DYNAMIC VOLTAGE RESTORER FOR VOLTAGE QUALITY IMPROVEMENT

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ABSTRACT

Power quality has become a major area of concern in present era due to the increase in modern sensitive and sophisticated loads connected to the Distribution System. The various power quality problems are voltage sag, swell, transient, disturbances, etc. These power quality related problems can be solved with the help of various custom power devices.

Dynamic voltage restorer (DVR) is one of the most effective custom power devices which have been popular for the protection of sensitive loads from voltage sags. It is fast, flexible and efficient solution to voltage sag problem and is 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. It can restore the load voltage within few milliseconds. They employ a series of voltage boost technology using solid state switches for compensating voltage sags/swells. The DVR applications are mainly for sensitive loads that may be drastically affected by fluctuations in system voltage. The DVRs are used for providing reliable distribution power quality.

In this paper, an overview of the dynamic voltage restorer (DVR), its components, functions, compensation and control methods are reviewed along with the device capabilities and limitations.

Keyword - *Dynamic Voltage Restorer (DVR), Medium Voltage, Power Quality, Voltage Sag, Distribution Transformer, Filter, Energy Storage Unit, Voltage sag and swells.*

1.INTRODUCTION

Power Quality (PQ) related problems are of most concern nowadays. The widespread application of electronic equipments, like, information technology equipment, power electronic based equipments such as adjustable speed drives (ASD), programmable logic controllers (PLC), energy-efficient lighting, are completely changing the nature of electric loads. The applications of such kind of electric loads are the major victims of power quality problems. Power quality is an umbrella concept for multitude of individual types of power system disturbances. Quality of Supply may be categorized as in Figure 1.

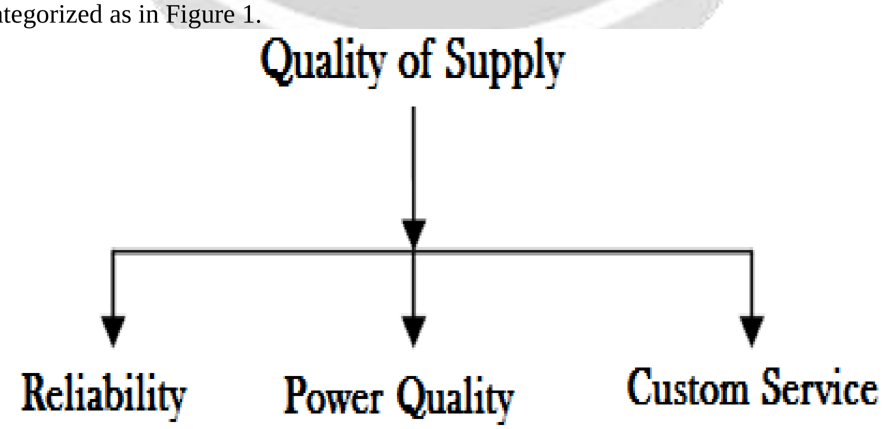

Fig. 1 Quality of Supply Categories

Distribution system is mainly affected by power quality issues such as voltage sag and swell. Voltage sags are mainly caused due to Short circuits, lightning strokes, faults and inrush currents. The use of custom power devices CPDs is one of the most efficient methods to mitigate voltage sag and swells. There are many custom power devices and each has its own benefits and limitations.

Dynamic Voltage Restorer (DVR) is one of the most efficient custom power devices and becomes popular in industry to mitigate the effect of voltage disturbances on sensitive loads. The Dynamic Voltage Restorer (DVR) is a device that detects the sag or swells and connects a voltage source in series with the supply voltage in such a way that the load voltage is kept inside the established tolerance limits. It is normally installed in a distribution system between the supply and the critical load feeder at the point of common coupling (PCC). DVR can also perform line voltage harmonics compensation, reduction of transients in voltage and fault current limitations.

2. POWER QUALITY PROBLEMS

Power distribution systems, should ideally provide their customers with an uninterrupted flow of energy with a smooth sinusoidal voltage at the contracted magnitude level and frequency. However, in practice, power systems, especially distribution systems, have numerous nonlinear loads, which significantly affect the quality of the power supply. Due to their non-linearity, such kind of electric loads cause disturbances in the voltage waveform. The change in voltage waveform produces many power quality problems. The main power quality problems due to disturbances of the voltage waveform are voltage sags and swells, harmonics, interharmonics and voltage imbalances. The voltage quality problems are as follows:

2.1. **Voltage Sag:** A Voltage Sag is a momentary decrease in the root mean square (RMS) voltage between 0.1 to 0.9 per unit, with a duration ranging from half cycle up to 1 min. The voltage sag is considered as the most serious problem of power quality and it is due to faults in the power system or by the starting of large induction motors.

