Necessity of DC Voltage Storage for Dynamic Voltage Restorer

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Abstract **- Problems of voltage sags and swells and its severe impact on sensitive load is well known. To solve the problems custom power devices are used, one of those devices is DVR which is most efficient and effective modern custom power device used in power distribution network. DVR is a very effective series-compensation device for mitigating voltage sags. The mitigation capability of these devices is mainly limited by the energy storage capacity. This paper presents the application of DVR on power distribution systems for mitigation of voltage sag and swell. An adequate modeling and simulation of DVR, including controls in MATLAB, shows the flexibility and easiness of MATLAB environment in analyzing such compensating devices. DVR which is based on forced commutated voltage source converter has been proved suitable for the task of compensating voltage sags and swells. Simulation results are presented to illustrate and understand the performance of DVR in supporting load voltage under voltage sag or swell conditions and also to assimilate voltage capacity of DC storage unit of a DVR with transmission voltage, by considering various factors.**

Keywords: **DVR, Power Quality, Voltage Sags, Voltage Source Inverter**

I. Introduction

Nowadays electric industry including customer utilities and electrical equipment manufacturers are more concerned with power quality issues. Due to modernization and automation of industry involving use of digital computers and power electronics devices are sensitive to different power quality problems. Typical power quality problems include voltage sag, harmonics, notching, transients like surge, swell etc. Voltage sag is very important problem as compared to harmonics flicker. Voltage sag is sudden drop in RMS voltage and is usually characterized by retained voltage. Most severe sags are caused by faults in power system and distribution level [1&2]. Characteristics of sag depend upon type and location of fault in system. Main cause of voltage sags are faults, starting of motor and transformer energization.

Voltage sag mitigation devices are classified into three categories; (i) Traditional Solutions: Voltage Control included Transformer, Tap Changers both mechanical and SCR switched units and servo-variac technology and ferro-resonant transformers are used as a voltage sag mitigation devices [3]. These devices are heavy, bulky and inefficient so they are rarely used. (ii) Uninterruptible Power Supplies (UPS): The main disadvantage, with the UPS is that it uses batteries as its DC storage system making it more expensive than the DVR which uses a bank of capacitors. (iii) Dynamic Voltage Restorer (DVR): The voltage source converter (VSC) connected in series with the grid as a static series compensator (SSC) is also known as the Dynamic Voltage Restorer (DVR). It is power electronics based device and used to protect for any voltage sags caused by different types of faults and abnormal condition.

To compensate the voltage sag in a power distribution system, appropriate devices need to be installed at suitable locations [3]. These devices are typically placed at the point of common coupling [PCC] which is defined as the point of the network changes. Dynamic Voltage Restorer (DVR) is one of the custom power devices which can improve power quality, especially, voltage sags [4]. DVR is utility customer interface equipment designed to mitigate power quality problems associated with voltage sags, swells and interruption.

In present work, control scheme implemented consist of p.u. three phase RMS voltage at the load terminal (which is sagged due to fault) as input to the control scheme and it is compared with desired value i.e., 1p.u.[5]. The difference between these two quantities is an error signal, which is passed through PI controller to produce a phase angle delta. Delta is input to the PWM firing scheme, to control the firing pulses of VSC in order to minimize the three phase voltage sag. Simulation model is developed using MATLAB/ Simulink environment are results are presented with and without considering DVR for different sag conditions.

II. Dynamic Voltage Restorer

DVR is the most efficient and effective modern custom power device used in power distribution networks. It is a series connected solid state device that injects voltage into the system to regulate load side voltage. Other than voltage sag and swell compensation, DVR can contribute to other features like line voltage harmonics compensation, reduction of transient in voltage.

The general configuration of the DVR consists of:

1. An Injection/ Booster transformer
2. Harmonic filter
3. Storage Devices

4. Voltage Source Converter (VSC)
5. DC charging circuit
6. Control and Protection system

Basic block diagram of DVR is shown in Figure 1.

