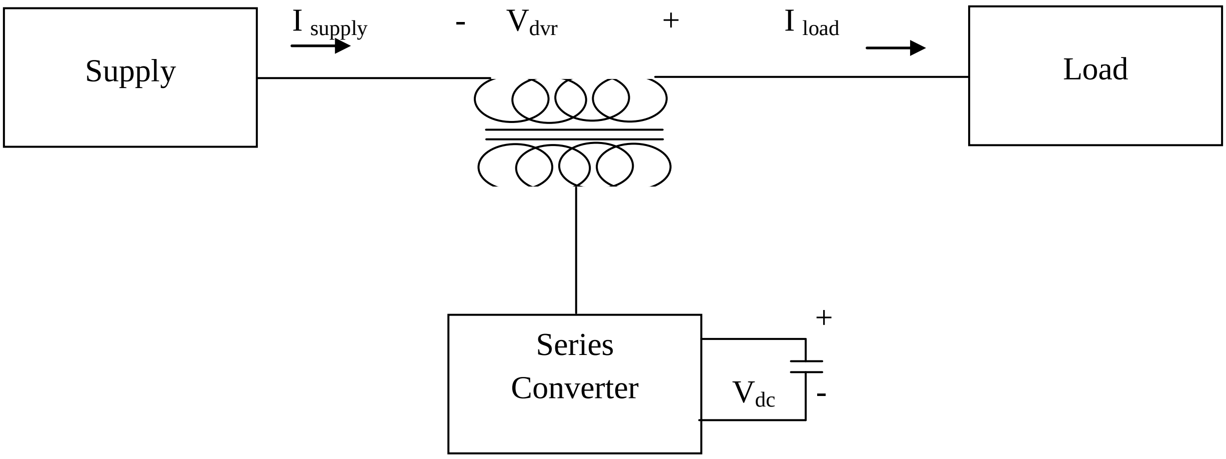


Fig 3.13 DVR with energy storage and with variable dc link voltage

A DVR with variable DC-link voltage offers benefits in simplicity due to only one high rated converter and only DC-link capacitors as the only storage. The voltage injection capacity depends on the actual level of the DC-link voltage, and energy saving control strategies is urgent to fully utilize the energy storage system. The variable dc-link voltage solution has a relatively simple power converter topology and the dc-link energy storage may be re-charged by the series converter or by a low-rated auxiliary charging converter when the grid is in normal operation. However, the energy storage is difficult to use efficiently and during severe sags a large fraction of the energy storage may not be used as the power converter rapidly enters into over modulation in an effort to inject as high a voltage as is possible.

System 4 Constant DC-Link Voltage

As shown in Fig 3.14, an arbitrary type of energy storage feeding into a controllable dc link, the voltage of which can be held constant. Direct energy storage methods, such as SMES, batteries, or super capacitors, can be used in a DVR by adding a separate high-power-rating converter to the system. Energy is then transferred from large energy storage to a smaller rated dc-link storage using this converter during the sag. Hence, the dc voltage is held almost constant.

The performance of this system is improved compared to the variable dc-link solution, but the equipment costs are higher as energy storage is needed and a separate high-rated power converter is also necessary.

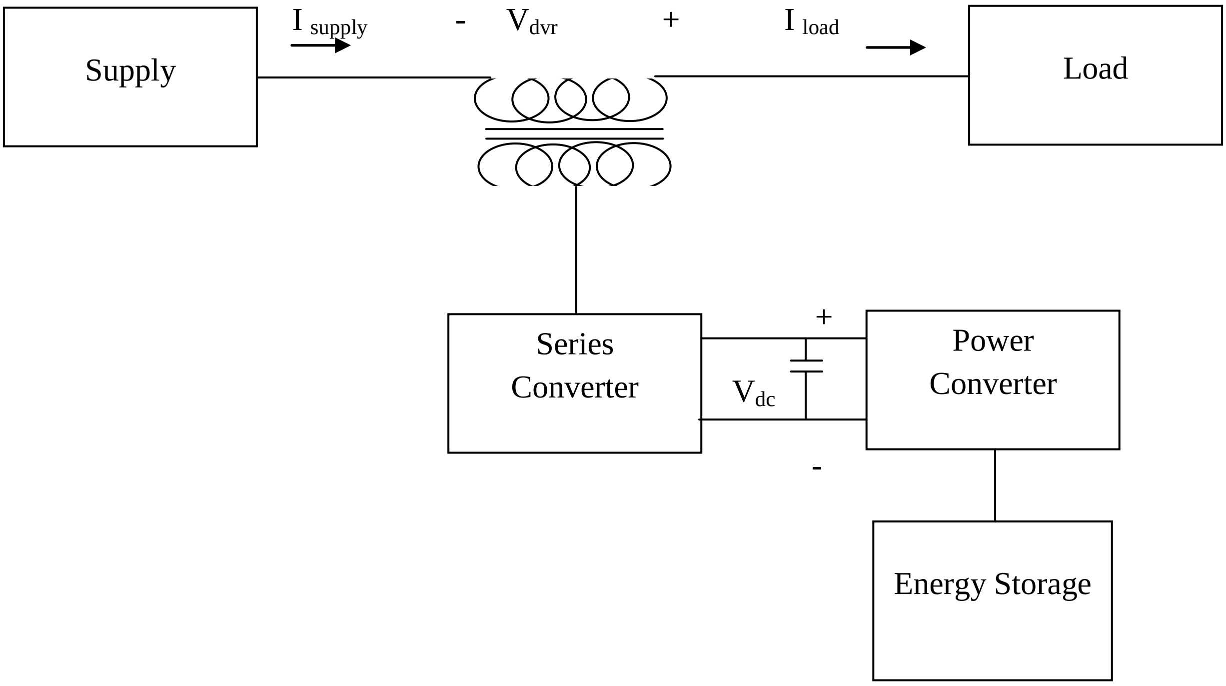


Fig 3.14: DVR with energy storage and with constant dc link voltage

An additional converter is expected to convert energy from the main storage to a small DC-link and thereby control and stabilize the DC-link voltage. The DVR with a constant voltage is here considered to be a reference topology by which the other DVR topologies are evaluated. It offers a constant DC-link voltage at all times and does not increase the current drawn from the supply.

These topologies vary in performance, complexity, cost, and control structure. The load-side-connected converter (System 2) requires the highest rating followed by the supply-side-connected converter (System 1), constant dc link (System 4) and variable dc link (System 3). [7]

3.7 OPERATING MODES OF DVR

The basic function of the DVR is to inject a dynamically controlled voltage VDVR generated by a forced commutated converter in series to the bus voltage by means of a booster transformer. The momentary amplitudes of the three injected phase voltages are controlled such as to eliminate any detrimental effects of a bus fault to the load voltage VL. This means that any differential voltages caused by transient disturbances in the ac feeder will be compensated by an equivalent voltage generated by the converter and injected on the medium voltage level through the booster transformer.

The DVR has three modes of operation which are: protection mode, standby mode, injection/boost mode. [3]

3.7.1 Protection mode

If the over current on the load side exceeds a permissible limit due to short circuit on the load or large inrush current, the DVR will be isolated from the systems by using the bypass switches (S2 and S3 will open) and supplying another path for current (S1 will be closed).[5] Protection mode is shown in Fig 3.15

3.7.2 Standby Mode: (V_{DVR}= 0)

As shown in Fig 3.16, in standby mode the booster transformer’s low voltage winding is shorted through the converter. No switching of semiconductors occurs in this mode of operation and the full load current will pass through the primary. [10]

3.7.3 Injection/Boost Mode: (V_{DVR}>0)

In the Injection/Boost mode the DVR is injecting a compensating voltage through the booster transformer due to the detection of a disturbance in the supply voltage.

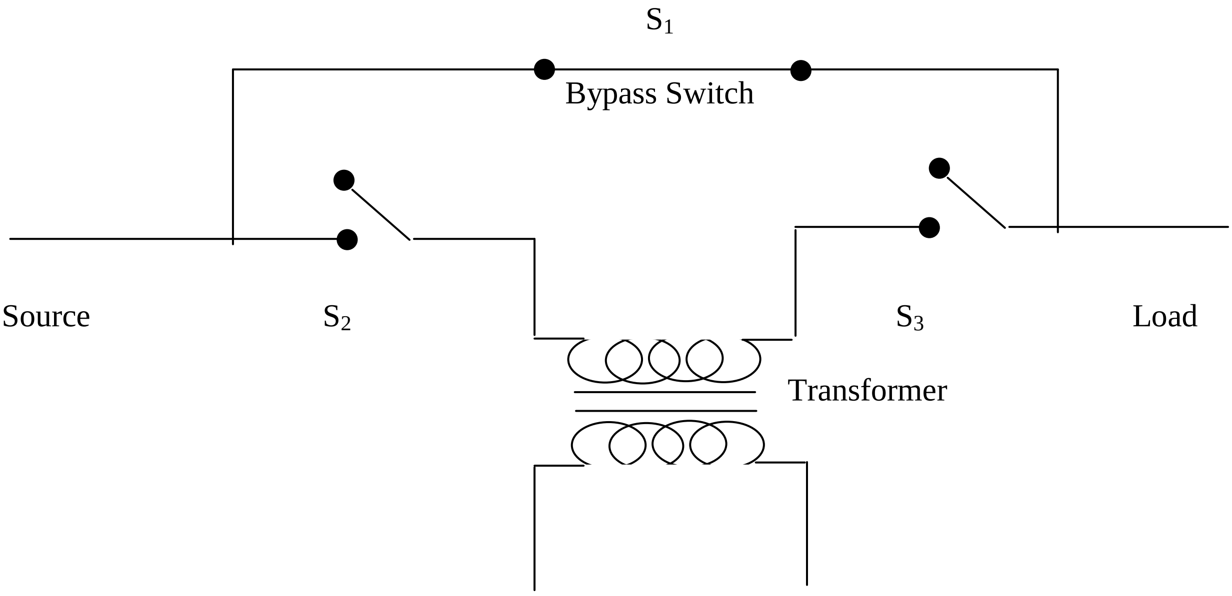


Fig 3.15: Protection Mode

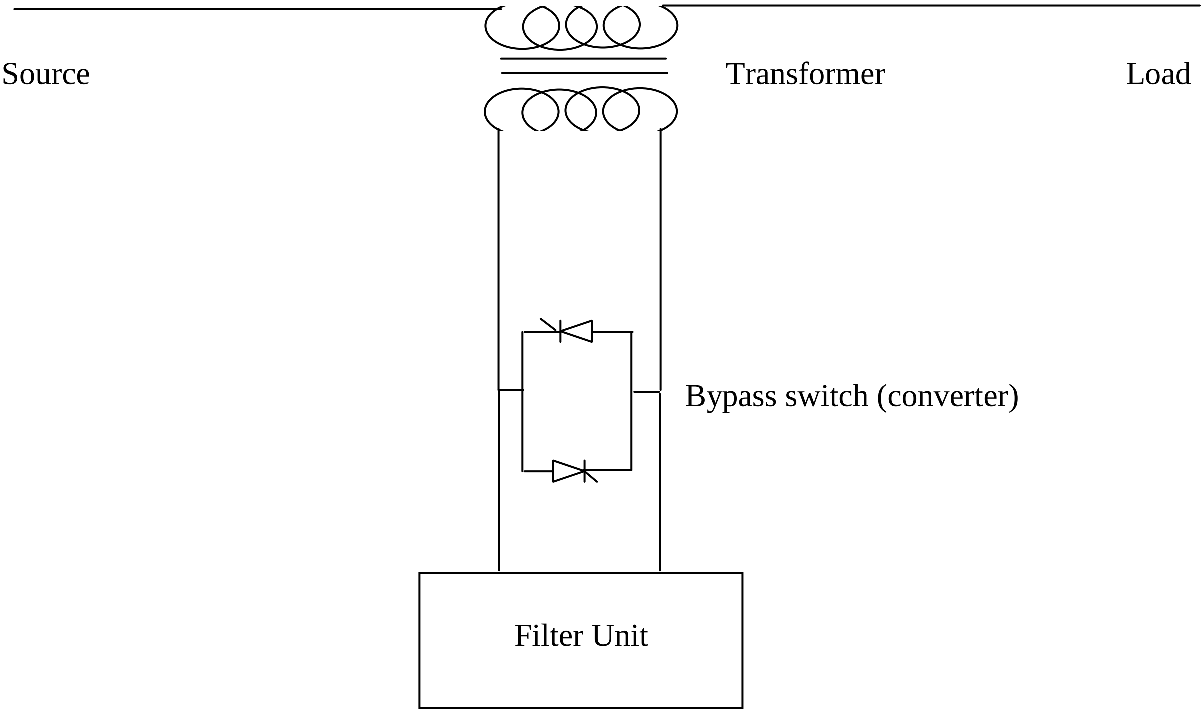


Fig 3.16 Standby mode

3.8 DVR RATING

DVR is a series compensation device which is connected in series with the feeder, the full feeder current flows through it. This current mainly depends on the load voltage and impedance. Thus the power rating of DVR will mainly depends on the series compensator voltage. Thus, DVR is not capable of supplying unlimited amount of voltage.

Thus, the capital cost of the installation, maintenance and running cost of the DVR will increase with the increase in power level rating.. If we regulate the load voltage at a lower value instead, the magnitude of the required voltage injection reduces.

3.9 VOLTAGE INJECTION METHODS OF DVR

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

There are four different methods of DVR voltage injection which are

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

3.9.1 In-phase compensation method

This is the most straight forward method. In this method the injected voltage is in phase with the supply side voltage irrespective of the load current and pre-fault voltage. The phase angles of the pre-sag and load voltage are different but the most important criteria for power quality that is the constant magnitude of load voltage are satisfied. In the in-phase compensation method (IPC), the boost voltage is injected in phase with the dipped voltage. Thus, the load voltage phase during compensation changes to that of the source voltage. Therefore, if the phase of the supply voltage jumps a certain angle due to the dip, the phase of the load voltage will jump by the same angle. [9]

As shown in Fig 3.17,

$$|V_L| = |V_{prefault}| \tag{3.8}$$

One of the advantages of this method is that the amplitude of DVR injection voltage is minimum for certain voltage sag in comparison with other strategies. Practical application of this method is in non-sensitive loads to phase angle jump.

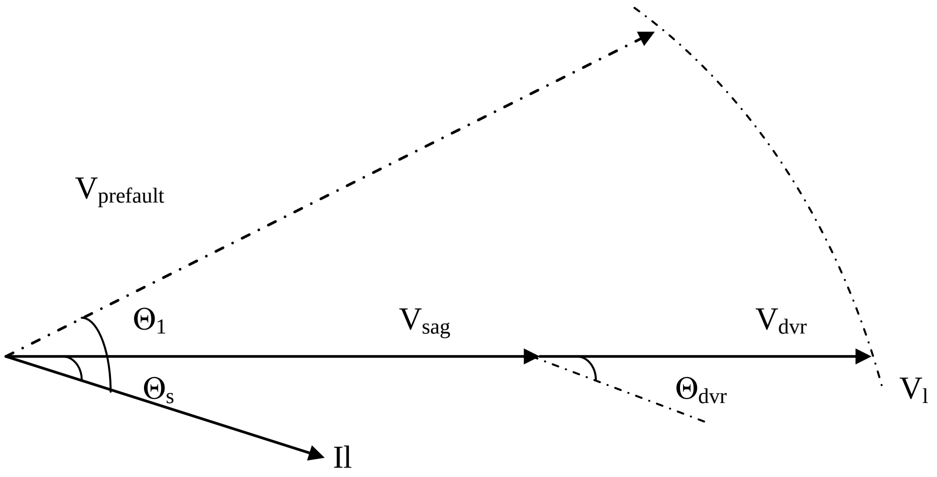


Fig. 3.17 In-phase compensation method

3.9.2 Pre-sag/dip compensation method

The pre-sag method tracks the supply voltage continuously and if it detects any disturbances in supply voltage it will inject the difference voltage between the sag or voltage at PCC and pre-fault condition, so that the load voltage can be restored back to the pre-fault condition. Compensation of voltage sags in the both phase angle and amplitude sensitive loads would be achieved by pre-sag compensation method. In this method the injected active power cannot be controlled and it is determined by external conditions such as the type of faults and some loads are very sensitive to phase angle jump. [13]

In these cases is needed to make the boosted load bus voltage in phase with the pre-dip voltage. That means that the DVR should inject a voltage vector that is the difference between the reference of the load voltage and the grid voltage. This is accomplished by the pre-dip compensation method (PDC). From the power quality point of view, PDC is the best compensation strategy that can be applied to restore the load voltage because it is restored to its pre-dip magnitude and its phase is unchanged, as shown in Fig 3.18

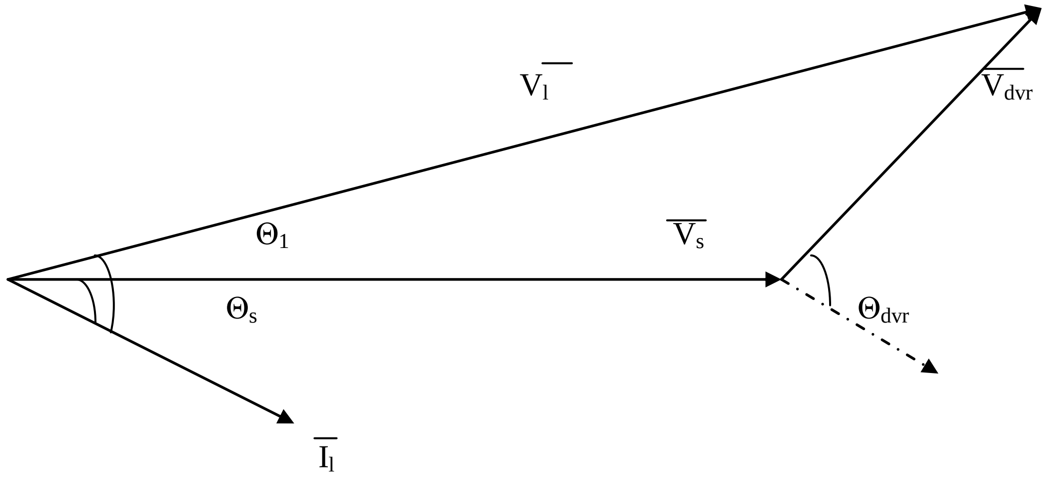


Fig. 3.18: Pre-sag compensation method

3.9.3 In-phase advanced compensation method

In this method the real power spent by the DVR is decreased by minimizing the power angle between the sag voltage and load current. In case of pre-sag and in-phase compensation method the active power is injected into the system during disturbances. The active power supply is limited stored energy in the DC links and this part is one of the most expensive parts of DVR. The minimization of injected energy is achieved by making the active power component zero by having the injection voltage phasor perpendicular to the load current phasor. As shown below in Fig 3.19.

In this method the values of load current and voltage are fixed in the system so we can change only the phase of the sag voltage. IPAC method uses only reactive power and unfortunately, not al1 the sags can be mitigated without real power, as a consequence, this method is only suitable for a limited range of sags.

