DYNAMIC VOLTAGE RESTORATION

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DYNAMIC VOLTAGE RESTORATION

A Project

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Abstract

of

DYNAMIC VOLTAGE RESTORATION

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There were no problems in quality of power for the past few decades, since it had no effect on majority of the loads connected to the electrical distribution system. An Induction motor's output is considerably lowered while in operation it is contingent to the phase when there is Voltage sag. Now-a-days, power quality has been a major concern to utilities and customers after the augmented use of advanced electronics such as high efficiency variable speed drive, electronic power controller etc. Frequently occurring "Voltage sag" is a prominent power quality disturbance in the distribution system. It is mainly caused by fault in the electrical network or by the starting of a large induction motor. Although, the electric utilities have made ample of investments to improve the reliability of the network, they are incapable of controlling the external factor that causes the fault.

On distribution side, for sensitive load applications superior quality and uninterrupted connection of electrical supply are of great significance. The device used to a great extent as a series device is Dynamic Voltage Restorer (DVR) that injects AC voltage in series with the supply voltage sag to maintain the pre fault voltage. For fault cases possible in various situations, simulations on MATLAB TOOL and associated waveforms showing operation of DVR will be carried out to serve the efficacy of our proposed technique.

The basic flow of the project would include:

i. Basic power quality concepts. Voltage Sag, its occurrence and effects.
ii. Propitious choice of DVR from other custom power devices and other equipments used for voltage sag mitigations.
iii. DVR construction, functional working and various operating modes.
iv. Different working schemes of DVR along with concept of "Minimal Active Voltage Injection Method".
v. Results of simulation done for various faults in MATLAB and conclusion of the behavior of DVR in 1 phase voltage sags.
vi. Views about the above research activity in overall and future use.

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Date

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Chapter 1

INTRODUCTION

The fulfillments of the industrial goals were possible only because the modern industries were able to find innovative technologies that have successfully become technological developments. Continuous production throughout the period is ensured only when the final objective is to optimize the production while achieving maximum profits and achieving minimized production costs.

The reason for demanding high quality un-interruptible power during production process is mainly because of the modern manufacturing and process equipments that operate at high efficiency requires stable and defect free power supply for the successful operation of their machines. Machines, sensitive to power supply variations are to be designed more precisely. For instance, some instruments like adjustable speed drives, automation devices, power electronic components etc. fall into the above category.

Cessation to provide the required quality power output may sometimes cause complete shutdown of the industries which will make a significant financial loss to the industry concerned. However blame due to degraded quality cannot be simply put on to the hands of the utility itself. It has been observed that in industries, most of the conditions that can disrupt the process are generated within the industry itself. For example, most of the non-linear loads cause transients which can affect the reliability of the power supply.

Following mentioned are some aberrant electrical conditions that can disrupt a process caused both at the utility and the customer end.

1. Voltage Sags

2. Phase Outages

3. Voltage Interruptions

4. Transients due to Lighting loads, capacitor switching, non linear loads, etc.

5. Harmonics

The industries may undergo burned-out motors, lost data on volatile memories, erroneous motion of robotics, unnecessary downtime, increased maintenance costs and burning core materials especially in plastic industries, paper mills & semiconductor plants as an outcome of the above irregularities.

The solutions put forth as a consequence of the above mentioned anomalies are called as utility based solutions and customer based solutions respectively. The finest examples for those two types of solutions are FACTS devices (Flexible AC Transmission Systems) and Custom power devices that are based on solid state power electronic components. FACTS devices are controlled by the utility, whereas the Custom power devices are operated, maintained and controlled by the customer itself and installed at the customer premises.

1.1 Introduction to DVR

Manufacturing cost and the reliability of those solid state devices have been improved as new technologies emerged. So, the protection devices which include such solid state devices can be purchased at a reasonable price with superior performance than the conventional electrical or pneumatic devices available in the market. Uninterruptible Power Supplies (UPS), Dynamic Voltage Restorers (DVR) and Active Power Filters (APF) are examples for commonly used custom power devices. Among those APF is used to mitigate harmonic problems occurring due to non-linear loading conditions, whereas UPS and DVR are used to compensate for voltage sag and surge conditions.

Voltage sag may occur from single phase to three phases. But it has been found that single phase voltage sags are routine and most frequent in the power industry. Thus, the industries that use single and three phase supply will undergo several interruptions during their production process and they are forced to use some form of voltage compensation equipment.

As soon as the fault occurs the action of DVR starts. On event of fault which results in voltage sag, the magnitude reduction is accompanied by phase angle shift and the remaining voltage magnitude with respective phase angle shift is provided by the DVR. Employing minimum active voltage injection mode in the DVR with some phase angle shift in the post fault voltage can result in miraculous use of DVR. If active voltage is less prominent in DVR then it can be delivered to the load for maintaining stability.

Considering this, a transition process is proposed such that voltage restoration is achieved by injecting the voltage difference between the pre sag and the in sag (source side) voltages during the initial first cycle or so the sag. When the sag voltage phasor is available, the injection voltage is controlled to move progressively from the in phase injection point to the corresponding minimum active voltage injection point. The initial voltage injection magnitude and phase angle of DVR can be categorized into different cases considering the injection limit that will be discussed further.

The simulation of various 1 phase and 3 phase faults are done using MATLAB. The present project deals with only voltage sag, voltage swell can be simulated in same way. The simulation results show the very good performance of the controller theoretically. The performance of DVR theoretically is tested. Therefore this project has contributed a strong knowledge to the research and development targeting industrial application to compensate the single-phase voltage sags and 3 phase balanced voltage sags.

Chapter 2

POWER QUALITY, VOLTAGE SAG MITIGATIONS AND EQUIPMENTS

2.1 Power Quality in Present Day World

The name power quality has become one of the most productive concepts in the power industry since late 1980s. Power Quality concept mainly deals with 3 factors namely Reliability, Quality of Supply and Customer service.

2.2 Definitions of Power Quality

Power quality may be defined as the *"Degree to which both the utilization and delivery of electric power affects the performance of electrical equipment."*[14]

From a customer perspective, a power quality problem is defined as *"Any power problem manifested in voltage, current, or frequency deviations that results in power failure or disoperation of customer equipment."*[13]

In a three-phase system, unbalanced voltages also are a power quality problem. Among them, two power quality problems have been identified to be of major concern to the customers are voltage sags and harmonics, but this project will be focusing on voltage sags. Figure 2.3[10] describe the demarcation of the various power quality issues defined by IEEE Std. 1159-1995.

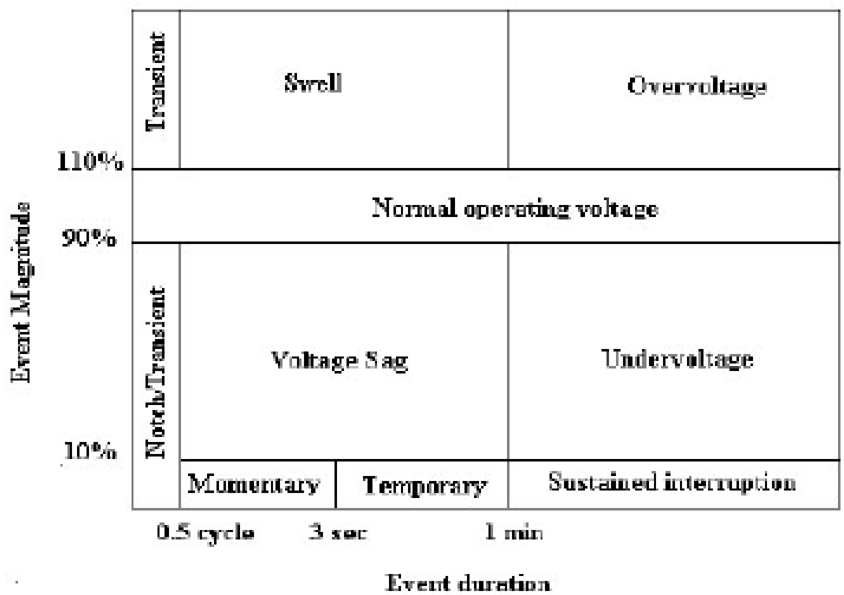


Figure 2.1 IEEE Standard 1159-1995[10]

2.3 Effects of Poor Power Quality

Some industries like Manufacturing Business machineries, Computers and Semiconductors are very sensitive to slightest change in the power supply. It is very important for them to take care of the frequently occurring power quality defects in order for production and revenue to not suffer. [15]

The five most common PQ defects defined by IEEE Std. 1159-1995[11] are:

i. Under Voltage: When the operating falls to a low value due to fault voltage.

ii. Dips or Surges: Fluctuations leading to frequent increase and decrease in the magnitude of the supply.

iii. Transient: A Spike in the sinusoidal voltage of the supply.

iv. Harmonics: Voltage or Currents that are some integer multiple of operating specifications which cause distortion

v. Burnouts: Period of very low frequency voltage or sometimes even zero leading to reduced power delivery.

Power Quality problems happen when these ranges are crossed and this can occur in three ways:

i. Frequency events: change of the supply frequency outside of the normal range.

ii. Voltage events: change of the voltage amplitude outside its normal range (may occur for very short periods or be sustained.)

iii. Waveform events: distortion of the voltage waveform outside the normal range.

These disturbances can degrade power quality by:

i. Interrupting supply, Trip out variable speed drives and cause annoying light flicker.

ii. Cause damage to sensitive data processing, control and instrumentation equipment to malfunction.

iii. Cause capacitors, transformers and induction motors to overheat.