2.2. Voltage Swell: Voltage swell is defined as an increase in the root mean square (RMS) voltage from 1.1 to 1.8 per unit for duration from 0.5 cycles to 1 min. Voltage swells are not as important as voltage sags because they are less common in distribution systems. The main causes for voltage swell are switching of large capacitors or start/stop of heavy loads.

2.3. **Harmonics:** 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. The main causes for harmonic distortion are rectifiers and all non-linear loads, such as power electronics equipment including VSDs.

2.4. Voltage transients: They are temporary and 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.

2.5. Flicker: Oscillation of voltage value, amplitude modulated by a signal with frequency of 0 to 30 Hz. The main causes are frequent start/stop of electric motors (for instance elevators), oscillating loads.

3.POWER QUALITY SOLUTIONS

There are two approaches for the mitigation of power quality problems. The solution to the power quality can be done from customer side or from utility side. First approach is called *load conditioning*, which ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install *line conditioning systems* that suppress or counteracts the power system disturbances. Dynamic Voltage Restorer (DVR) is suitable device for voltage sag reduction.

4. DYNAMIC VOLTAGE RESTORER (DVR)

Dynamic Voltage Restorer (DVR) is a recently proposed *series compensating device*, which can protect a sensitive load from the voltage distortions. Commercially, *static series compensator* is known as Dynamic Voltage Restorer (DVR). The DVR is installed in series with the line to inject voltage into the system in order to regulate the load side voltage. The first DVR was installed in North America in 1996 - a 12.47 kV system located in Anderson, South Carolina. Since then, DVRs have been applied to protect critical loads in utilities, semiconductor and food processing. DVR is one of the most efficient and effective modern custom power devices that used to mitigate the power quality problems in the distribution networks. The location of a DVR installed into a distribution network is shown in Fig. 2.

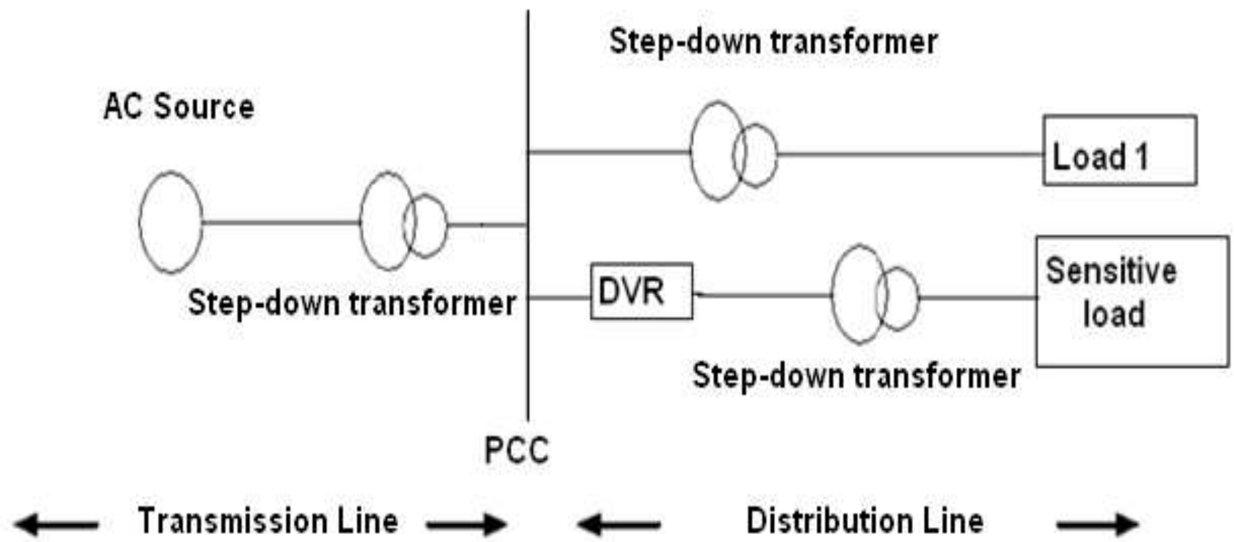

Fig-2. Location a DVR in a distribution network

5.BASIC DESGIN OF DVR

The basic configuration of a dynamic voltage restorer (DVR) is shown in Fig-3. The DVR consists of