In phase advance compensation method (PAC), a voltage is injected with a phase lead compared to the source voltage in order to reduce the injected energy. The injected power is minimum when $\theta_S=0$, or V_S and I_L are in phase. This implies that to keep the injected active power minimum in the compensation process, the load voltage vector will move in a circle whose radius is equal to the load voltage magnitude, experiencing a natural phase advance with respect to the source voltage. This situation could be unacceptable to loads that are very sensitive to phase angle jump. Another factor, which limits the applicability of the PAC, is the magnitude of the injected voltage that should be within the ratings of the PDC.

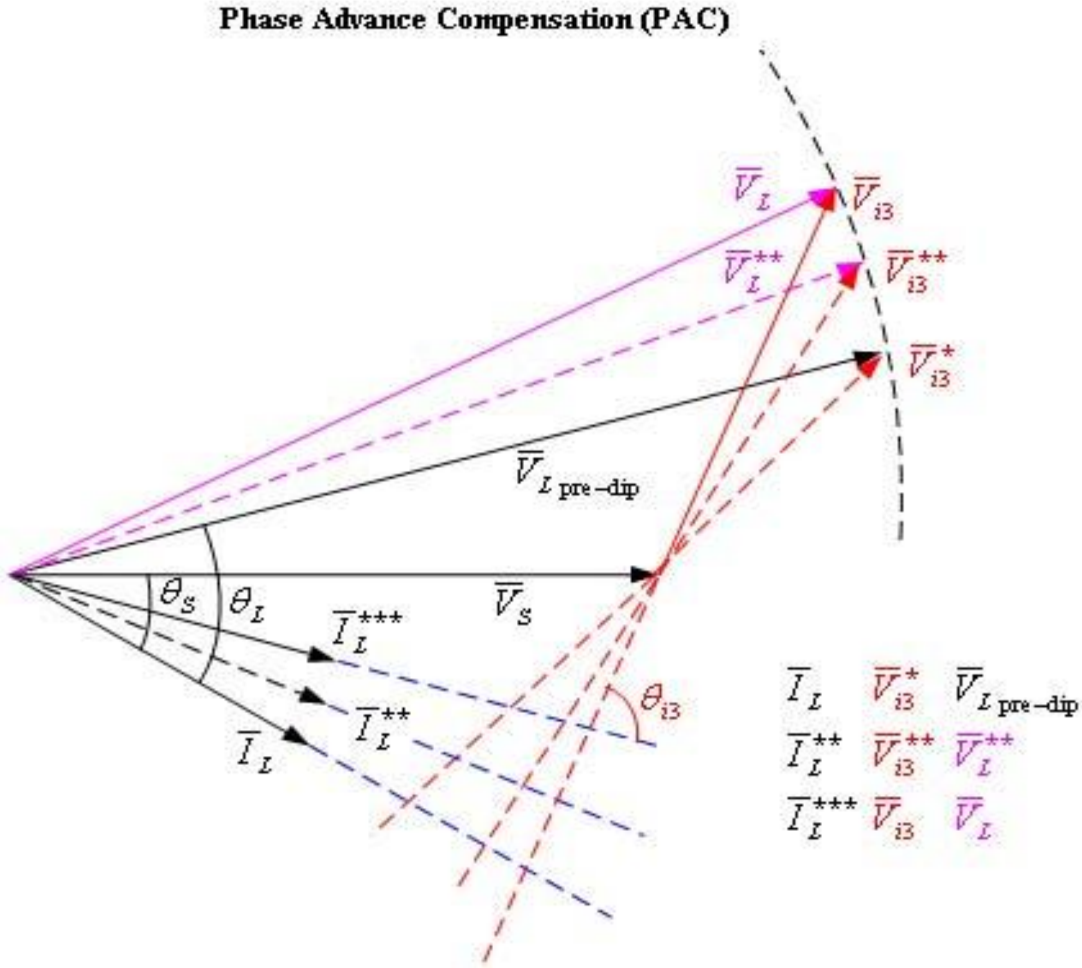


Fig. 3.19: Phase -Advance compensation method

The DVR should inject a voltage in such way that V_S and I_L are kept in phase ($\theta_S = 0$) while maintaining the desired load voltage magnitude. If active power becomes negative, such a situation can be avoided by adjusting $\theta_S \neq 0$ so that the active power becomes zero. Therefore, the voltage dip is compensated using only reactive power.

3.9.4 Voltage tolerance method with minimum energy injection

A small drop in voltage and small jump in phase angle can be tolerated by the load itself. If the voltage magnitude lies between 90%-110% of nominal voltage and 5%-10% of nominal state that will not disturb the operation characteristics of loads. Both magnitude and phase are the control parameter for this method which can be achieved by small energy injection, as shown in Fig 3.20.

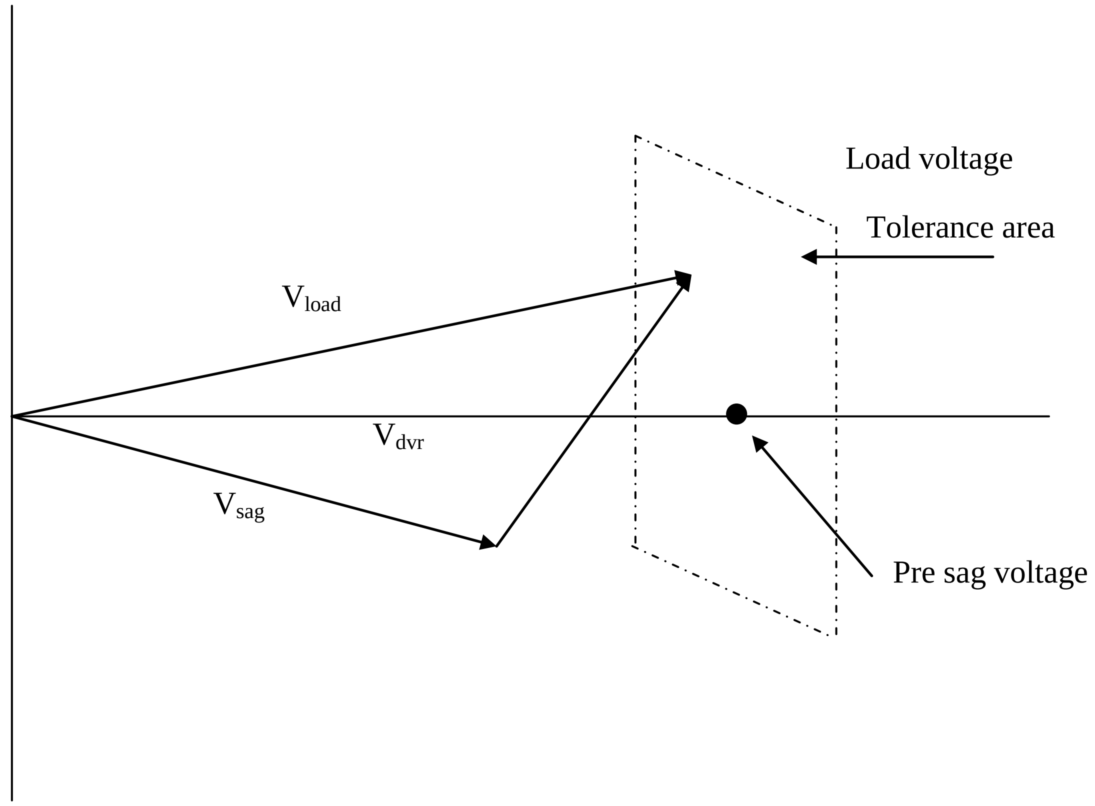


Fig. 3.20: Voltage tolerance method with minimum energy injection

3.10 CONCLUSIONS

In this chapter a systematic study of a dynamic voltage restorer (DVR) that can regulate voltage at the load terminals against any variation in the supply side voltage has been presented. Its operating principle, configuration and structure is also discussed. It has been shown that the DVR can get a dc voltage support externally or it can operate through a dc capacitor in which it contains no real power in steady state. The capability of the device is also demonstrated. Finally a suitable topology to realize the DVR by voltage source inverters (VSIs) is also discussed. Some of the main conclusions are:

- The placement of a large DVR at the medium voltage level can simplify the DVR topology and minimize the losses and voltage drop across the DVR.
- A DVR topology using a injection transformer is expected to give certain benefits regarding the converter topology, the charging circuit and the protection of the DVR.
- In a strong grid and with a rare intensity of severe voltage dips DVR topologies without any significant energy storage can be an interesting alternative. A shunt converter at the load side of the series converter can have a good performance, but at the expense of a high installed converter capacity.
- Protection of the DVR must be ensured.

CHAPTER 4

MATHEMATICAL MODELLING OF DYNAMIC VOLTAGE RESTORER

- *Introduction*
- *Voltage Control of Distribution System with DVR*
- *Simulation and Results*
- *Conclusions*

CHAPTER 4

MATHEMATICAL MODELLING OF DYNAMIC VOLTAGE RESTORER

INTRODUCTION

The proliferation of voltage-sensitive equipment has made industrial processes more vulnerable to supply voltage deviations. Such voltage deviations, commonly in the form of voltage sags, can cause severe process disruptions and result in substantial production loss. Therefore, there has been much research interest recently in seeking cost-effective solutions which can help sensitive loads ride-through momentary power supply disturbances. Among the several novel custom power devices, the dynamic voltage restorer (DVR) for application in distribution systems is a recent invention. Thus the performance of dynamic voltage restorer (DVR) in improving the quality of power supply should be examined. [4]

Most of the DVR output voltage depends on the accuracy and dynamic behavior of the pulse width modulated (PWM) voltage synthesis scheme and the control system adopted. The general requirement of such control scheme is to obtain an ac waveform with low distortion and good response characteristics against supply and load disturbances. Usually, the control voltage of the DVR is derived by comparing the supply voltage against a reference waveform to guarantee the system stability.

The switching process of PWM inverter can result in distortion in the output voltage which can be poor due to the presence of the switching harmonic. Poor results in sustained voltage oscillations in the distribution network which could have serious adverse effects on sensitive loads and equipment, such as adjustable speed drives. It is therefore, essential that DVR should be able to correct the load voltage toward a desirable reference value by including a load voltage feedback.[7]

The DVR controls the voltage across the sensitive load by injecting an appropriate voltage phasor through the series-connected injection transformer. If an up-stream voltage disturbance can be compensated effectively, then the impact of the disturbance on the load is minimized. In most voltage disturbance correction techniques, the DVR is required to inject active power into the distribution line during the period of compensation. Hence, the capacity of the energy storage unit can become a limiting factor in the disturbance compensation process especially for disturbances of long duration. A phasor diagram describing the electrical conditions during voltage sag is shown in Fig 4.1

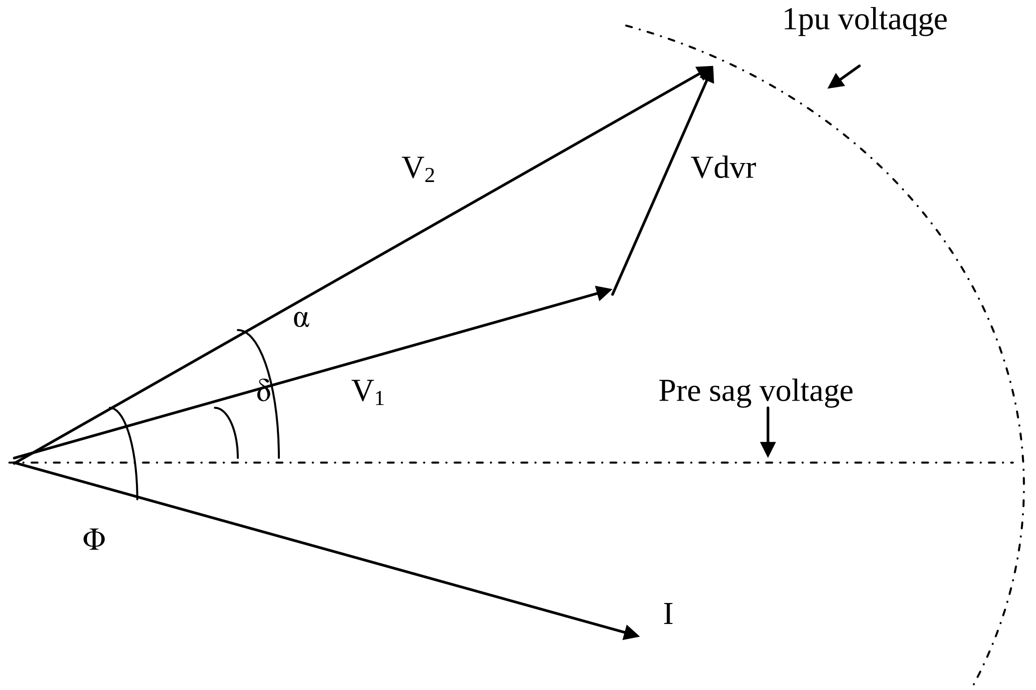


Fig: 4.1 Phasor diagram

V_1, V_2 and V_{dvr} are the supply voltage, compensated load-side voltage and the DVR injected voltage, respectively. Moreover I, Φ, δ, and α represent load current, load power factor angle, supply voltage phase angle, and load voltage advance angle, respectively. The phase advance compensation technique has been shown here. One distinct advantage of the scheme described is that less real power needs to be injected from the DVR energy storage unit into the distribution system. Reduced real power injection therefore permits the DVR to help the load ride-through more severe voltage sags. The DVR is a nonlinear device due to the presence of power semiconductor switches in the inverter bridge. However, with the application of state-space averaging technique it is possible to express the DVR behavior in differential equation form. The dynamic characteristic of the DVR is very much determined by the filter and the connected load. A linear constant impedance load is assumed here and the purpose is to design the control for distribution system with DVR.[5]

The state–space equations (3.1)- (3.5) can be obtained from Fig 3.5 as discussed in chapter 3. These equations will be used for the design.

4.2 VOLTAGE CONTROL OF DISTRIBUTION SYSTEM WITH DVR

The DVR consists of a controllable voltage source, a fixed resistance, which is equivalent to the losses in the DVR and a fixed reactance, which is equivalent to the reactive elements in the DVR. The main design parameters for the DVR are the voltage injection capability, the current handling capability and the size of the energy storage. The voltage injection capability should be chosen as low as necessary in order to reduce equipment cost and standby losses. Losses tend to increase if the voltage rating of the DVR is increased. The losses in the DVR can be grouped into losses in the transformer, filter and the converter. The voltage injection is mostly fixed by the requirements to compensate symmetrical and non-symmetrical voltage disturbances. Voltage, current and energy rating, information about the voltage dip distribution and voltage dip frequency at the location of the inserted DVR is necessary. A one year pre-recording can be necessary to get statistically valid data. [4]

As shown in Fig 4.2, the basic configuration of DVR with all its components and control structure should be considered so that the resulting load voltage is regulated to track a sinusoidal reference.

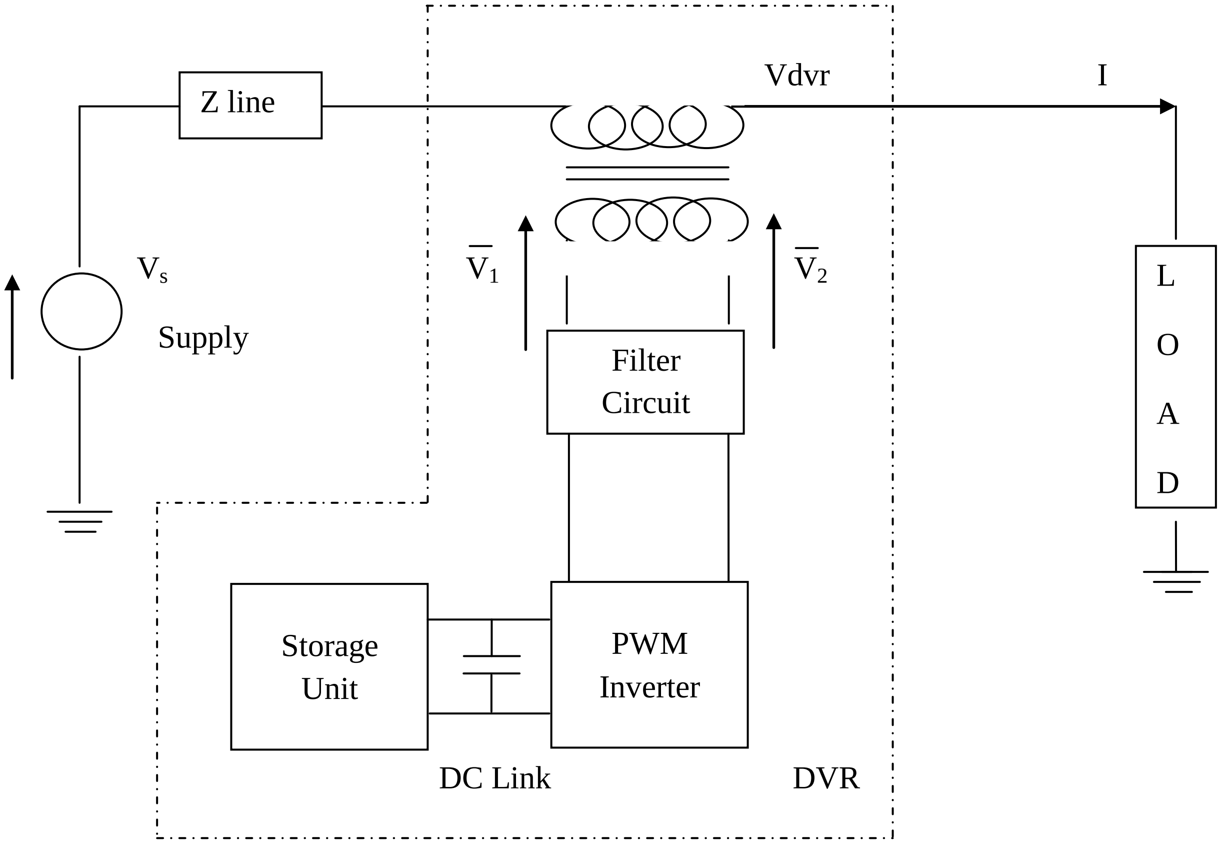


Fig 4.2: Distribution system compensated by a DVR

4.2.1 Open Loop Voltage Control Scheme [4]

In this scheme the voltage on the source side of the DVR is compared with a load-side reference voltage and the error is fed to the PWM pulse generator. Using (3.1)–(3.5), a schematic diagram describing the open loop voltage control scheme is as shown in Fig. 4.3. In this figure, V_2^* denotes the load-side reference voltage. An inverter gain of K_i is assumed in the analysis. The load-side voltage V_2 for this control configuration can be written as

$$V_2 = G_2 V_2^* + G_1 V_1 \tag{4.1}$$

Where G_2 is the transfer function from the reference signal to V_2 while G_1 is the transfer function from V_1 to V_2. From (4.1). The transfer functions are given by (4.2) and (4.3).

$$G_2(s) = \frac{\{n K_i (L_l s + r_l)\}}{\{a_{10} s^3 + a_{20} s^2 + a_{30} s + a_{40}\}} \tag{4.2}$$

$$G_1(s) = \frac{\{(L_l L_f C_f s^3) + (L_f r_l + L_l r_f) C_f s^2 + (r_f r_l C_f + (1 - nK_i) L_l) s + (1 - nK_i) r_l\}}{\{a_{10} s^3 + a_{20} s^2 + a_{30} s + a_{40}\}} \tag{4.3}$$

where a_{10}, a_{20}, a_{30} and a_{40} are given in the appendix A.

