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Simulation of DVR in Power Systems to Compensate Voltage Sag

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***Abstract*-The term Power Quality is something that tellsabout the quality of power. While "power quality" is a convenient term for many, it is the quality of the voltage rather than power or current. Power quality problems in industrial application concern a wide range of disturbances, such as voltage sags and swells, flicker interruption, harmonics distortion. Ideally any electric utility is supposed to supply a pure sinusoidal voltage of required magnitude and frequency for all the time without any deviation. But in reality it is not possible to meet the ideal requirements. Thus, practically there are deviations in the voltage which can have adverse effects on the load. Of all the power quality problems, 92% of the interruptions in industrial installations are due to voltage sags. Due to the increasing of new technology, a lot of devices had been created and developed for mitigation of voltage sag. To solve this problem, custom power devices are used. One of those devices is Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks. The DVR is fast, flexible and cost effective solution to voltage sag problems. This project presents modelling, analysis and simulation of Dynamic Voltage Restorer (DVR) using MATLAB.**

***Keywords*-DVR, Power quality, Voltage sag compensation,MATLAB/SIMULINK.**

I . INTRODUCTION

Power distribution systems, ideally, should provide their customs with an uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency however, in practice, power systems, especially the distribution systems, have numerous nonlinear loads, which significantly affect the quality of power supplies. As a result of nonlinear loads, the purity of the waveform of the supplies is lost. This ends up producing many power quality problems. Power quality is an issue that is becoming increasingly important to electricity customers at all levels of usage [1]. There are various types' power quality problems such as transients, short duration voltage variation, long duration voltage variation, voltage imbalance, waveform distortion and voltage flicker. Under short duration voltage variation, there are voltage sag, voltage swell and interruption. Among the disturbances, voltage sag is considered the most severe since the sensitive loads are very susceptible to temporary changes in the voltage [9].

Voltage support at a load can be achieved by reactive power injection at the load point of common coupling. The common method for this is to install mechanically switched shunt capacitors in the primary terminal of the distribution transformer. The mechanical switching may be on a schedule, via signals from a supervisory control and data acquisition (SCADA) system [5], with some timing schedule, or with no switching at all. The disadvantage is that, high speed transients cannot be compensated. Some sags are not corrected within the limited time frame of mechanical switching devices. Transformer taps may be used, but tap changing under load is costly.

There are many different methods to mitigate voltage sags and swells, but the use of a custom power device is considered to be the most efficient method. There are many custom power devices to solve the problem of voltage sag and each has its own benefits and limitations. The most effective type of these devices is considered to be Dynamic voltage Restorer (DVR). There are numerous reasons why DVR is preferred over the others. A few reasons are presented as follows: The SVC pre-dates the DVR, but the DVR is still preferred because the SVC has no ability to control active power flow [1].

Another reason is that the DVR costs less compared to the UPS [1]. Not only the UPS is costly, it also requires a high level of maintenance because batteries leak and have to be replaced as often as every five years [1]. Other reasons include that the DVR has a higher energy capacity and lower costs compared to the SMES device [1]. Furthermore, the DVR is smaller in size and costs less compared to the DSTATCOM [1]. Based on these reasons, it is no surprise that the DVR is widely considered as an effective custom power device in mitigating voltage sag [1]. In addition to sags and swells compensation, DVR can also added other features such as harmonics and Power Factor

Correction. Compared to the other devices, the DVR clearly provides the best economic solution for its size and capabilities.

