DYNAMIC VOLTAGE RESTORER FOR COMPENSATION OF VOLTAGE SAG AND SWELL: A LITERATURE REVIEW

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ABSTRACT

The power quality (PQ) requirement is one of the most important issues for power companies and their customers. The power quality disturbances are voltage sag, swell, notch, spike and transients etc. The voltage sag and swell is very severe problem for an industrial customer which needs urgent attention for its compensation. There are various methods for the compensation of voltage sag and swell. One of the most popular methods of sag and swell compensation is Dynamic Voltage Restorer (DVR), which is used in both low voltage and medium voltage applications. In this paper, the comprehensive reviews of various articles, the advantages and disadvantages of each possible configuration and control techniques pertaining to DVR are presented. The compensation strategies and controllers have been presented in literature, aiming at fast response, accurate compensation and low costs. This review will help the researchers to select the optimum control strategy and power circuit configuration for DVR applications. This will also very helpful in finalizing the method of analysis and recommendations relating to the power quality problems.

KEYWORDS: *Power quality, dynamic voltage restorer, control strategies, compensation techniques, control algorithm.*

I. INTRODUCTION

Power quality issues and resulting problems are consequences of the increasing use of solid state switching devices, nonlinear and power electronically switched loads, electronic type loads .The advent and wide spread of high power semiconductor switches at utilization, distribution and transmission lines have non sinusoidal currents [1]. The electronic type load causes voltage distortions, harmonics and distortion. Power quality problems can cause system equipment mal function, computer data loss and memory mal function of the sensitive equipment such as computer, programmable logic devices [PLC] controls, and protection and relaying equipment [1].

Voltage sag and swell are most wide spread power quality issue affecting distribution systems, especially industries, where involved losses can reach very high values. Short and shallow voltage sag can produce dropout of a whole industry. In general, it is possible to consider voltage sag and swell as the origin of 10 to 90% power quality problems [2]. The main causes of voltage sag are faults and short circuits, lightning strokes, and inrush currents and swell can occur due to a single line-to ground fault on the system, which can also result in a temporary voltage rise on the unfaulted phases [3].

Power quality in the distribution system can be improved by using a custom power device DVR for voltage disturbances such as voltage sags, swells, harmonics, and unbalanced voltage. The function of the DVR is a protection device to protect the precision manufacturing process and sophisticate sensitive electronic equipments from the voltage fluctuation and power outages [4]. The DVR has been developed by Westinghouse for advance distribution. The DVR is able to inject a set of three single-phase voltages of an appropriate magnitude and duration in series with the supply voltage in

synchronism through injection transformer to restore the power quality. The DVR is a series conditioner based on a pulse width modulated voltage source inverter, which is generating or absorbing real or reactive power independently. 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, the DVR injects the independent voltages to restore and maintained sensitive to its nominal value. The injection power of the DVR with zero or minimum power for compensation purposes can be achieved by choosing an appropriate amplitude and phase angle [4] [5].
Section 2 discusses the basic configuration of DVR. The various operating modes of DVR are discussed in section 3. Section 4 presents the type of control strategies in DVR with linear and non –linear control. Section 5 discusses the compensation techniques in DVR. The control algorithm and conclusion are discussed in section 6 and 7 respectively.

II. DYNAMIC VOLTAGE RESTORER

Dynamic Voltage Restorer is series connected voltage source converter based compensator which has been designed to protect sensitive equipments like Programmable Logic Controllers (PLCs), adjustable speed drives etc from voltage sag and swell. Its main function is to monitor the load voltage waveform constantly by injecting missing voltage in case of sag/swell [4] [5]. To obtain above function a reference voltage waveform has to be created which is similar in magnitude and phase angle to that of supply voltage. During any abnormality of voltage waveform it can be detected by comparing the reference and the actual waveform of the voltage. As it is series connected device so it cannot mitigate voltage interruptions. The first DVR was installed for rug manufacturing industry in North Carolina. Another was used in Australia for large dairy food processing plant [4] [5] [6].
A Dynamic Voltage Restorer is basically controlled voltage source converter that is connected in series with the network. It injects a voltage on the system to compensate any disturbance affecting the load voltage. The compensation capacity depends on maximum voltage injection ability and real power supplied by the DVR. Energy storage devices like batteries and SMES are used to provide the real power to load when voltage sag occurs [6]. If a fault occurs on any feeder, DVR inserts series voltage and compensates load voltage to pre-fault voltage. A basic block diagram for open loop DVR is shown in figure 1 [6] [7].