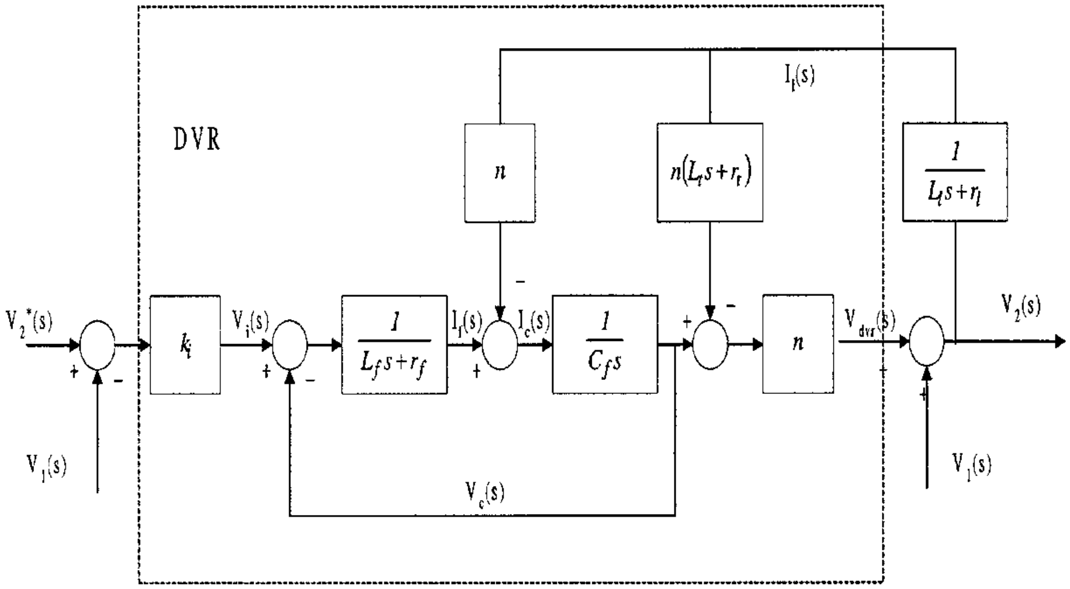


Fig 4.3: Open loop voltsge control Scheme

The stability of the system shown in Fig. 4.2 can be assessed using Routh–Hurwitz criteria. For the system to be stable, the term $(a_{20} a_{30} - a_{10} a_{40})$ must be greater than zero as $(a_{20} > 0)$. Indeed, it can be readily shown that this condition can be satisfied for all possible values of L_f, r_f, L_t, r_t, L_l, r_l and n. The pole of the system characteristic equation $\{a_{10} s^3 + a_{20} s^2 + a_{30} s + a_{40}\}$ is approximately located at $\{-(r_l + n^2 r_t) / (L_l + n^2 L_t)\}$. Therefore, the characteristic equation can be factorized as,

$$\{a_{10} s^3 + a_{20} s^2 + a_{30} s + a_{40}\} \sim \{b_{10} (L_l + n^2 L_t) s + b_{10} (r_l + n^2 r_t)\} \{(s^2 + b_{20} s + b_{30})\} \tag{4.4}$$

and by equating the coefficients on both sides, the coefficients b_{10}, b_{20} and b_{30} can be determined. They are given in the appendix A. Therefore in the open-loop voltage control scheme, the system is inherently stable. As a safeguard against voltage sag, the DVR is expected to be on-line at all time so that there is minimal delay in providing the voltage support as and when it is needed. Hence, it is desirable that the restorer has low loss and thus the filter resistance r_f is kept to as low a value as practicable.[4]

This analysis reveals that the damping of the network with the open-loop controlled DVR can be unsatisfactory. The two complex conjugate roots are located at $-42 \pm j\,3268$ which shows poor damping level. When open loop voltage control scheme has been simulated in Matlab/Simulink the output of the control scheme can be viewed and it has been seen that it contains disturbance although it traces the sinusoidal reference. Thus, the open-loop voltage control scheme needs to be improved on by including inner feedback loop(s).

4.2.2 Closed Loop Voltage Control Scheme [4]

Current mode control techniques are usually applied to power electronic circuits wherein an inner current loop is employed within the outer voltage loop in the closed loop regulation of power converters .Notice that from equation (3.3), the rate of change of the DVR output voltage is proportional to the current of the filter capacitor. If this current can be regulated appropriately, the load voltage can also be controlled in the event of load changes. This control feature, together with the outer voltage feedback loop described in open loop voltage control scheme, can be readily incorporated into the closed loop voltage control scheme.

This is shown in Fig. 4.4 where it is shown that the DVR load-side voltage is compared with its reference value and the error is multiplied with the voltage error feedback gain K_v and fed to the second stage as a reference for the capacitor current. This virtual capacitor current reference is compared with the actual capacitor current and the error is multiplied with the current error gain K_c to form the inner feedback loop. The resulting quantity of this loop is subsequently fed to the PWM generator of the inverter. A feed forward control signal has also been added to the inverter input voltage signal in order to provide instantaneous response to the change in V_1. [4]

The load side voltage for this control configuration is given by,

$$V_2 = G_4 V_2^* + G_3 V_1 \tag{4.5}$$

Where G_4 is the closed-loop transfer function from the reference signal V_2^* to V_2 while G_3 is the closed-loop transfer function from the supply voltage to V_2. The transfer functions can be given by,

$$G_4 = \frac{\{(n K_i K_c K_v + n K_i)(L_l s + r_l)\}}{\{a_5 s^3 + a_6 s^2 + a_7 s + a_8\}} \tag{4.6}$$

$$G_3 = \frac{(L_l L_f C_f s^3) + (L_f r_l + L_l r_f + K_i K_c L_l) C_f s^2 +(r_f r_l C_f + (1- n K_i) Ll + Ki Kc r_l C_f) s + (1- n K_i) r_l}{\{a_5 s^3 + a_6 s^2 + a_7 s + a_8\}} \tag{4.7}$$

Where, a_5, a_6, a_7 and a_8 are given in appendix A. The pole of the system characteristic equation $\{a_5 s^3 + a_6 s^2 + a_7 s + a_8\}$ is approximately located at $\{-(r_l + n^2 r_t) / (L_l + n^2 L_t) \}$. Therefore, the characteristic equation can be factorized as,

$$\{a_5 s^3 + a_6 s^2 + a_7 s + a_8\} \sim \{b_4 (L_l + n^2 L_t) s + b_4 (r_l + n^2 r_t) \} \{ (s^2 + b_5 s + b_6)\} \tag{4.8}$$

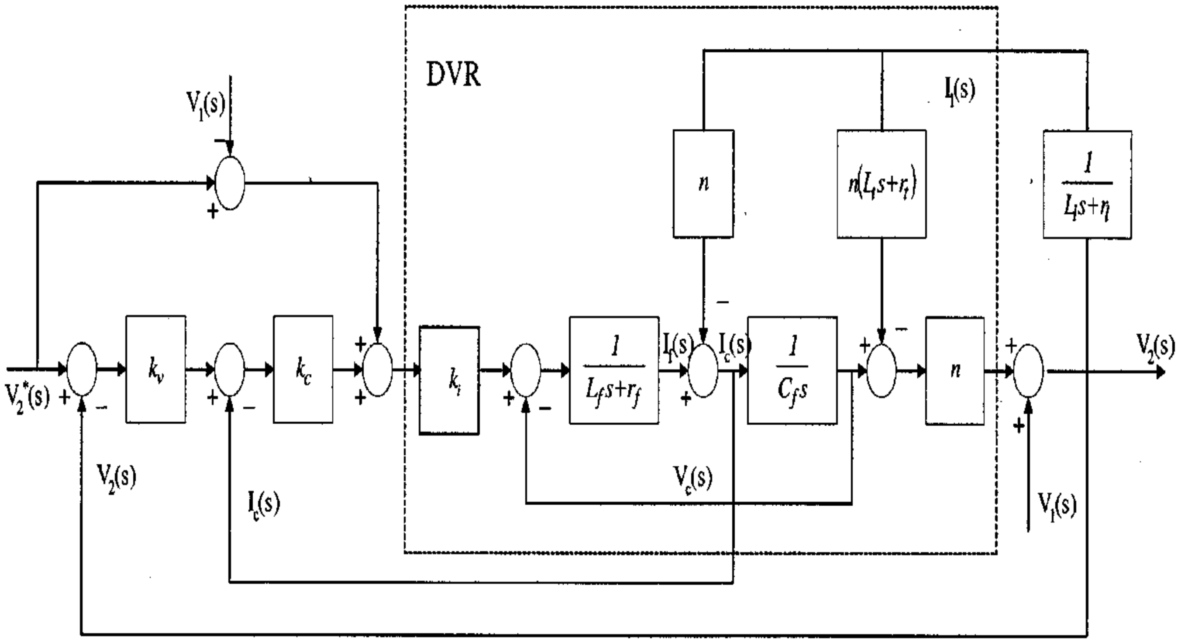


Fig 4.4: Closed loop voltage control scheme

and by equating the coefficients on both sides, the coefficients b_4, b_5 and b_6 can be determined. They are given in the appendix A. The expressions for the coefficients b_4, b_5 and b_6 show that the two dominant complex poles depend largely on the values of the filter inductance, filter resistance as well as the capacitor current loop gain and the real part of these poles is $\{ - (r_f + K_i K_c) / (2 L_f) \}$. This expression is flexible as it depends on the value of K_c. For a given Ki, the value of K_c can be chosen such that $K_i K_c >> r_f$ and a corresponding increase in the real part of the complex poles is obtained. Thus the damping level can be increased with an increase of the capacitor gain. Hence, in this closed loop voltage control scheme the disturbance has been minimized.

4.3 SIMULATION AND RESULTS

A detailed simulation of the voltage control of distribution system with DVR using MATLAB/SIMULINK was carried out in order to verify the effectiveness of both the voltage control technique. The parameters for the DVR simulation are obtained using the configuration as shown in Fig. 4.2. Table in the appendix A shows the DVR system parameters used in the experimental tests.

i. **Open Loop Voltgae Control Scheme:** When simulated, the output obtained is as shown in Fig 4.5. It can be seen from the output that although, it traces the sinusoidal reference but it contains disturbances and have poor damping which are undesirable.

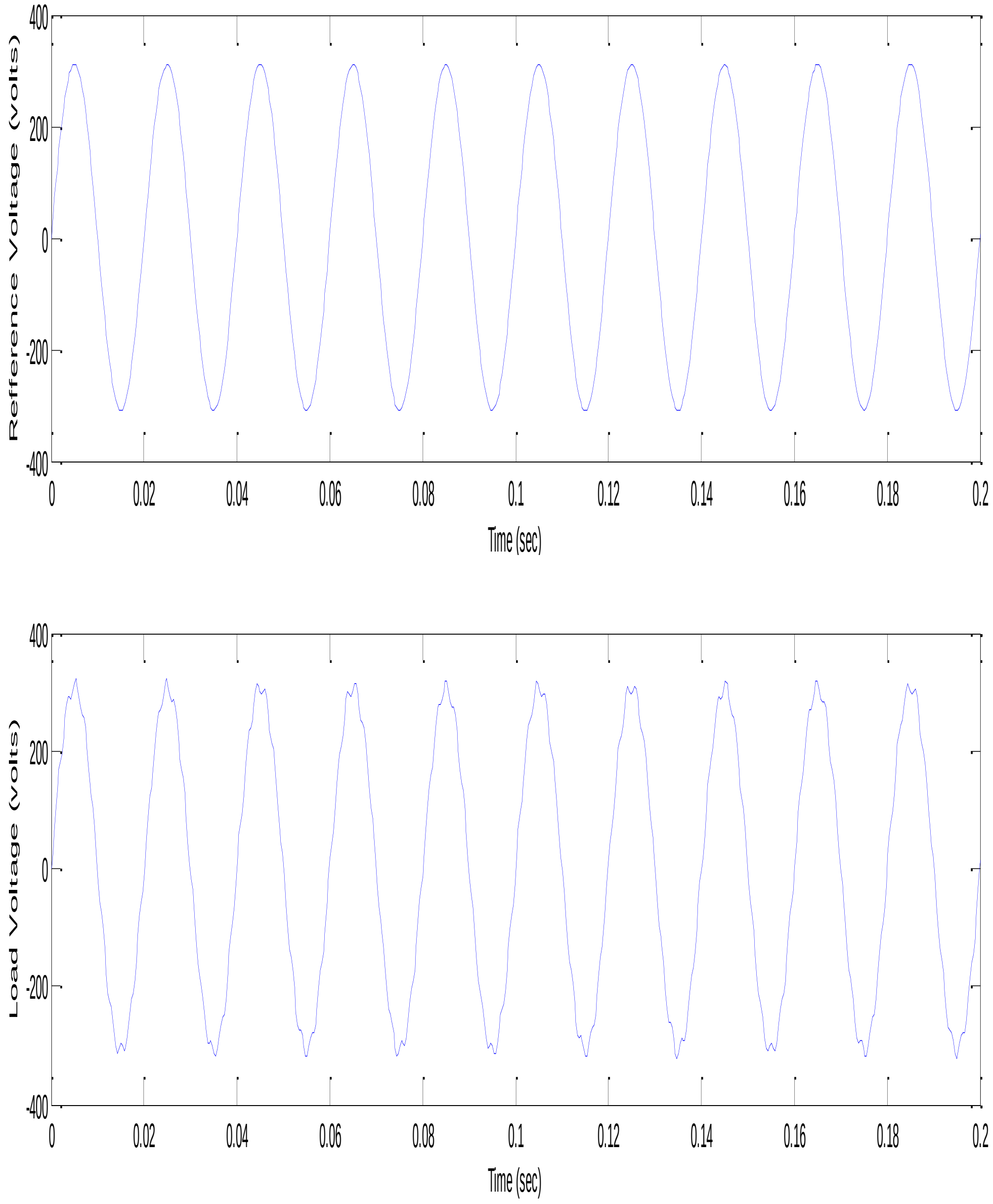


Fig 4.5: Result for open loop voltage Control scheme

ii. **Closed Loop Voltage Control Scheme:** When simulated it has been seen that it traces the sinusoidal reference and it is disturbance free with improved damping. Thus the distribution network with DVR having the closed-loop voltage control scheme can be satisfactory. Fig 4.6 shows the simulation results of the load voltage using closed loop voltage control scheme.

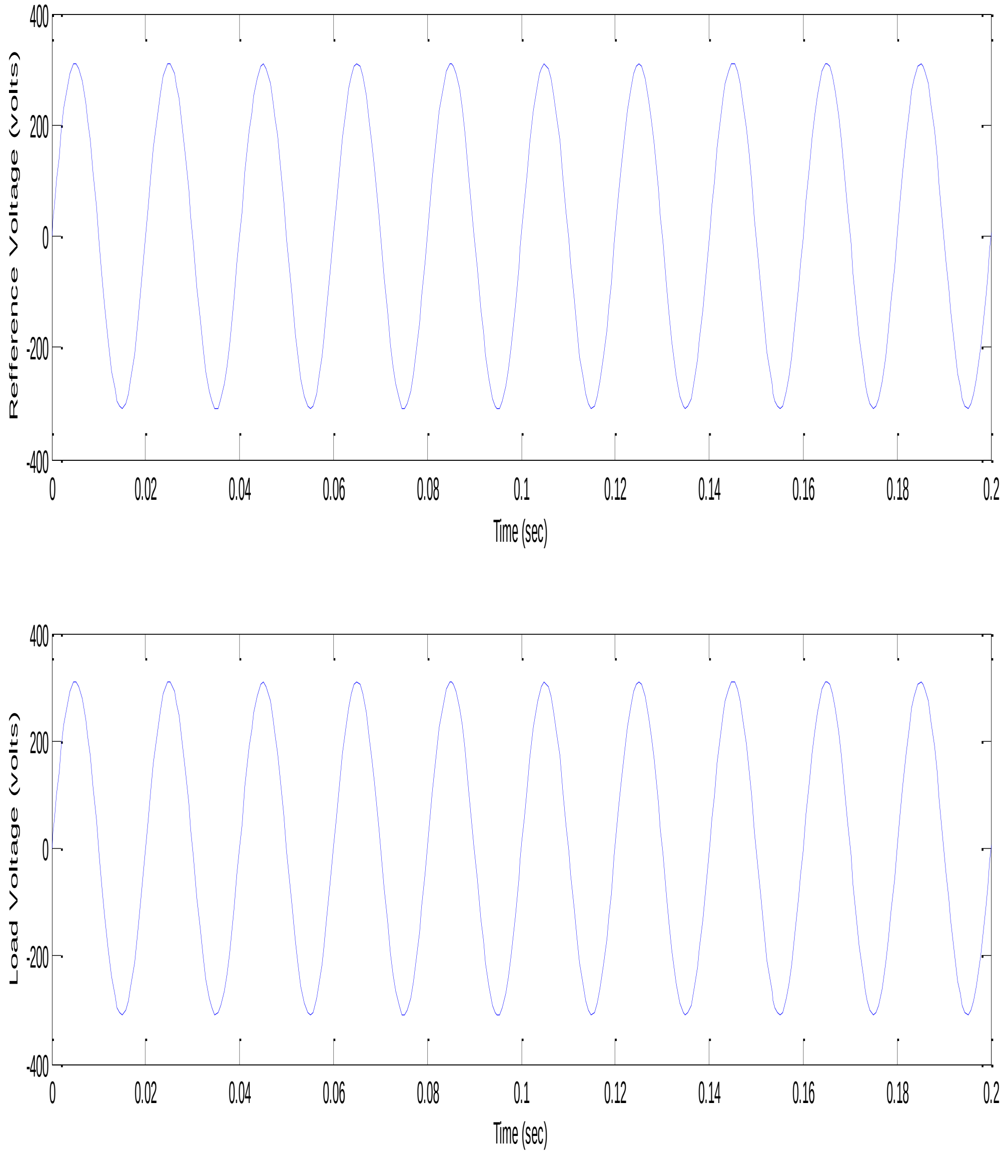


Fig 4.6: Result for closed loop voltage control scheme

The waveforms are obtained with a detailed model of the dynamic voltage restorer where the PWM process has been included. It can be seen that the output voltage of open loop voltage control scheme is distorted while distortion is waived off in output voltage of closed loop voltage control scheme. The damping of the closed loop voltage control scheme is better than the open loop voltage control scheme when $K_c = 30$ and $K_i = 0.06$ has been selected.

4.4 CONCLUSION

The design procedure for the DVR has been the topic for this chapter. The open loop voltage control and closed loop voltage control scheme for DVR has been simulated. The control voltage of DVR is derived by comparing the supply voltage against the reference voltage. It has been seen that the closed loop voltage control scheme is better than the open loop voltage control scheme. As in open loop voltage control scheme load voltage traces the reference voltage but it contains distortions which can adversely affect the sensitive load and equipments. Whereas, in close loop voltage control scheme disturbances are waived off.