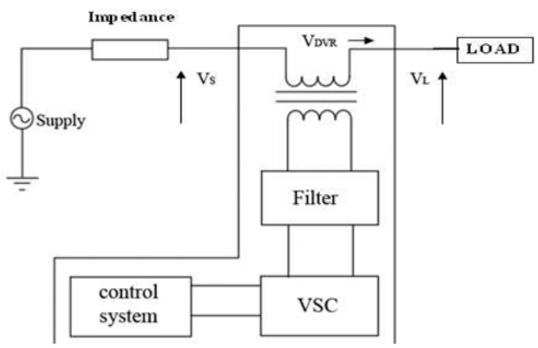

Fig. 1 Schematic diagram of DVR

1. Injection/ Booster 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 is to connect the DVR to the distribution network via the HV-windings and it transforms and couples the injected compensating 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).

2. Harmonic Filter

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

3. Voltage Source Converter

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.

4. 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 [6,7,8]. It is capable of working beyond the 20 kHz frequency [15]. 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. 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'. 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. Storage Devices

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 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.

6. DC Charging Circuit

The dc charging circuit has two main tasks.

a. The first task is to charge the energy source after a sag compensation event and second task is to maintain dc link voltage at the nominal dc link voltage.
b. Control Techniques: Control of DVR is very important and it involves detection of voltage sag by appropriate detection algorithm which works in real time. The effectiveness of sag detection algorithm and controller plays an important role in mitigating the short duration reductions in RMS supply voltages.

III. DVR: Operating Principle

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 VL. 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.

The DVR works independently of the type of fault or any event that happens in the system, provided that the whole system remains connected to the supply grid, i.e. the line breaker does not trip. For most practical cases, a more economical design can be achieved by only compensating the positive and negative sequence components of the voltage disturbance seen at the input of the DVR. This option is Reasonable because for a typical distribution bus configuration, the zero sequence part of a disturbance will not pass through the step down transformer because of infinite impedance for this component.

The DVR has two modes of operation which are: standby mode and boost mode. In standby mode (VDVR=0), the booster transformer's low voltage winding is shorted through the converter. No switching of semiconductors occurs in this mode of operation, because the individual converter legs are triggered such as to establish a short-circuit path for the transformer connection. Therefore, only the comparatively low conduction losses of the semiconductors in this current loop contribute to the losses. The DVR will be most of the time in this mode. In boost mode (VDVR>0), the DVR is injecting a compensation voltage through the booster transformer due to a detection of a supply voltage disturbance.

IV. Control Philosophy

Voltage sag is created at load terminals by a three-phase fault as shown in Fig.3. Load voltage is sensed and passed through a sequence analyzer. The magnitude is compared with reference voltage (V_{ref}). Pulse width modulated (PWM) control technique 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 a few KHz. The IGBT inverter is controlled with PI controller in order to maintain1 p.u. voltage at the load terminals i.e., considered as base voltage =1p.u.

A proportional-integral (PI) controller (shown in Fig. 2) drives the plant to be controlled with a weighted sum of the error (difference between the actual sensed output and desired set-point) and the integral of that value. An advantage of a proportional plus integral controller is that its integral term 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 V_{ref} and V_{in}. Output of the controller Block is of the form of an angle δ, which introduces additional phase-lag/lead in the three-phase voltages. The output of error detector is

$$V_{ref} - V_{in} \tag{1}$$

V_{ref} equal to 1 p.u. voltage

V_{in} voltage in p.u. at the load terminals

The controller output when compared at PWM signal generator results in the desired firing sequence.

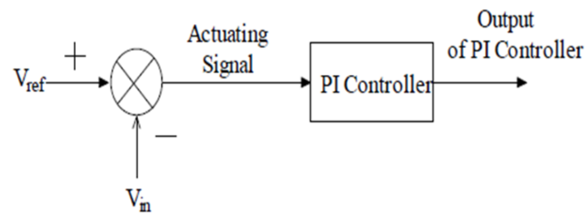

Fig.2 Schematic of a typical PI Controller

The modulated angle is applied to the PWM generators in phase A as shown in (2). The angles for phases B and C are shifted by 120° and 240°, respectively as shown in (3) and (4). In this PI controller only voltage magnitude is taken as a feedback parameter in the control scheme [4].