2.4 Voltage Sag and Swell Definitions

Over the last fifteen years, based on how the power quality instruments measure voltage sags and swells the definitions have been developed. Power system communities state sags or dips as a reduction in voltage below a user- defined low limit for between one cycle and 2.55 seconds. Surges are now called as swells, except that the voltage exceeds a particular user-defined high limit. While different definitions pertaining to the amplitude and duration are still in use, the IEEE 1159-1995 Recommended Practice on Monitoring Electric Power Quality has defined them as follows:

Sag (dip) can be defined as, "*A decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycles to 1 minute*."[11]

Swell can be defined as, "*An increase to between 1.1 pu and 1.8 pu in rms voltage or current at the power frequency durations from 0.5 to 1 minute*."[11]

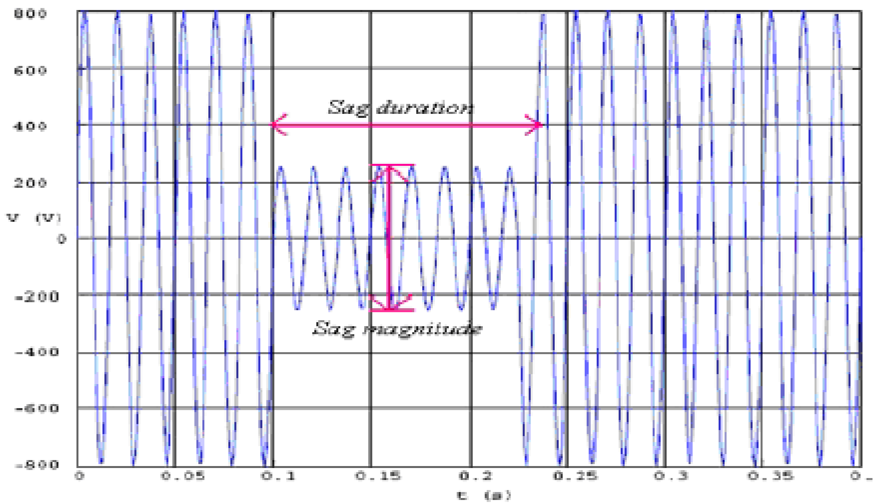


Figure 2.2 Voltage Sag Depiction [3]

With respect to an outage or interruption, sag is differentiated by the amplitude being greater than or equal to 0.1 per unit (of nominal voltage). The IEEE 1159 document further categorizes the duration values into: Instantaneous, momentary, and temporary, as illustrated in the following table2.

According to the IEEE Std. 1995-2009 a voltage sag is "*A decrease in rms voltage or current at the power frequency for duration of 0.5 cycle to 1 minute*". [1]

IEC has the following definition for a dip (IEC 61000-2-1, 1990) "*A voltage dip is a sudden reduction of the voltage at a point in the electrical system, followed by a voltage recovery after a short period of time, from half a cycle to a few seconds*".[1]

Disturbance	Voltage	Duration
Voltage Sag	0.1 – 0.9 pu	0.5 – 30 cycle
Voltage Swell	1.1 – 1.8 pu	0.5 – 30 cycle

Table 2.1 IEEE definitions of Voltage Sags and Voltage Swells [11]

It is blatant from the previous definitions that both voltage sag and voltage dip relate to the same disturbance. Moreover, IEC states that "voltage sag is an alternative name for the phenomenon voltage dip" (IEC 61000-2-8, 2002).

Categories		Typical Duration	Typical Magnitude
2.1 Instantaneous			
	2.1.1 Sag	0.5-30 cycles	0.1-0.9 pu
	2.1.2 Swell	0.5-30 cycles	1.1-1.8 pu
2.2 Momentary			
	2.2.1 Interruption	0.5-3 seconds	<0.1 pu
	2.2.2 Sag	0.5-3 seconds	0.1-0.9 pu
	2.2.3 Swell	0.5-3 seconds	1.1-1.8 pu
2.3 Temporary			
	2.3.1 Interruption	3 sec-1 minute	<0.1 pu
	2.3.2 Sag	3 sec-1 minute	0.1-0.9 pu
	2.3.3 Swell	3 sec-1 minute	1.1-1.8 pu

Table 2.2 Categories and Characteristics of Power Systems Electromagnetic Phenomena [12]

2.5 Amplitude Limits of Voltage Sag

The duration and amplitude value limits that are likely to cause problems with equipments are already defined by both the ANSI C84.1-1989 Utility Power Profile and the CBEMA (Computer and Business Equipment Manufacturers Association) curve. The smaller the amplitude of a sag or higher the value of a swell, the shorter the duration should be for equipment to follow through the disturbance, as in the following table derived from such. The typical industrial utility power after building line losses is in the range of +6%, -13% from the nominal value.

DURATION	AMPLITUDE LIMITS
8-50 msec:	-30%, +20%,
50ms-500 msec:	+15%, -20%;
longer than .5sec:	residential +/-5%;
	industrial +/-10%

Table 2.3 Amplitude limits of Voltage Sag [12]

2.6 Effects of Voltage Sag

The prime interest about voltage sags is their effect on sensitive electrical devices, such as personal computers, adjustable speed drives, programmable logic controllers, and other power electronic equipment. The least sensitive loads failed when the voltage dropped to 30 % of the specified voltage. On the other hand, the most sensitive components failed when the voltage dropped to 80-86 % of rated value. From the test results, the calculated sag threshold to affect production at the utility PCC - point of common coupling was 87 % of the nominal voltage for more than 8.3 ms.

Voltage Sag Classification based on type of Sag, duration and magnitude as shown in Table 2.4

Type of Sag	Duration	Magnitude
Instantaneous	0.5 - 30 cycles	0.10 - 0.90 pu
Momentary	30 cycles - 3 s	0.10 - 0.90 pu
Temporary	3 s – 1 min	0.10 - 0.90 pu

Table 2.4 Classification of Voltage Sags according to IEEE 1159 [11]

The power system voltage can be given by a sine wave. A reduction in the amplitude of the waveform indicates a Voltage Sag. Figure 3.3 shows the voltage waveform during voltage sag. The sag magnitude is characterized by the amplitude of the instantaneous voltage.

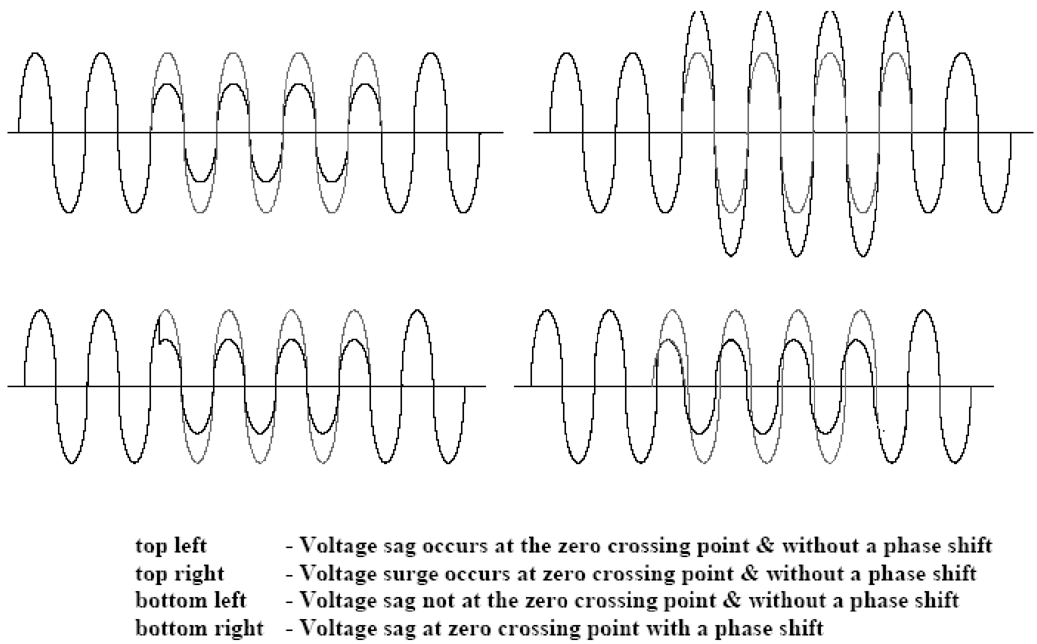


Figure 2.3 Classification of Voltage Sags [13]

2.6.1 A Typical Voltage Sag Waveform

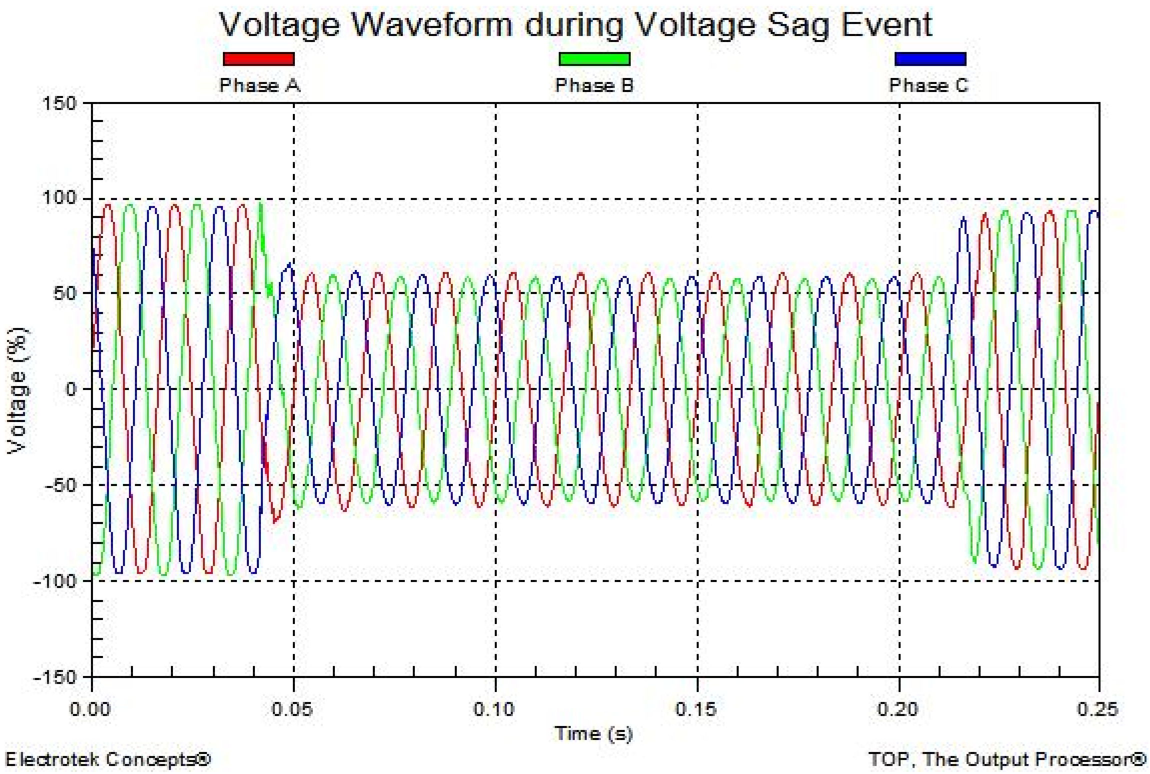


Figure 2.4 A Typical Voltage Sag Waveform [8]

2.7 General Causes and Effects of Voltage Sags

There are various causes of voltage sags in a power system. Voltage sags can be caused by lightning faults on the transmission or distribution system or by switching of loads with large amounts of initial starting or inrush current such as motors, transformers, and large dc power supply.