The closed loop voltage control scheme proves to be better than the open loop voltage control scheme. In the open-loop voltage control scheme, two feedback loops which utilize the DVR load-side voltage and the filter capacitor current have been considered whereas in closed loop voltage control scheme current mode control techniques are applied. With only a slight increase in the complexity of the control scheme, the improvement in load voltage is achieved.

CHAPTER 5

CONTROLLING OF DYNAMIC VOLTAGE RESTORER

- *Introduction*
- *Operation of DVR*
- *Control of DVR*
- *Simulation and Results*
- *Conclusion*

CHAPTER 5

CONTROLLING OF DYNAMIC VOLTAGE RESTORER

INTRODUCTION

Voltage sags and swells in an electric power grid cannot be avoided. Voltage sags and swells are the common reasons for interruption in production plants and for end user equipment malfunctions. In particular, tripping of equipment in a production line can cause production interruption and significant costs due to loss of production. One solution to this problem is to make the equipment itself more tolerant to disturbances, either by intelligent control or by storing "ride-through" energy in the equipment. An alternative solution, instead of modifying each component in a plant to be tolerant against voltage disturbances, is to install a dynamic voltage restorer (DVR) on the incoming supply to mitigate them for shorter periods. DVRs can eliminate most of the sags and swell, and minimize the risk of load tripping for them. Thus, the control and performance of a DVR is highly required so that DVR can inject appropriate amount of voltage to maintain the load side voltage. [38]

Control of dynamic voltage restorer is described in this chapter. The control and operation of a DVR is demonstrated with reduced rating VSC. The reference load voltage is estimated using the synchronous reference frame (SRF). SRF theory is used for the control of DVR. First, the basic DVR control with direct method is analyzed and here after the control of a DVR with indirect method is done using SRF theory. The compensations of sag and swell in supply voltage using the reduced rating DVR are demonstrated using MATLAB / Simulink.

5.2 OPERATION OF DYNAMIC VOLTAGE RESTORER

Fig 5.1 shows a schematic diagram of DVR connected in a system. The voltage V_{dvr} is inserted such that the load voltage V_{load} is constant in magnitude and undistorted, whenever the supply voltage V, is not constant in magnitude or distorted. As also discussed in chapter 3 voltage injection methods of DVR Fig. 5.2 shows the phasor diagram of different voltage injection schemes of the DVR.

From the Fig 5.2, $V_{pre\text{-}sag}$ is the voltage across the critical load prior to voltage sag condition. During the sag, the voltage is reduced to V_s with a phase lag angle of θ. Now the DVR has to inject a voltage so that the load voltage magnitude is maintained during sag or swell conditions at the pre-sag condition. According to the phase angle of the load voltage, the injection of voltages can be realized in four ways.[41]

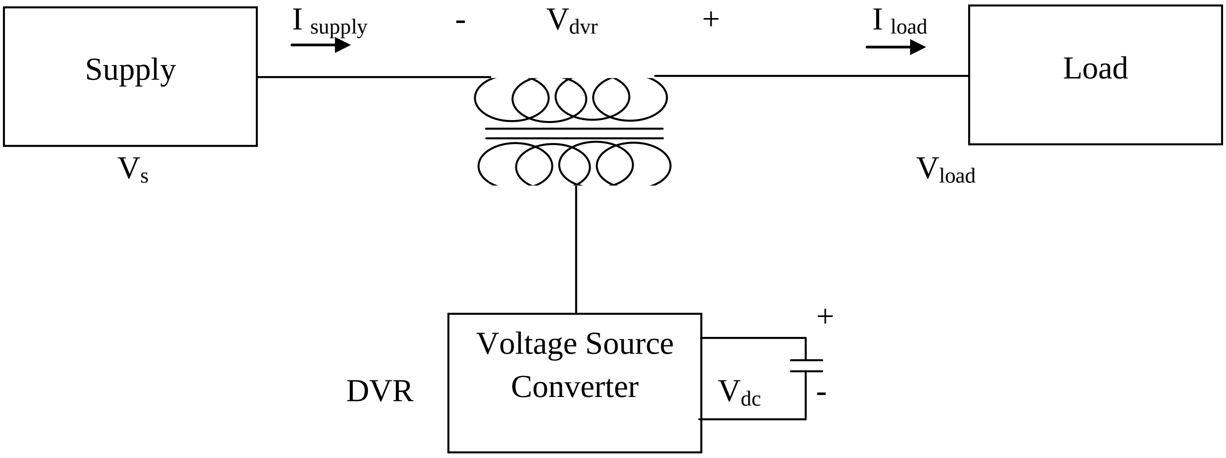


Fig 5.1: Block diagram of a DVR

In the phasor diagram, V_{dvr1}, V_{dvr2}, V_{dvr3} and V_{dvr4} present the four ways of voltage injection method. Here, V_{dvr1} represents the voltage-injected in-phase with the supply voltage where V_{dvr2} shows the injection of the load voltage where magnitude remains same but it leads V_s by a small angle say Φ. In V_{dvr3}, the load voltage retains the same phase as that of the pre-sag condition, which may be an optimum angle considering the energy source and in V_{dvr4}, it’s the condition where the injected voltage is in quadrature with the current and this case is suitable for a capacitor supported DVR as this injection involves no active power. However, the minimum possible rating of the converter is achieved by the V_{dvr1}. [38]

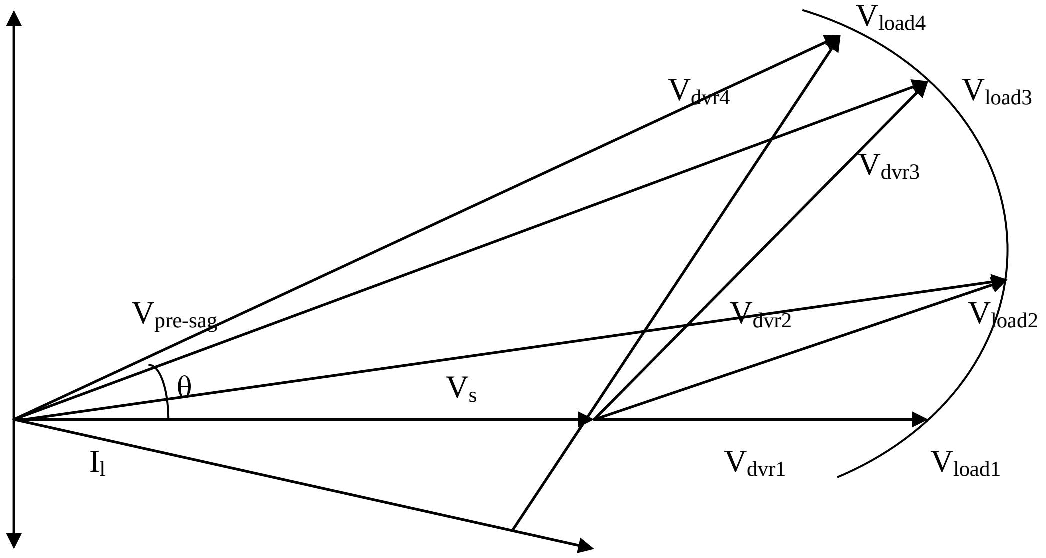


Fig 5.2: Phasor diagram for DVR voltage injection schemes

Block diagram of a DVR connected to a three phase system is as shown in Fig 5.3. The three phase supply is connected to a critical, sensitive load through a three phase series injection transformer through which DVR restores the voltage of a three phase load.

The voltage of the supply of phase A is V_a, is connected to the point of common coupling (PCC) as V_{sa} through a impedance of Z_{sa} similarly in rest of the two phases. The voltage injected by the DVR in phase A is V_{dvr-a} is such that the load voltage V_{la} is of rated magnitude and undistorted. The three phase DVR is connected in the line to inject a voltage in series with the help of three single-phase transformers. The L_f, and C_f, represents the filter component used to filter the ripple in the injected voltage. A voltage source converter (VSC) with IGBTs (insulated gate bipolar transistors) is used.[39]

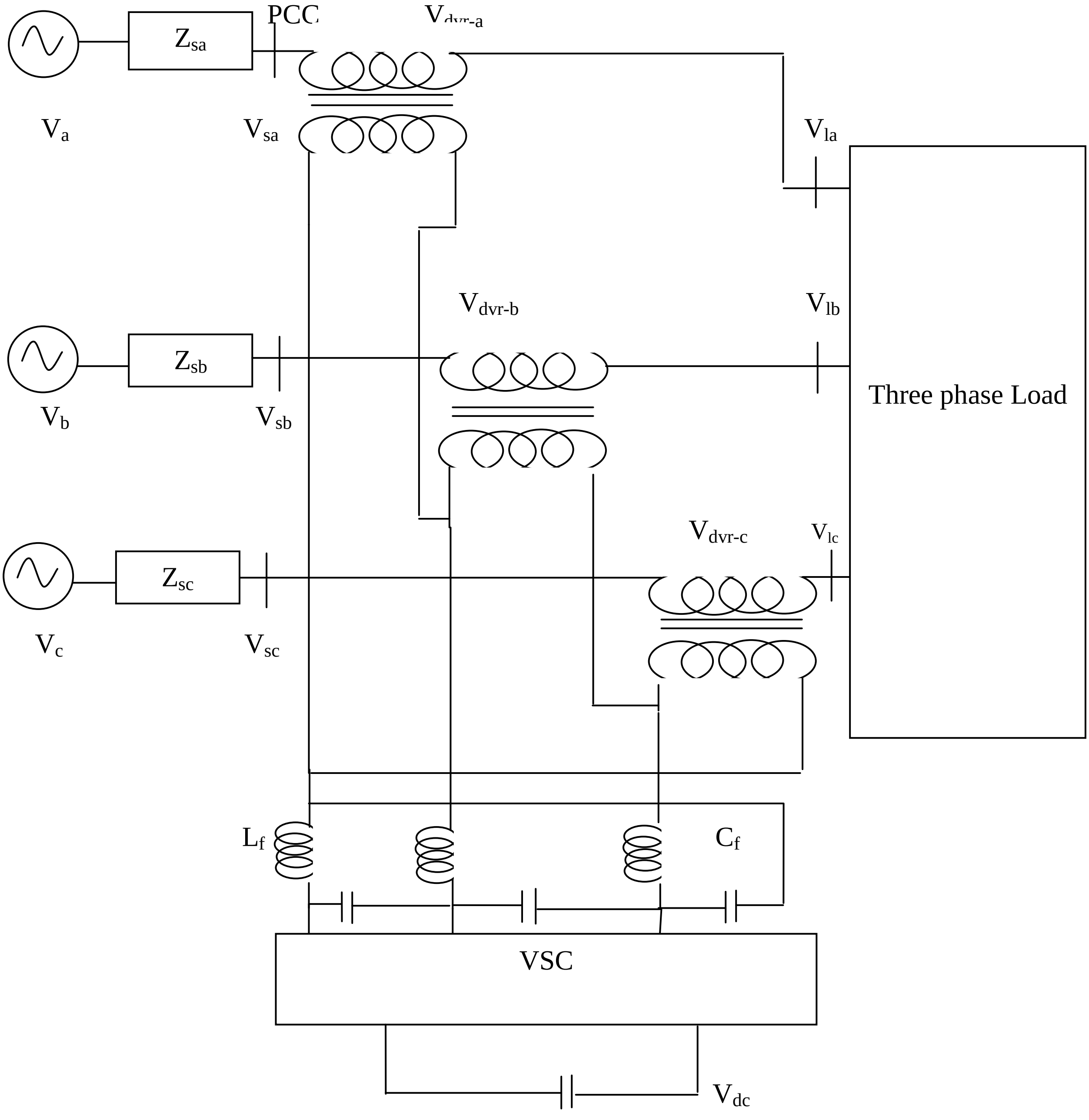


Fig 5.3: DVR connected in three phase system

Firstly a simple system without DVR is simulated as shown in Fig 5.4 it is as same as of Fig 5.3 but without any compensation device.

In the present work a three phase source with a three phase series load is considered. Two parallel loads are used for creating sag and swell in the supply. They are connected via three phase circuit breaker so that three phase load 1 can create voltage swell whereas three phase load 2 can create voltage sag in the source voltage by setting the transient time of the two breakers. When this system is simulated it can be seen that the load voltage also suffers from voltage dip and voltage swell and also it is not of required magnitude. Hence, a compensation device is needed as to compensate the voltage so to provide a load a constant voltage.

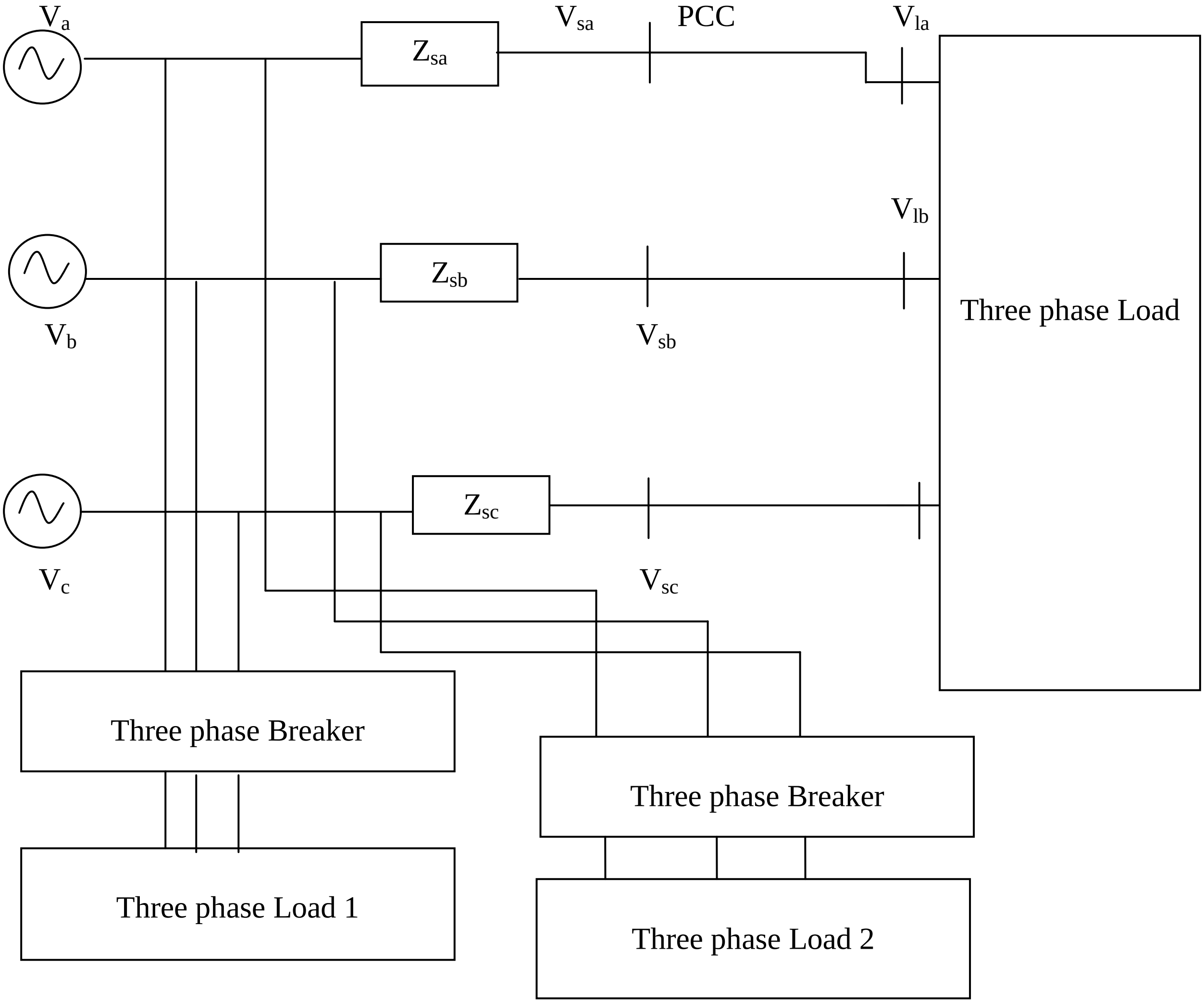


Fig 5.4: Three phase distribution system without DVR

5.3 CONTROL OF DVR

Two control strategies for a dynamic voltage controller are analyzed. The compensation for voltage sags using a DVR can be performed by injecting/absorbing reactive power or real power. When the injected voltage is in quadrature with the current at the fundamental frequency, compensation is by injecting reactive power and the DVR is with self supported mode. The control technique adopted should consider the limitations such as the voltage injection capability, transformer rating and size of the energy storage.

5.3.1 Control of DVR using Self generated PWM Technique

Fig 5.5 represents the direct control block. A system is same as shown in Fig 5.3 but with direct control method as described. In direct control block a self generated PWM inverter is used and the controlling is done by adjusting the modulation index of the inverter. It is a kind of open loop strategy in which DVR can only inject a fix amount of voltage. This injected voltage cannot be varied from load to load. If the load is varied, modulation index has to be varied.

When simulated in MATLAB/SIMULINK it has been seen that the voltage injected by the DVR can be varied by adjusting the modulation index. The appropriate index is selected keeping in view the load voltage and thus DVR compensates the load voltage

This method is not feasible as it is a kind of manual control because for every load voltage we need a separate modulation index that has to be set which is very hard to do.