II. DYNAMIC VOLTAGE RESTORER

Dynamic voltage restorer (DVR) is a series compensator which is able to protect a sensitive load from the distortion in the supply side during fault or overloaded in power system. The basic principle of a seriescompensator is simple, by inserting a voltage of required magnitude and frequency, the series compensator can restore the load side voltage to the desired amplitude and waveform even when the source voltage is unbalanced or distorted [3].This DVR device employs 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. The DVR also 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 feeder voltages [3]. The amplitude and phase angle of the injected voltages are variable thereby allowing control of the real and reactive power exchange between the DVR and the distribution system [3]. The dc input terminal of a DVR is connected to an energy source or an energy storage device of appropriate capacity. The reactive power exchange between the DVR and the distribution system is internally generated by the DVR without ac passive reactive components. The real power exchanged at the DVR output ac terminals is provided by the DVR input dc terminal by an external energy source or energy storage system.

A. Basic Configuration Of DVR

The general configuration of the DVR consists of:

I. A Voltage Source Converter (VSC)
II. DC charging circuit
III. Storage Devices
IV. An Injection/ Booster transformer V. A Harmonic filter
V. A Control and Protection system
VI. Switching devices

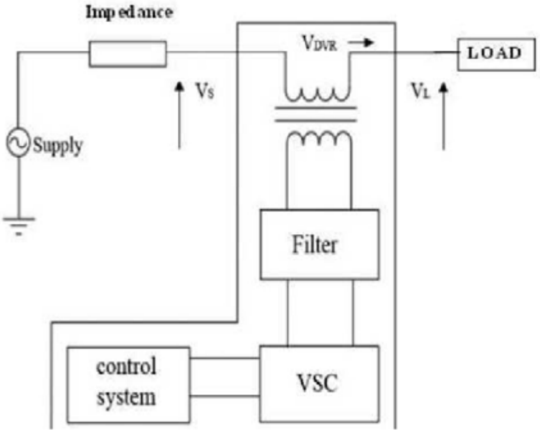

Figure 1: Schematic diagram of DVR

A. Voltage Source Converter

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.

The purpose of storage devices is to supply the necessary energy to the VSC via a dc link for the generation of injected voltages. The different kinds of energy storage devices are Superconductive magnetic energy storage (SMES), batteries and capacitance.

B. DC Charging Unit

The dc charging circuit has two main tasks:

- The first task is to charge the energy source after a sag compensation event.
- The second task is to maintain dc link voltage at the nominal dc link voltage.

C. DC Link

The purpose is to supply the necessary energy to the VSC via a dc link for the generation of injected voltages. The different kinds of energy storage devices are superconductive magnetic energy storage (SMES), batteries, and capacitance. In fact, the capacity of the stored energy directly determines the duration of the sag which can be mitigating by the DVR. Batteries are the common choice and can be highly effective if a high voltage battery configuration is used. This high voltage string of batteries can be placed across the regulated dc bus with little or no additional circuitry. However, batteries in general have a short lifetime and often require some type of battery management system, which can be quite costly. An interesting alternative to batteries is the use of ultra capacitors, which have a wider voltage range than batteries and can be directly paralleled across the input bus. Ultra capacitors 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. Certain ultra capacitors (unsymmetrical electrochemical) can hold charge over extended periods of time, so as to act like a battery. However, unlike batteries, these ultra capacitors have a short charge time and much longer lifetime.

D. Injection/Boost 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. Its main tasks are:

☐ It connects the DVR to the distribution network via the HV-windings and transforms and couples the injectedcompensating voltages generated by the voltage source converters to the incoming supply voltage.

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

E. Harmonic Filter

The main task of harmonic filter is to keep the harmonic voltage content generated by the VSC to the permissible level.

F. Control Mechanism

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.

G. Switching Devices

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 MOSFET requires a high on-resistance and has fast switching times. It is capable of working beyond the 20 kHz frequency. The limitations are that the increasing on-resistance with increasing voltage limits the device to applications with just a few hundred volts. The GTO is a latching device that can be turned off by a negative pulse of current to its gate. The GTO is best suited for high voltage applications. The disadvantages of the GTO are that GTO based devices are not able to meet the dynamic requirements of a DVR. The IGBT is considered to be a newer device compared to the MOSFET and GTO. It was first introduced in the early 1980s and has become a popular device because of its superior characteristics. In essence, it is a three terminal controllable switch that combines the fast switching times of the MOSFET with the high voltage capabilities of the GTO. The result of this combination is a medium speed controllable switch capable of supporting the medium power range. 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.

