Mitigation of Voltage Sags by Dynamic Voltage Restorer

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***Abstract*—Voltage sag is the most severe type of power quality disturbance faced by many commercial and industrial customers. The proliferation of voltage sag load equipment used in industrial plants may cause tremendous economic and financial losses up to millions of dollars attributed to a single disruption. Therefore, it is very important to mitigate the impact of voltage sags on sensitive equipment. In this paper, Dynamic Voltage Restorer (DVR) is used to mitigate the voltage sag during fault condition. DVR is considered to be the most efficient and effective mitigation device. The method to calculate the DVR devices for the fault calculation, were consider in this paper, as well as the control strategy. The mitigation technique was applied to an IEEE 30-buses electrical network to illustrate its application.The results show that the mitigation technique is able to mitigate voltage sag. Analyses of the voltage sag magnitude had shown the different with and without DVR for the network system.**

***Index Terms*—dynamic voltage restorer, voltage sag, power quality, voltage sags, balanced and unbalanced faults**

I. Introduction

Power quality is a customer-driven issue concerning the characteristics of power supply that affect the performance of customer equipment such as micro-electronic devices and power electronic devices. Unexplained equipment trips or shutdowns; occasional equipment damage or component failure; erratic control of process performance; random lockups and data errors, power system component overheating are mainly caused by poor power quality [1], [2].

Due to the associated significant financial losses, problems of the quality of power delivered to the customers have become an important issue. Recent studies show that 80-90% of all power quality issues are from onsite problems, rather than utility problems [3]. Harmonics, voltage sags, voltage swells and short interruptions are the most common types of voltageabnormalities [3]. Voltage sag accounts for the highest percentage of equipment interruptions, about 31% [4].

Voltage magnitude and duration are essential characteristics of voltage sag. The voltage sag magnitude, which is the remaining voltage during the event, depends not only on the fault type and fault location but also on other factors such as pre-fault voltages, transformer connection and fault impedance. The duration of voltage sag is defined as the time during which the voltage magnitude (RMS voltage) is below a given voltage threshold. In the event of a fault in the network, the ensuing voltage sag will last until protective devices acts to interrupt the flow of fault current.

Due to this uncontrollable voltage sag phenomena, sensitive equipment used in industrial plants, such as process controllers, adjustable speed drives, computers, programmable logic controllers, robotics, banks, data centers and customer service centers may cause tremendous economic and financial losses up to millions of dollars attributed to a single disruption [5], [6].

An increasing demand for high quality, reliable electrical power an increasing number of distorting loads have led to an increased awareness of power quality by customer and utilities. Therefore it is very important to mitigate the impact of voltage sags on sensitive equipment. For voltage sag mitigation, power electronic or static controllers in medium and low voltage distribution systems use mitigation devices for the purpose of supplying a nominal voltage [7], [8]. The most commonly used devices to mitigate voltage sag are the DVR and STATCOM as illustrated in [8], [9].

In this paper, a series compensation mitigation device, commonly called dynamic voltage restorer (DVR), has been applied as a definitive solution due to the advantages of the series compensation over the shunt compensation [9], [10]. DVR is commonly used to mitigate voltage sag, voltage swell, voltage harmonic and voltage fluctuations as it is a compensating type mitigation device.

II. Dynamic Voltage Restorer

As shown in Fig. 1, a DVR is a device that injects a dynamically controlled voltage $V_{inj}(t)$ in series to the bus voltage by means of a booster transformer. The DVR is designed to feed an additional voltage source between system feeder and load site. The feature of DVR is to improve the voltage magnitude when the load in down-stream of its series connection.

Normally, the energy storage capacity of DVR will be sufficient enough to compensate a 50% of voltage sag for up to 10 cycles. This is enough to recover the fault. Although it may be rated to compensate up to a 90% voltage drop, DVR does not support complete outages. A

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typical power range to be covered by DVR is from 3 MVA up to 50 MVA.