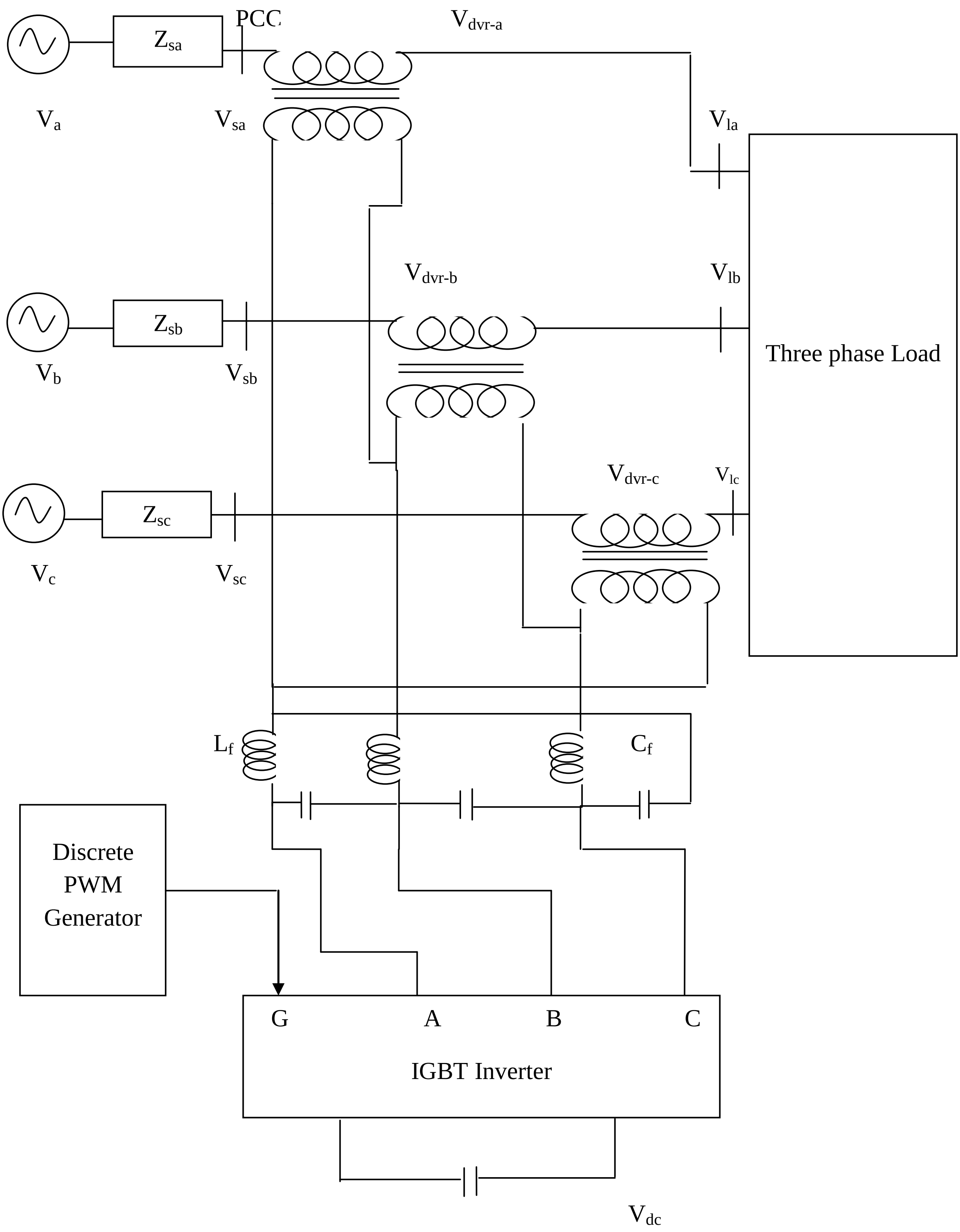


Fig 5.5: Block diagram of DVR using self generated PWM technique

5.3.2 Control of DVR using SRF Theory

As shown in fig 5.1 a capacitor supported DVR connected to three phase critical loads system is controlled here by SRF (synchronous reference frame) theory. Here the control block of the DVR in which the synchronous reference frame (SRF) theory is used for the control of self supported DVR. The voltages at PCC i.e V_{sa}, V_{sb}, V_{sc} and the load terminal V_{la}, V_{lb}, V_{lc} are sensed for deriving the IGBT gate signals. The voltages at PCC i.e V_{sa}, V_{sb}, V_{sc} are converted to the rotating reference frame using the abc-dqo conversion using the Park's transformation. [41]

$$\begin{bmatrix} V_{lq} \\ V_{ld} \\ V_{l0} \end{bmatrix} = 2/3 \begin{pmatrix} \sin\theta & \sin(\theta - (2\pi/3)) & \sin(\theta + (2\pi/3)) \\ \cos\theta & \cos(\theta - (2\pi/3)) & \cos(\theta + (2\pi/3)) \\ 0.5 & 0.5 & 0.5 \end{pmatrix} \begin{bmatrix} V_{la}^{*} \\ V_{lb}^{*} \\ V_{lc}^{*} \end{bmatrix} \tag{5.1}$$

Harmonics and the oscillatory component of the voltage is eliminated using low pass filters (LPF). The componenets of voltages in d-axis and q-axis are,

$$V_{sd} = V_{sd\text{-}dc} + V_{sd\text{-}ac} \tag{5.2}$$

$$V_{sq} = V_{sq\text{-}dc} + V_{sq\text{-}ac} \tag{5.3}$$

The main function of any control strategy or the compensating strategy for compensation of voltage quality problems is to provide the rated load voltage of rated magnitude and undistorted. The amplitude of load terminal voltage $V_{la,}$ V_{lb} and V_{lc} is controlled to its reference voltage $V_{la}^{*}{}_{,}$ V_{lb}^{*} and V_{lc}^{*} using PI controller. The output of PI controller is considered as the reactive component of voltage for voltage regulation of load voltage. The amplitude of load voltage V_l is calculated from the ac voltages $V_{la,}$ V_{lb}, V_{lc} as,

$$V_l = (2/3)^{1/2} (V_{la}^2 + V_{lb}^2 + V_{lc}^2)^{1/2} \tag{5.4}$$

Then, a PI controller is used to regulate this to a reference value. The reference load voltages $V_{la}^{*}{}_{,}$ V_{lb}^{*} and V_{lc}^{*} in abc frame is obtained from the reverse Park's transformation as

$$\begin{pmatrix} V_{la}^{*} \\ V_{lb}^{*} \\ V_{lc}^{*} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - (2\pi/3)) & \sin(\theta - (2\pi/3)) & 1 \\ \cos(\theta + (2\pi/3)) & \sin(\theta + (2\pi/3)) & 1 \end{pmatrix} \begin{pmatrix} V_{lq} \\ V_{ld} \\ V_{l0} \end{pmatrix} \qquad (5.5)$$

The error between the sensed load voltage V_{la}, V_{lb} and V_{lc} and the reference load voltages V_{la}^{*}, V_{lb}^{*} and V_{lc}^{*} are used over a controller to generate the gating pulses to the VSC of DVR. Fig. 5.6 shows the control block of the DVR in which the synchronous reference frame (SRF) theory is used for the control of self supported DVR.[38]

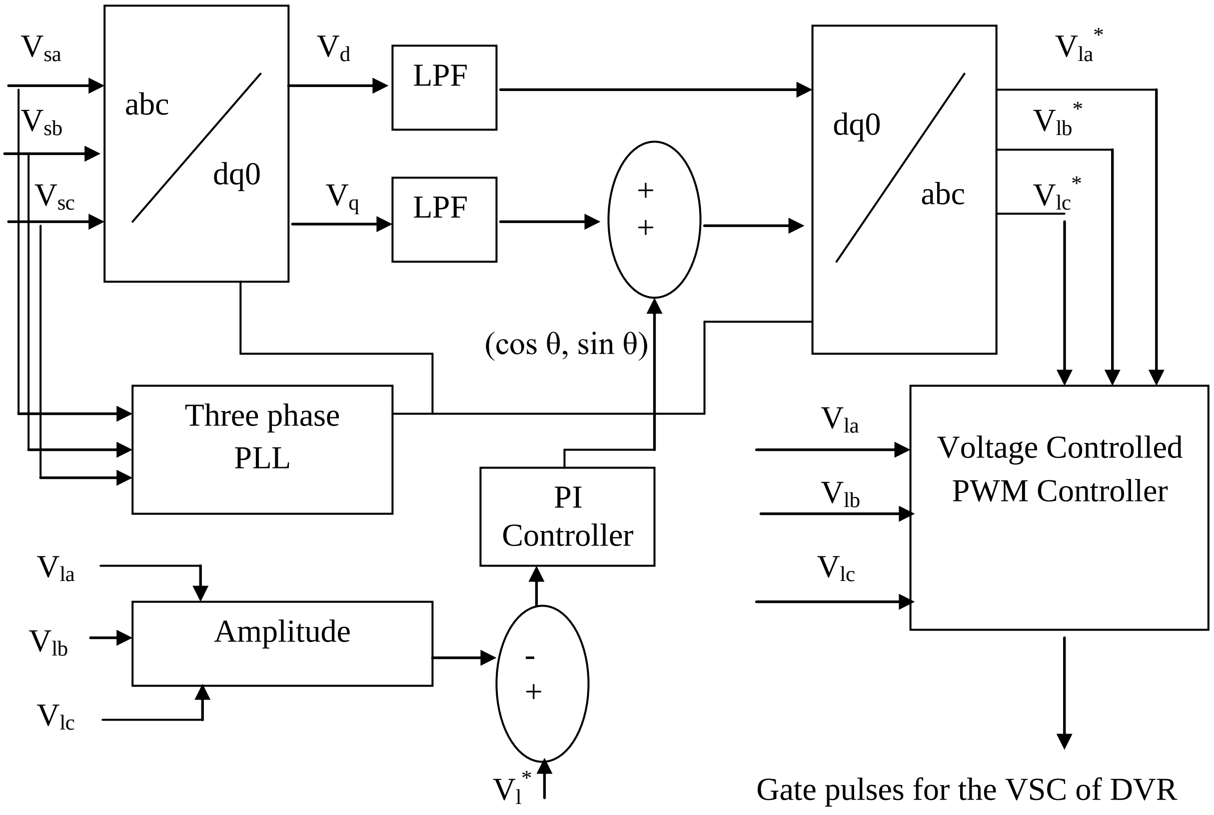


Fig 5.6: Control block of DVR using SRF theory

5.4 SIMULATION AND RESULTS

i. **Three phase system without DVR:** The DVR three phase connected system is as shown in Fig 5.4 is modeled using the MATLAB / Simulink. The sag and swell is created in the source voltage from 0.2 sec to 0.4 sec and 0.6 sec to 0.8 sec respectively. Fig 5.7 shows the wave forms of source voltage and load voltage under these conditions it has been observed that load voltage also experiences the sag and swell which is not acceptable. This voltage fluctuation can cause damage to loads etc.

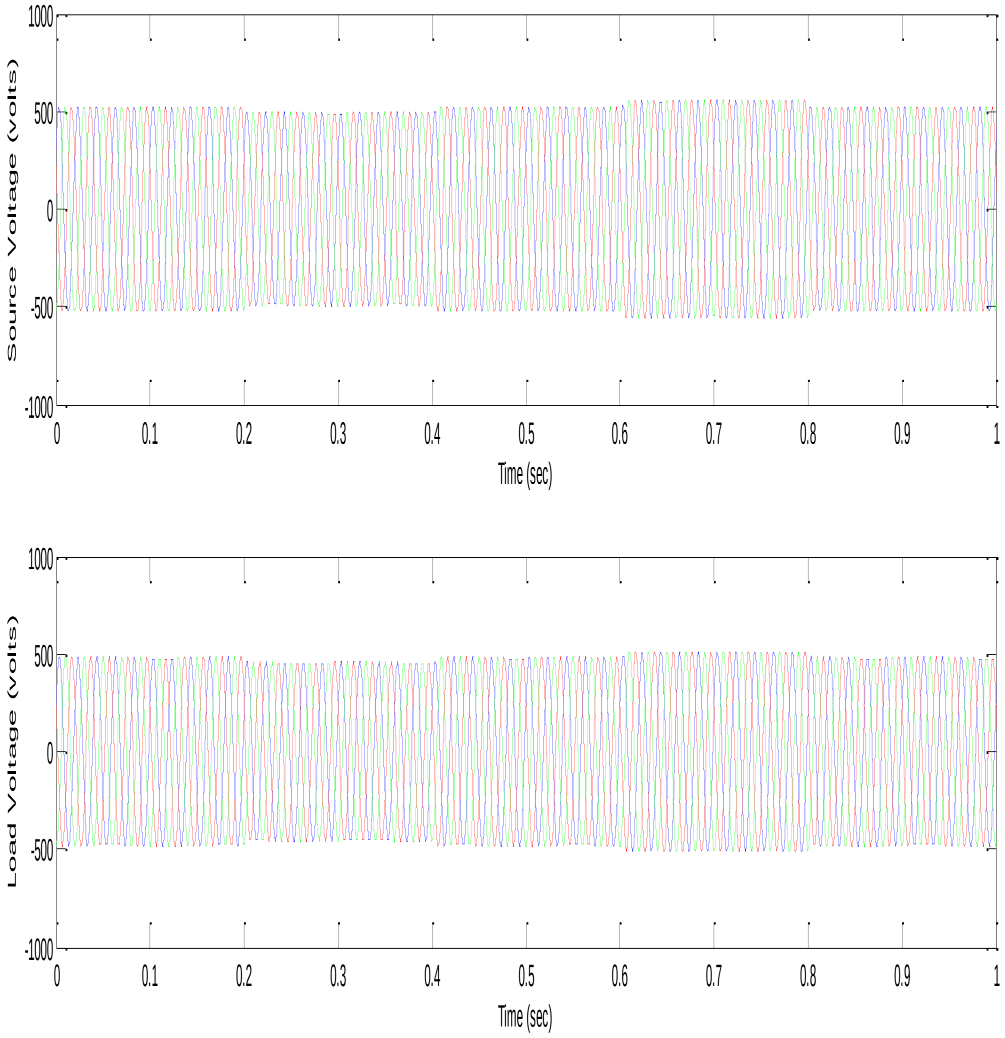


Fig 5.7: Simulation results for three phase connected system without DVR

ii. **DVR control by self generated PWM technique:** Fig 5.8 presents the results obtained from the self generated PWM control strategy. It can be seen from the graphs that source voltage experiences the sag and swell but load voltage do not suffer from these voltage fluctuations as voltage at load side is constantly maintained by the help of DVR. The load considered is a l5 kVA, 0.8 pf lag linear load. The modulation index of discrete PWM generator is so adjusted that DVR is able to maintain the load side voltage.

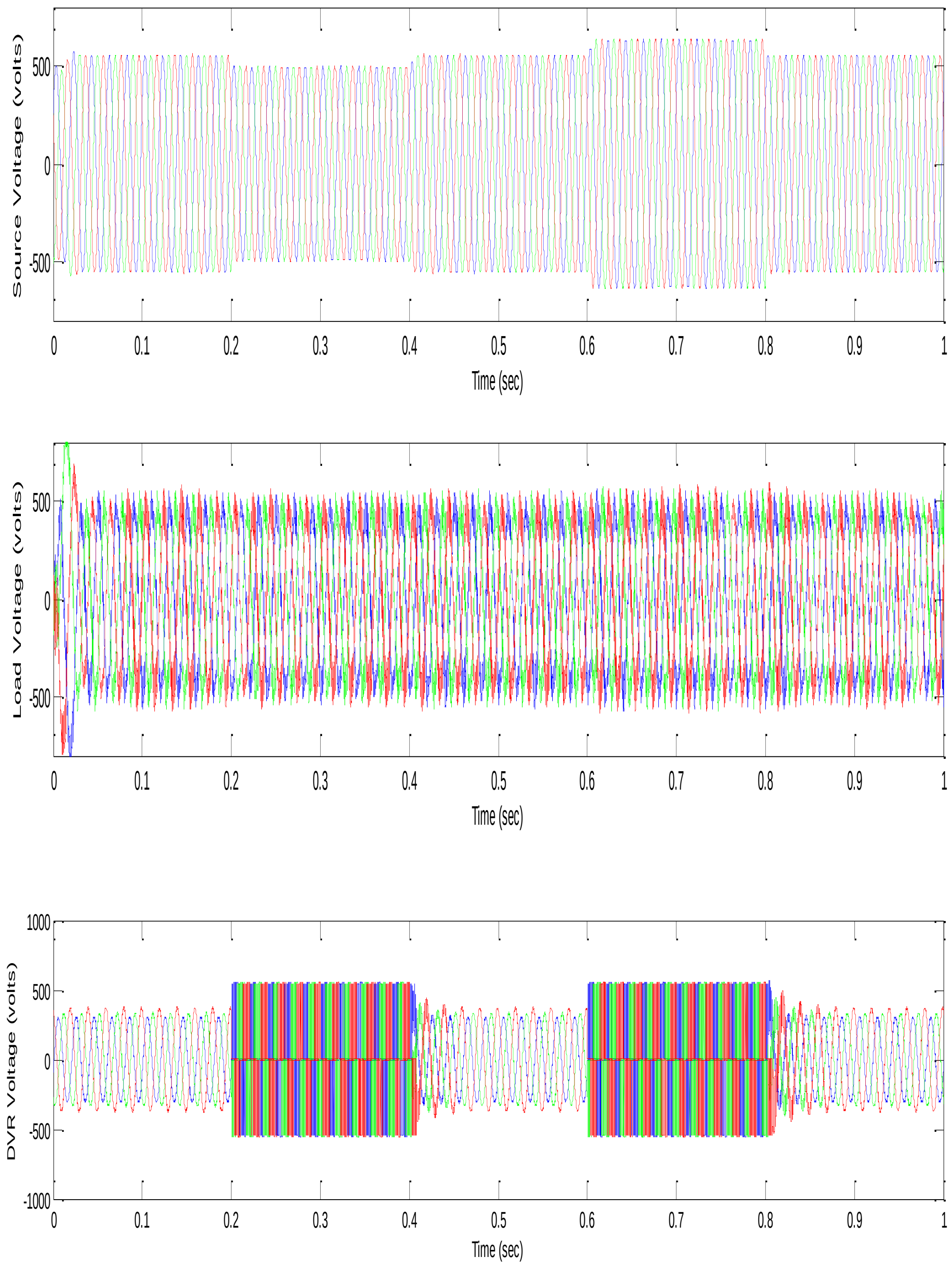


Fig 5.8: Simulation results for self generated PWM technique

Fig 5.9 shows the source voltage and load voltage and DVR voltage with same modulation index but different load i.e 20 kVA, 0.8 p.f. It is observed that now the load voltage is not fully compensated. The values used in the designing of the self generated PWM technique are given in appendix B.