III. EQUATIONS RELATED TO DVR

Consider the schematic diagram shown in Fig. 2.

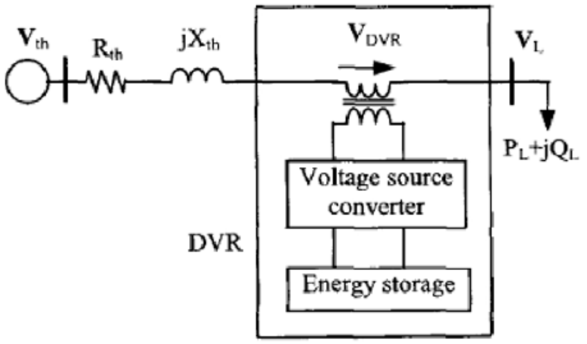

Figure 2: Calculation for DVR voltage injection

The impedance is given as:

$^{Z}TH^{=\,R}TH^{+\,jX}TH$ (1)

$^{V}DVR^{+\,V}TH^{=\,V}L^{+\,Z}TH^{I}L$ (2)

When dropped voltage happened 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

$V_{DVR} = V_L + Z_{TH}I_L - V_{TH}$ (3)

The equivalent circuit of the DVR is shown in Fig. 3. When the source voltage drops or increases, the DVR injects a series voltage V_{INJ} through the injection transformer so that the desiredload voltage magnitude V_L can be maintained.

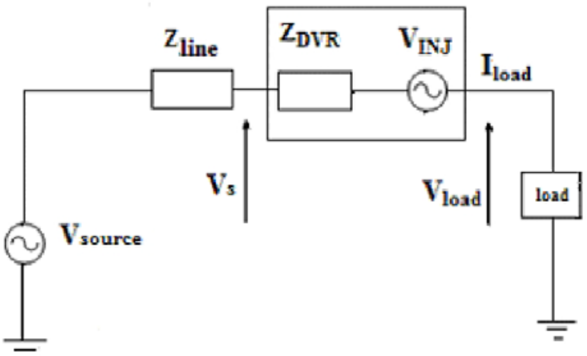

Figure 3: Equivalent circuit diagram of DVR

The load current I_L is given as:

$I_L = (P_L \pm Q_L) / V_L$ (4)

The power injection of the DVR can be written as:

$^{S}DVR^{=\,V}DVR^{I}L^{*}$ (5)

IV. PRINCIPLE OF DVR

The principle of DVR is simple i.e. whenever the source voltage is unbalanced or distorted the DVR restores theload-side voltage to the desired amplitude by injecting a voltage of required magnitude [5]. In other words we can say that the main function of the DVR is to regulate the load voltage waveform constantly and if any sag or swell occurs, the required voltage will be injected to the load point. In short, the principle of DVR can be explained with the help of the following equation which has to be satisfied for all the time.Source voltage + DVR voltage = load voltage (6) The DVR has to work only when there is a sag/swell in the source voltage. Depending on that there are actually three modes of operation for a DVR. They are

i. Protection Mode
ii. Standby Mode
iii. Injection Mode

i. Protection Mode

Whenever there is a fault on the line, very high fault currents will be flowing through the line. Since the DVR is series connected, the fault currents will be flowing through the DVR also which is not desired. The DVR should be protected from these over currents or large inrush currents [6]. The bypass switches remove the DVR from system by supplying another path through switch S1 for current as shown in fig.4

