Dynamic Voltage Restorer (DVR) System for Compensation of Voltage Sags, State-of-the-Art Review

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Abstract:

The problem of voltage sags and its severe impact on sensitive loads is well known. To solve this problem, The DVR is a modern and important custom power device for compensation voltage sags in power distribution systems. The Dynamic Voltage Restorer (DVR) is fast, flexible and efficient solution to voltage sag problem. The DVR is a series compensator used to mitigate voltage sags and to restore load voltage to its rated value. In this paper, an overview of the DVR, its functions, configurations, components, operating modes, voltage injection methods and closed-loop control of the DVR output voltage are reviewed along with the device capabilities and limitations.

Keywords: Power Quality, Voltage Sag, Dynamic Voltage Restorer (DVR), Control Strategy, Voltage Source Converter.

1. Introduction

Power quality is a very important issue due to its impact on electricity suppliers, equipment manufactures and customers. "Power quality is described as the variation of voltage, current and frequency in a power system. It refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location in the power system" [1], [2]. Both, electric utilities and end users of electrical power are becoming increasingly concerned about the quality of electric power. Sensitive loads such as computers, programmable logic controllers (PLC), variable speed drives (VSD)-etc. need high quality supplies [3], [4]. 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 [5].
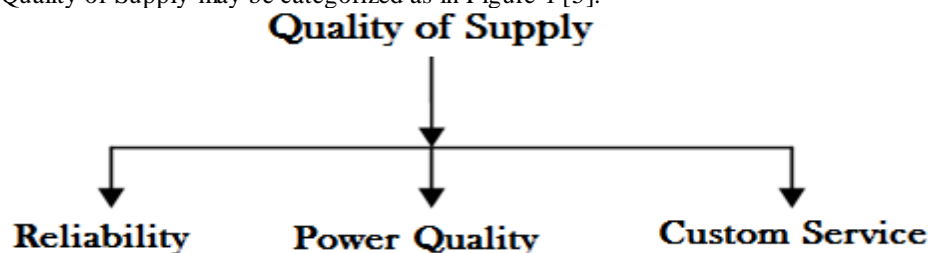

Fig. 1 Quality of Supply Categories

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. As a result of these nonlinear loads, the purity of the supply waveform is lost in many places. This ends up producing many power quality problems [6], [7]. An important percentage of all power quality problems are of the voltage-quality type where what matters is the deviation of the voltage waveform from its ideal form. The best known disturbances of the voltage waveform are voltage sags and swells, harmonics, interharmonics and voltage imbalances. Voltage-quality problems are as follows [8]-[15]:

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. It is considered as the most serious problem of power quality. It is caused by faults in the power system or by the starting of large induction motor [13, 22].

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 [7, 8].

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 [17].

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.

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 [17]. Figure 2 shows the sketch of a voltage waveform with physical power- quality problems.

This paper is structured as follows: Section 2 presents solutions to voltage quality problems. Section 3 discusses an overview of the DVR, its functions, configurations, components and operating modes of DVR. Voltage injection methods of DVR are presented in section 4. Section 5 presents closed-loop control of the DVR's output voltage. At the end, some conclusions are given in section 6.
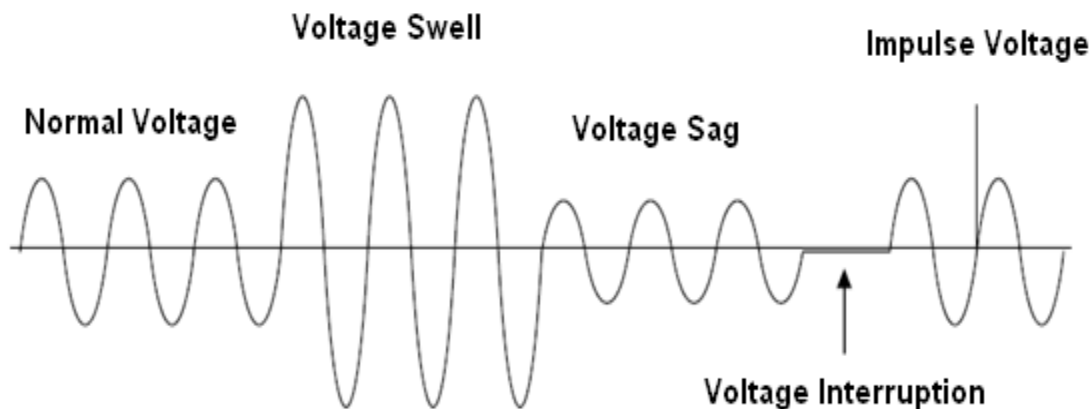

Fig. 2 Regular power- quality problems in power system [16], [17].

