Power Quality Enhancement using Dynamic Voltage Restorer (DVR): An Overview

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Abstract- The problem of voltage unbalance and its impacts on sensitive loads is well known. To solve these problems, custom power devices are used such as dynamic voltage restorer (DVR), which is most efficient and effective modern device. This paper discusses a review of the researches on the Dynamic voltage restorer (DVR) for power quality Improvement in power distribution networks. Sensitivity industrial loads, critical commercial operations, Utility distribution networks affected from different types of outages and service interruptions and which results in financial losses. This paper describes DVR principle of operation, basic component, DVRs topologies system in distribution system, types of DVR control strategies, and compensation techniques.

I. Introduction

Power quality is the delivery of sufficiently high grade electrical services to the customer. A power quality problem is an occurrence manifested as a non-standard voltage, current or frequency that results in failure or mis-operation of end user equipment's. Power distribution systems, ideally should provide customer with an uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency [1], but in practice distribution systems, have nonlinear loads, which affects the purity of waveform of supply. Some events both usual (e.g. Capacitor switching, motor starting) and unusual (e.g. Faults) could also inflict power quality problems [7]. Faults at distribution level causes voltage sag or swell, which can cause sensitive equipment to fail as well as create a large current unbalance that could blow fuses or trip breakers. Under heavy load conditions, a significant voltage drop may occur in the system. A dip is usually taken as an event lasting less than one minute when voltage decreases to between 0.1 and 0.9 p.u. (dip greater than 0.1 p.u. is usually treated as an interruption) or Voltage sag can occur at any instant of time, with amplitudes ranging from 10-90 % and a duration lasting for half cycle to one minute [2]. These effects can be very expensive for the customer, ranging from minor quality variation to production downtime and equipment damage [8].

The concept of custom power was introduced by N.G.Hingorani in 1995. Custom Power Devices (CPD) is a powerful tool based on semiconductor switches to protect sensitive loads [9]. The most effective type of CPD devices is considered to be dynamic voltage restorer (DVR).

Power quality in the distribution system can be improved by using DVR, as assures pre-specified quality and reliability of supply. This pre-specified quality may contain a combination of specification of following: low phase unbalance, low harmonic distortion in load voltage, no power interruptions, acceptance of fluctuations, and poor power factor loads without significant effect on the terminal voltage, low flicker at the load voltage, magnitude and duration of overvoltage and under voltage within specified limits [10].

DVR is still preferred because the SVC has no ability to control active power flow [3]. Secondly DVR costs less compared to the UPS and it also requires a high level of maintenance because batteries leak and have to be replaced every five years [4,11] .Other reasons include that DVR is smaller in size and costs less compared to DSTATCOM [3,10,16].

II. Dynamic Voltage Restorer (DVR)

First Dynamic voltage restorer was built in U.S by Westinghouse for the Electric Power Research Institute (EPRI), and first installed in 1996 on Duke Power Company grid system to protect an automated yarn manufacturing and weaving factory [63]. DVR is a series connected solid state device that is used for mitigating voltage disturbances in the distribution system by injecting voltage into the system in order to regulate the load side voltage [17]. . DVR maintains the load voltage at a nominal magnitude and phase by compensating the voltage sag/swell, voltage unbalance and voltage harmonics presented at the point of common coupling [18,19,20]. Its primary function is to rapidly boost up the load side voltage in the event of a disturbance in order to avoid any power disruption to load [4,13].

IEEE 519-1992 and IEEE 1159-1995 describe the voltage sags/swells shown in fig.1.

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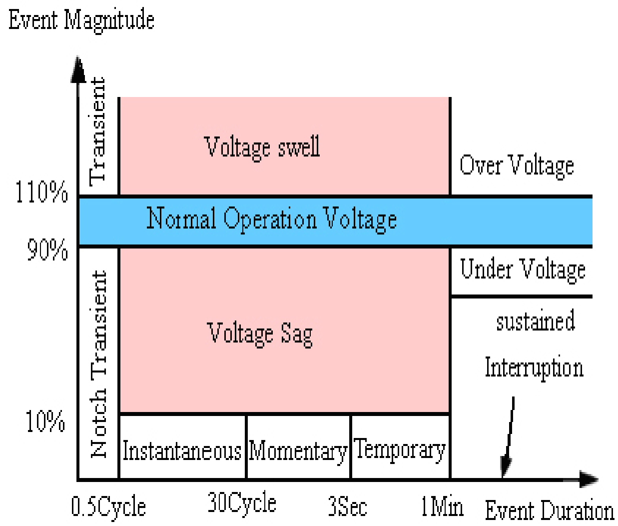

Fig.1.Voltage Reduction Standard of IEEE Std. 1159-1995 [88].