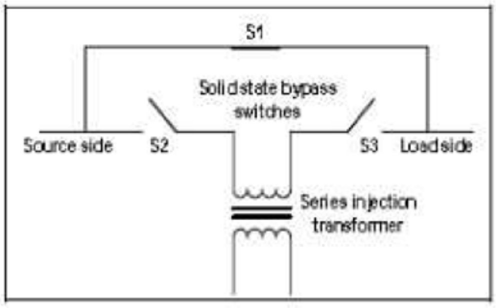

Figure 4: configuration of switches in protection mode

ii. Standby Mode

In standby mode (normal steady state conditions), the DVR may either go into short circuit operation or inject small voltage to compensate the voltage drop for transformer reactance or losses as shown in Fig. 6. Short circuit operation of DVR is the general preferred solution in steady state [6]. (Because the small voltage drops due to transformer reactance do not disturb the load requirements).

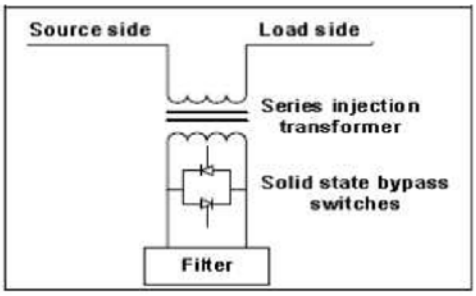

Figure 5: configuration of switches in standby mode

iii. Injection Mode

The DVR goes into injection mode as soon as the sag is detected. Three single-phase ac voltages are injected in series with required magnitude, phase and wave shape for compensation. The types of voltage sags, load conditions and power rating of DVR will determine the possibility of compensating voltage sag [6].

A. Voltage injection methods

Voltage injection or compensation methods by means of a DVR depend upon the limitingfactors 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.There are four different methods of DVR voltage injection which are

i. Pre-sag compensation method
ii. Voltage tolerance method with minimum energy injection
iii. In-phase advanced compensation method
iv. In-phase compensation method

i. Pre-sag compensation method

This method injects the difference voltage between sag and pre-fault voltages to the system. It is the best solution to obtain the same load voltage as the pre-fault voltage but there is no control on injected active power so high capacity energy storage is required.

ii. Voltage tolerance method with minimum energy injection

Generally the voltage magnitude between 90%-110% of nominal voltage and phase angle variation between 5%-10% of normal state do not disturb the operation characteristics of loads. This method can maintain load voltage in the tolerance area with small change of voltage magnitude.

iii. In-phase advanced compensation method

The real power spent by DVR is minimized by decreasing the power angle between the sag voltage and load current. The values of load current and voltage are fixed in the system so we can change only the phase of the sag voltage.

iv. In-phase compensation method

The injected voltage is in phase with supply voltage. As shown in Fig.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 is satisfied.

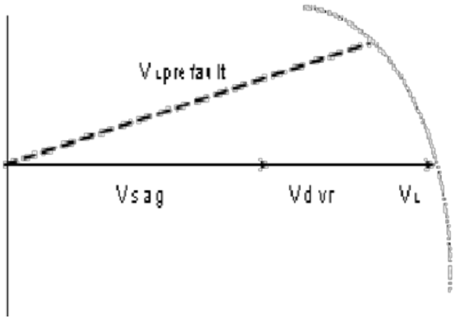

Figure 6: Vector diagram of In-phase method

É$_{33}$É = É$_{3}$HJJ$_{33}$I$_{33}$É (7)

VL, Vsag, Vdvr and VLprefault represent load voltage vector, remaining voltage vector at PCC, DVR voltage vector (injected) and voltage before sag vector respectively. The rms values of load voltage on the arc are the same (1 p.u) with different phase angles. The method ii and iii inject smaller active energy than method i and iv but the complexity and expenses increases.

V. SIMULATION AND RESULTS

A. PI Controller

Voltage sag is created at the load terminals via a three phase fault. The above voltage problems are sensed separately and passed through the sequence analyzer. The magnitude component is compared with reference voltage (Vref). Pulse width Modulation (PWM) control technique [6] is applied for inverter switching so as to produce a three phase 50 Hz sinusoidal voltage at the load terminals. Chopping frequency is in the range of few KHz. The MOSFET inverter is controlled with PI controller in order to maintain 1 per unit voltage at the load terminals.