2. Solutions to Voltage Quality Problems

There are two approaches to tackle power-quality problems. (a) Actions taken from the customer side or (b) Actions taken from the utility side. The 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 second approach consists of line-conditioning systems that suppress or counteracts the power system disturbances. Currently, line-conditioning systems are based on pulse width modulation (PWM) converters connected to low-voltage and medium-voltage distribution system in shunt mode or in series. However, with the restructuring of the power sector and with shifting trend towards distributed and dispersed generation, the line-conditioning systems or utility side solutions will play a major role in improving the inherent supply quality [18], [19].Though there are many different methods to mitigate voltage sags and swells, the use of a custom Power device is considered to be the most efficient method. The term custom power refers to the use of power electronics controllers in a distribution system, especially, to deal with various power-quality problems [2].There are many types of Custom Power devices. Some of these devices include: Active Power Filters (APF), Battery Energy Storage Systems (BESS), Distribution STATic synchronous COMpensators (DSTATCOM), Distribution Series Capacitors (DSC), Dynamic Voltage Restorer (DVR), Surge Arresters (SA), Super-conducting Magnetic Energy Systems (SMES), Static Electronic Tap Changers (SETC), Solid-State Transfer Switches (SSTS), Solid State Fault Current Limiter (SSFCL), Static Var Compensator (SVC), Thyristor-Switched Capacitors (TSC), and Uninterruptible Power Supplies (UPS) [7,15,20]. In this paper, an overview of the DVR, its functions, configurations, components, operating modes, voltage injection methods and closed-loop control of the DVR output voltage are reviewed along with the device capabilities and limitations.

3. Dynamic Voltage Restorer (DVR) System

Among the power quality problems (sags, swells, harmonics…) voltage sags are probably the most severe disturbances [7]. In order to overcome these problems the concept of custom power device has become introduced recently. One of those devices is the Dynamic Voltage Restorer (DVR), which is one of the most efficient and modern custom power device used in power distribution networks [7, 31]. A DVR is a series-connected solid-state device that injects voltage into the system in order to regulate the load side voltage. It is normally installed in a distribution system between the supply and a critical load feeder at the so-called point of common coupling (PCC).Its primary function is to rapidly boost up the load-side voltage in the event of a voltage sag in order to avoid any power disruption to that load. There are various circuit topologies and control schemes that can be used to implement a DVR [9, 12, 22].Together with voltage sags and swells compensation, DVR can also have other

features like: line voltage harmonics compensation, reduction of transients in voltage and fault current limitations [8, 27]. Figure 3 shows the location of dynamic voltage restorer (DVR) in an electrical power system.
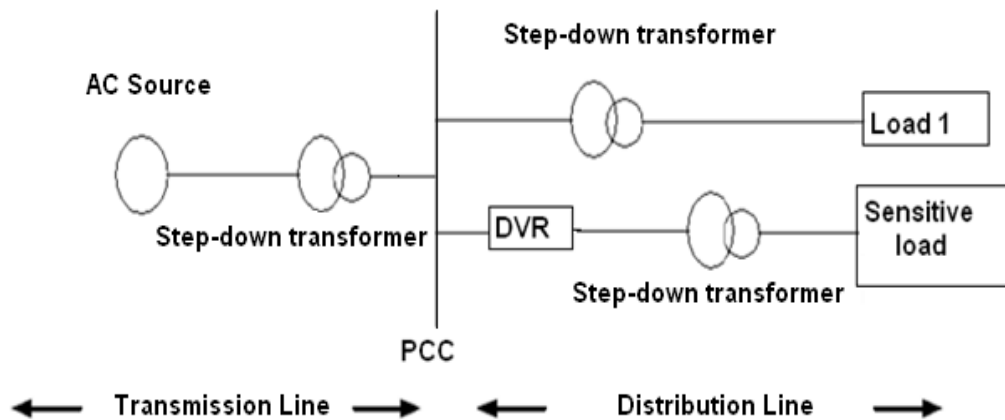

Fig. 3 Location of a dynamic voltage restorer (DVR)

The DVR is a power-electronic-converter-based device capable of protecting sensitive loads from most supply-side disturbances. As shown in Figure 4 the general configuration of the DVR consists of [7, 21, 23, 24, 25]:

3.1. Injection / Booster transformer

The Injection / Booster transformer has two purposes [8, 15, 32]: It connects the DVR to the distribution network via the HV-winding and transforms and couples the injected compensating voltages generated by the voltage source converter (VSC) in series with the incoming supply voltage. In addition, the Injection / Booster transformer serves the purpose of isolating the load from the system (VSC and control mechanism). In [8] a transformer-less DVR based on the multilevel inverter is presented. As a result of employing this inverter, the proposed DVR has lower number of switches in comparison with other multilevel DVR topologies. In [22] transformer-less and Neutral Point Connected DVRs use inductors instead of transformers to inject voltage in the system and are presented as the cheapest solutions. In [33] the proposed transformer-less DVR can satisfactorily mitigate the voltage-sag problems. The design is promising as it points at a less costly restorer of a more compact structure. It also possesses a superior voltage regulation property and has lower losses.

3.2. Harmonic filter

The main task of the harmonic filter is to keep the harmonic voltage content generated by the voltage source converters (VSC) below the permissible level. (i.e. eliminate high-frequency switching harmonics) [23].

3.3. Energy-Storage Unit

It is responsible for the energy storage in DC form. Flywheels, batteries, superconducting magnetic energy storage (SMES) and super capacitors can be used as energy storage devices. It will supply the real-power requirements of the system when DVR is used for compensation [24], [26].

3.4. Voltage Source Converter (VSC)

A voltage-source converter is a power electronic system consisting of switching devices like: Metal Oxide Semiconductor Field Effect Transistor (MOSFET), Gate Turn-Off-Thyristors (GTO), Insulated Gate Bipolar Transistors (IGBT), and Integrated Gate Commutated Thyristors (IGCT), which can generate a sinusoidal voltage at any required frequency, magnitude, and phase angle [23].The output voltage does not need to be of a single frequency. Voltage source converters are widely used in Variable-speed drives (VSD), but can also be used to mitigate voltage dips. The VSC is used to either completely replace the supply voltage or to inject the 'missing voltage'. The 'missing voltage' is the difference between the nominal voltage and the actual one. Normally the VSC is not only used for voltage dip mitigation, but also for other power quality issues, e.g. flicker and harmonics [27, 28].

3.5. Control System

The main purpose of the control system is to maintain a constant voltage magnitude at the point where a sensitive load is connected, under system disturbances. It will also look after the D.C. link voltage using the DC-charging unit [23], [25].
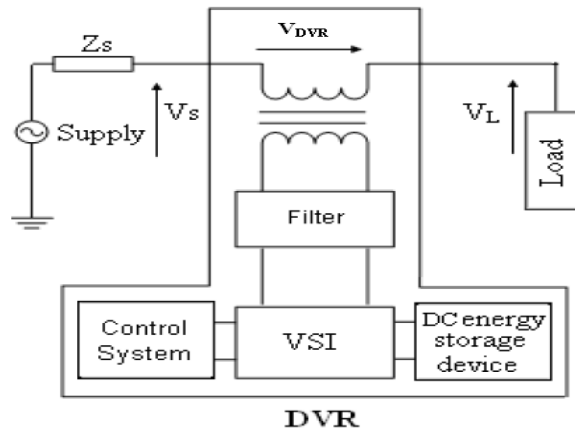
Fig. 4 Dynamic Voltage Restorer (DVR) general configuration

The DVR has three modes of operation which are: protection mode, standby mode (during steady state), and injection/boost mode (during sag) [29].

A- Protection Mode

If the current on the load side exceeds a permissible limit due to a short circuit on the load or large inrush current, the DVR will be isolated from the systems by using the bypass switches as shown in Figure 5, S2 and S3 will open and S1 will be closed to provide an alternative path for the load current.
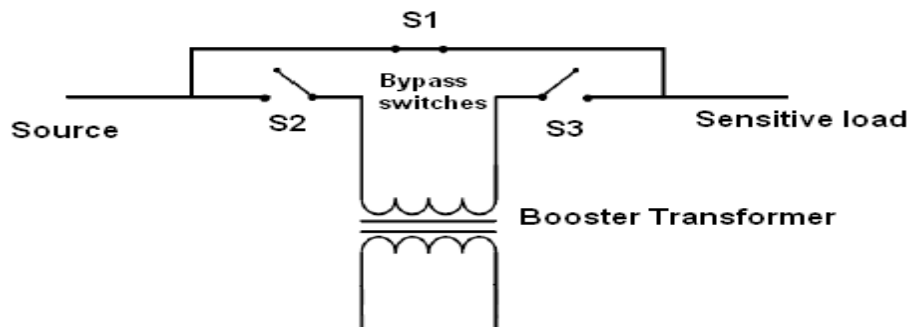