Voltage sags caused by unsymmetrical line-to line, line to ground, double-line-to-ground and symmetrical three phase faults is affected to sensitive loads [5].

The basic components of a DVR:

DVR can be applied for medium voltage [16, 23, 24] and in low voltage application [25]. The DVR components have been discussed in [26, 27]. Figure 2 shows conventional circuit configuration of the DVR .

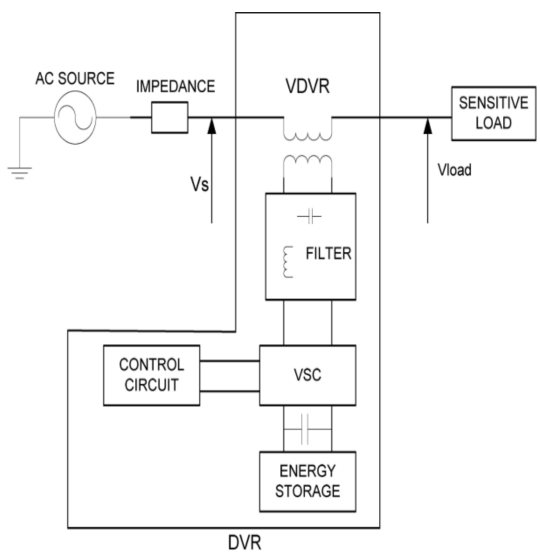

Fig.2.conventional circuit configuration of the DVR [14].

DVR is connected in series between the source voltage or grid and sensitive loads through injection transformer [6,21]. DVR inject the difference between voltage source and the sensitive load. The DC energy storage rating determines the maximum injection capability of DVR. Controller is an important part of the DVR for switching purposes. The switching converter is responsible to do conversion process from DC to AC. The inverter ensures that only the swells or sag voltage is injected to the injection transformer.

This device is based on voltage source converter a PWM that can produce a sinusoidal voltage with any angle required of the amplitude, frequency and phase [34]. The DVR system consists of two important components: a power circuit and a control unit. Power circuit of DVR basically consists of a voltage source inverter, a series connected injection transformer, an inverter output passive filter, and an energy storage device that is connected to the dc link [31, 28,29,32,30] as follows:

- Series Voltage Injection/booster Transformers
- Voltage Source Inverter (VSI)
- Passive Filters
- DC charging circuit
- Control and Protection

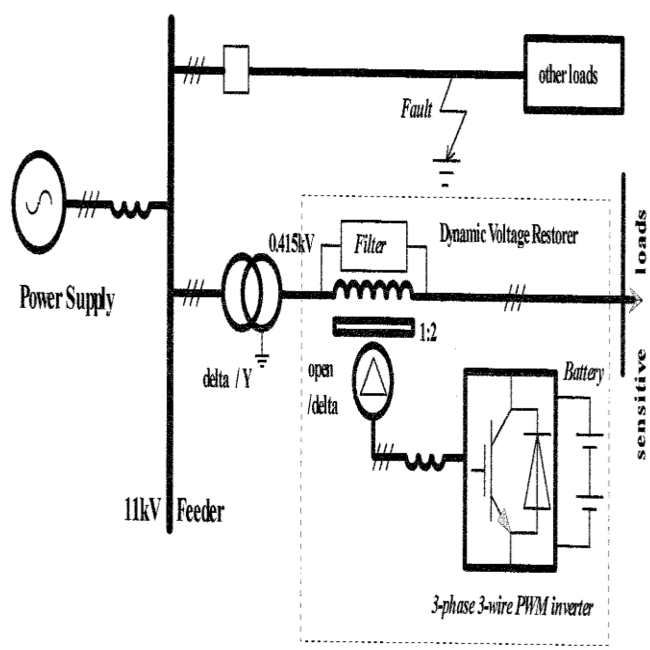

Fig.3. Schematic power circuit diagram of a DVR [37].

Power Circuit of a DVR is shown in Figure 3. It has VSI and the injection transformer. The VSC consist of six IGBT's (insulated gate bipolar transistor), three ac inductors and capacitor's respectively, one dc capacitor and energy storage [9, 33, 35].