1. Voltage Source Converter (VSC)
2. Injection/coupling transformer
3. Energy storage device
4. Harmonic filter
5. DC charging circuit
6. Control and Protection system

5.1.Voltage Source Converter (VSC): 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 four main types of switching devices: Metal Oxide Semiconductor Field Effect Transistors (MOSFET), Gate Turn-Off thyristors (GTO), Insulated Gate Bipolar Transistors (IGBT), and 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. Because of the highly sophisticated converter design with IGCTs, the DVR can compensate dips which are beyond the capability of the past DVRs using conventional devices.

5.2. Injection Transformer: The Injection / Booster transformer is a specially designed transformer that attempts to limit the coupling of noise and transient energy from the primary side to the secondary side. The main tasks of injection transformers are:

i. It connects the DVR to the distribution network through the HV-windings and transforms and couples the injected compensating voltages generated by the -voltage source converters to the incoming supply voltage.

ii. In addition, the Injection / Booster transformer serves the purpose of isolating the load from the system (VSC and control mechanism).

5.3. Energy Storage Unit: The purpose of storage devices is to supply the necessary energy to the VSC via a dc link for the generation of injected voltages. During voltage sag, the DVR injects a voltage to restore the load supply voltages. The different kinds of energy storage devices are superconductive magnetic energy storage (SMES), batteries, and capacitance. The energy storage can be different depending on the needs of compensating. The DVR often has limitations on the depth and duration of the voltage dip that it can compensate.

5.4. Harmonic filter: The main function of a harmonic filter is to maintain the harmonic voltage content generated by the voltage source converter (VSC) to the permissible level. It has a small rating approximately 2% of the load MVA connected to delta-connected tertiary winding of the injection transformer.

5.5 DC Charging Circuit: The dc charging circuit has two main tasks.

i. The first task is to charge the energy source after a sag compensation event.

ii. The second task is to maintain dc link voltage at the nominal dc link voltage.

5.6 Control and protection: 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.

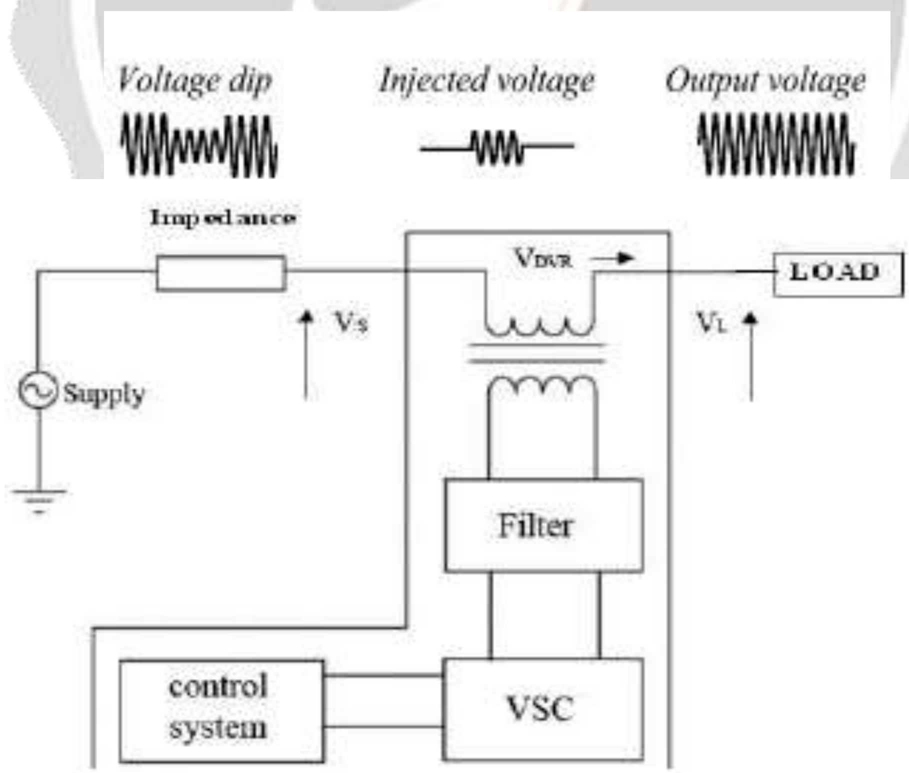

Fig-3 Basic configuration of a DVR.