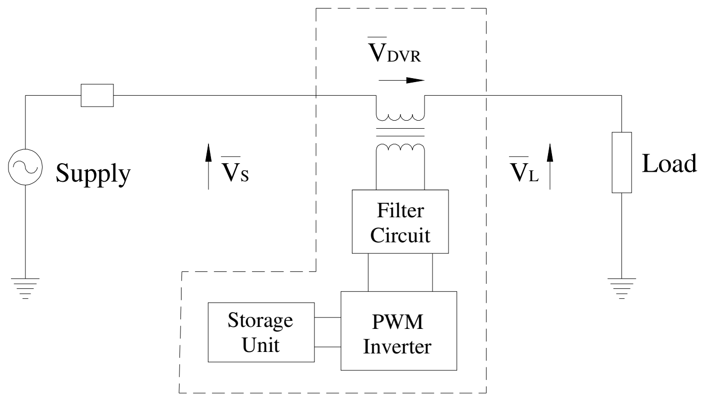

Figure 1 Dynamic Voltage Restorer (DVR) schematic diagram

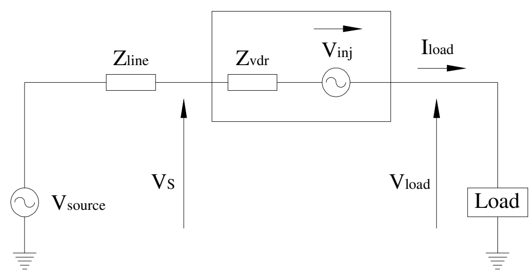

Figure 2 Equivalent circuit of DVR

Figure 2 shows the equivalent circuit of the DVR, when the source voltage is drop or increase, the DVR injects a series voltage V_{inj} through the injection transformer so that the desired load voltage magnitude V_{Load} can be maintained [4] [7]. The series injected voltage of the DVR can be written as:

$$V_{inj} = V_{Load} + V_s \quad (1)$$

Where,
V_{Load} is the desired load voltage magnitude.
V_s is the source voltage during sags/swells condition.
The basic principle of the dynamic voltage restorer is to inject a voltage of required magnitude and frequency, so that it can restore the load side voltage to the desired amplitude and waveform even when the source voltage is unbalanced or distorted. Generally, it employs a gate turn off thyristor (GTO) solid state power electronic switches in a pulse width modulated (PWM) inverter structure. The DVR can generate or absorb independently controllable real and reactive power at the load side. In other words, the DVR is made of a solid state DC to AC switching power converter that injects a set of three phase AC output voltages in series and synchronism with the distribution and transmission line voltages. The source of the injected voltage is the commutation process for reactive power demand and an energy source for the real power demand [4] [7]. The energy source may vary according to the design and manufacturer of the DVR. Some examples of energy sources applied are DC capacitors, batteries and that drawn from the line through a rectifier.
The general configuration of the DVR consists of the following equipment:

(a) Series injection transformer

(b) Energy storage unit
(c) Inverter circuit
(d) Filter unit
(e) DC charging circuit
(f) A Control and Protection system

III. OPERATING MODES OF DVR

The basic function of the DVR is to inject a dynamically controlled voltage VDVR generated by a forced commutated converter in series to the bus voltage by means of a booster transformer. The momentary amplitudes of the three injected phase voltages are controlled such as to eliminate any detrimental effects of a bus fault to the load voltage [8]. This means that any differential voltages caused by transient disturbances in the ac feeder will be compensated by an equivalent voltage generated by the converter and injected on the medium voltage level through the booster transformer [4] [8]. The DVR has three modes of operation which are: protection mode, standby mode, injection/boost mode.

3.1. PROTECTION MODE

If the over current on the load side exceeds a permissible limit due to short circuit on the load or large inrush current, the DVR will be isolated from the systems by using the bypass switches (S2 and S3 will open) and supplying another path for current (S1 will be closed) as shown in figure 3 [4] [8].