PI controller (Proportional Integral Controller) is a closed loop controller which drives the plant to be controlled with a weighted sum of the error (difference between the output and the desired set point) and the integral of that value. One advantage of a proportional plus integral controller is that the integral term in a PI controller causes the steady-state error to be zero for a step input. PI controller input is an actuating signal which is the difference between the Vref and Vin. Output of the controller block is of the form of δ.

$$\text{Output of comparator} = \text{Vref} - \text{Vin} \qquad (8)$$

Where (1p.u. =Base Voltage)

Vref equal to 1 p.u. voltage
Vin voltage in p.u. at the load terminals.

The angle δ is provided to the PWM signal generator to obtain desired firing sequence.

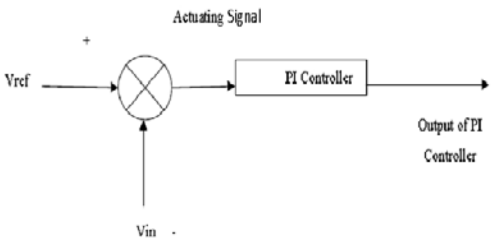

Figure 7: Indirect PI controller

The sinusoidal signal Vcontrol is phase-modulated by means of the angle δ. In this way the angle δ is produced in three phases.

i.e., $V_R = \text{Sin}(\omega t + \delta) \qquad (9)$

$$V_Y = \text{Sin}(\omega t + \delta + 2\pi/3) \qquad (10)$$

$$V_B = \text{Sin}(\omega t + \delta + 4\pi/3) \qquad (11)$$

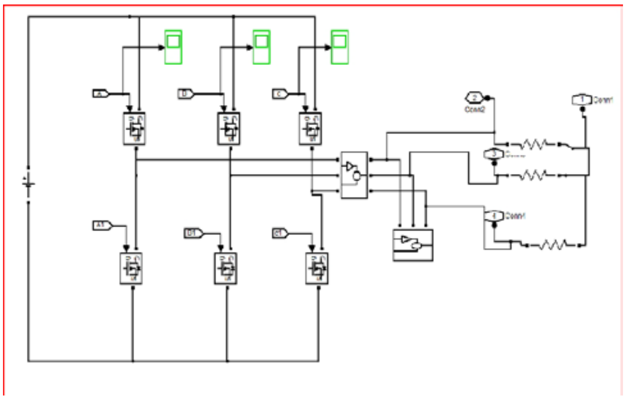

Figure 8: Voltage Source Converter

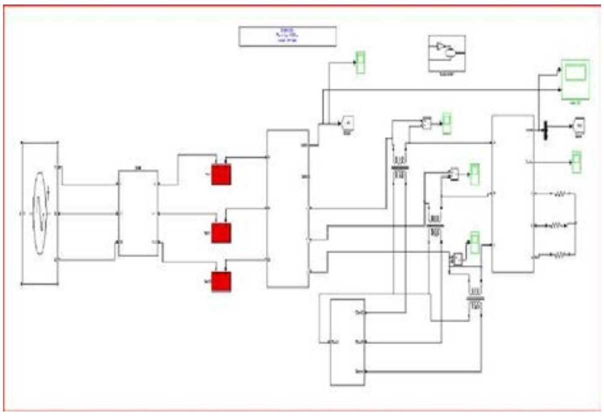

Figure 9: Simulink model of DVR

B. Results

The first simulation was done with no DVR and a three phase fault is applied to the system at point with fault resistance of 35 Ω for a time duration of 200 ms. The second simulation is carried out at the same scenario as above but a DVR is now introduced at the load side to compensate the voltage sag occurred due to the three phase fault applied.