6.PROPERTIOUS CHOICE OF DVR

There are numerous reasons why DVR is preferred over other devices:
1. Although, SVC predominates the DVR but the latter is still preferred because the SVC has no ability to control active power flow.
2. DVR is less expensive compared to the UPS.
3. UPS also needs high level of maintenance because it has problem of battery leak and have to be replace as often as five years.
4. DVR has a relatively higher energy capacity and costs less compared to SMES device.
5. DVR is smaller in size and costs less compared to DSTATCOM
6. DVR is power efficient device compared to the UPS.

7. EQUIVALENT CIRCUIT DIAGRAM OF DVR

The equivalent circuit diagram of a DVR is shown in Fig-4. When the source voltage drops or increases, the DVR injects a series voltage V_{INJ}, through the injection transformer so that the desired load voltage magnitude V_L can be maintained. The series injected voltage of the DVR can be written as:

$$V_{INJ} = V_L - V_S \quad (1)$$

Where,
V_L = desired load voltage magnitude.
V_S = source voltage during sags / swells condition.

And, the load current I_L is given by:

$$I_L = \left(\frac{P_L \pm jQ_L}{V_L}\right) \quad (2)$$

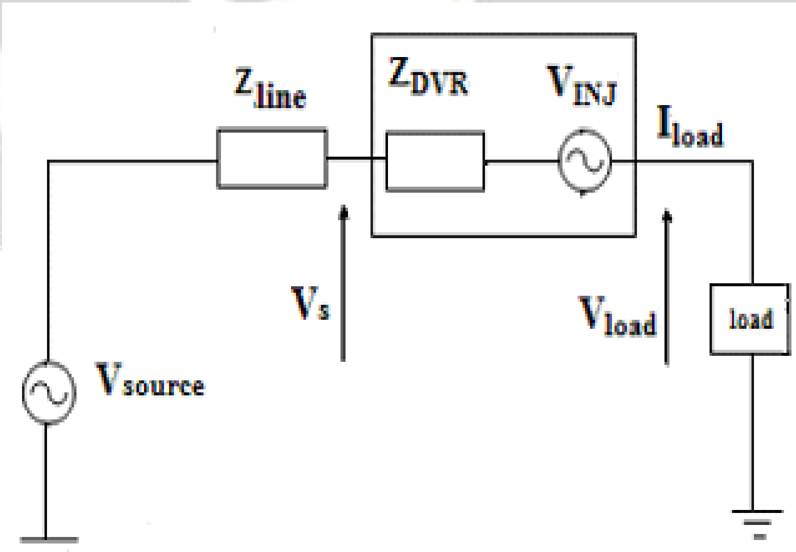

Fig-4 Equivalent circuit diagram of DVR.

8. MATHEMATICAL MODEL OF DVR

To understand the mathematical model of a dynamic restorer considered the Fig-5.

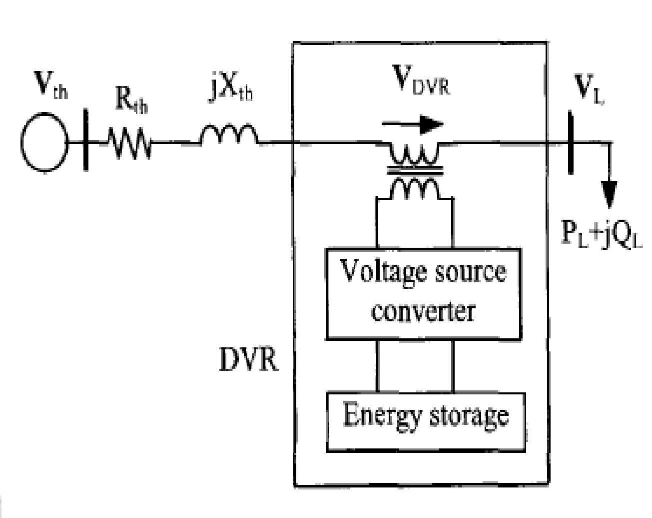

Fig-5 Mathematical model of a dynamic restorer for voltage injection.