2.7.1 Voltage Sags Due to Faults

One of the major factors critical to the operation of the power plant is voltage sags due to faults. The magnitudes of the voltage sags can be equal in each phase or unequal depending on the types of the fault such as symmetrical or unsymmetrical, respectively. For faults in the transmission system, customers do not experience interruption since transmission systems are looped or networked.

At a certain point in the system parameters affecting the sag magnitude due to faults are:

i. Distance to the fault

ii Fault impedance

iii. Type of fault

iv. Pre-sag voltage level

v. System configuration, System impedance and Transformer connections.

2.8 Multi-Phase Sags and Single Phase Sags

2.8.1 Single Phase Sags

The frequently occurring voltage sags are single phase events which are basically due to a phase to ground fault occurring somewhere on the system. On other feeders from the same substation this phase to ground fault appears as single phase voltage sag. Typical causes are lightning strikes, tree branches, animal contact etc. It is common to see single phase voltage sags to 30% of nominal voltage or less in industrial plants.

2.8.2 Phase to Phase Sags

The 2 Phase or Phase to phase sags may be caused by tree branches, adverse weather, animals or vehicle collision with utility poles. These types of sags typically appear on other feeders from the same substation.

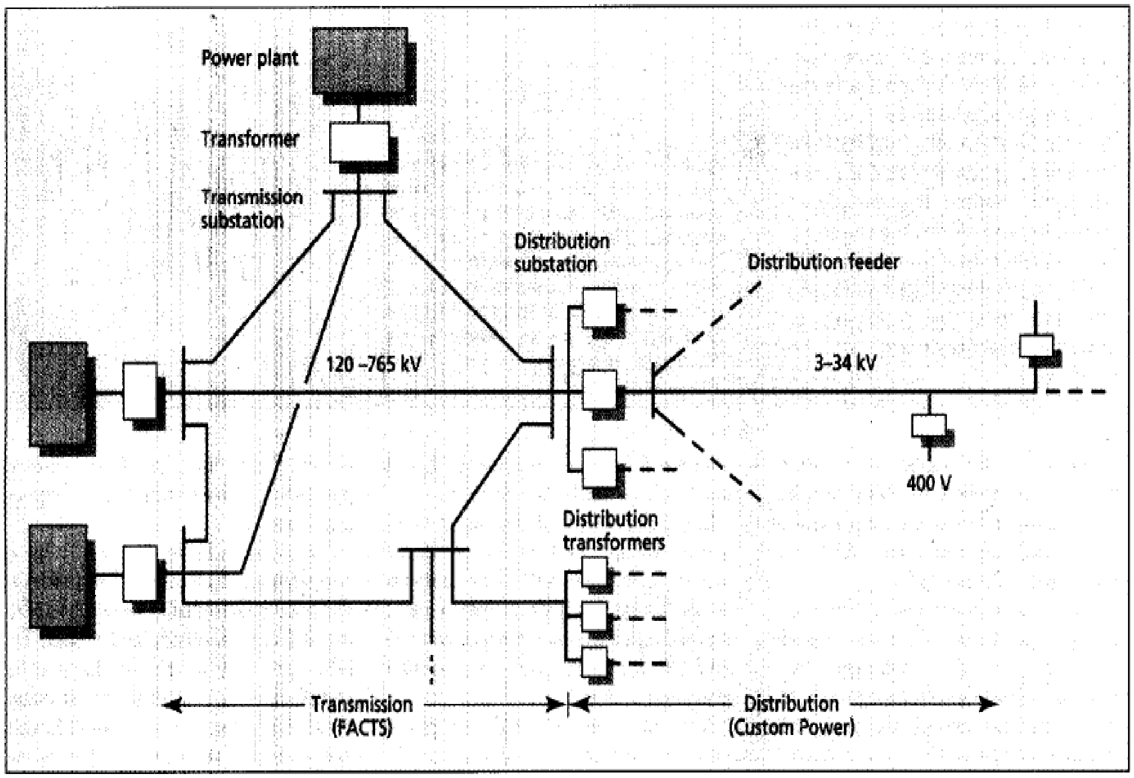
2.8.3 Three Phase Sags

These are caused by switching or tripping of a 3 phase circuit breaker, switch or recloser which will create three phase voltage sag on other lines fed from the same substation. Symmetrical 3 phase sags arise from starting large motors and they account for less than

20% of all sag events and are usually confined to an industrial plant or its immediate neighbors.

2.9 Classification of Equipments used for Voltage Sag Mitigations

A greater awareness of voltage quality has been created with the recent growth in the use of digital computers and PWM adjustable speed drives. Voltage dips and its associated phase angle jumps can cause equipment to fail or malfunction which in turn can lead to production downtime. Since a very long time interval is needed to restart industrial processes, these effects can be greatly expensive for the clients/customers who are continuously seeking for cost effective sag mitigation techniques. These interests have resulted in the development of power electronics based devices with sag mitigation capability. These devices can be classified into two classes, namely Custom Power Devices and Power Line conditioners.



▲ A simplified one-line diagram of a power system shows connection of power plants to an interconnected transmission system, whose capacity and control may be enhanced by the application of the flexible ac transmission system (FACTS) concept. In the distribution system, application of Custom Power can help utilities provide value-added, highly reliable, high-quality power.

Figure 2.5 Custom Power Distribution System [16]

N G Hingorani put forward the idea of custom power devices in 1995 as shown in the figure above. Like Flexible AC Transmission Systems (FACTS), the term custom power devices relates to the use of power electronics controllers in a distribution system, to deal with various power quality problems. Just as FACTS improves the power transfer capabilities and stability margins, custom power devices ascertain that customers get pre-specified quality and reliability of supply. Without significant effect on the terminal voltages this pre-specified quality may contain a combination of the following, low phase unbalance, no power interruptions, low flicker at the load voltage, low harmonics distortion in load voltage, magnitude and duration of over voltages and under voltages within specified limits, acceptance of fluctuations and poor power factor loads.

Custom Power Devices are recently being developed under the Custom Power Program initiated by the Electric Power Research Institute (EPRI). Typical custom power applications include the Dynamic Voltage Restorer (DVR), Distribution Static Compensator (D-STATCOM), Solid State Fault Current Limiter (SSFCL). These devices are also known as source side solutions.

There are many types of Custom power devices like those listed below:

1) Active Power filters(APF)
2) Battery Energy storage systems(BESS)
3) Distributed Static Compensators(DSTATCOM)
4) Distribution series Capacitors(DSC)
5) Dynamic Voltage Restorer(DVR)
6) Super conducting Magnetic Energy systems(SEMES)
7) Static Electronics Tap Changers(SETC)
8) Solid State Transfer Switches (SSTS)
9) Solid state Fault Current Limiters(SSSFCL)

10) Static VAR Compensators(SVC)

11) Thyristor Switched Capacitors(TSC)

12) Uninterruptible Power Supplies (UPS)[2]

The conventional approach is adding Power Line Conditioners to the distribution systems as a form of load side solution. These devices work by providing voltage sag ride through capability to critical loads. Examples of these devices include motor-generator sets (M-G sets) uninterruptible power supplies (UPSs), magnetic synthesisers and super conducting storage devices (SSDs).

Uninterruptible Power Supplies (UPS), Dynamic Voltage Restorers (DVR) and Active Power Filters (APF) with voltage sag compensation facility are the most common custom power devices to compensate for the voltage sags and swells. UPS is ubiquitous whereas DVR and APF are less popular due to the fact that they are still in the developing stage, even though they are highly efficient and cost effective than UPSs. Due to the rapid ongoing development in the power electronic industry, low cost power devices like DVR and APF will become much popular among the industries in the near future.

DVR and APF are normally used to eliminate two different types of abnormalities that affect the power quality. They are discussed based on two different load situations namely linear loads and non-linear loads. The load is considered to be a linear when both the dependent variable and the independent variable show linear changes to each other.

Example: Resistors. The non-linear load on the other hand does not show a linear change. Example: Capacitors and inductors.

i. When the supply voltage/current consists of abnormalities, with a linear load

Here, the custom power device together with the defected supply should be capable of supplying a defect free voltage/current to the load. In other words, the device should be able to supply the missing voltage/current component of the source. A reliable device that can be used for the above case (for voltage abnormalities) is the DVR. It compensates for voltage sags/swells either by injecting or absorbing real and reactive power.

ii. When the Power supplied is in normal condition with a non linear load

In this case, when non-linear loads are connected to the system, the supply current also becomes non-linear and this will cause harmonic problems in the supply waveform. In such a situation, a shunt APF is connected to inject/absorb the current to make the supply current sinusoidal. So, the supply treats both the non-linear load and the APF as a single load, which draws a fundamental sinusoidal current.