The sinusoidal signal $V_{control}$ is phase-modulated by means of the angle δ and the modulated three-phase voltages are given by

$$V_a = \sin(\omega t + \delta) \tag{2}$$

$$V_b = \sin(\omega t + \delta + 2\pi/3) \tag{3}$$

$$V_c = \sin(\omega t + \delta + 4\pi/3) \tag{4}$$

V. Parameters of DVR Test System

Electrical circuit model of DVR test system is shown in Fig.3. System parameters are listed in Table I. Voltage sag is created at load terminals via a three-phase fault as shown in Fig.3. Load voltage is sensed and passed through a sequence analyzer. The magnitude is compared with reference voltage (V_{ref}).

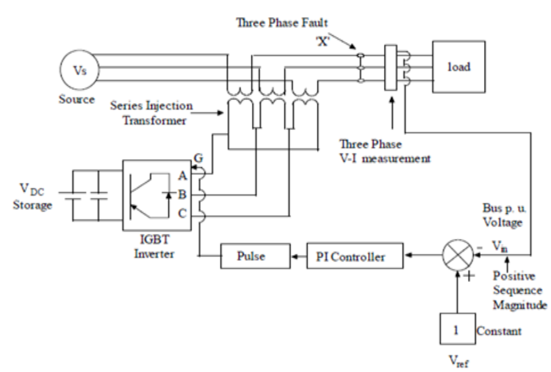

Fig.3 Circuit Model of DVR Test System

TABLE I SYSTEM PARAMETERS

Sl. No.	System Quantities	Standards
1	Inverter Specifications	IGBT based,3 arms , 6 Pulse, Carrier Frequency =1080 Hz, Sample Time= 5 µs
2	Transmission Line Parameter	R=0.001 ohms ,L=0.005H
3	PI Controller	KP=0.5 Ki=50 Sample time=50 µs

VI. Modeling Of DVR In Matlab

In order to mitigate the simulated voltage sags in the test system of each compensation technique, also to compensate voltage sags in practical application, a discrete PWM-based control scheme is implemented, with reference to DVR. The aim of the control scheme is to maintain a constant voltage magnitude at the sensitive load point, under the system disturbance.

The control system only measures the RMS voltage at load point, for example, no reactive power measurement is required. The DVR control system exerts a voltage angle control as follows: an error signal is obtained by comparing the reference voltage with the RMS voltage measured at the load point. The PI controller processes the error signal and generates the required angle δ to drive the error to zero, for example; the load RMS voltage is brought back to the reference voltage.

It should be noted that, an assumption of balanced network and operating conditions are made. The modulating angle δ or delta is applied to the PWM generators in phase A, whereas the angles for phase B and C are shifted by 240° or -120° and 120° respectively.

MATLAB Simulation diagram of the test system is shown in Fig.4. System comprises of 13 kV, 50 Hz generator, feeding transmission lines through a 3-winding transformer connected in Y/Δ/Δ, 13/115/ 11 kV.

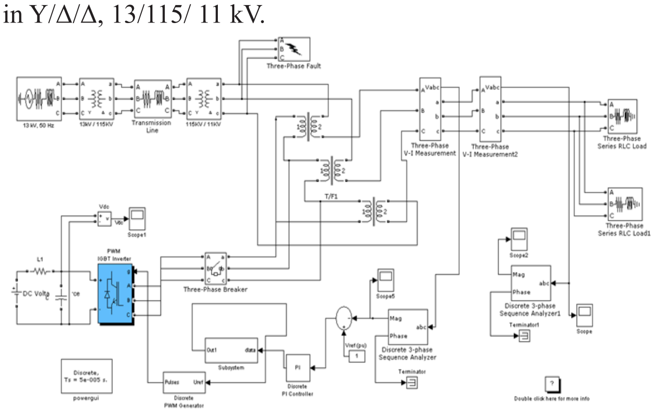

Fig.4 Simulation Model of DVR Test System

VII. Results And Discussion

To evaluate the performance of DVR for compensating voltage sags, detail simulation is performed on DVR test system using MATLAB/ Simulink. System performance is evaluated for compensating voltage sag with different DC storage capacity to achieve the rated voltage at a given load. Various cases; such as change in load or fault resistance or different energy storage capacities are considered to study the impact of DC storage on sag compensation.