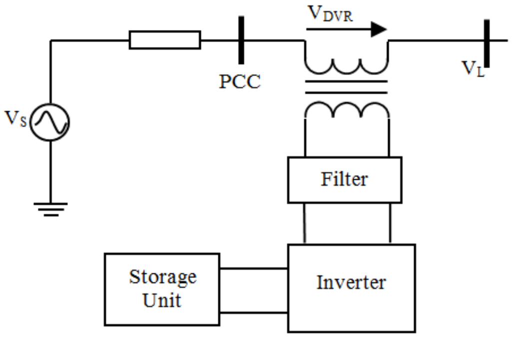


Figure 1. Basic structure of DVR

The DVR consists of the following components [10]:

A. Energy Storage Unit

During voltage sag condition, energy storage is used to provide the shortage of missing energy. Commercially available DVRs use large capacitor banks. The capacity of the energy storage device has a big impact on the compensation capability of the system. DVRs can be configured alternatively to use line energy supply, that is, they absorb the energy that is to be injected from the utility feeder itself into the distribution circuit.

B. Voltage Source Inverter

The DC voltage is converted from the energy storage unit to a controllable AC voltage which is to be injected to the line voltage.

C. Filter Circuit

Normally, a second-order LC filter is introduced between the inverter and the transformer to cancel high frequency harmonic components in the inverter output voltage.

D. Bypass Switches and Control Circuits

The DVR may be configured to operate as a standby compensator where the inverter is passive in the circuit until triggered by a voltage sag event. Alternatively, the DVR may be working continuously during normal and abnormal conditions.

E. Injection Transformer

Its primary connected in parallel to the output of the VSI and its secondary connected in series between the Point of Common Coupling (PCC) and the load bus, and which injects the controllable three phase voltage V_{DVR} to the PCC voltage.This ensures that the load bus voltage, V_L remains almost unaffected by the sag condition.

III. Control Strategy

Different type of voltage sag and load conditions can limit the possibility of compensating voltage sag. Therefore, the control strategy depends on the type of load characteristics. There are three different methods to inject DVR compensating voltage.

A. Pre-fault Compensation

Pre-fault control strategy restores voltage to the pre-fault value, i.e. both sag magnitude and phase shift are compensated. The reference voltage is set as pre-fault voltage magnitude and phase angle. Fig. 2 shows the single-phase vector diagram of pre-fault compensation method [10].

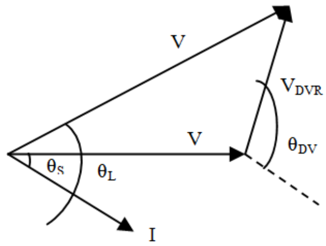


Figure 2. Pre-fault compensation method.

B. In-phase Compensation

In-phase voltage compensation method restores voltage to be in phase with the voltage sag. In other words, the phase angle will be same as the angle of sagged voltage while the voltage magnitude is restored to pre-fault value. Fig 3 shows the single-phase vector diagram for in-phase compensation method [10].

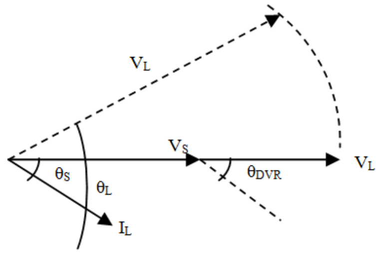


Figure 3. In-phase compensation method

For restore the voltage sag or disturbance by applying pre-sag and in-phase compensation method, must inject active power to loads. The disadvantage of the active power is the amount of injection which depends on the stored energy in the storage unit. DVR restoration time and performance are important in pre-sag and in-phase compensation methods, due to the limited energy storage of the capacity unit.

C. In-phase Advance Compensation

The advantage of in-phase advance compensation is that less active power needs to be injected from DVR energy storage unit into the distribution system. Fig. 4 shows the single-phase vector diagram of in-phase advance compensation method [10].