In DVR the control circuit is used to derive the parameters (magnitude, frequency, phase shift, etc.) of the control signal that has to be injected by the DVR. Based on the control signal, the injected voltage is generated by the switches in the power circuit, in order to protect DVR from any disturbances a hybrid switch been used [26,17].

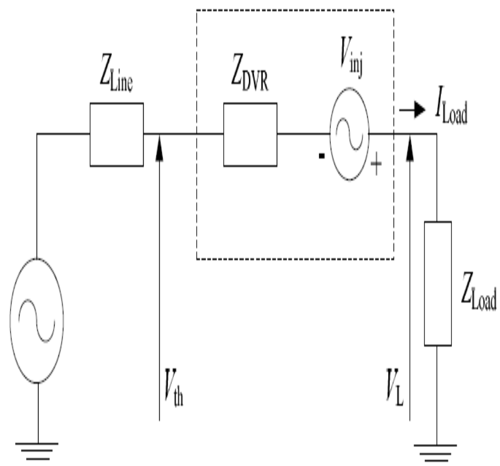

Fig.4. DVR equivalent circuit.

I. Series Voltage Injection/booster Transformers:

The injection/booster transformer limits coupling of noise and transient energy from primary to secondary side[36]. Generally High voltage side of the injection transformer is connected in series to the distribution system and the power circuit of the DVR can be connected at the low voltage side[37]. When unbalance fault occur in the high voltage side, the zero sequence current flowing is almost zero, if the distribution transformer connection is Δ-Y with the grounded neutral. In such connection, the DVR only mitigate the positive and negative sequence components [38].

II. Voltage Source converter (VSC):

A VSC is power electronic system consists of a storage device and switching devices. It generates a sinusoidal voltage at any required frequency, magnitude, and phase angle.

The function of an inverter system in DVR is used to convert the DC voltage supplied by the energy storage device into an AC voltage [60] and to temporarily replace the supply voltage or to generate part of supply voltage which is missing[50].

Various circuit topologies are available for VSC [12,51]. Widely used method is two level or multilevel three-phase converter [62] which shares a dc capacitor between all phases, which absorbs harmonic ripple and has a relatively small energy storage requirement.

- ***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) are four main types of switching devices. IGBT is considered to be a newer device compared to MOSFET and GTO, first introduced in the early 1980s and has become a popular device because of its superior characteristics [53]. It is a three terminal controllable switch that combines the fast switching times of the MOSFET with the high voltage capabilities of the GTO and it has a medium speed controllable switch capable of supporting the medium power range [36, 52, 53, 54, 57].

- ***Storage devices***

The DVR needs real power for compensation during voltage disturbances in the distribution network which must be supplied by energy storage when the voltage disturbances exit.

Storage devices supply the necessary energy to the VSC via a dc link for the generation of injected voltages. The application of the energy storage in DVR depends on the design rating required and total cost [39]. The capacity of the stored energy directly determines the duration of the sag which can be mitigating by the DVR. There are different kinds of energy storage devices [12,29]:

Superconductive magnetic energy storage (SMES) has been used for very critical applications, but its cost limits its use to industries where the losses are great if there is a disturbance e.g. semiconductor fabrication.

Batteries can be highly effective if a high voltage battery configuration is used, and have a short lifetime which requires battery management system, which can be costly.

Storage systems with auxiliary supply are used to increase the system performance when the grid of DVR is weak [40, 41].

Ultra-capacitors have a wider voltage range than batteries and can be directly paralleled across the input bus and have a specific energy density less than that of a battery, but a specific power greater than a battery, making them ideal for short (up to several seconds) pulses of power.

Flywheel Energy Storage system utilizes a single AC/AC power converter for the grid interface as opposed to a more conventional AC/DC/AC converter, leading to higher power density and increased system reliability but has the disadvantage of high maintenance cost (bearings etc.) [42,46,47].

III. LC Filter:

In DVR, filters convert the inverted PWM waveform into a sinusoidal waveform, by eliminating the unwanted harmonic components generated by the VSI action[37,43]. Higher orders harmonic components distort the compensated output voltage [44]. The unnecessary switching harmonics must be removed from the injected voltage waveform to maintain an acceptable Total Harmonics Distortion (THD) level. The passive filters can be placed either in the high voltage or in low voltage side winding of the series injection transformer [45, 48, 49].

IV. DC charging circuit:

The dc charging circuit has two main functions: The first is to charge the energy source after a sag compensation event and second is to maintain dc link voltage at the nominal dc link voltage. To charge the dc-link various topologies are used.