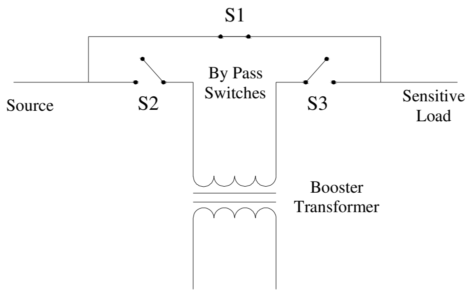

Figure 3 Protection Mode (creating another path for current)

3.2. Standby Mode: (VDVR= 0)

In the standby mode the booster transformer's low voltage winding is shorted through the converter. No switching of semiconductors occurs in this mode of operation and the full load current will pass through the primary as shown in figure 4 [8] [9].

3.3. Injection/Boost Mode: (VDVR>0)

In the Injection/Boost mode the DVR is injecting a compensating voltage through the booster transformer due to the detection of a disturbance in the supply voltage [8] [9].

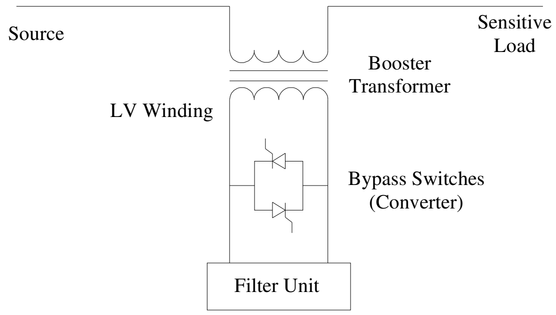

Figure 4 Standby Mode

IV. Type of Control Strategies in DVR

There are several techniques to implement and control philosophy of the DVR for power quality improvement in the distribution system. Most of the reported DVR systems are equipped with a control system that is configure to mitigate voltage sags/swells. Other DVR applications that include power flow control, reactive power compensation, as well as limited responses to power quality problems. The aim of the control scheme is to maintain constant voltage magnitude at the point where a sensitive load is connected under system disturbances [9]. The control system only measures the r.m.s voltage at the load point, i.e., no reactive power measurements are required. 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 voltage sags can last from a few milliseconds to a few cycles, with typical depths ranging from 0.9 pu to 0.5 pu of a 1 pu nominal. Inverter is an important component of DVR. The performance of the DVR is directly affected to the control strategy of inverter. There have many studied been done by the researchers about the inverter control strategy for the DVR implementation [10] [11]. The inverter control strategy comprises of following two types of control as following:

(a) Linear Control and
(b) Non Linear Control

4.1. Linear Control

Linear control is considered as a common method of DVR control. Among the linear control been used in DVR are feed forward control, feedback control and composite control. Feed forward control is a simple method of DVR. The feed forward control technique does not sense the load voltage and it calculates the injected voltage based on the difference between the pre-sag and during-sag voltages. The feedback control strategy measures the load and the difference between the voltage reference of the load and actual load voltage is injected voltage required [10] [11].

The feedback control methods based on state space systems, which can be set up closed-loop poles in order to make faster time response. Both the feed forward and the feedback control strategy may be implemented by scalar or vector control techniques. Composite control strategy 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, so it can improve voltage compensation effect. 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. The combination with feed forward control can improve the system dynamic response rate, shortening the time of compensation significantly. The control method with inductor current feedback and feed forward load current is designed without series transformers thus the size and cost of a DVR can be reduced.

4.2. NON- LINEAR CONTROL

Due to the usage of power semiconductor switches in the VSI, then the DVR is categorized as non-linear device. In case of when the system is unstable, the model developed does not explicitly control target so all the linear control methods cannot work properly due to their limitation.

4.2.1. ARTIFICIAL NEURAL NETWORK (ANN) CONTROL

One of the non-linear methods of control is artificial neural network (ANN) control and it equipped with adaptive and self organization capacity. ANN control can monitor the non linear relationship based on input and output without the detail mathematical model. Normally ANN control can be classified into feed forward neural networks, feedback neural network, local approximation neural networks and fuzzy neural network based on structure [10] [11].

4.2.2. FUZZY CONTROL

Fuzzy logic (FL) control of DVR for voltage injection is also a controlling method. Its design philosophy deviates from all the previous methods by accommodating expert knowledge in controller design. It is derived from fuzzy set theory. FL controllers are an attractive choice when precise mathematical formulations are not possible. The advantages of this controller are capability to reduce the error and transient overshoot of pulse width modulation (PWM) [11].