A. Different Energy Storage Capacities

System performance is analyzed for compensating voltage sag with different energy storage capacities so as to achieve rated voltage at load. Various cases (I to V) of different voltage levels are considered for studying the impact of energy storage capacity on sag compensation. An exhaust study is made for five cases.

A three-phase fault is created at point X via a resistance of 0.66 Ω which results in a voltage sag of 17.02 % Transition time for the fault is considered from 0.4sec to 0.6sec as shown in Fig.5. The simulation results without an energy storage system are shown in Fig.6.

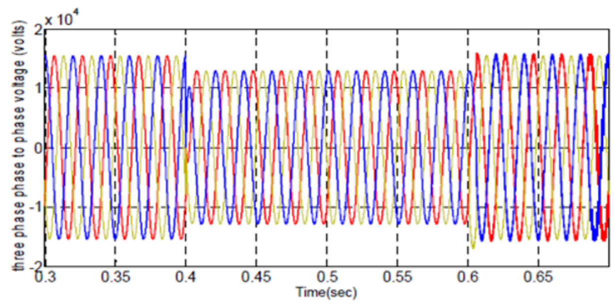

Fig.5 Phase to Phase Voltage with Out DVR Energy Storage

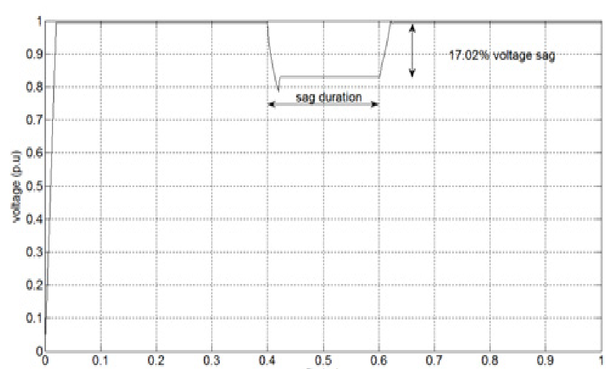

Fig.6 Voltage p.u. at the Load Point: without DVR Energy Storage.

Table II shows the DVR performance in presence of DC energy storage devices of different capacities of viz.1 kV, 2 kV, 3 kV, 4 kV, 5 kV, and 6 kV respectively.

TABLE II SYSTEM PERFORMANCE

D.C. Voltage Supply	Voltage (p.u.)	Voltage Sag
1kV	0.83	17%
2kV	0.835	16.5%
3kV	0.86	14%
4kV	0.88	12%
5kV	1	0%
6kV	1.09	9% Swell

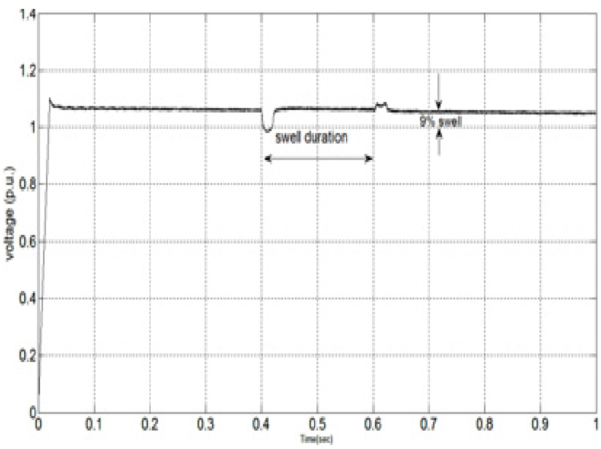

Fig.7 Voltage p.u. with DVR Energy Storage of 6 KV

The simulation results with an energy storage system of 6kV are shown in Fig.7. It shows the continuous swell of 9%.

B. Various Load Conditions

Detailed simulations are performed on the DVR test system using MATLAB SIMULINK. System performance is analyzed for compensating voltage sag with different DC storage capacity so as to achieve rated voltage at a given load. Various cases of different load condition are considered to study the impact DC storage on sag compensation. These various cases are discussed below:

A three-phase fault is created at point X via a resistance of 0.66 Ω which results in a voltage sag of 17.02%. Transition time for the fault is considered from 0.4 sec to 0.6 sec with

Load-1 having :

Active power = 10 Kw

Inductive Reactive Power =400 Var and

Load-2 having:

Active power = 10 Kw

Inductive Reactive Power =400 Var, as shown in Fig. 5 and Fig .6.