V. Control and protection:

The control process generally consists of hardware with programmable logic. In past it consists of Digital Signal Processing boards which provide controls like detection and correction. Filters can also be used. There are different types of filter algorithm: Fourier Transform (FT), Phase-Locked Loop (PLL), and Wavelet Transform (WT), out of which Fourier Transform is the most common type. Direct feed forward type control architecture maximizes dynamic performance of DVR and compensation of voltage sags can be achieved in a fast response time (approximately 1ms) [58,59].

III. OPERATION OF THE DVR

A typical DVR configuration is used for voltage compensation in the distribution line. Operation of the DVR consists of three operation mode:

Protection mode: Bypass switch can be used as a protection device to protect DVR from the over current in the load side due to short circuit on the load or large inrush currents [20]. The DVR can be protected by the action of the bypass switches by supplying another path for current.

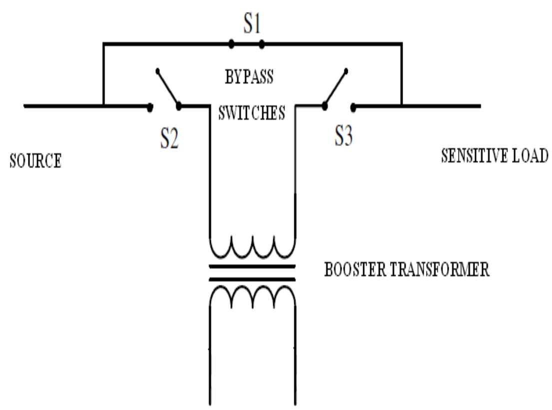

Fig 5: Protection mode

Standby mode: DVR will be most of the time in this mode (VDVR = 0). The two lower IGBT's in each phase of the inverter remains turned on where as two upper IGBT's turned off. Low voltage winding of injection transformer is shorted through inverter. A short circuit across the secondary (inverter side) windings of the series transformer through LF is obtained eliminating the use of bypass switches. In this mode of operation, no switching of semiconductors occurs so as to create a short-circuit path for the transformer connection, individual inverter legs are triggered. As a result, in this current loop, only comparatively low conduction losses of the semiconductors, contribute to the losses [67].

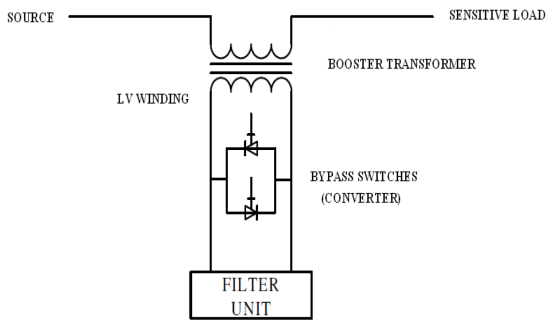

Fig 6 Standby mode

Injection mode: The DVR goes into injection mode (VDVR > 0) when the sag is detected [38]. Various voltage injection strategies are: pre-sag, phase advance, voltage tolerance and in phase method. DVR should have unchanged load voltage with minimum energy dissipation for injection due to the high cost of capacitors [20]. With required magnitude, phase and wave shape, three single-phase ac voltages are injected in series for compensating voltage sag, whose possibility is determined by types of voltage sags, load conditions and power rating of DVR [64].

IV. DVRS TOPOLOGIES IN DISTRIBUTION SYSTEM

DVR injects an appropriate voltage to recover the voltage at the load during disturbances in a network, by exchanging active and reactive power with the system. There are two types of DVR topologies system comprising of no energy storage and with energy storage [14].

DVR with no Energy Storage:

This can be divided into:

Type 1: The energy is taken from the incoming supply or grid connected side through a passive shunt converter connected to the supply side or source side.

Type 2: The energy is taken from the grid connected side through a passive shunt converter connected to the load side.

This type of DVR system with no energy storage utilizes the fact that a considerable part of the source voltage is maintained during the disturbances and this can be used to provide the boost energy required to maintain full power at its nominal voltage [63].

DVR with Energy Storage:

The performance of the DVR can be improved by using energy storage even though storing electrical energy is expensive. If DVR is used for compensation process and there is a disturbance in the distribution system, stored energy supplies the real power requirements of the system.

Type 3: This type of topology is simple and a variable dc-link voltage is utilized. The energy storage required to activate the DVR is proportional to the square of the rated dc-link voltage. In this system DVR with energy storage is employed where the variable DC-Link Voltage is used and energy is stored in the DC Link Capacitor [14].