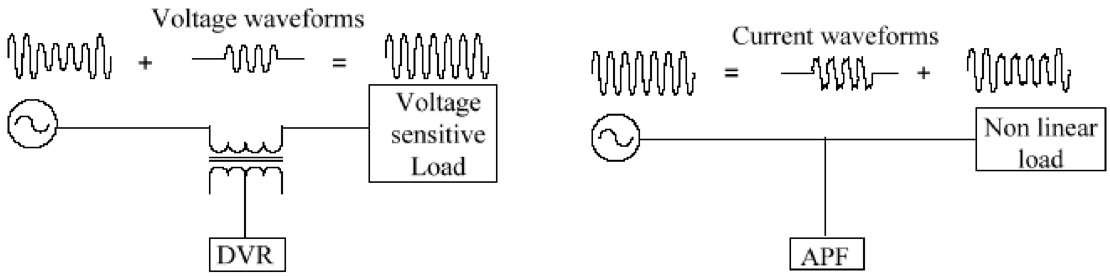


Fig 2.6 Basic Operation of DVR (left) and APF (right)

It is clear from Figure2.6 that the DVR is series connected to the power line, while APF is shunt connected. Among the custom power devices, UPS and DVR can be qualified as the devices that inject a voltage waveform to the distribution line. The UPS is always supplying the full voltage to the load irrespective of whether the wave form is distorted or not unlike DVR. This property of the UPS leaves it always operating at its full power whereas the DVR injects only the difference between the pre-sag and the sagged voltage and that also only during the sagged period. Therefore as compared to UPS, DVR operating losses and the required power rating are very low. Hence DVR is considered as a power efficient device compared to the UPS. [17][18][19]

2.10 Propitious choice of DVR

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

i. Although, SVC predominates the DVR but the latter is still preferred because the SVC has no ability to control active power flow.

ii. DVR is less expensive compared to the UPS.

iii. UPS also needs high level of maintenance because it has problem of battery leak and have to be replace as often as five years.

iv. DVR has a relatively higher energy capacity and costs less compared to SMES device.

v. DVR is smaller in size and costs less compared to DSTATCOM

vi. DVR is power efficient device compared to the UPS.

Chapter 3

WORKING PRINCIPLE, CONSTRUCTION AND MODES OF DYNAMIC VOLTAGE RESTORER (DVR)

One of the major factors that determine the quality of power supply is the voltage magnitude. For various reasons frequent voltage sags are often experienced by loads at distribution level. For some sensitive loads such as those in high-tech industries voltage sags are highly undesirable. It is a challenging task to maintain the load voltage requirements with proper magnitude and correct the voltage sag during voltage disturbances and fluctuations.

Generally voltage sag can be very expensive and cause severe problems for the customers as it may lead to production damage and downtime. By using power electronics devices also known as customer power device a certain amount of voltage and power can be injected into the distribution system and this severe problem of voltage sag can be minimized. Out of the various approaches that have been have been proposed to limit the cost causes by voltage sag, dynamic voltage restorer (DVR) is one of the best methods to address voltage sag problems. This method is briefly discussed in our thesis and it can be used to correct voltage sag at distribution level.

3.1 Principles of DVR Operation

A DVR is a solid state power electronics switching device which comprises of either GTO or IGBT, a capacitor bank as energy storage device and injection transformers. From the figure it can be seen that DVR is connected in between the distribution system and the load. The basic idea of DVR is that by means of an injecting transformer a control voltage is generated by a forced commuted convertor which is in series to the bus voltage. A regulated DC voltage source is provided by a DC capacitor bank which acts an energy storage device.

Under normal operating conditions when there is no voltage sag, DVR provides very less magnitude of voltage to compensate for the voltage drop of transformer and device losses. But when there is a voltage sag in distribution system, DVR will generate a required controlled voltage of high magnitude and desired phase angle which ensures that load voltage is uninterrupted and is maintained. In this case the capacitor will be discharged to keep the load supply constant. [3]

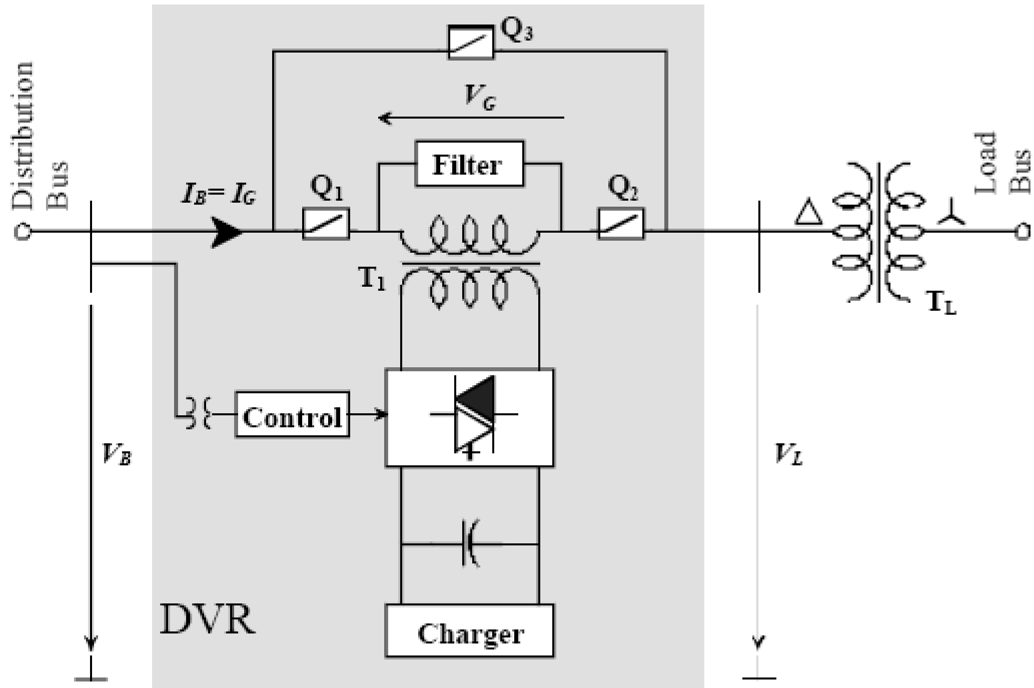


Figure 3.1 Principle of DVR with a Response Time of Less Then One Millisecond [21]

Note that the DVR capable of generating or absorbing reactive power but the reactive power injection of the device must be provided by an external energy source or energy storage system. The response time of DVD is very short and is limited by the power electronics devices and the voltage sag detection time. The expected response time is about 25 milliseconds, and which is much less than some of the traditional methods of voltage correction such as tap-changing transformers.

3.2 Construction of DVR:

Power circuit and the control circuit are the 2 main parts of the DVR. There are various critical parameters of control signals such as magnitude, phase shift, frequency etc. which are injected by DVR. These parameters are derived by the control circuit. This injected voltage is generated by the switches in the power circuit based on the control signals. Furthermore the basic structure of DVR is described by the power circuit and is discussed in this section. The 5 main important parts of power circuit, their function and requirements are discussed ahead.

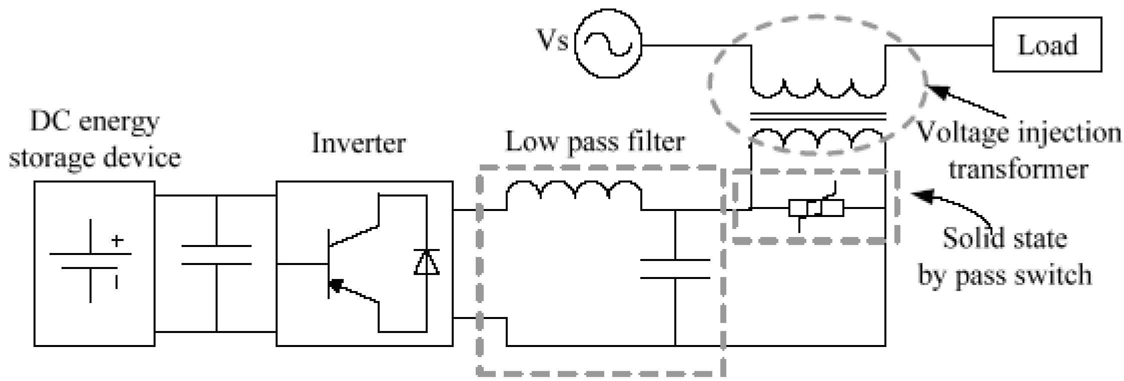


Figure 3.2 DVR Power Circuit [20]

3.2.1 Energy Storage Unit

Various devices such as Flywheels, Lead acid batteries, Superconducting Magnetic energy storage (SMES) and Super-Capacitors can be used as energy storage devices. The main function of these energy storage units is to provide the desired real power during voltage sag. The amount of active power generated by the energy storage device is a key factor, as it decides the compensation ability of DVR. Among all others, lead batteries are popular because of their high response during charging and discharging

But the discharge rate is dependent on the chemical reaction rate of the battery so that the available energy inside the battery is determined by its discharge rate.

3.2.2 Voltage Source Inverter

Generally Pulse-Width Modulated Voltage Source Inverter (PWMVSI) is used. In the previous section we saw that an energy storage device generates a DC voltage. To convert this DC voltage into an AC voltage a Voltage Source Inverter is used. In order to boost the magnitude of voltage during sag, in DVR power circuit a step up voltage injection transformer is used. Thus a VSI with a low voltage rating is sufficient.

3.2.3 Passive Filters

To convert the PWM inverted pulse waveform into a sinusoidal waveform, low pass passive filters are used. In order to achieve this it is necessary to eliminate the higher order harmonic components during DC to AC conversion in Voltage Source Inverter which will also distort the compensated output voltage. These filters which play a vital role can be placed either on high voltage side i.e. load side or on low voltage side i.e. inverter side of the injection transformers. We can avoid higher order harmonics from passing through the voltage transformer by placing the filters in the inverter side. Thus it also reduces the stress on the injection transformer. One of the problems which arise when placing the filter in the inverter side is that there might be a phase shift and voltage drop in the inverted output. So this could be resolved by placing the filter in the load side. But this would allow higher order harmonic currents to penetrate to the secondary side of the transformer, so transformer with higher rating is essential.