From Fig-5,

$Z_{th}= R_{th}+jX_{th}$ (3)

And,

$V_{DVR} + V_{th} = V_L + Z_{th} I_L$ (4)

When Voltage drops at V_L, DVR will inject a series voltage V_{DVR} through the injection transformer so that the desired load voltage magnitude V_L can be maintained. Hence:

$V_{DVR} = V_L + Z_{th} I_L - V_{th}$ (5)

Let V_L be considered as reference, therefore

$$V_{DVR}\angle\alpha = V_L\angle 0° + Z_{th}I_L\angle(\beta-\theta) - V_{th}\angle\delta \quad (6)$$

Here, α,β,δ are the angles of V_{DVR}, Z_{th} and V_{th} respectively and θ is the load power factor angle with

$$\theta = \tan^{-1}\left(\frac{Q_L}{P_L}\right).$$

And, the power injection to the DVR is,

$S_{DVR} = V_{DVR} I_L$ (7)

9. DVR VOLTAGE INJECTION METHODS

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

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

9.1. Pre-Dip Compensation (PDC) Method

The **Pre-Dip Compensation (PDC) Method** tracks the supply voltage continuously. If DVR detects any disturbance in the voltage it will inject the difference voltage between the pre-sag and sag voltage at the PCC. In this way, load voltage can be restored back to the pre-fault condition. Compensation of voltage sags in both phase-angle and an amplitude sensitive load has to be achieved by pre-sag compensation (PDC) method. In this method the injected active power cannot be controlled and it is determined by external conditions such as the type of faults and load conditions. The pre-sag compensation (PDC) method is achieved by using a fault detector to freeze the output from the Phase Locked Loop (PLL) circuit, when the fault occurs. Then, the frozen angle is used to restore the previous balanced load voltages by using the Park transform. The lack of the negative sequence detection in this method leads to the phase-oscillation in the case of single-line faults. Fig-6 shows the single-phase vector diagram of this method.

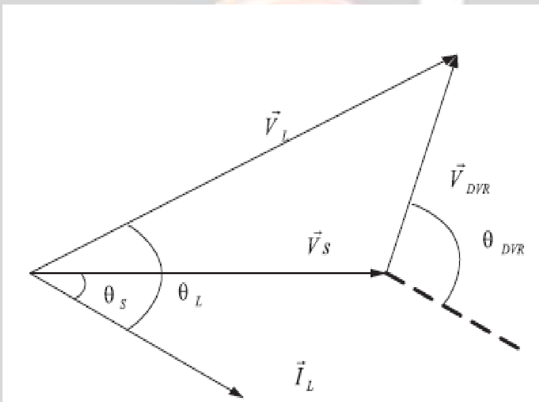

Fig-6 Single-phase vector diagram of Pre-Dip Compensation (PDC) Method.

From Fig-6, the apparent power of DVR is,

$S_{DVR}= I_L V_{DVR}$

$$= I_L\sqrt{V_L^2+V_S^2-2V_LV_S\cos(\theta_L-\theta_S)} \quad (8)$$

And, active power of DVR is,

$$P_{DVR} = I_L (V_L \text{Cos}\theta_L - V_S \text{ Cos}\theta_S) \quad (9)$$

$V_{pre\text{-}sag}=V_L$, $V_{sag}=V_S$

Voltage Injected by DVR is,

$$V_{DVR}= V_{pre\text{-}sag} - V_{sag} = V_L - V_S \quad (10)$$

Voltage injected V_{DVR} by a DVR can also be written as:

$$=\sqrt{V_L^2+V_S^2-2V_LV_S\cos(\theta_L-\theta_S)} \quad (11)$$

And, the phase angle injected by DVR is,

$\theta_{DVR}=\theta_{INJ}$

$$=\tan^{-1}\left(\frac{V_L\sin\theta_L-V_S\sin\theta_S}{V_L\cos\theta_L-V_S\cos\theta_S}\right) \quad (12)$$

9.2. In-Phase Compensation (IPC) Method

In-Phase Compensation (IPC) Method is the most straight-forward method. In this method the injected voltage is in phase with the PCC voltage regardless of the load current and pre-fault voltage. The phase angles of the pre-sag and load voltage are different but the attention is placed on maintaining a constant voltage magnitude on the load. 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 loads which are not sensitive to phase-angle jumps. Figure 7 shows the single-phase vector diagram of this method.