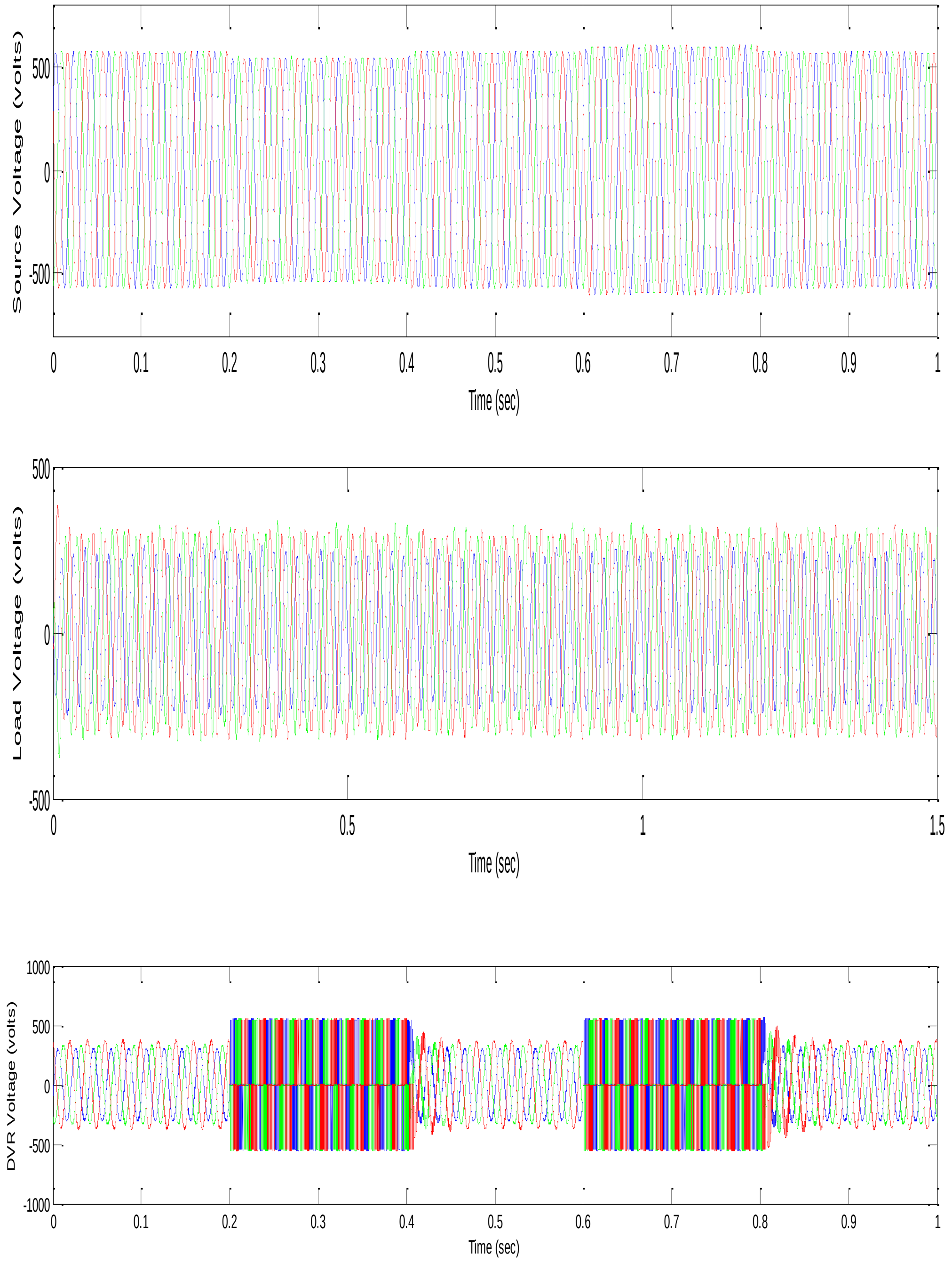
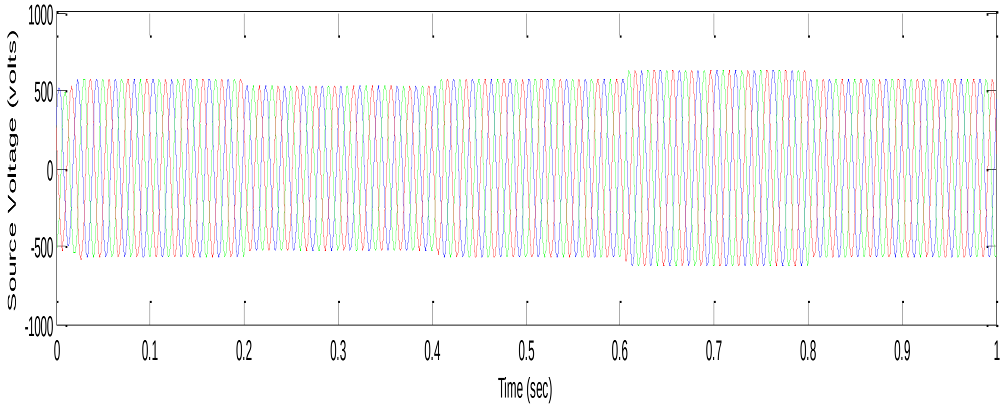
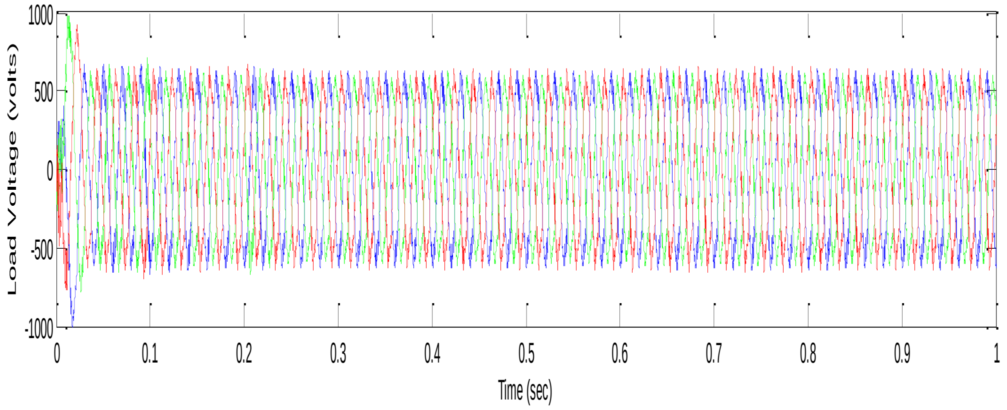
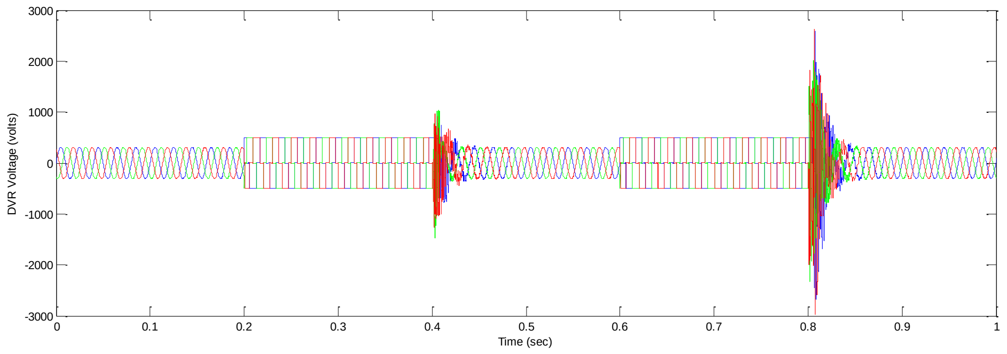


Fig 5.9: Simulation results for self generated PWM technique with increased load

iii. **Control of DVR using SRF method:** The control algorithm for the DVR using SRF method is as shown in Fig.5.6 is also modeled in MATLAB / SIMULINK. The load considered is a l5 kVA, 0.8pf lag linear load. The parameters of the considered system for the simulation study are shown in appendix B. Through this system the performance of the DVR is demonstrated for different supply voltage disturbances such as sag and swells in supply voltage. Fig 5.10 shows the performance of the system under voltage sag and swell conditions. The load and PCC voltages of phase A are shown in Fig. 5.11, which shows the in-phase injection of voltage by the DVR







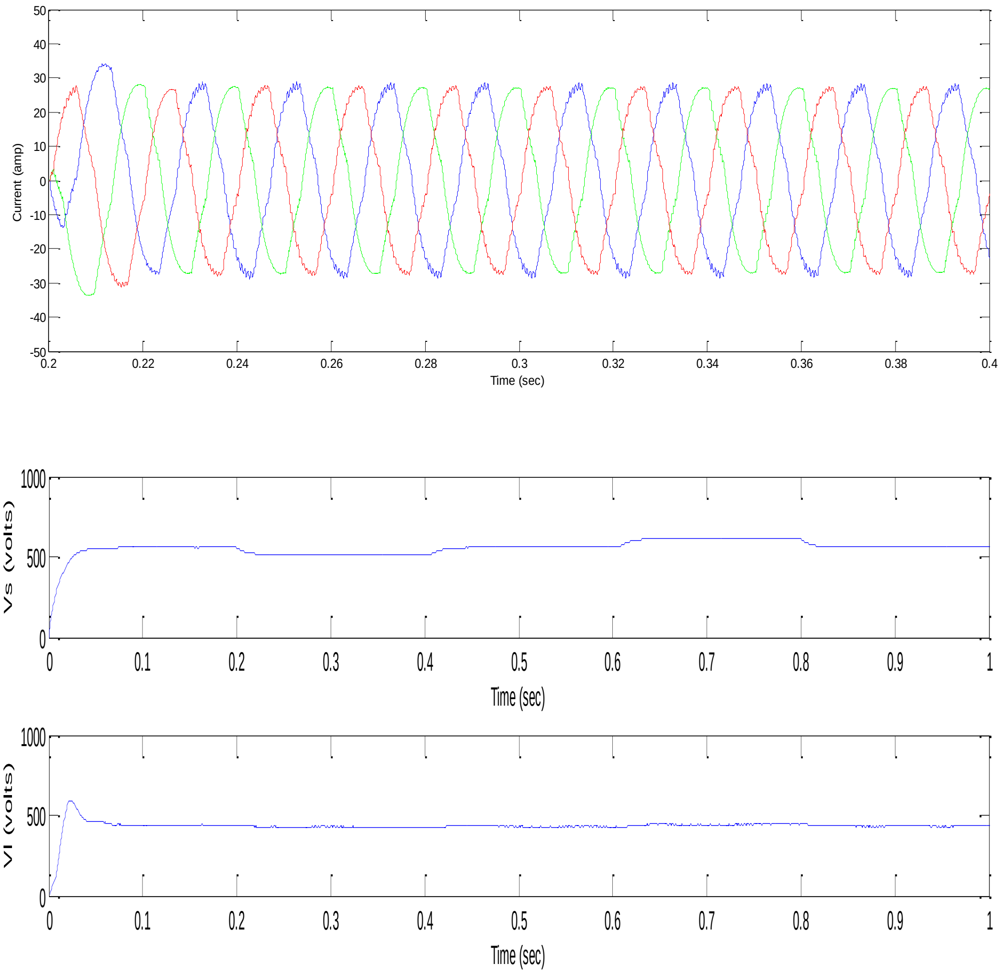


Fig 5.10: Simulation results by SRF control strategy

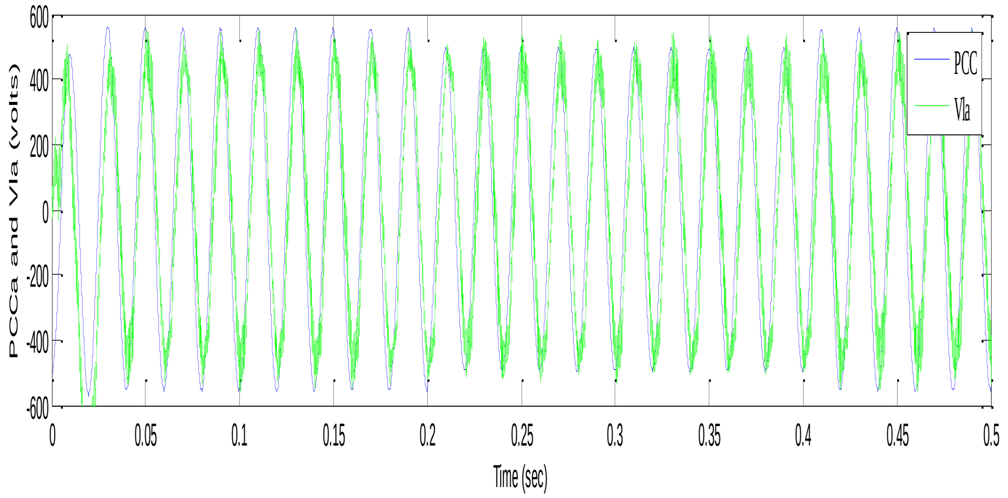


Fig 5.11: In-phase injection of voltage by DVR

Fig 5.12 shows the source voltage and load voltage and DVR voltage different load i.e 20 kVA, 0.8 p.f. It is observed that now also the load voltage is fully compensated. The values used in the designing of the SRF method are given in appendix B.

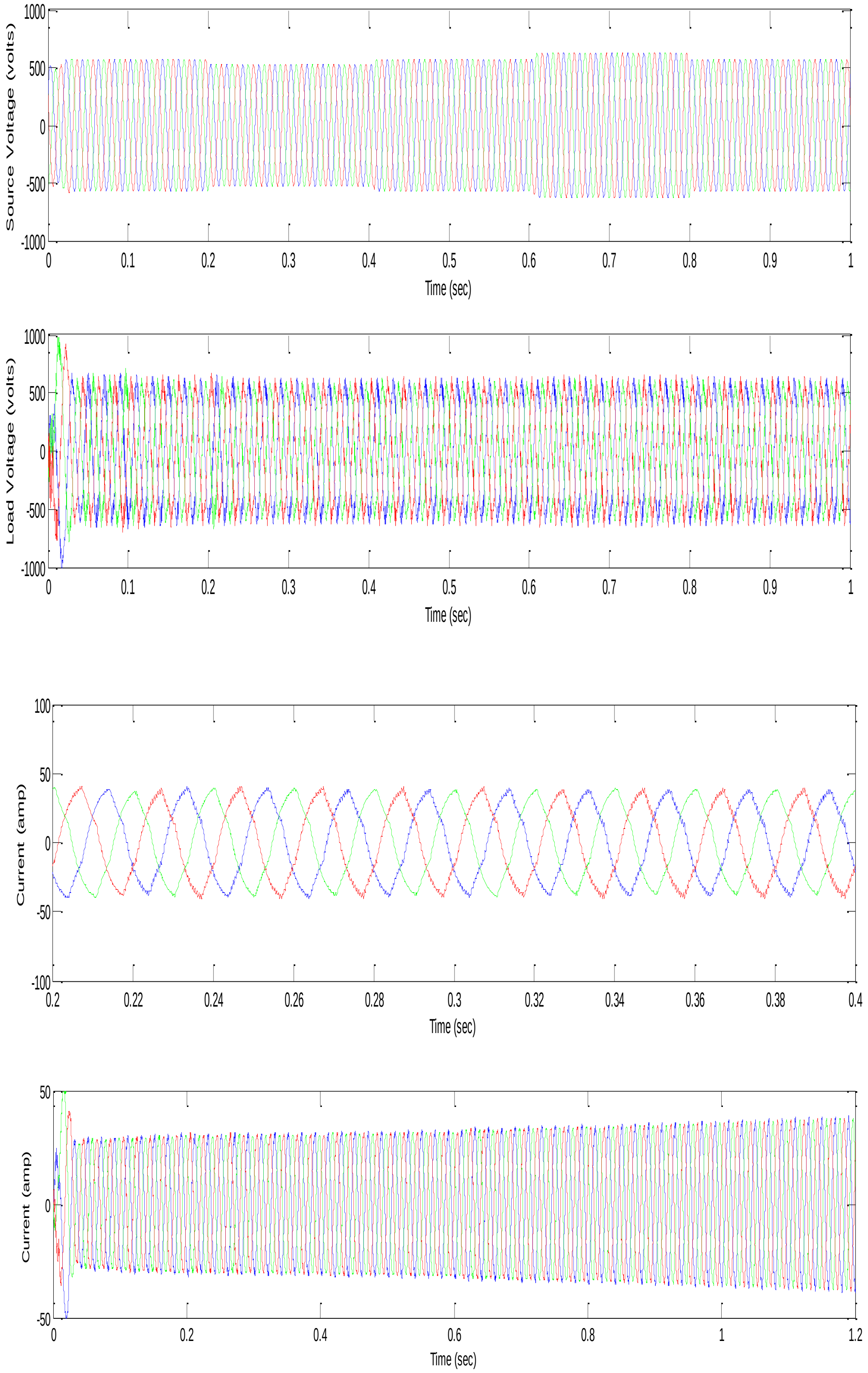


Fig 5.12: Simulation results by SRF control strategy with increased load

5.5 CONCLUSION

The performance of a distribution system has been demonstrated under various conditions such as system without any compensation device (DVR), system with compensation device. When distribution system is simulated without any compensation device i.e without DVR it has been seen that load voltage also suffers from same voltage disturbances as that of source voltage.

Two methods are used for the control of DVR. When DVR is controlled by a self generated PWM technique the load voltage is regulated with the help of modulation index. When the same control scheme is implemented with a changed load, the control scheme is no more effective i.e. load voltage is no more maintained. Hence, the modulation index has to be changed, if the load is changed.

In the second method, DVR is controlled using SRF theory. It is seen that the load voltage is maintained if there is disturbance in the source voltage. Even with the change of load DVR is able to maintain the load side voltage. The voltage injection by the DVR is in phase with the PCC voltage i.e the control is by a in-phase injection method. .Thus, it can be concluded that the DVR control using SRF theory is better and more feasible than PWM technique.

CHAPTER 6

INTERLINE DYNAMIC VOLTAGE RESTORER

- *Introduction*
- *Principle of IDVR*
- *Operation of IDVR*
- *Elements of IDVR*
- *Energy Storage Requirement for an IDVR System*
- *Voltage Compensation in a Two Feeder IDVR System*
- *Summary*

CHAPTER 6

INTERLINE DYNAMIC VOLTAGE RESTORER

INTRODUCTION

The need of the electrical power is increasing and simultaneously the problems while transmitting the power through the distribution system are also increasing. The Dynamic Voltage Restorer (DVR) provides an advanced and economical solution for both voltage sag and swell problems. This increase or decrease of voltage is compensated by injecting the voltage in series with the supply at the time of disturbances using DVR. DVR is a DC-to-AC solid-state switching converter which injects three single phase AC output voltages in series and in synchronism with the distribution feeder. It is designed to mitigate voltage sags, swells and harmonic voltages for large sensitive loads served at distribution voltage.

The voltage-restoration process involves real-power injection into the distribution system. The Interline DVR (IDVR) discussed in this chapter provides a way to compensate the voltage deviation caused in a feeder. The IDVR consists of several DVRs connected to different distribution feeders in the power system sharing common energy storage. Here, one DVR in the IDVR system works in voltage-sag/swell compensation mode while the other DVR in the IDVR system operate in power-flow control mode. The single phase model of the IDVR system operates by Multiple Pulse Width Modulation (PWM). This IDVR system is presently one of the most cost-effective and a highly efficient method to mitigate voltage sag or swell. The concept of Interline Dynamic Voltage Restorer (IDVR) is similar to the Interline Power Flow Controller (IPFC) concept. [42]

6.2 PRINCIPLE OF IDVR

In this chapter, a two-line IDVR system is explained which employs two DVRs connected to two different feeders originating from two grid substations, could be of the same or different voltage level. However the DC-link of these two DVRs could be connected to a common DC-link. This would cut down the cost as sharing a common DC-link reduces the DC-link storage capacity significantly compared to that of a system whose loads are protected by clusters of DVRs with separate energy storages.

When one of the DVRs compensates for voltage sag or swell produced, the other DVR in IDVR system operates in power-flow control mode. This is to replenish DC- link energy storage, which is depleted due to the power taken by the DVR working in the voltage-sag/swell compensation mode. The DVR is operated in such a fashion that it does not supply or absorb any active power during the steady-state operation. It is desirable to have a minimum VA rating of the DVR, for a given system without compromising compensation capability. The voltage-restoration process involves real- power injection into the distribution system, the capability of a particular DVR topology, especially for compensating long-duration voltage sags, depends on the energy storage capacity of the DVR. The main factor which limits capabilities of a particular DVR in compensating long-duration voltage sags is the amount of stored energy within the restorer.[42]

6.3 OPERATION OF IDVR

DVR is a recently proposed series connected solid state device that injects voltage into the system in order to regulate the load side voltage. It is normally installed in a distribution system between the supply and the critical load feeder at the point of common coupling (PCC). Other than voltage sags and swells compensation, DVR can also compensate other features like: line voltage harmonics compensation, reduction of transients in voltage and fault current limitations.