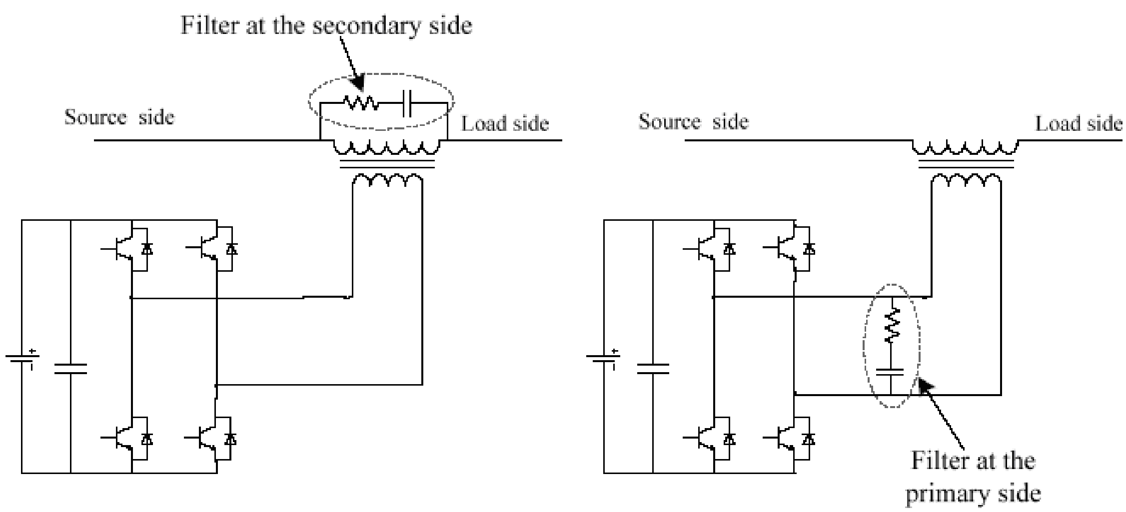


Figure 3.3 Different Filter Placements [18]

3.2.4 By-Pass Switch

Now DVR is a series connected device. If there is a fault current due to fault in the downstream, it will flow through the inverter. Now the power components of inverter are not highly rated but normally rated due to its cost. So in order to protect the inverter a By-pass switch is used. Generally a crowbar switch is used which bypasses the inverter circuit. So crowbar switch will sense the magnitude of the current, if it is normal and within the handling range of inverter components it (the crowbar switch) will be inactive. On the other hand if current is high it will bypass the components of inverter.[18]

3.2.5 Voltage Injection Transformers

The primary side of the injection transformer is connected in series to the distribution line, while the secondary side is connected to the DVR power circuit. Now 3 single phase transformers or 1 three phase transformer can be used for 3 phase DVR whereas 1 single phase transformer can be used for 1 phase DVR. The type of connection used for 3 phase DVR if 3 single phase transformers are used is called “Delta-Delta” type connection as shown in Figure 3.4 a [22]. If a winding is missing on primary and secondary side then such a connection is called “Open-Delta” connection which is as widely used in DVR systems as shown in Figure 3.4 b [22].

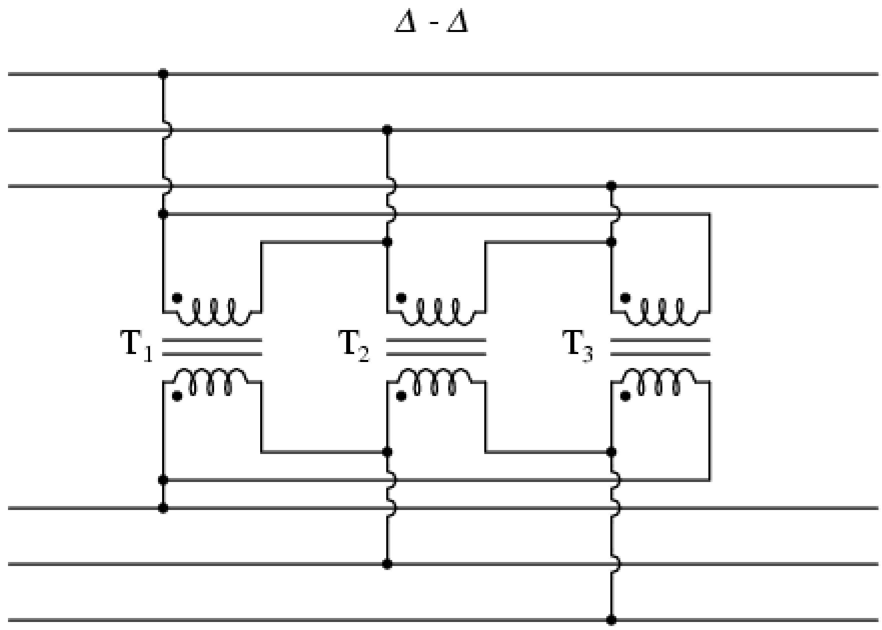


Figure 3.4 a Connection Method for Injection Transformer Delta-Delta Connection [22]

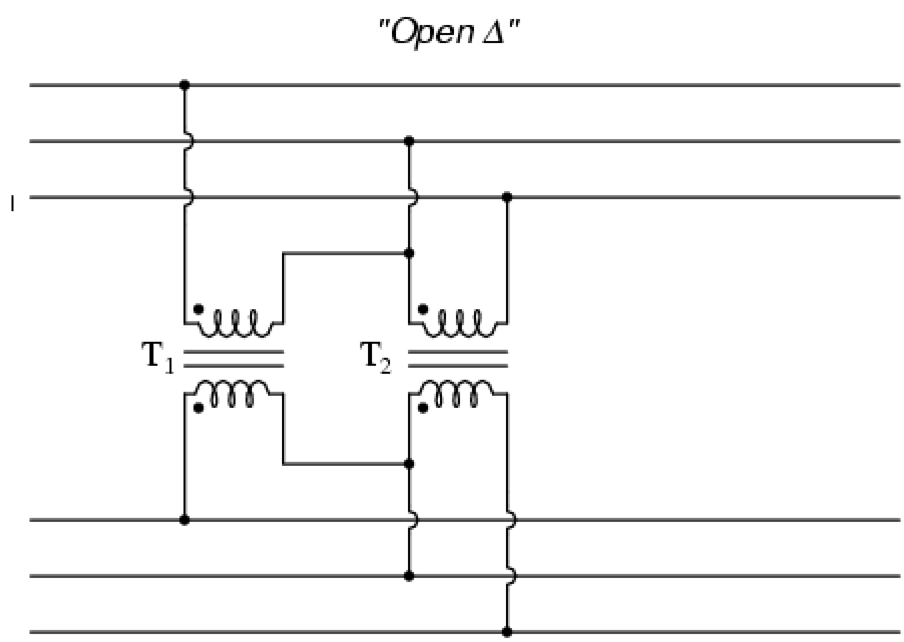


Figure 3.4 b Connection Method for Injection Transformer Open-Delta Connection [22]

Basically the injection transformer is a step up transformer which increases the voltage supplied by filtered VSI output to a desired level and it also isolates the DVR circuit from the distribution network. Winding ratios are very important and it is predetermined according to the required voltage at the secondary side. High winding ratios would mean high magnitude currents on the primary side which may affect the components of inverter circuit. When deciding the performance of DVR, the rating of the transformer is an important factor. The winding configuration of the injection transformer is very important and it mainly depends on the upstream distribution transformer. In case of a Δ-Y connection with the grounded neutral there will not be any zero sequence current flowing into the secondary during an unbalance fault or an earth fault in the high voltage side. Thus only the positive and negative sequence components are compensated by the DVR.

3.3 DVR Operating Modes

3.3.1 During a voltage sag/swell on the line

The difference between the pre sag voltage and the sag voltage is injected by the DVR by supplying the real power from the energy storage element and the reactive power. The DVR injects the difference between the pre-sag and the sag voltage, by supplying the real power requirement from the energy storage device together with the reactive power. Due to the ratings of DC energy storage and the voltage injection transformer ratio the maximum capability of DVR is limited. The magnitude of the injected voltage can be controlled individually in the case of three single-phase DVRs. With the network voltages the injected voltages are made synchronized (i.e. same frequency and the phase angle)

3.3.2 During the normal operation

During the normal operation as there is no sag, DVR will not supply any voltage to the load. It will be in a standby mode or it operates in the self charging mode if the energy storage device is fully charged. The energy storage device can be charged either from the power supply itself or from a different source.

3.3.3 During a short circuit or fault in the downstream of the distribution line

In this case we have seen before that a bypass switch (crossbar switch) will be activated and it will bypass the inverter circuit in order to protect the electronic components of the inverter.

3.4 Compensation Techniques

3.4.1 Pre-sag Compensation

Pre-sag compensation is a method which is generally used for non linear loads such as thyristor controlled drives. In non linear loads the voltage magnitude as well as he phase angle needs to be compensated. Figure 3.5 below describes the pre-sag compensation technique. A higher rated energy storage device and voltage injection transformers are needed for this technique.

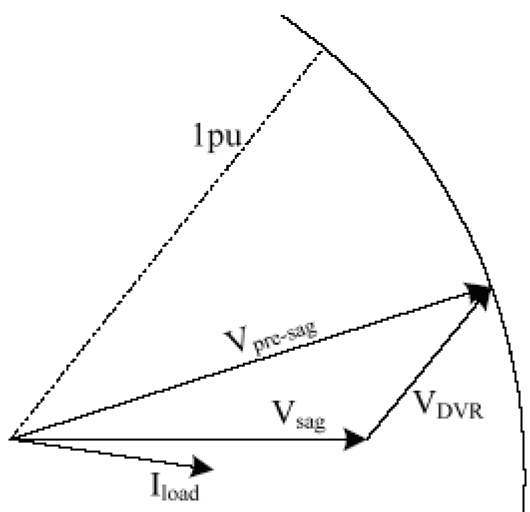


Figure 3.5 Pre-Sag Compensation Techniques [17]

3.4.2 In-phase Compensation

This technique of compensation is generally used for active loads. Only compensation for voltage magnitude is required whereas no phase compensation is required. In this particular method the compensated voltage is in phase with the sagged voltage. [1] This particular compensation technique is shown in Figure 5.6. It is clear from the Figure 3.6, that there is a phase shift between the voltages before the sag and after the sag.