Type 4 : Energy storage such as SMES, batteries or super-capacitors can be used as a direct energy storage which is applied in DVR. Constant DC-Link Voltage is applied to this topology. Using an inverter, large energy storage can be transferred to smaller rated dc-link storage, during the disturbances in the network.

V. CONTROL STRATEGIES IN DVR

The main purpose of control scheme is to maintain constant voltage magnitude at the point where a sensitive load is connected under system disturbances .Most of the DVR systems are equipped with a control system that mitigates voltage sags/swells. Some DVR applications include power flow control, reactive power compensation, and limited responses to power quality problems [22, 28, 72, 73]. The control of DVR is very important and it involves detection of voltage sags (start, end and depth of the voltage sag) by appropriate detection algorithms which work in real time. The control system only measures the r.m.s voltage at the load point, hence no reactive power measurements are required. The voltage sags can last from a few milliseconds to a few cycles, with typical depths ranging from 0.9 p.u. to 0.5 p.u. of a 1-pu nominal [37, 29]. Inverter is an important component of DVR and performance of the DVR is directly affected by the control strategy of inverter. The inverter control strategy comprises of two types of control as following:

1.LINEAR CONTROL: Linear control is most common method of DVR control.

(a).feed forward control: is a simple method of DVR. This technique does not sense the load voltage. It calculates the injected voltage based on the difference between the pre-sag and during-sag voltages [81, 63, 82].

(b).feedback control strategy: It calculates the load. The difference between the reference load voltage and actual load voltage is required injection voltage [82]. The feedback control methods based on state space systems, which can be set up closed-loop poles in order to make faster time response can also be used. Feedback and the feed forward control strategy may be implemented by vector or scalar control techniques [85,86,65,87].

(c).composite control strategy: it can improve voltage compensation effect. It is a control method with grid voltage feed forward and load side voltage feedback, which has the strengths of feed-forward and feedback control strategy [83]. The combination with feed forward control can improve the system dynamic response rate, shortening the time of compensation significantly. If the feedback control in the composite control is designed to double-loop, it can improve system stability, system performance and the adaptability of dynamic load. [85].

2.NON LINEAR CONTROL

DVR is categorized as non-linear device due to the usage of power semiconductor switches in the VSI. When the system is unstable, model developed does not fully control target so all the linear control methods cannot work properly due to their limitations.

(a).artificial neural network control (ANN): It has adaptive and self-organization capacity and can be classified in: local approximation neural networks, feedback neural networks, feed forward neural network, and fuzzy neural network based on structure. Without detail mathematical model, ANN control can keep a careful check on the nonlinear relationship based on input and output [80].

(b).fuzzy control: This can be used in DVR for voltage injection [78]. These controllers are implemented into DVR when precise mathematical formulations are not possible. It is derived from fuzzy set theory introduced [79]. The advantage of this controller is its capability to reduce error and transient overshoot of PWM .

(c).space vector PWM control: In low switching frequency conditions, this strategy uses a voltage inverter space vector of the switch to get quasi-circular rotating magnetic field instead of the original SPWM, so better performance of the exchange is gained [17]. A double-loop vector control can also be used [74]. Controls for single phase voltage sag detection methods in distribution system are also available: Mathematical Morphology theory based low-pass filter [76], Soft Phase Locked Loop (PLL) [75], Instantaneous Value Comparison Method [77].

VI. COMPENSATION TECHNIQUES IN DVR

Concept of compensation techniques which are applied in DVR, can be divided into categories as follows;

1.REACTIVE POWER COMPENSATION:

In this only small energy storage is required and it does not require any active power, DVR provides reactive power compensation. The phasor diagram is illustrated in Figure [69]. The injected voltage is in quadrature with the load current. [28,70].

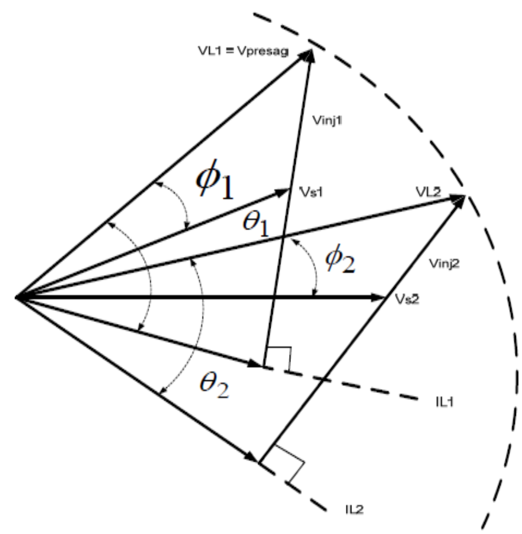

Fig.7 : Reactive Power Compensation .