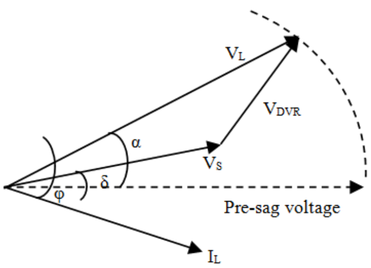


Figure 4. In-phase advance compensation method

IV. Methodology to Determine DVR Injection Voltage

The injection of voltage by DVR depends on fault type, location and system impedance. All the voltages are balanced before occurs of fault, therefore negative and zero sequence will be zero. An analytical technique is used to predict voltage sag magnitude due to balanced and unbalanced fault [11]-[14]. First, calculations of pre-fault voltages need to be done along with sequence admittance matrices for each fault type. Based on the provided information, Z_{Bus} impedance matrices algorithm are formulated for positive, negative and zero sequence for each type of faults. Secondly, the remaining phase voltage magnitudes for each type of faults are determined. By selecting the upper and lower voltage sag magnitude range, for a particular type of faults, the quadratic equation can be determined [14].

Therefore, in the event of a fault, the reactive power will be injected to compensate the voltage magnitude. If the reactive power cannot be fully compensate the voltage magnitude, then the active power will be injected. The main concern here is the restoration of voltage magnitude only. The DVR device should restore the bus voltage to its pre-fault value if possible.

For the 3PF, all phases are compensated equally so that the voltage is balance after the compensation. For the SLG and DLG, voltage compensation is carried out phase by phase since the unbalanced current can flow in zero sequence. Finally for LL, voltage compensation will be equal in magnitude for two faulted phase due to no zero sequence injection.

Injection Calculation

There are various methods used to compensate sag by DVR that has been developed [14]. Most of the previous studies, were focused towards the devices connected and simulation results for individual buses. This approach tends to ignore the effect of DVR devices on neighboring buses in the system network. Therefore, this paper focuses on proper use of DVR devices to the system network which can simulate the entire network.

In this study the pre-fault compensation method was used. The load voltage can express, when there is sag voltage and the voltage injected by the DVR is given by:

$$V_l = V_{sag} + V_{DVR} \quad (1)$$

where: V_l is the load voltage, V_{sag} is the sagged supply voltage and V_{DVR} is the voltage injected by DVR.

A. Injection of Reactive Power.

When injected reactive power only from DVR, the power equation given by:

$$jQ = V_{DVR} + I_l \quad (2)$$

$$S_l = V_l + I_l \quad (3)$$

where: Q is the injected reactive power by DVR, S_l is the load at bus and I_l is the load current.

The magnitude and angle of the DVR is given by:

$$V_{DVR} = \sqrt{V_L^2 + V_s^2 - 2V_L V_s cos\theta} \quad (4)$$

$$\theta_{DVR} = \tan^{-1}\left(\frac{V_L sin\theta_L - V_s sin\theta_s}{V_L cos\theta_L - V_s cos\theta_s}\right) \quad (5)$$

B. Injection of Active Power.

When injected active power only from DVR, the power equation given by:

$$P = V_{DVR} + I_l \quad (6)$$

If the injected reactive power is unable to compensate the voltage sag (voltage magnitude), then restoration continues with injection of active power. From eq. (7), the different value of sag magnitude obtained after restoration with reactive power. The magnitude of the DVR is given by eq. (7) and phase angle is given by eq. (5).

$$V_{DVR} = \sqrt{V_L^2 + V_{s1}^2 - 2V_L V_s cos\theta} \quad (7)$$

V. Case Studies

Faults are simulated for all busses with the proposed algorithm and applied to the IEEE 30 bus test to evaluate its viability with and without DVR. The system data and system network is provided in [15]. The zero, positive and negative sequence internal impedance of all generators is j0.05, j0.3 and j0.2, respectively.

Simulation has been carried out by using Matlab to view the response of voltage sag and voltage magnitude with and without DVR. The duration of the voltage sag is start at 100 ms and it is kept until 300 ms, with total voltage sag duration of 200ms. The result was simulated at the maximum voltage magnitude drop of 50 %. The results shows the voltage at buses ranging from 0.1 p.u. to 0.9 p.u. Bus 4 was analyses to study the behavior of voltage sag magnitudes for different type of faults and fault locations.