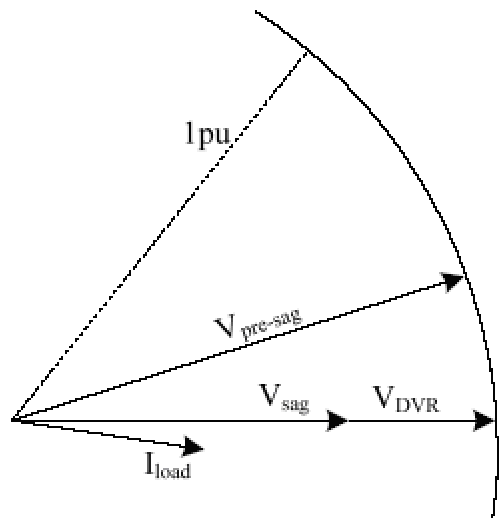


Figure 3.6 In-Phase Compensation Techniques [17]

It should be noted that the techniques mentioned in 3.4.1 and 3.4.2 need both the real and reactive power1 for the compensation and the DVR is supported by an Energy storage device.

Chapter 4

ACTIVE AND REACTIVE POWER CONFIGURATIONS OF DVR

4.1 Active and Reactive Configurations:

Depending upon the compensation that DVR provides, various modes of operation can be designed. The figure below shows the mode which only deals with the reactive power. From the phasor diagram we can see that minute control in voltage magnitudes difficult and V desired and V obtained are somewhat deviating. Now on the other hand when we observe the phasor diagram 4.2 it can be seen that V desired and V obtained can be accurately same. Thus we can conclude by saying the DVR with active and reactive mode of conversion is a efficient way of controlling the DVR operation.

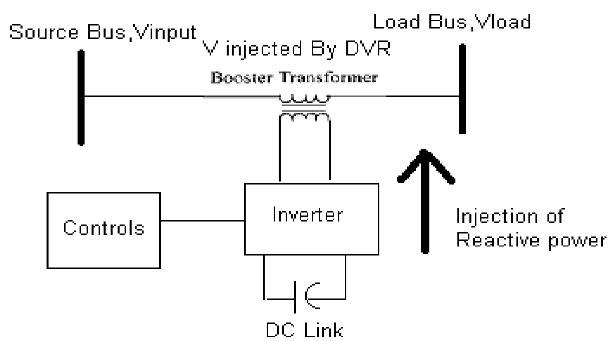


Figure 4.1 a Reactive Power Configuration of DVR [9]

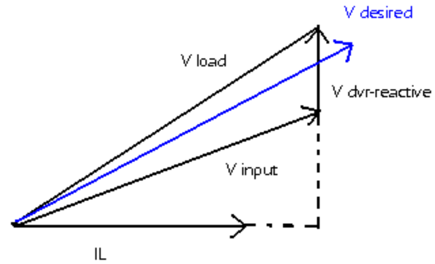


Figure 4.1 b Phasor Diagram of Reactive Power Compensating DVR [9]

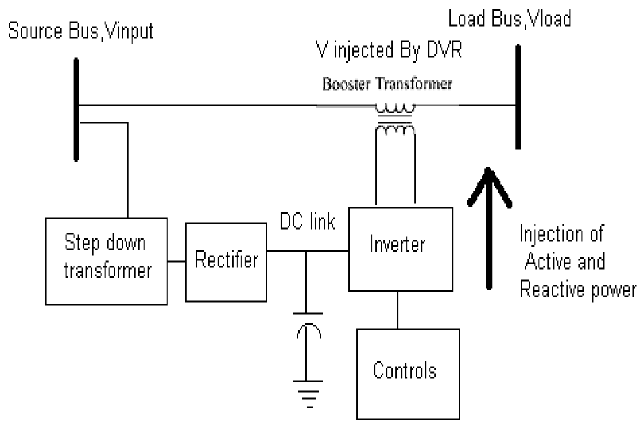


Figure 4.2 a Active and Reactive Power Configuration of DVR [9]

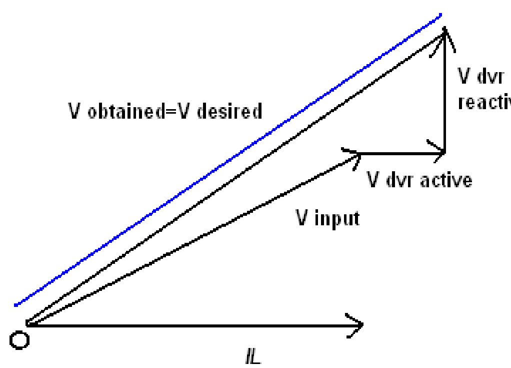


Figure 4.2 b Phasor Diagram of Active and Reactive Power Configuration in DVR [9]

4.2 Review of the Existing Method used for DVR Voltage Injection

One of the methods that are widely used in DVR is briefly discussed in this section. We can see from the figure 4.3 that the phasor diagram for pre fault and post fault conditions are illustrated. When the system behaves normally the pre fault voltage is Uo whereas in abnormal conditions the voltage locus lies anywhere in the range of Uo. We can also see that when there is an effect of voltage sag, Us is a post fault voltage. Furthermore there is also reduction in phase angle and magnitude as shown in figure 4.3. Voltage injected by DVR for compensation is Uin and Uon is the pre fault voltage obtained from Us and Uin. Also there is phase angle advancement of Uin which is done in minute steps. The simplest process is to compare the Uin voltage and the max injection limit of DVR termed as Uinj. If injection is less compared to max limit than the system conditions will be restored. On the other hand when limit is exceeded the pre fault magnitude is more than the output voltage. This method is highly accurate and hence widely used.

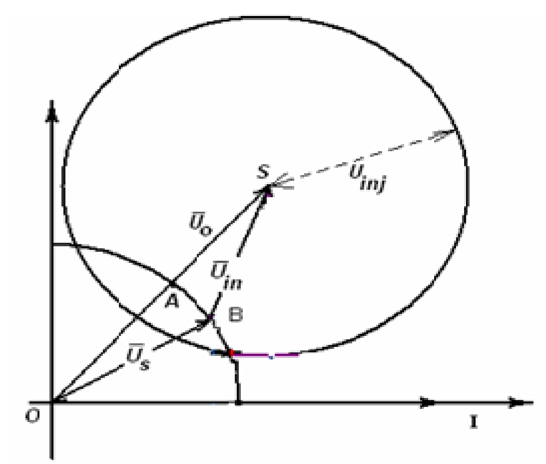


Figure 4.3 Existing method used for DVR voltage Injection [6]

4.3 Introduction to Minimal Active Voltage Injection Scheme:

The previous method described is good but it is not the best. As discussed earlier the existing method is good but not the best. Now if the active voltage is minimal then more voltage can be fed to the load area from the source. So active voltage should be minimum and reactive voltage should be dominating. We can see from the figure 4.4 that Uin is the compensated voltage generated by DVR to maintain the pre sag voltage. The active voltage Uia1 is given to produce Ui1. Similarly Uia2 is the voltage injected to produce the desired output. In both the cases the supply voltage as well as the voltage injected by the DVR will produce same results. Thus we define 2 important operating points P1 and P2. Now the size of DVR is reduced when there is a minimal active power injection at operating point P2. Thus operating point P2 is proffered over P1.Thus this scheme can be given the name as “MINIMAL ACTIVE VOLTAGE INJECTION SCHEME” of DVR.

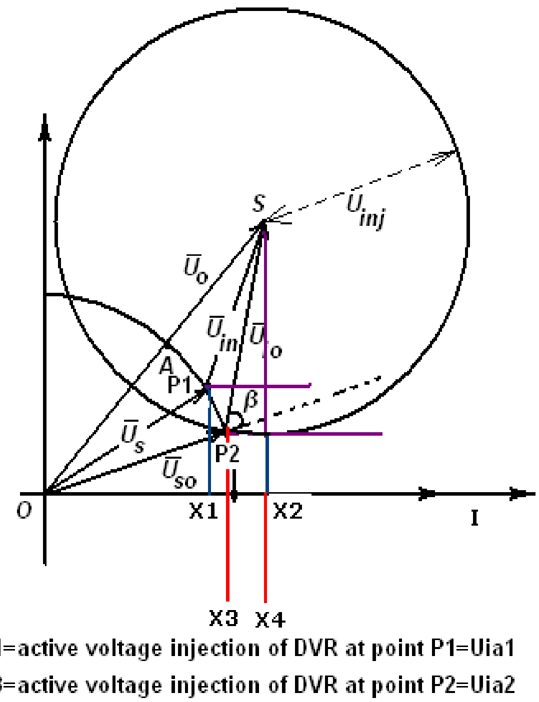


Figure 4.4 Minimal Active Voltage Injection Scheme of DVR [6]

Chapter 5

SIMULATION IN MATLAB AND RESULTS

5.1 CASE A: When Nominal Operating Voltage Decreases Because of Sag

Matlab Code

%-----------------"%" in MATLAB is a comment--------------------------%
%---------------- "ONE-PHASE ANALYSIS"-----------------------------%

%CASEA: When operating voltage falls below the nominal voltage due to Sag

```
%------------starting of program --------------------------
%
clc;
clear all;
close all;

%data: input voltage and phase angle before fault ---------
>

uo_m=input('data:input u0mag(voltage magnitude b4 fault)---
--->')
uo_pad=input('data:input u0phase angle(phase angle in
degree b4 fault)------>')

uo_pa=uo_pad*pi/180;
uo_r=uo_m*cos(uo_pa);
uo_i=uo_m*sin(uo_pa);

uo=uo_r+j*uo_i;

% compute freq in rad/sec

freq_Hz = 10;        %define freq in Hz;
freq_RPS=2*pi*freq_Hz
t=0:0.005:0.5;
uo_plot=uo_m*sin(t*freq_RPS+uo_pa);
plot(t,uo_plot)
```

```
%data:input voltage and phase angle after fault -----------
>

us_m=input('data:input usmag(voltage magnitude after
fault)------->')
us_pad=input('data:input uspa in degree(phase angle after
fault in degrees)------>')
us_pa=us_pad*pi/180;
us_r=us_m*cos(us_pa);
us_i=us_m*sin(us_pa);
us_plot=us_m*sin(t*freq_RPS+us_pa);

plot(t,uo_plot, t, us_plot)

%data:maximum capacity of dvr

uinj=input('data:input value of uinj(maximum limit of DVR)-
----->')
uinj_pa=input('data:input value of uinj_pa(maximum limit of
DVR)------->')


%finding restore voltage provided by DVRs----------->

x=uinj+us_m
y=uo_pa-us_pa

uinj_plot=x*sin(t*freq_RPS+y);

plot(t,uo_plot, t, uinj_plot)

%-------------- END OF CASE A------------------------------
-----------%
```

Data Selected for Analysis

Case A: When the event of a Voltage Sag decreases the Operating supply Voltage magnitude and phase.