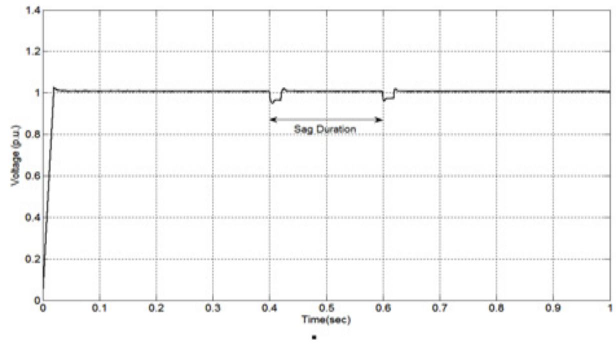

Fig.8 Voltage p.u. at the Load Point with DC storage of 3.1 kV

Fig.8 shows the DVR performance in presence of capacitor rating of 750×10^{-6} F with energy storage devices viz. 3.1kV.

Voltage sag compensation is done through DVR power circuit by using DC storage units. It is used for maintaining the load terminal voltage at 11kV transmission level as shown above. Comparison results show in tabular form in Table III.

TABLE III DESIRED VOLTAGE SAG COMPENSATION

Sl. No.	Load-1	Load-2	Remark
1	10 Kw,400 Var	10 Kw,400 Var	DC voltage = 3.1KV
2	100 Kw,400 Var	100 Kw,400 Var	DC voltage = 3.4KV
3	1Mw,400 Var	1Mw,400 Var	DC voltage = 5.9KV
4	2Mw,400 Var	2Mw,400 Var	DC voltage = 8.5KV
5	4Mw,400 Var	4Mw,400 Var	Above 3kV
6	10 Mw, 400 Var 1	0 Mw, 400 Var	Above 3kV

C. Different Fault Resistance Values

Detailed simulations are performed on the DVR test system using MATLAB SIMULINK. System performance is analyzed for compensating voltage sag with different DC storage capacity so as to achieve rated voltage at a given load. Various cases of different fault resistance are considered to study the impact DC storage on sag compensation.

A three-phase fault is created at point X via a resistance of 0.66 Ω which results in a voltage sag of 17.02 %. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig. 5 and 6.

TABLE IV DESIRED VOLTAGE SAG COMPENSATION

Sl. No.	Percentage Voltage Sag	Fault Resistance Value	Required DC Voltage
1	17.02 %	0.66 Ω	3.1
2	19 %	0.60 Ω	3.3
3	23 %	0.50 Ω	3.5
4	26 %	0.45 Ω	3.7
5	29 %	0.40 Ω	Above 3.7kV

The simulation results without DVR compensation technique are shown in Fig. 6 on p.u basis. Fig. 8 shows the DVR performance in presence of capacitor rating of 750×10^{-6} F with energy storage devices viz. 3.1kv.

In this case the load is kept constant but the fault resistance is decreased so as to increase the voltage sag and the required DC voltage is obtained.

In the above Table IV it is shown that required DC storage values are not same for different voltage sag conditions, when the load is fixed on 11 kV feeders. The amount of DC energy storage is increased with increase in the percentage voltage sag as shown above. It is observed that when percentage voltage sag is increased above 28% (approximate). The per unit voltage fall below 1 per unit value and it is continuously decreases with increase in percentage voltage sag for 11 kV feeder.

VIII. Conclusion

Based on the analysis of test system, it is suggested that voltage sag values are major factors in estimating the DC storage value. The role of a DVR in mitigating the power quality problems in terms of voltage sag, swell and interruptions is explained the investigations were carried out for various cases of load at 11kV feeder. The effectiveness of a DVR system mainly depends upon the rating of DC storage rating and the percentage voltage sag. In the test system it is observed that after a particular amount of voltage sag, the voltage level at the load terminal decreases.

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