Fig. 5 Protection Mode (creating another path for the load current)

B- Standby Mode: (VDVR = 0)

In the standby mode the booster transformer's low-voltage winding is shorted through the converter as shown in Figure 6. No switching of semiconductors occurs in this mode of operation and the full load current will pass through the transformer primary [15, 23].
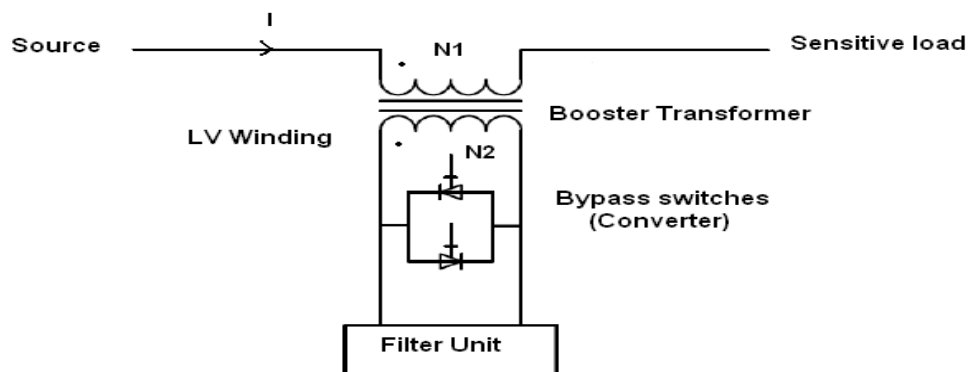

Fig. 6 Standby Mode

C- Injection/Boost Mode: (VDVR≠0)

In the Injection/Boost mode the DVR is injecting a compensating voltage through the booster transformer after the detection of a disturbance in the supply voltage [15, 23].
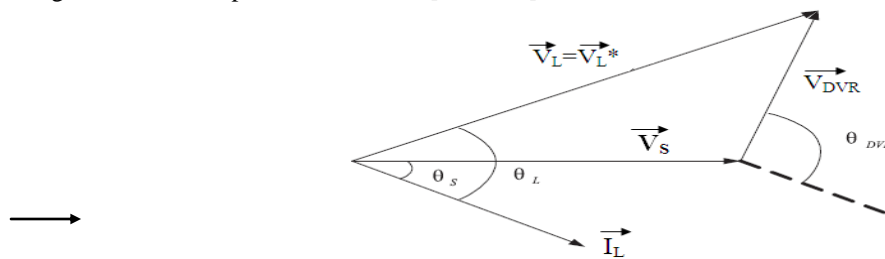
4. Voltage Injection Methods of DVR

The way in which the dynamic voltage restorer (DVR) is used during the voltage injection mode depends upon several limiting factors such as: DVR power rating, load conditions, and voltage-sag type. For example, some loads are sensitive to phase-angel jumps, some others are sensitive to a change in voltage magnitude and some others are tolerant to all these disturbances. Therefore the control strategies to be applied depend upon the load characteristics [7, 12, 13, 21]. There are four different methods of DVR voltage injection [18, 29]

4.1. Pre-sag/dip compensation method.
4.2. In-phase compensation method.
4.3. In-phase advanced compensation method.
4.4. Voltage tolerance method with minimum energy injection.

4.1. Pre-Sag/Dip Compensation Method (PDC)

The pre-sag method tracks the supply voltage continuously and if it detects any disturbance in that voltage it will inject the difference voltage between the sag or voltage at the PCC and the ideal pre-fault condition. In this way, the load voltage can be restored back to the pre-fault conditions. Compensation of voltage sags in both phase-angle and an amplitude sensitive load has to be achieved by pre-sag compensation method. In this method, the active power injected by the DVR cannot be controlled and it is determined by external conditions such as the type of faults and the load conditions. Figure 7 shows the single-phase vector diagram of this compensation method [7, 21, 30].
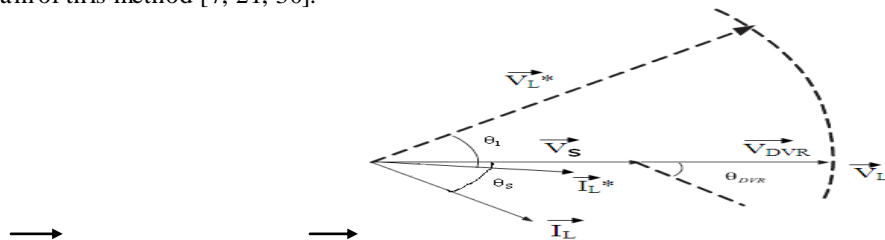

Where VL* ——→ Pre-sag voltage

Fig. 7 Single-phase vector diagram of the PDC method

4.2. In-Phase Compensation Method (IPC)

This 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 a 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 8 shows the single-phase vector diagram of this method [7, 21, 30].