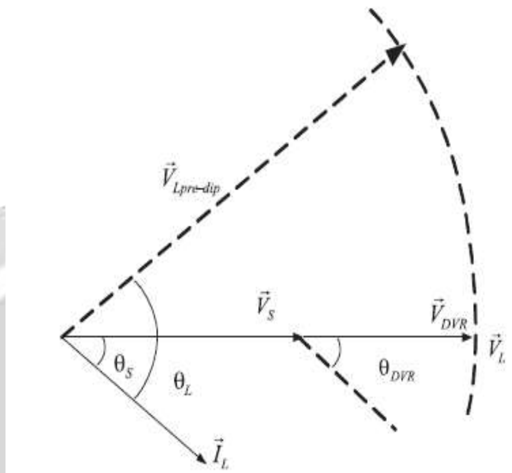

Fig- 7. Single-phase vector diagram of In-Phase Compensation (IPC) method.

In-Phase Compensation (IPC) Method can be achieved by two different ways.

i. In first way a synchronized PLL is used with the post fault voltage. It is a fast control algorithm but it cannot avoid phase jumps on the load voltage at the fault occurrence which can disturb the phase-angle controlled rectifier loads.
ii. In second way, the symmetrical components method is used. This method has a delay time introduced by the Fortescue transform calculation, and parameter dependence of the filter sequence. Also, the symmetrical components method can tolerate the effect of a phase jump by using the pre-fault phase angle.

The In-Phase Compensation (IPC) Method is suitable for minimum voltage or minimum energy operation strategies. This method also requires large amounts of real power to mitigate the voltage sag, which means a large energy storage device.

According to Fig-8, the apparent power of DVR is:

$$S_{DVR}=I_L V_{DVR} = I_L (V_L-V_S) \tag{13}$$

And, the active power of DVR is:

$$S_{DVR}=I_L V_{DVR} \cos\theta_S = I_L (V_L-V_S) \cos\theta_S \tag{14}$$

The magnitude and the angle of DVR are:

$$V_{DVR} = (V_L-V_S) \tag{15}$$

And,

$$\theta_{DVR} = \theta_S \tag{16}$$

9.3. In Phase Advance Compensation (IPAC) Method

In case of both Pre-Dip Compensation (PDC) and In-Phase Compensation (IPC) voltage injection methods active power is injected for the correction of voltage disturbance. The active power supply is limited stored energy in the

DC link. Dc link is one of the most expensive components of a DVR. Due to the limit of energy storage capacity of DC link, the DVR restoration time and performance are confined in both voltage injection methods. The minimization of injected energy is achieved by making the active power component zero by having the injection voltage phasor perpendicular to the load current phasor. In this method the values of load current and voltage are fixed in the system so we can change only the phase of the sag voltage.

The voltage injection method has been proposed to reduce the energy storage in the DC link is known as **In Phase Advance Compensation (IPAC) Method.** This method reduces the consumption of energy stored in a DC link by injecting the reactive power instead of active power. In IPAC method the magnitude of voltage injected is larger than both Pre-Dip Compensation (PDC) and In-Phase Compensation (IPC) voltage injection methods and the voltage phase shift can cause voltage waveform discontinuity, inaccurate zero crossing and load power swing. In short, 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 IPAC method, active power P_{DVR} depends on the angle α. During the sag, the phase of the load voltage will jump a certain step that causes problems for the load.

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.

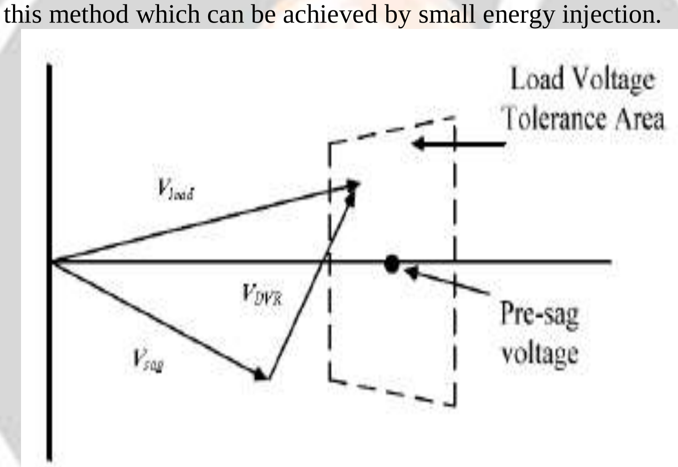

Fig-8 Voltage tolerance method with minimum energy injection .