One DVR in IDVR act for compensation in a feeder and other in power flow control mode. DVR working in compensation mode has to inject a voltage of required magnitude and frequency, so that it can restore the load side voltage to the desired amplitude and waveform even when the source voltage is unbalanced or distorted. It injects the missing voltage cycles into the system through series injection transformer whenever voltage sags are present in the system supply voltage. It operates in stand-by mode during normal condition. During disturbances, nominal system voltage will be compared to the voltage variation. This is to get the differential voltage that should be injected by the DVR in order to maintain supply voltage to the load within limits. The DVR is operated in such a fashion that it does not supply or absorb any active power during the steady-state operation. The location of IDVR in distribution system is as shown in the following figure 6.1.

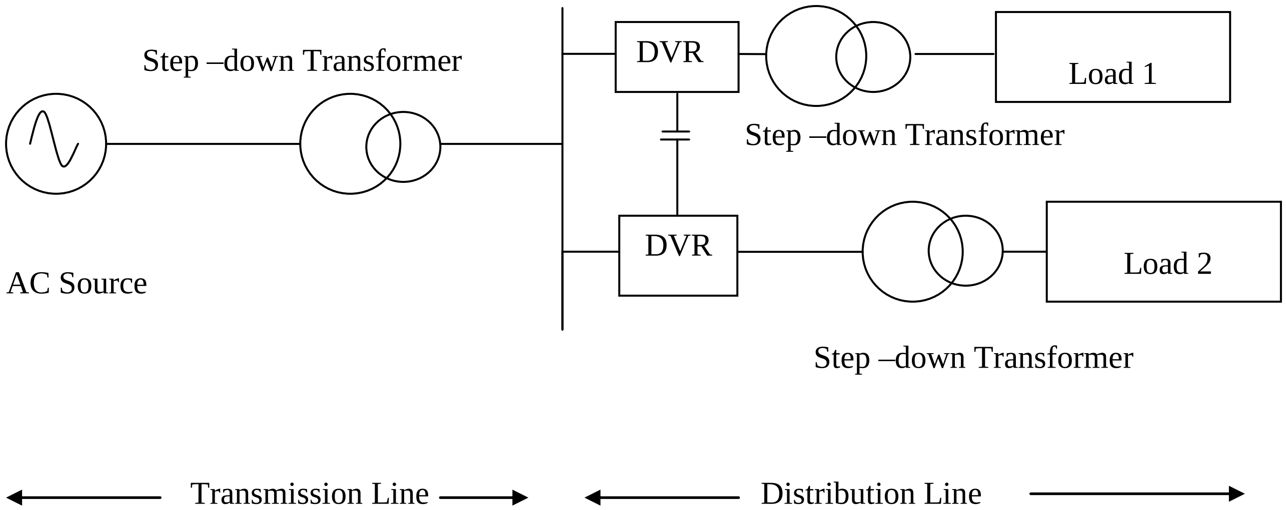


Fig 6.1 Location of IDVR

6.4 ELEMENTS OF IDVR [42]

The IDVR system consists of several DVRs in different feeders, sharing a common DC-link. A two-line IDVR system shown in Figure 6.2 employs ~~two~~ DVRs are connected to two different feeders where one of the DVRs compensates for voltage sag or swell produced, the other DVR in IDVR system operates in power-flow control mode. Voltage sag/swell in a transmission system is likely to propagate to larger electrical distance than that in a distribution system. Due to these factors, the two feeders of the IDVR system in Figure 3 are considered to be connected to two different grid substations. It is assumed that the voltage distortion in Feeder_1 would have a lesser impact on Feeder_2.

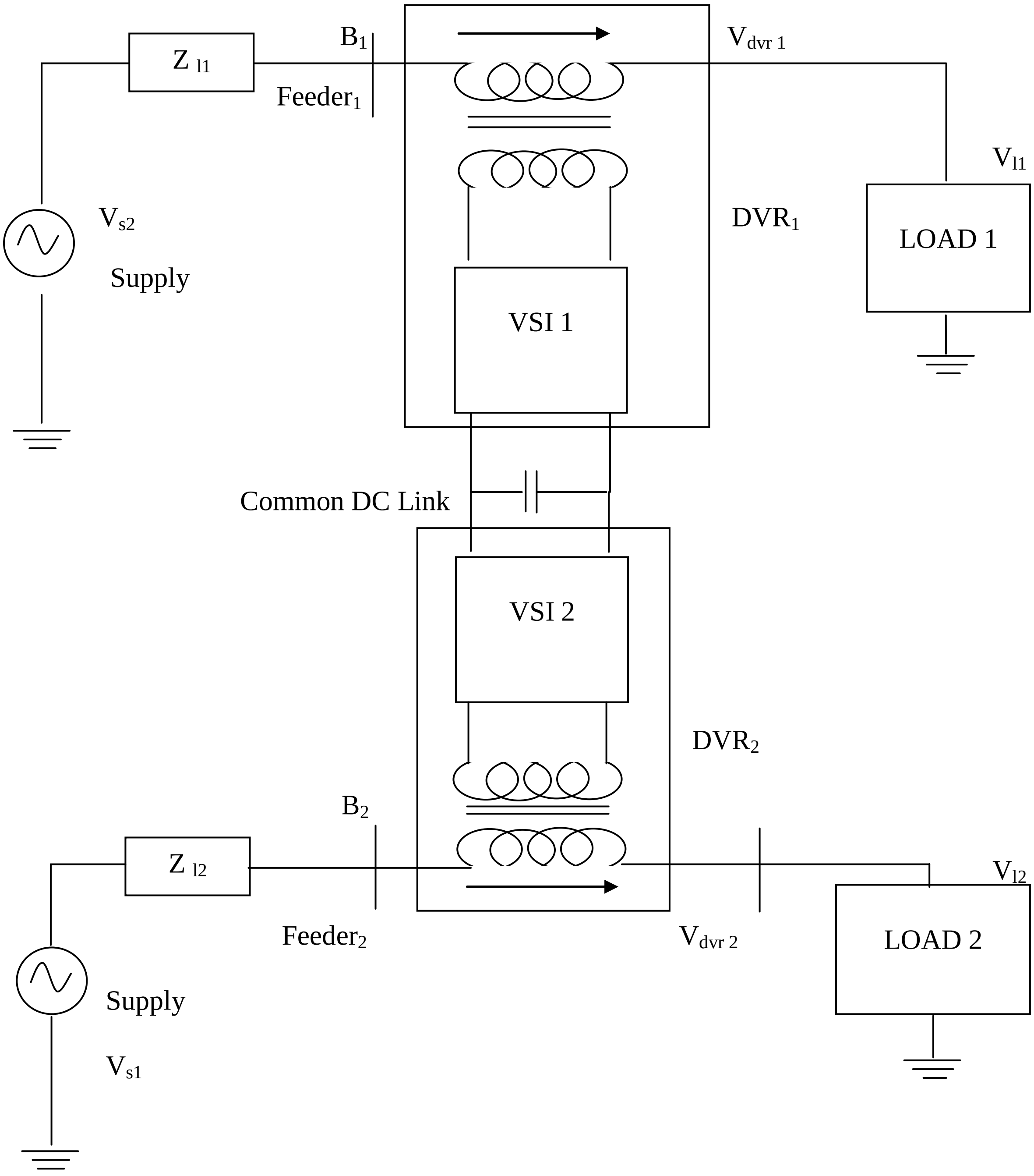


Fig 6.2 Schematic Diagram of IDVR

The upstream generation-transmission system is applied and the two feeders can be considered as two independent sources. These two voltage sources V_{s1} and V_{s2} are connected in series with the line impedances Z_{l1} and Zl_2 which is in-turn connected to the buses B_1 and B_2 as in Figure 6.2. The DVR is connected in series with the feeder and the DVRs across different feeders are connected by a common DC-link. The common DC-link indicated between the two DVRs is a large capacitor that acts as a voltage storage device. A Voltage Source Inverter (VSI) is present to invert the DC supply to AC voltage, which is injected to the transformer. The load across each feeder is connected in series to the DVR, where V_{l1} and V_{l2} are the voltages across the load. The pulse can be generated using various modulation techniques. In DVR, the pulse for the switch is generated using Multiple Pulse Width Modulation (PWM).

6.5 ENERGY STORAGE REQUIREMENT OF AN IDVR SYSTEM

The injection of an appropriate voltage needs a certain amount of real and reactive power which must be supplied by the DVR. Supply of real power is met by means of an energy storage facility connected in the DC-link. Large capacitors are used as a source of energy storage in most of the DVRs. Generally, capacitors are used to generate reactive power in an AC power system. However, in a DC system, capacitors can be used to store energy. When the energy is drawn from the energy storage capacitors, the capacitor terminal voltage decreases. Hence, large capacitors in the DC-link energy storage are needed to effectively mitigate voltage sag/swell of large depths and long durations.

6.6 VOLTAGE COMPENSATION IN A TWO FEEDER IDVR SYSTEM

6.6.1 Voltage Sag Compensation

The voltage sag in a two-feeder IDVR system is caused due to sudden increase of the load across a feeder. Consider the condition when the DVR_1 in the IDVR system operates in voltage-sag compensating mode while the DVR_2 operates in power-flow control mode to keep the DC-link voltage at a desired level. When there is no voltage disturbance, the load voltage of $Feeder_2$ is equal to the bus voltage V_{b2}. During voltage sag, the DVR_2 should be operated to meet this condition while supplying real power to the common DC-link. The control schemes can be used to control the DVR. [48]

The simulink model for the control of IDVR for voltage sag compensation can be made and analyzed. The general requirement of such control scheme is to obtain an AC waveform with low Total Harmonic Distortion (THD) and good dynamic response against supply and load disturbance whether the DVR in the IDVR system operates in voltage sag compensation or power flow control mode.

6.6.2Voltage Swell Compensation

The voltage swell in a two-feeder IDVR system is caused due to sudden decrease of the load across a feeder. Consider the condition when the DVR_1 in the IDVR system operates in voltage-swell compensating mode while the DVR_2 operates in power-flow control mode to keep the DC-link voltage at a desired level. When there is no voltage disturbance, the load voltage of $Feeder_2$ is equal to the bus voltage V_{b2}. During voltage swell, the DVR_2 should be operated to meet this condition while supplying real power to the common DC link.

The simulink model for the control of IDVR for voltage sag compensation can be made and analyzed. The general requirement of such control scheme is to obtain an AC waveform with low Total Harmonic Distortion (THD) and good dynamic response against supply and load disturbance whether the DVR in the IDVR system operates in voltage swell compensation or power flow control mode.

6.7 SUMMARY

In this chapter a systematic study of a interline dynamic voltage restorer (IDVR), in which one DVR can regulate voltage at the load terminals against any variation in the supply side voltage and other DVR operates in power flow control mode, has been presented. Its operating principle, configuration and structure are also discussed. It has been shown that both the DVR’s in IDVR uses a common dc voltage source. The operation of one DVR in IDVR system which is acting in compensation mode acts as any single DVR connected in a system for compensation. The capability of the device is also demonstrated. Some of the main conclusions are:

- DVR acts as interface equipment between utility and customer, static var device provide series compensation. It is efficient and effective modern custom power device with lower cost, smaller size, and fast dynamic response to the disturbance.
- IDVR is designed to mitigate voltage sags, swells and harmonic voltages for large sensitive loads served at distribution voltage. This IDVR system is presently one of the most cost-effective and a highly efficient method to mitigate voltage sag or swell.
- IDVR is cost-effective and it is useful for sag-free transmission with high power quality. The capability of injection voltage by DVR system is 50% of nominal voltage. This allows IDVRs to successfully provide protection against sags up to 50%.
- IDVR can also be used to mitigate the damaging effects of voltage swells, voltage unbalance, harmonics and other waveform distortions.
- IDVR is effective device for power quality enhancement due to its quick response and high reliability.
- IDVR is an effective apparatus to protect sensitive loads and the series connection makes it effective at locations where voltage dips are the primary problem.
- IDVR system is presently one of the most cost-effective as sharing a common DC-link. Highly efficient method to mitigate voltage sag or swell.

CHAPTER 7 *CONCLUSION AND FUTURE SCOPE*

- *Introduction*
- *Conclusion*
- *Future Work*

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

INTRODUCTION

New power electronic solutions have gained increased interest to solve well known power quality problems. Voltage disturbances have been reported as a major power quality problem and a series connected converter, like the DVR, is considered to be an effective and cost-effective solution to mitigate voltage disturbances. To gain a better understanding of voltage dip and swell compensation with a dynamic voltage restorer in the distribution system a number of aspects regarding the dynamic voltage restorer have been analyzed and tested in this thesis.

7.2 CONCLUSION

By the results presented in this thesis it is believed that all objectives of the research project have been fulfilled. The main conclusions are identified as:

- DVR’s different modes and injection methods are discussed and it has been seen that DVR do not exchange real and reactive power in normal state.
- Regarding the system topology for a DVR four topologies have been studied. It includes two topologies with stored energy and two methods, which uses the remaining supply voltages and increase the supply current to restorer the load voltages.
- Modelling of DVR has been studied and two schemes are used for voltage control. The closed loop voltage control scheme shows better output voltage and better damping as compared to open loop scheme.
- Different control strategies have been analyzed and simulated for different load conditions. The DVR restores the load voltages to the pre-voltage levels. The load voltages are not phase shifted that is it is in phase injection scheme. The SRF theory based control scheme proves to be better than self generated PWM technique.
- The inter line dynamic voltage restorer has been discussed.

7.3 FUTURE WORK

Several topics, worthwhile, have not been pursued in this thesis. Interesting topics for the future research in DVRs include:

- Verification of the HV-DVR performance at a location with different types of voltage dips originated from faults at the transmission level and distribution level.
- Further investigation of DVR topologies including the direct connected DVR.

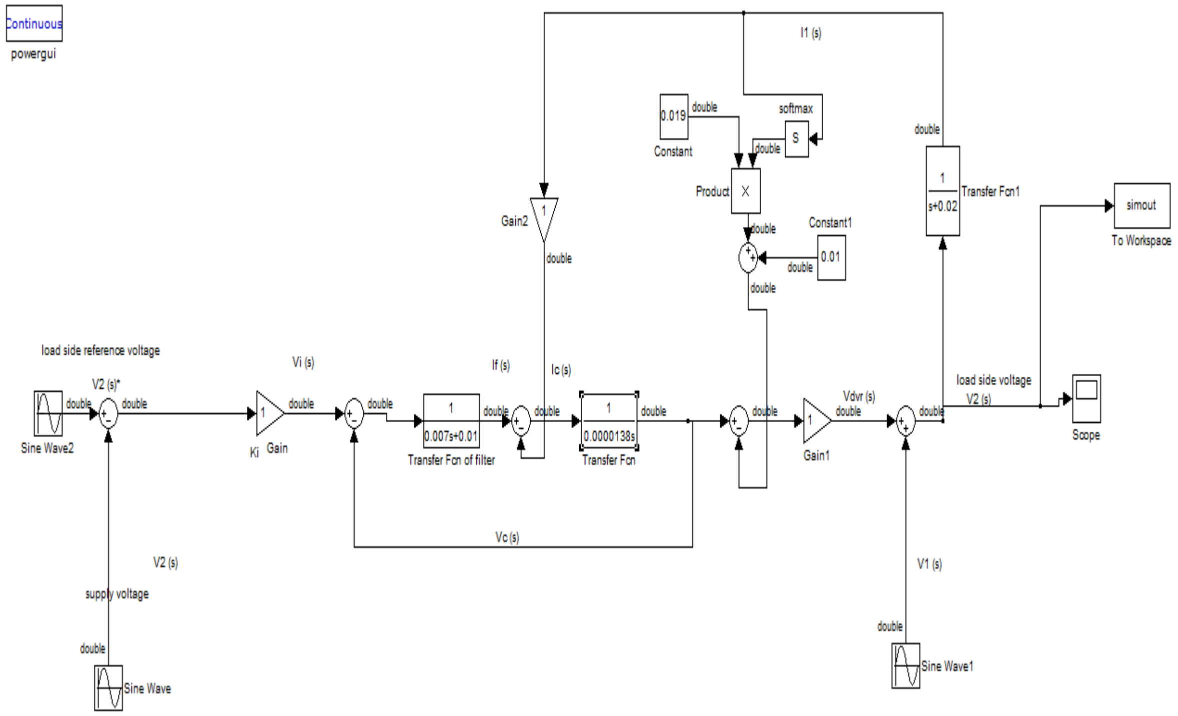
- Testing a number of different loads, such as thyristor loads, motor loads, active rectifier loads.
- Thoroughly design of the line-filter, to have an optimum damping of the switching harmonics generated by the VSC and to avoid the oscillations at non-linear load. Furthermore, oscillations at the beginning and at the end of the voltage dip are expected to be reduced by an appropriate filter design.
- Control improvements to reduce the line-filter oscillations
- Cost calculations compared to the value of the improved voltage quality.
- Use of inter line dynamic voltage restorer (IDVR) for power quality improvement.