4.2.3. SPACE VECTOR PWM (SVPWM) CONTROL

Space Vector PWM (SVPWM) control strategy used in AC motor variable speed drives by the Japanese scholars in the early 1980s. The main idea is to adopt 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 in low switching frequency conditions. Besides the types of these controls, there is also available control for single phase sag detection methods used in DVR. Soft phase locked loop (SPLL), Mathematical Morphology theory based low-pass filter, Instantaneous Value Comparison Method are commonly used control for single phase voltage sag detection in the distribution system [10] [11].

V. COMPENSATION TECHNIQUES IN DVR

Voltage injection or compensation methods by means of a DVR depend upon the limiting factors such as; DVR power ratings, various conditions of load, and different types of voltage sags. Some loads are sensitive towards phase angel jump and some are sensitive towards change in magnitude and others are tolerant to these. Therefore, the control strategies depend upon the type of load characteristics [11] [12]. There are four different methods of DVR voltage injection which are:
(a) Pre-sag compensation method
(b) In-phase compensation method
(c) In-phase advanced compensation method
(d) Voltage tolerance method with minimum energy injection

5.1. PRE-SAG/DIP COMPENSATION METHOD

The pre-sag method tracks the supply voltage continuously and if it detects any disturbances in supply voltage it will inject the difference voltage between the sag or voltage at PCC and pre-fault condition, so that the load voltage can be restored back to the pre-fault condition. Compensation of voltage sags in the both phase angle and amplitude sensitive loads would be achieved by pre-sag compensation method as shown in figure 5 [12] [13]. 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 voltage of DVR is given below:

$$V_{DVR} = V_{prefault} - V_{sag} \quad (2)$$

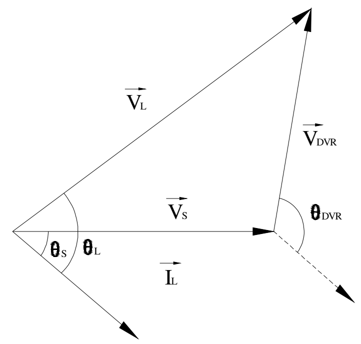

Figure 5 Pre-Sag compensation method

5.2. In-Phase Compensation Method

This is the most straight forward method. In this method the injected voltage is in phase with the supply side voltage irrespective of the load current and pre-fault voltage as shown in figure 6. The phase angles of the pre-sag and load voltage are different but the most important criteria for power quality that is the constant magnitude of load voltage are satisfied [12] [13]. The load voltage is given below:

$$|V_L|=|V_{prefault}| \quad (3)$$

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

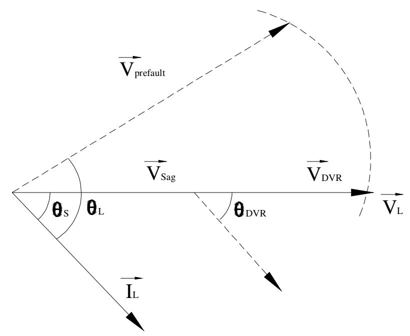

Figure 6 In-Phase compensation method

5.3. In-Phase Advanced Compensation Method

In this method the real power spent by the DVR is decreased by minimizing the power angle between the sag voltage and load current. In case of pre-sag and in-phase compensation method the active power is injected into the system during disturbances. The active power supply is limited stored energy in the DC links and this part is one of the most expensive parts of DVR. The minimization of injected energy is achieved by making the active power component zero by having the injection voltage phasor perpendicular to the load current phasor. In this method the values of load current and voltage are fixed in the system so we can change only the phase of the sag voltage. IPAC method uses only reactive power and unfortunately, not al1 the sags can be mitigated without real power, as a consequence, this method is only suitable for a limited range of sags [12] [13] [14].

5.4. 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 (figure 7). Both magnitude and phase are the control parameter for this method which can be achieved by small energy injection [13] [14].