Uo_m	Uo_pad	Us_m	Us_pad	U_inj(X&Y)

120V	60	20V	40	100,20

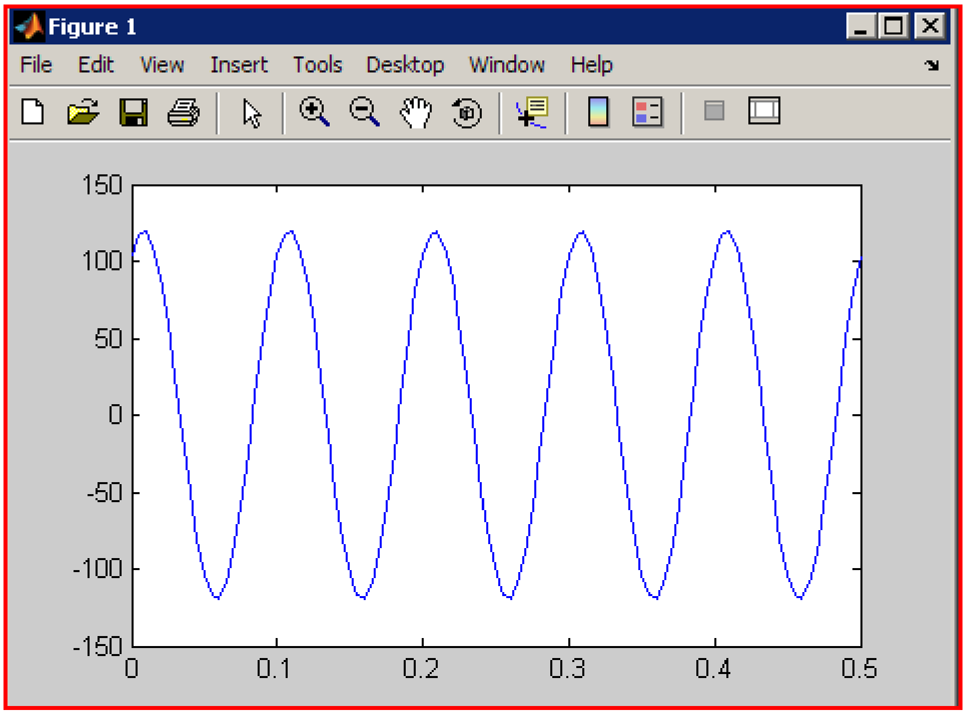
Table 5.1 Case A Voltage Sag Reduces Operating Voltage.

Output Window: Snapshot of Data entered by User

Command Window

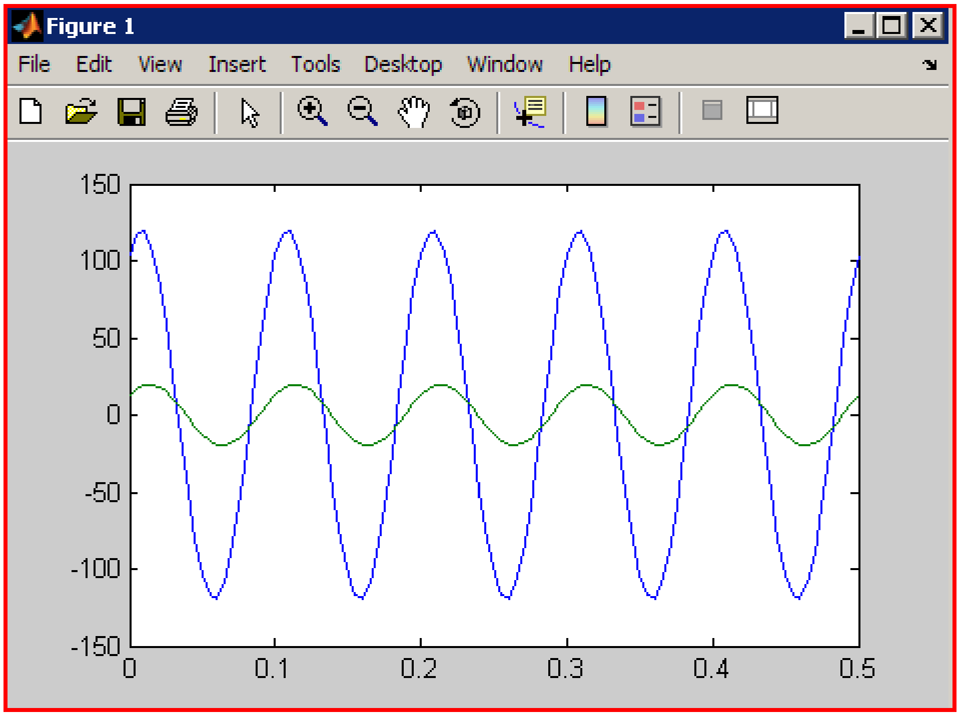
```
data:input u0mag(voltage magnitude b4 fault)------>120

uo_m =

   120

 data:input u0phase angle(phase angle in degree b4 fault)------>60

 uo_pad =

     60


 freq_RPS =

    62.8319

 data:input usmag(voltage magnitude after fault)------->20

 us_m =

     20

 data:input uspa in degree(phase angle after fault in degrees)------>40

 us_pad =

     40

 data:input value of uinj(maximum limit of DVR)------>100

uinj =

   100

data:input value of uinj_pa(maximum limit of DVR)------->20

uinj_pa =

    20


x =

   120


 y =

     0.3491
```

The graph below represents Single Phase supply voltage used in America with Magnitude of 120 V and Frequency of 60 Hz.

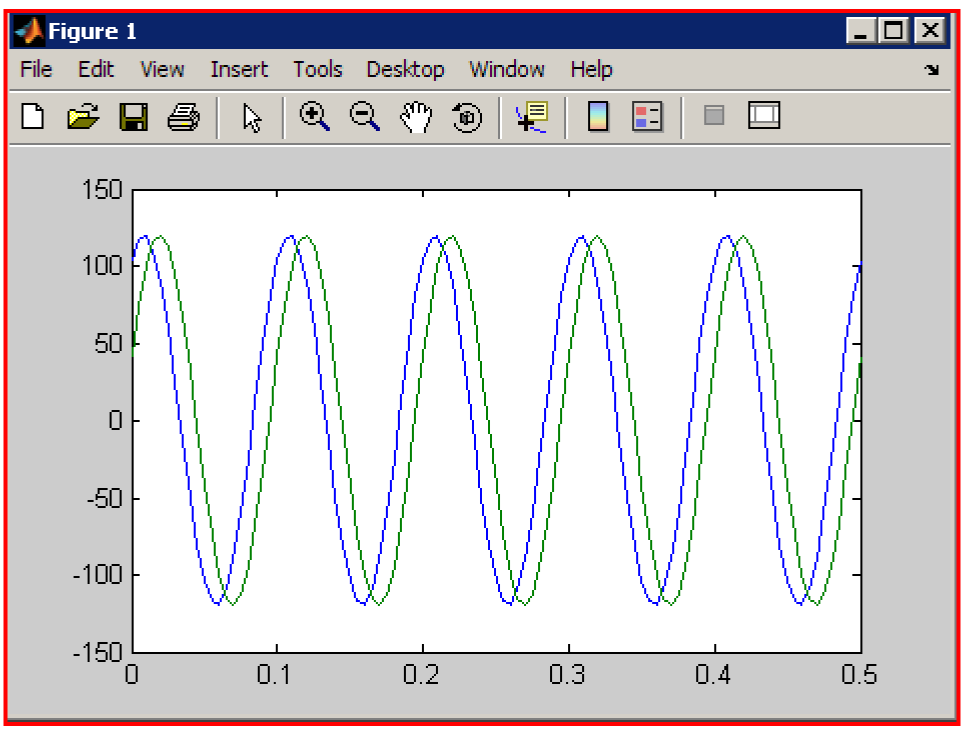


Graph 5.1 Case A Normal Supply Operation

In our example as shown in graph 5.2 the supply voltage and frequency drops down drastically.



Graph 5.2 Case A Post-Sag Operation



Graph 5.3 Case A Restoring Action of DVR.

5.2 CASE B: When Operating Voltage Increases Because of Sag

Matlab Code

```
% CASE B: When the Operating Voltage exceeds the nominal
voltage due to Sag

%------------starting of program --------------------------
%
clc;
clear all;
close all;

%data: input voltage and phase angle before fault ---------
>

uo_m=input('data:input u0mag(voltage magnitude b4 fault)---
--->')
uo_pad=input('data:input u0phase angle(phase angle in
degree b4 fault)------>')
uo_pa=uo_pad*pi/180;
uo_r=uo_m*cos(uo_pa);
uo_i=uo_m*sin(uo_pa);

uo=uo_r+j*uo_i;

freq_Hz = 10;        %define freq in Hz;
freq_RPS=2*pi*freq_Hz       % compute freq in rad/sec
t=0:0.005:0.5;
uo_plot=uo_m*sin(t*freq_RPS+uo_pa);
plot(t,uo_plot)

%data:input voltage and phase angle after fault -----------

us_m=input('data:input usmag(voltage magnitude after
fault)------->')
us_pad=input('data:input uspa in degree(phase angle after
fault in degrees)------>')
us_pa=us_pad*pi/180;
us_r=us_m*cos(us_pa);
```

```
us_i=us_m*sin(us_pa);
us_plot=us_m*sin(t*freq_RPS+us_pa);

plot(t,uo_plot, t, us_plot)

%data:maximum capacity of dvr
uinj=input('data:input value of uinj(maximum limit of DVR)-
----->')
uinj_pa=input('data:input value of uinj_pa(maximum limit of
DVR)------->')

%finding restore voltage provided by DVRs----------->

x=us_m-uinj
y=us_pa-uo_pa
uinj_plot=x*sin(t*freq_RPS+y);

plot(t,uo_plot, t,uinj_plot)

%-------------End of Case B Program -----------------------
```

Case B: Fault Voltage Increases Operating Voltage

Uo_m	Uo_pad	Us_m	Us_pad	U_inj(X&Y)
140V	60	215V	80	75,20

Table 5.2 Case B Voltage Sag Increases Operating Voltage.