APPENDIX A

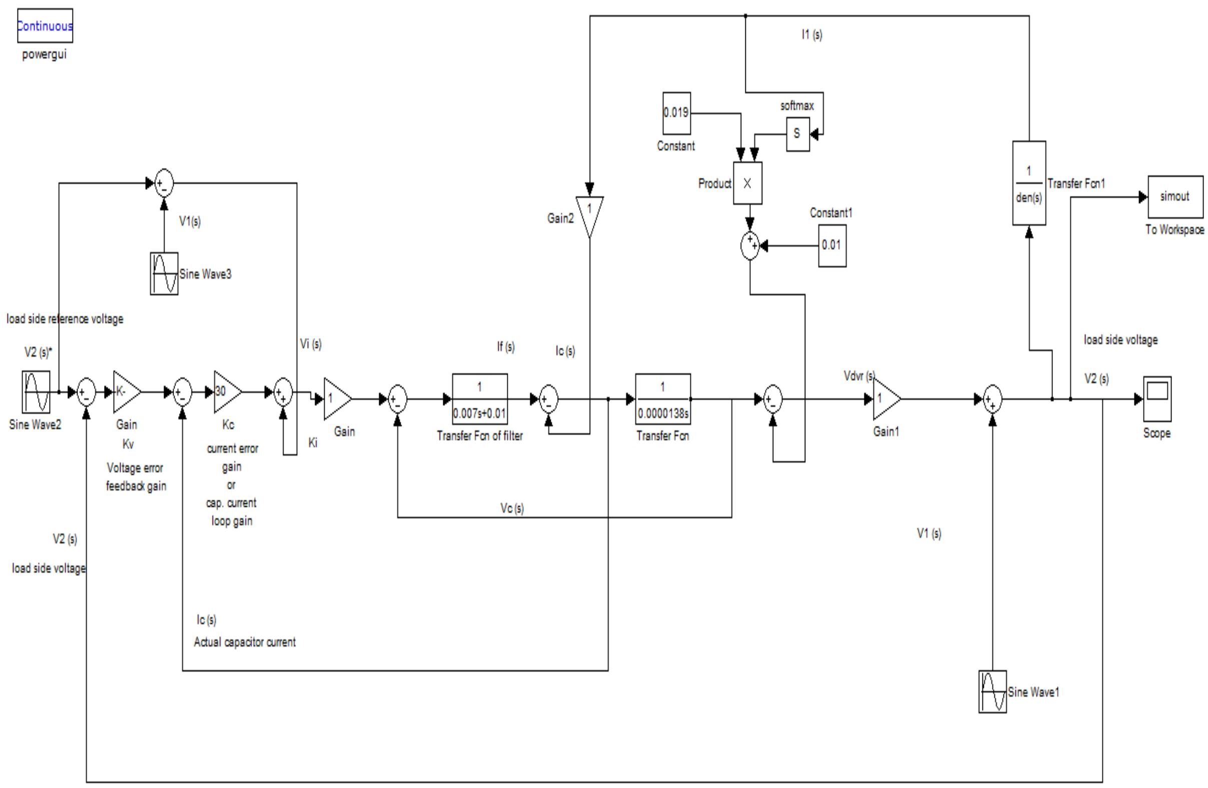
OPEN LOOP & CLOSED LOOP VOLTAGE CONTROL STRATEGIES

A.1 SIMULATION DIAGRAM

i. For Open Loop Voltage Control Scheme



ii. For Closed Loop Voltage Control Scheme



A.2 SYSTEM DATA

Parameters	**Values used in the model**
Distribution supply voltage	220 V
Series transformer turns ratio	1:1
DC link voltage	200 V
Filter capictance	13.8 µ F
Filter inductance	7 m H
Load	247 VA
Transformer series impedance	6 Ω

$a_{10} = (L_l + n^2 L_t) L_f C_f$

$a_{20} = (L_l + n^2 L_t) r_f C_f + (r_l + n^2 r_t) L_f C_f$

$a_{30} = r_f C_f (r_l + n^2 r_t) + n^2 L_f + n^2 L_t + L_l$

$a_{40} = n^2 r_f + n^2 r_t + r_l$

$$b_{10} = \frac{a_{10}}{(L_l + n^2 L_t)} = L_f C_f$$

$$b_{20} = \frac{a_{20} - (r_l + n^2 r_t) b_{10}}{(L_l + n^2 L_t) b_{10}} = \frac{r_f}{L_f}$$

$$b_{30} = \frac{a_{40}}{(r_l + n^2 r_t) b_{10}} = \frac{r_l + n^2 r_t + n^2 r_f}{(r_l + n^2 r_t) L_f C_f}$$

$a_5 = (L_l + n^2 L_t) L_f C_f = a_{10}$

$a_6 = (L_l + n^2 L_t) r_f C_f + (r_l + n^2 r_t) L_f C_f + K_i K_c (L_l + n^2 L_t) C_f$
$= a_{20} + K_i K_c (L_l + n^2 L_t) C_f$

$a_7 = r_f C_f (r_l + n^2 r_t) + n^2 L_f + n^2 L_t + L_l (1 + n K_i K_c K_v) + K_i K_c (r_l + n^2 r_t) C_f$

$= a_{30} + L_l n K_i K_c K_v + K_i K_c (r_l + n^2 r_t) C_f$

$a_8 = n^2 r_f + n^2 r_t + r_l (1 + n K_i K_c K_v)$

$= a_{40} + r_l n K_i K_c K_v$

$$b_4 = \frac{a_5}{(L_l + n^2 L_t)} = L_f C_f$$

$$b_5 = \frac{a_6 - (r_l + n^2 r_t) b_4}{(L_l + n^2 L_t) b_4} = \frac{r_f + K_i K_c}{L_f}$$

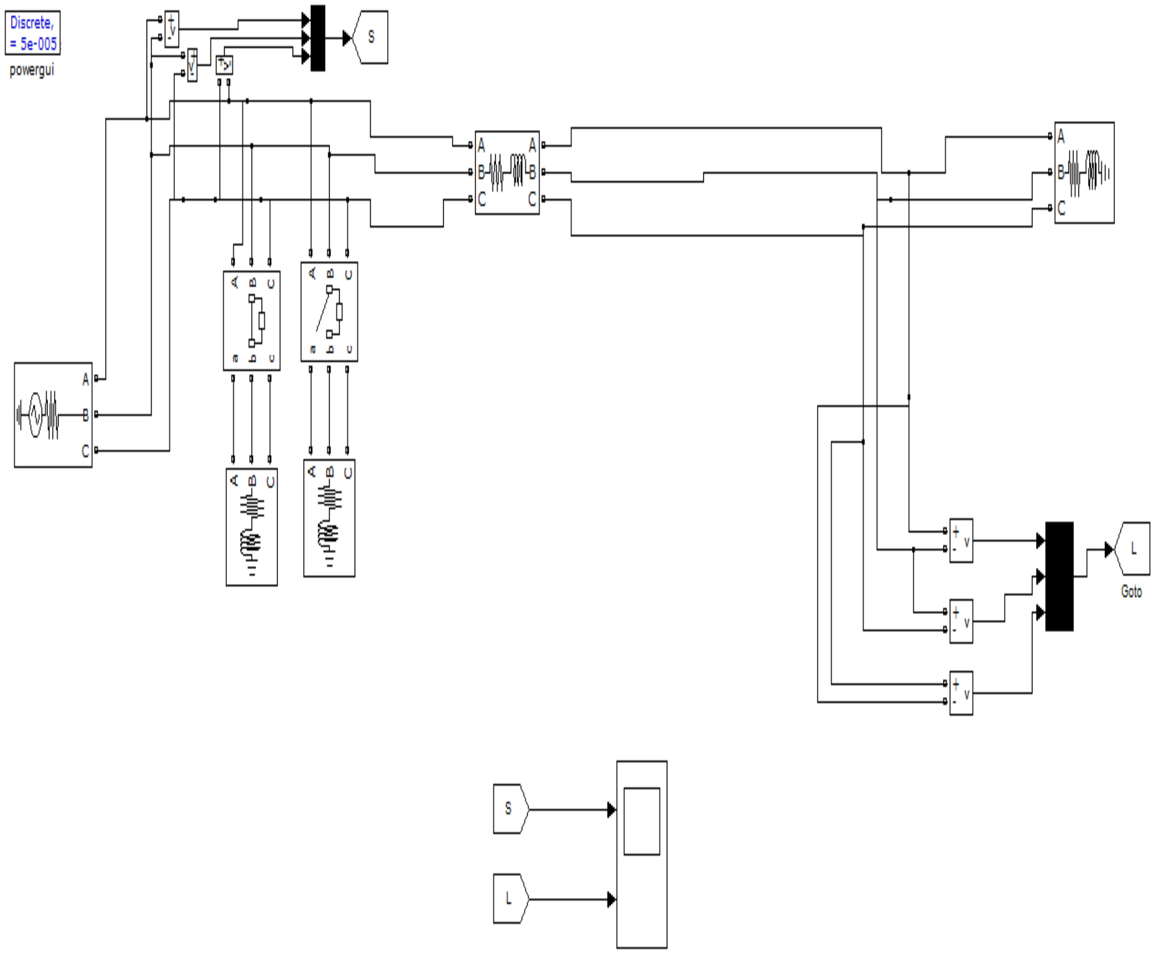
$$b_6 = \frac{a_8}{(r_l + n^2 r_t) b_{10}} = \frac{n^2 r_f + n^2 r_t + r_l n K_i K_c K_v + r_l}{(n^2 r_t + r_l) L_f C_f}$$

APPENDIX B

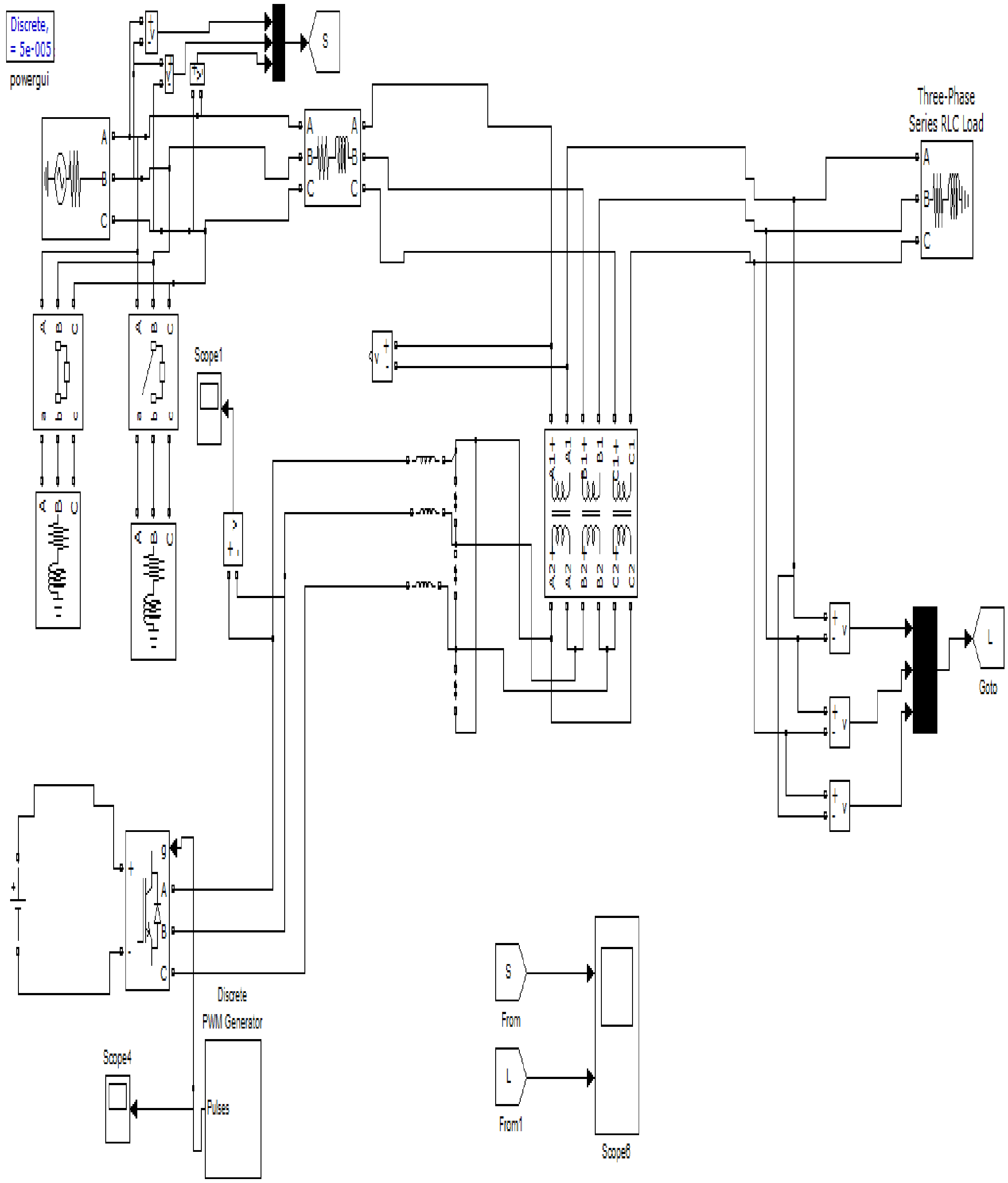
SELF GENERATED PWM & CONTROL STRATEGIES

B.1 SIMULATION DIAGRAM

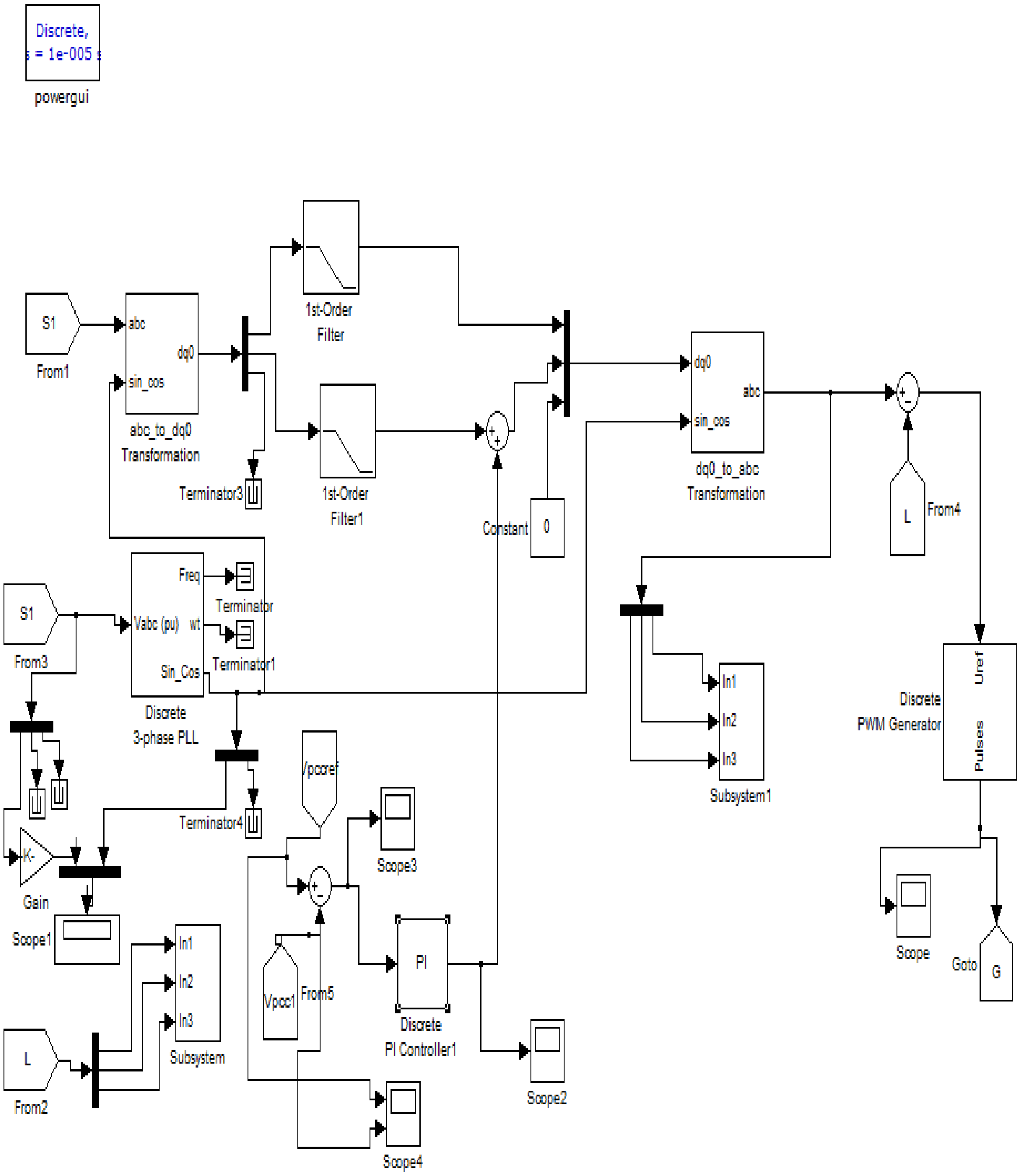
i. Three Phase System Without DVR



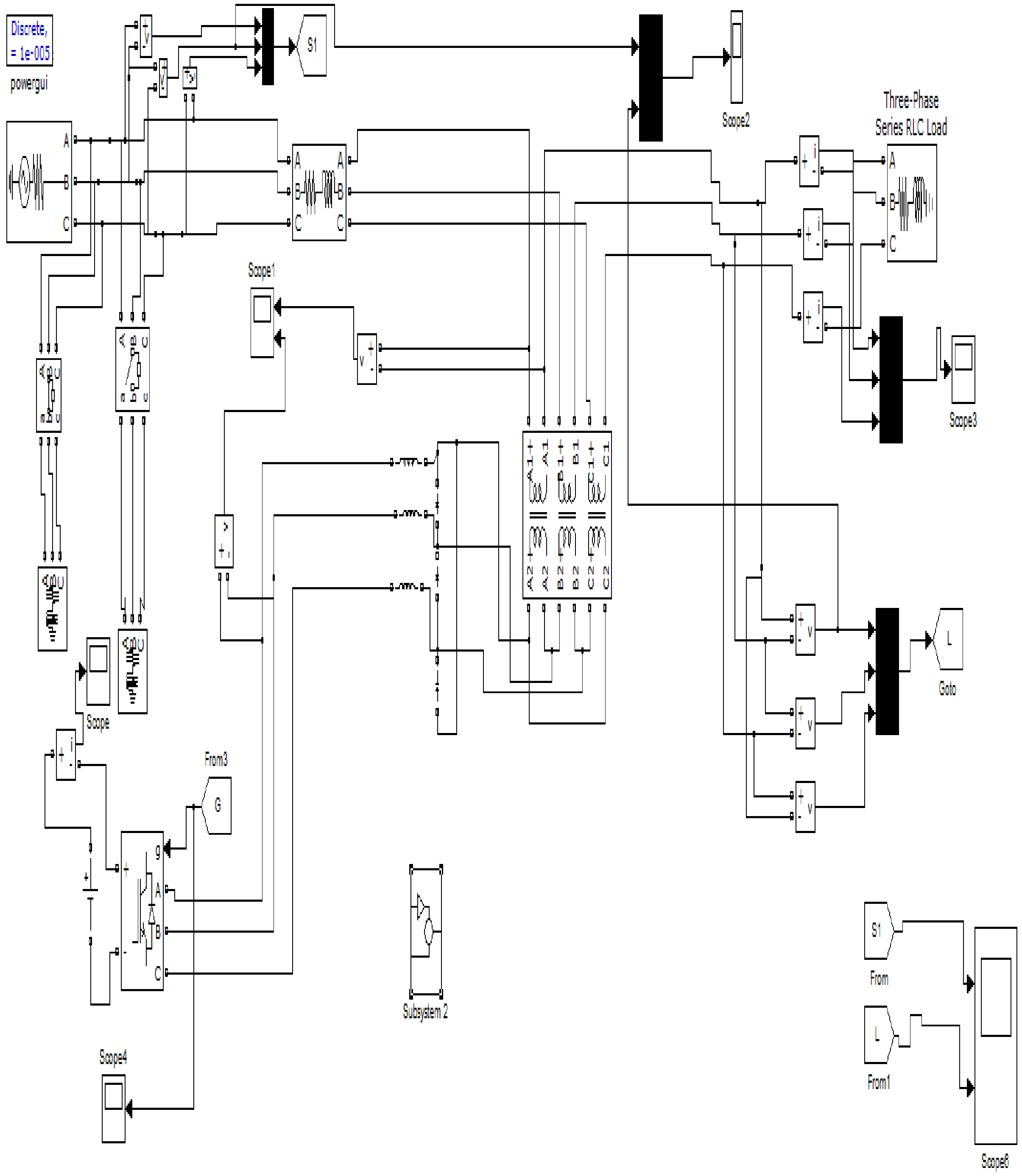
ii. Control of DVR using Self Generated PWM Technique



iii. DVR Control using SRF Control Theory



iv. System comprising SRF Theory Based Control



B.2 SYSTEM DATA

Parameters	**Values used in the model**
AC line voltage	415 V, 50 Hz
Line impedance	$R_s = 0.001\ \Omega$, $L_s = 5$ mH
Loads	Linear, 15 kVA, 0.80 p.f
Filter	$L_f = 2$ mH, $C_f = 1\mu$F
DC Voltage of DVR	550 V
PI Controller	$K_p = 0.003$, $K_i = 0.005$
PWM Switching frequency	10 kHz
Insertion Transformer	5 kVA, 500 V / 500 V

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