10. VOLTAGE SAG DETECTION TECHNIQUES

A voltage sag detection technique detects the occurrence of the sag, the start point, the end point, sag depth (magnitude to be restored) and phase shift. Common voltage sag detection techniques are summarized as follows:

10.1. Peak value method: The simplest method of monitoring the supply is to monitor the peak, or amplitude, of the supply voltage, then comparing it with a reference. A controller could be set to recognize if there is a difference greater than a specified value (10%) and switch in the inverter.

10.2. Root Mean Square (rms) method: The start time of the sag can be defined as the first point of Vrms when drops below 0.9 pu. To find the end time of the sag, search for an interval where Vrms drops below 0.9 pu for at least half a cycle. The recovery time is then chosen as the first point in this interval.

10. 3.Fourier Transform (FT): The FT is achieved through orthogonal decomposition of power system signal. In general, a trigonometrically orthogonal function set or exponential orthogonal function set is utilized. By applying FT to each supply phase, it is possible to obtain the magnitude and phase of each of the frequency components of the supply waveform. For practical digital implementation Windowed Fast Fourier Transform (WFFT) is used, which can easily be implemented in real time control system. The only drawback of this method is that it takes one cycle to return the accurate information about the sag depth and its phase, since FT uses an averaging technique.

10.4. Space Vector method: The three phase voltages Vabc are transformed into a two dimension voltage Vdq, which in turn can be transferred into magnitude and angle. Any deviation in any quantity reveals the occurrence of an event. Comparing these quantities with reference ones will quantify the disturbance in the dq-frame, which had to be transformed back to the abc frame. This method has no time delay, yet requires complex controller.

11. CONTROL TECHNIQUES OF THE DVR

In a control system of the DVR main consideration includes: detection of the start and finish of the sag, voltage reference generation, transient and steady-state control of the injected voltage, and protection of the system. There are two basic type of controllers are used for the controlling of DVR.

11.1. Linear Controllers: The three main voltage controllers, which have been proposed in literature, are Feedforward (open loop), Feedback (closed loop) and Multi-loop controller.

- The *feed-forward voltage controller* is the primary choice for the DVR, because of its simplicity and fastness. The supply voltage is continuously monitored and compared with a reference voltage; if the difference exceeds a certain tolerance, the DVR injects the required voltage. The drawback of the open loop controller is the high steady state error.
- In the *feedback control*, the load voltage is measured and compared with the reference voltage, the missing voltage is supplied by the DVR at the supply bus in a feedback loop. This controller has the advantage of accurate response, but it is complex and time-delayed.
- *Multi-loop control* is used with an outer voltage loop to control the DVR voltage and an inner loop to control the load current. This method has the strengths of feed-forward and feedback control strategies, on the expense of complexity and time delay.

11.2. Non-linear Controllers

It appears that the nonlinear controller is more suitable than the linear type since the DVR is truly a non-linear system due to the presence of power semiconductor switches in the inverter bridge. The most non-linear controllers are the Artificial Neural Networks (ANN), Fuzzy Logic (FL) and Space Vector Pulse Width Modulation (SVPWM).

- *ANN control method* has adaptive and self-organization capacity. The ANN has inherent learning capability that can give improved precision by interpolation.
- *FL controllers* are an attractive choice when precise mathematical formulations are not possible. When a FL controller is used, the tracking error and transient overshoots of PWM can be considerably reduced.
- *SVPWM* control strategy is to adopt a space vector of the inverter voltage to get better performance of the exchange is gained in low switching frequency conditions.

12. CONCLUSION

In this paper a review of performance of DVR is presented. DVRs are effective recent custom power devices used for voltage sag and swells compensation in distribution networks. The basic structure of DVR, its operation, compensation methods and control techniques are discussed in detail. They inject the appropriate voltage component to correct rapidly any anomaly in the supply voltage to keep the load voltage balanced and constant at the nominal value. By the use of different control techniques it is viewed that DVR is suitable for voltage sag and swell mitigation. DVR provides simpler implementation for voltage profile improvement. Linear controllers provide simpler operation and less computational efforts when compared to other methods.

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