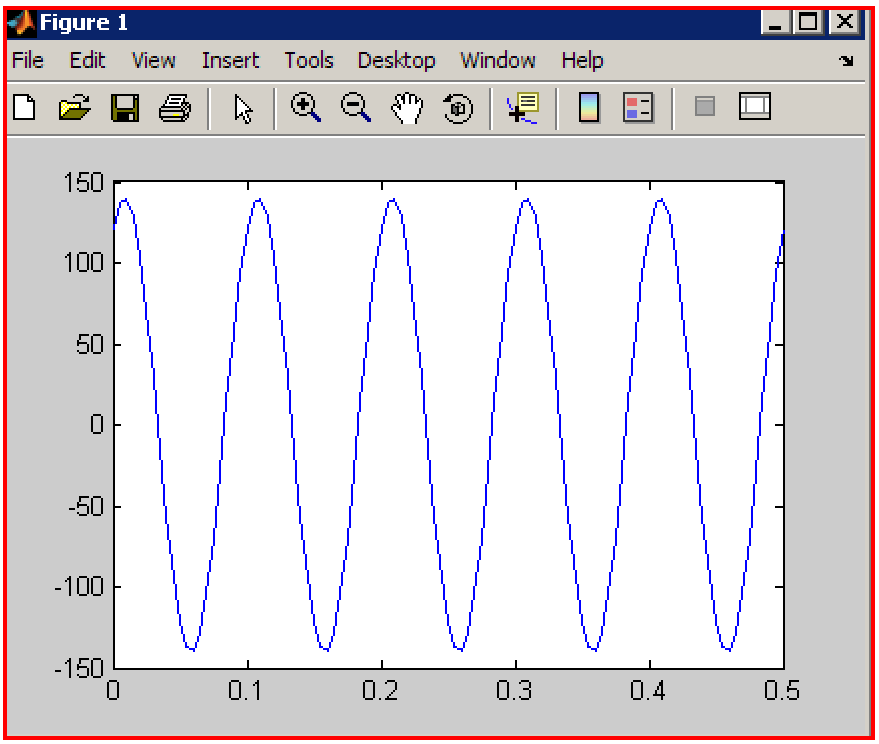
Output Window: Snapshot of Data entered by User

Command Window

```
data:input u0mag(voltage magnitude b4 fault)------>140

uo_m =

   140

data:input u0phase angle(phase angle in degree b4 fault)------>60

uo_pad =

    60


freq_RPS =

   62.8319

data:input usmag(voltage magnitude after fault)------->215

us_m =

   215

data:input uspa in degree(phase angle after fault in degrees)------>80

us_pad =

    80

data:input value of uinj(maximum limit of DVR)------>75

uinj =

    75

data:input value of uinj_pa(maximum limit of DVR)------->20

uinj_pa =

    20


x =

   140
```

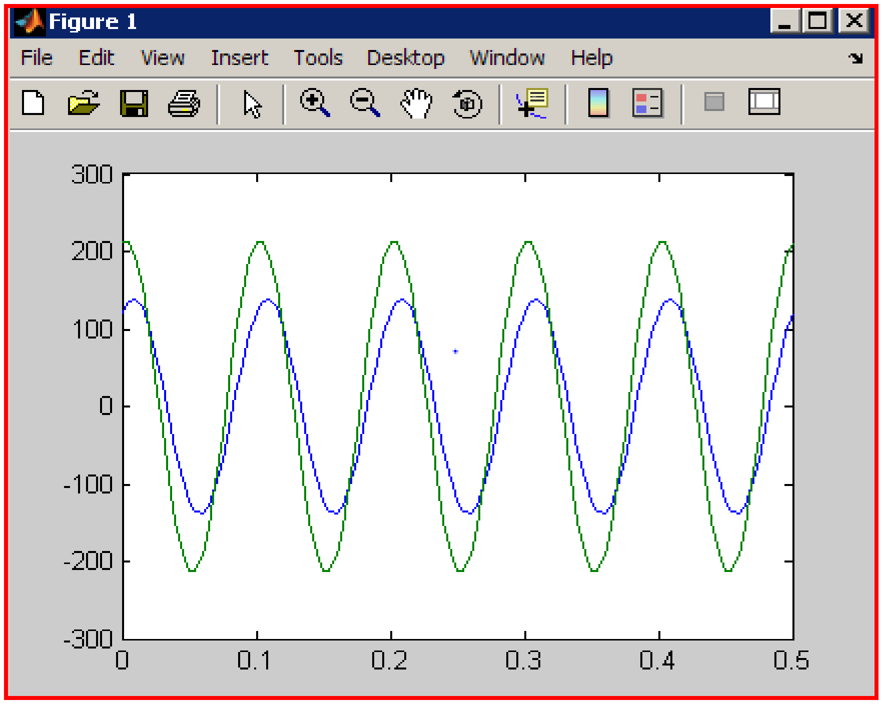
```
y =

    0.3491
```

The graph below represents Single Phase supply voltage with Magnitude of 140 V and Frequency of 60 Hz. We have changed the supply voltage to a value other than 120V used in America solely to utilize the exhaustive restore property of DVR.

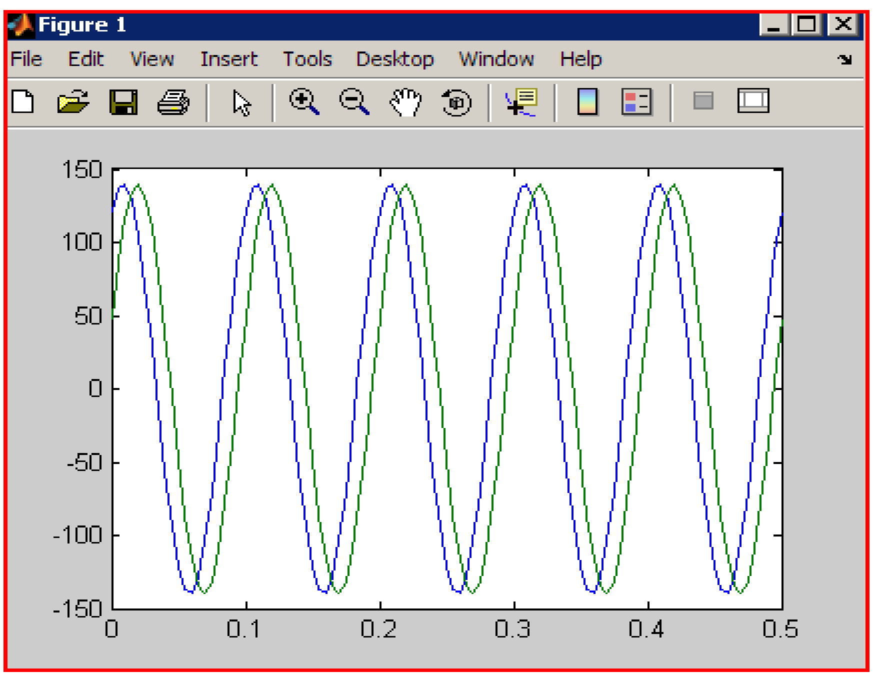


Graph 5.4 Case B Nominal Operation.

In our example as shown in graph 5.5 below the supply voltage and frequency increases catastrophically.



Graph 5.5 Case B Post-Sag Operation



Graph 5.6 Case B Restoring Action of DVR

Chapter 6

CONCLUSION AND FUTURE PERSPECTIVE

The main purpose of using DVR in industries is to maximize efficiency in production. Our project has proposed an improved progressive phase changing scheme of post fault voltage. For any fault situation of Voltage Sag this method is effective which is proved from the analysis and MATLAB simulation results. We chose MATLAB programming because it is easy and can be easily fed in any microprocessor chip. The sag transients can be easily mitigated and pre fault voltage can be established. For real time applications, this may necessitate the application of the microcontroller/processor with fast speed.

The analysis done in this paper are done for Voltage sag affecting Single Phase supply only. Similarly simulations can be carried for Voltage swells and Three-Phase Supply Fault. We have not shown Voltage Swell and Three-phase Simulation because that is out of scope as far as this project is concerned.

Hereby, the effectiveness of proposed method is tested and is proven error free. This proposed method is tested theoretically only however, exact practical testing is left. The effect of harmonic induction and voltage drop due to connection of DVR are to be tested in actual experimental setup. Lab Testing of DVR can be implemented as a part of future research work.

APPENDIX

Glossary and Abbreviations:

SYMBOL	DESCRIPTION
Uinj	Maximum Injection Limit of DVR
Uo	Pre sag voltage on the line
Us	Post sag voltage on the line(after fault)
Uin	Injected voltage by DVR
Uso	Voltage in the line at operating point(minimum active voltage).
Uo	Injected voltage by DVR at operating point(minimal active voltage).
Uinj_pa(X&Y)	Injection limit of DVR to be entered byUSER
Uo_m	Magnitude of Pre sag voltage on the line to be entered by USER
Uo_pad	Phase angle in degree of Pre sag voltage on the line to be entered by USER
Us_m	Magnitude of Post sag voltage on the line to be entered by USER
Us_pad	Phase angle in degree of Post sag voltage on the line to be entered by USER
FACTS	Flexible AC Transmission System
UPS	Uninterruptible Power Supply
APF	Active Power Filter
PLC	Programmable Logic Controller
IEEE	Institute Of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
CBEMA	Computer and Business Engg. Manufactuer Association
PCC	Point of Common Coupling
EPRI	Electrical Power Research Institute
D-STATCOM	Distribution Static Compensator
SSFCL	Solid State Fault Current Limiter
M-G	Motor-Generator
SSDs	Super Conducting Storage Devices
GTO	Gate Turn Off Thyristor
IGBT	Insulated Gate Bipolar Transistor
SMES	Super conducting Magnetic Emergency Storage
PWMVSI	Pulse Width Modulation Voltage Source Inverter

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