2.ACTIVE AND REACTIVE POWER COMPENSATION:

(a).Pre-Sag Compensation:

In this method it is important for both magnitude and the phase angle to be compensated. The difference during sag and pre-sag voltage are detected by DVR and it injects the detected voltage, hence phase and amplitude of the voltage before the sag has to be exactly restored [26,28]. Figure.6 shows the pre-sag compensation technique before and after the voltage sags. [66,70].

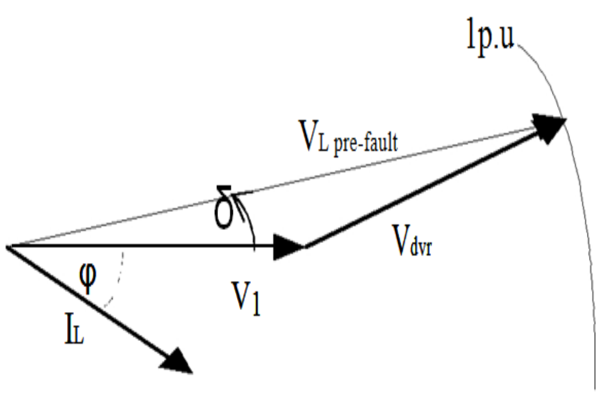

Fig.8 . Pre-sag compensation

(b).In- Phase Compensation:

In this method, injection voltage is in phase with the source voltage [68]. When the source voltage drops due to sag in the distribution network, then injection voltage produced by the Voltage Source Inverter (VSI) will inject the missing voltage according to voltage drop magnitude [28,70]. This method can be shown in Figure.7 [66].

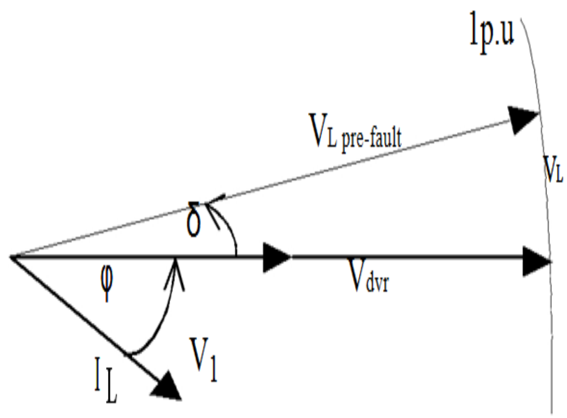

Fig.9 . In–Phase compensation

(c).Phase Advanced or Minimum Energy Compensation:

This method reduces the energy storage size. Active power P_{DVR} depends on the angle α. During the sag, phase of load voltage jump's a certain step that causes difficulties for load [28, 70, 71]. The magnitude of the restored load voltage that is maintained at pre-fault condition is shown in fig.8. [7].

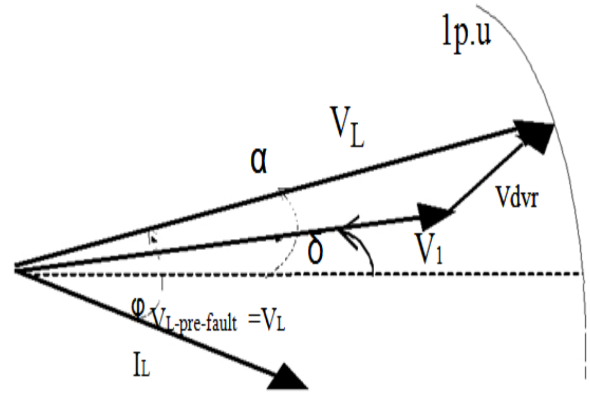

Fig.10 . Phase advanced compensation

VII. CONCLUSION

This paper represents a detailed review of power quality problems and DVR which is a powerful custom power device. The main function of a DVR is the protection of sensitive loads from voltage disturbances in the distribution system. Various topologies and their controllers applied in DVR are explained in this paper. It also provides knowledge for the researchers to build a new design of DVR to mitigate voltage disturbances in distribution system. There is more to come, both in terms of technical development and economic solutions to existing problems.

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