Where V_L^* ——→ Pre-sag voltage, I_L^* ——→ Pre-sag load current, $\theta_1 = \theta_S$

Fig. 8 Single-phase vector diagram of the IPC method

4.3. In-Phase Advanced Compensation Method (IPAC)

In this method the real power spent by DVR is minimized by decreasing the power angle between the sag voltage and the load current [29]. In the two previous cases, namely pre-sag and in-phase compensation, active power is injected into the system by the DVR during disturbances. Morever, the active power supplied is limited to the stored energy in the DC link and this part is one of the most expensive parts of the DVR. The minimization of injected energy is achieved by making 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 one can change only the phase of the sag voltage [7, 21, 29]. In short, IPAC method uses only reactive power and unfortunately, not all the sags can be mitigated without real power, as a consequence, this method is only suitable for a limited sag range.

4.4. Voltage Tolerance Method with Minimum Energy Injection

Generally voltage magnitudes between 90%-110% of the nominal voltage and phase angle variations between 5% - 10% of the normal state will not disturb the operation characteristics of loads. This compensation method will maintain the load voltage within the tolerance area with small change of voltage magnitude as shown in Figure 9 [29].
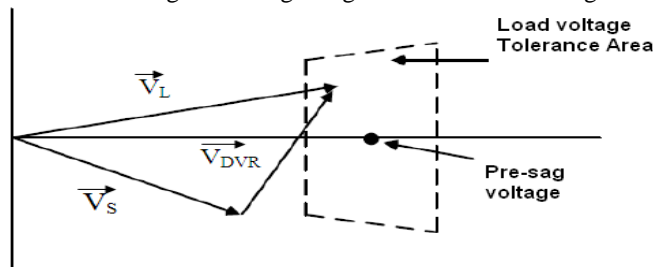

Fig. 9 Voltage tolerance method with minimum energy injection

5. Closed-Loop Control of the DVR's Output Voltage

The control system of a DVR plays an important role, with the requirements of fast response in the face of voltage sags and variations in the connected load. Generally, two control schemes are used in DVR applications, namely, open-loop controller [35] and closed-loop controller [36], [37].In [9] a repetitive controller is used in a DVR system to ameliorate voltage sags, harmonic voltages, and voltage imbalances. It has a wide range of applicability, a fast transient response and ensures zero error in steady state. In [23] the proposed controller combines fuzzy logic with a classical PI controller to adjust the PI gains. Authors report that the main advantage of an adaptive fuzzy PI controller over the classical one (PI) is its ability to compensate notching when the DVR is connected to a weak power system.In [34] the proposed control algorithm based on Space Vector Pulse Width Modulation (SVPWM) technique to generate the pulses for mitigation voltage sags are presented. The simulation and experimental results by using PSCAD / EMTDC showed clearly the performance of the dynamic voltage restorer (DVR) in mitigating voltage sags.In [38] a control method is developed and implemented in order to mitigate voltage sag in distribution systems. The main parts of the controller are the maximum block (Max), filter, lead-lag, PI controller and phase locked loop (PLL). The simulation results showed that the DVR compensates the voltage sag quickly and provides excellent voltage regulation, also better efficiency is achieved by using the proposed control.In [39] a survey on control strategies of Dynamic Voltage Restorer (DVR) is presented. Authors report that the inverter is the core component of DVR, this reference presents the inverter control strategies used in DVR recently, which are linear control and Non-linear control and their types.In [40] a fast repetitive controller based feedback control loop for dynamic voltage restorer (DVR) system is proposed. The Author reports that the fast repetitive controller has fast dynamic response when compared with traditional repetitive controller and Simulation results demonstrated the validity of proposed control system to mitigate voltage sag and maintain load voltage constant.

6. Conclusions

This paper presents power and voltage quality problems such as voltage sage, swells and others. Also an overview of dynamic voltage restorer (DVR) is presented. DVRs are effective recent custom power devices for voltage sags and swells compensation. 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. The Dynamic Voltage Restorer (DVR) is considered to be an efficient solution due to its relatively low cost and small size, also it has a fast dynamic response.

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