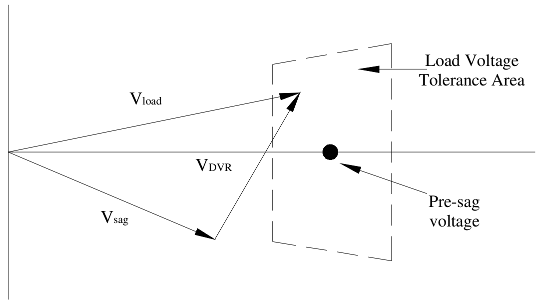

Figure 7 Voltage tolerance method with minimum energy injection

VI. CONTROL ALGORITHM

There are some techniques mentioned below for detection of voltage sag and swell:

(a) Fourier Transform
(b) Phase Locked Loop (PLL)
(c) Vector control (Software Phase Locked Loop –SPLL)
(d) Peak value detection
(e) Wavelet Transform

The basic functions of a controller in a DVR are the detection of voltage sag/swell events in the system; computation of the correcting voltage, generation of trigger pulses to the sinusoidal PWM based DC-AC inverter, correction of any anomalies in the series voltage injection and termination of the trigger pulses when the event has passed [14] [15]. The controller may also be used to shift the DC-AC inverter into rectifier mode to charge the capacitors in the DC energy link in the absence of voltage sags/swells. The d_{qo} transformation or Park's transformation is used to control of DVR. The d_{qo} method gives the sag depth and phase shift information with start and end times. The quantities are expressed as the instantaneous space vectors. Firstly convert the voltage from ab- c reference frame to d-q-o reference. For simplicity zero phase sequence components is ignored. Fig. 8 illustrates a flow chart of the feed forward dqo transformation for voltage sags/swells detection. The detection is carried out in each of the three phases. The control scheme for the proposed system is based on the comparison of a voltage reference and the measured terminal voltage (Va, Vb, Vc).The voltage sags is detected when the supply drops below 90% of the reference value whereas voltage swells is detected when supply voltage increases up to 25% of the reference value [14] [15] [16].

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & 1 \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (4)$$

Above equation 4 defines the transformation from three phase system a, b, c to d_{qo} stationary frame. In this transformation, phase A is aligned to the d axis that is in quadrature with the q-axis. The theta (θ) is defined by the angle between phases A to the d-axis. The error signal is used as a modulation signal that allows generating a commutation pattern for the power switches (IGBT's) constituting the voltage source converter. The commutation pattern is generated by means of the sinusoidal pulse width modulation technique (SPWM); voltages are controlled through the modulation [14] [15] [16]. The Flow chart of feed forward control technique for DVR based on dqo transformation is illustrated in figure 8 [15].

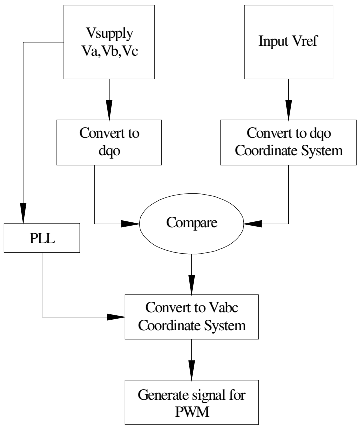

Figure 8 Flow chart of feed forward control technique for DVR based on dqo transformation

The PLL circuit is used to generate a unit sinusoidal wave in phase with mains voltage. Practically, the capability of injection voltage by DVR system is 50% of nominal voltage.This allows DVRs to successfully provide protection against sags to 50% for durations of up to 0.1 seconds. Furthermore, most voltage sags rarely reach less than 50%. The dynamic voltage restorer is also used to mitigate the damaging effects of voltage swells, voltage unbalance and other waveform distortions [17] [18].

VII. CONCLUSION

This paper has presented an exhaustive literature survey on performance of DVR. The above survey shows that the DVR is suitable for compensation of voltage sag and swell by the use of different controlling techniques. The linear control offer simpler implementation and require less computational efforts compared to other methods and therefore the most popular technique. The existing topologies, basic structure of DVR, operating modes, control strategies, compensation techniques and its control algorithm have been elaborated in detail. The main advantages of DVR are low cost, simpler implementation; require less computational efforts and its control is simple as compared to other methods. This study also gives useful knowledge for the researchers to develop a new design of DVR for voltage disturbances in electrical system. From the literature survey of DVR applications, this work concluded that the trends of DVR through the years are still assumed as a powerful area of research.

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