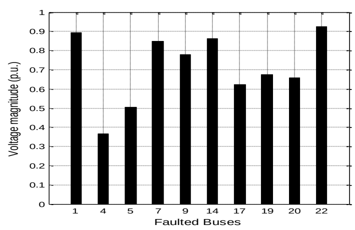
Comparison Study Without DVR and with DVR

A 3MVA DVR is connected at bus 4 to restore the voltage sag. Therefore, the selected rating of DVR can restore the voltage magnitude from 0.5 p.u. and ± 30° phase shift into the pre-fault voltage of 1p.u. Restoration of voltage magnitude depends on the availability of active power and reactive power.

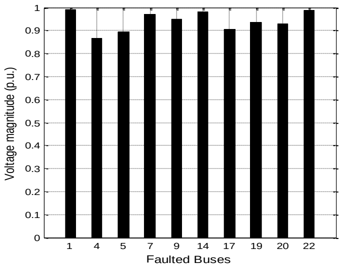
A. Single Phase to Ground Fault

Single phase to ground fault are simulated without DVR and then sag simulation repeated with the DVR connected. The results are illustrated in Fig. 5 (a) and (b).

From Fig. 5, it can be seen the effect of a DVR that improves voltage magnitude for single phase fault. The connected DVR injects reactive power when the sag voltage is below pre-fault value, so most of the voltages all close system buses are smoothened.



(a) Without DVR

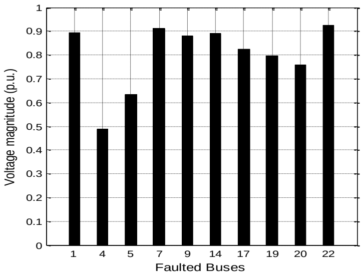


(b) With DVR

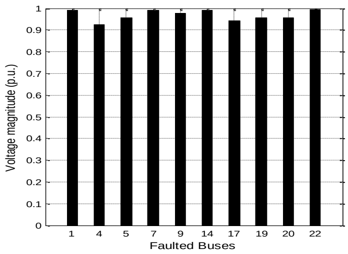
Figure 5. Single phase sag magnitude.

B. *Three Phase to Ground Fault*

Three phases to ground fault are simulated without DVR and then sag simulation repeated with the DVR connected. The results are illustrated in Fig. 6 (a) and (b).



(a) Without DVR



(b) With DVR

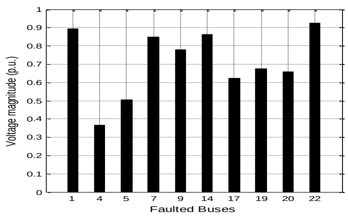
Figure 6. Three phase sag magnitude.

The effect of connecting with and without DVR can be clearly seen from Fig. 6. DVR improves voltage magnitude for all other buses and not only bus 4.

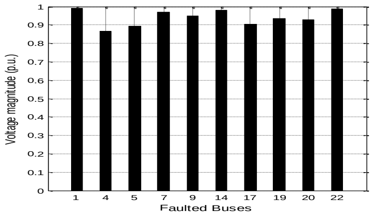
C. *Double Phase to Ground Fault*

Double phase to ground fault are simulated without DVR and then sag simulation repeated with the DVR connected. The results are illustrated in Fig. 7 (a) and (b).

From Fig. 7, it can be seen the effect of a DVR that improves voltage magnitude for double phase ground fault. The connected DVR injects reactive power when the sag voltage is below pre-fault value, so most of the voltages all close system buses are smoothened.



(a) Without DVR

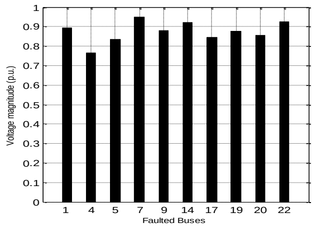


(b) With DVR

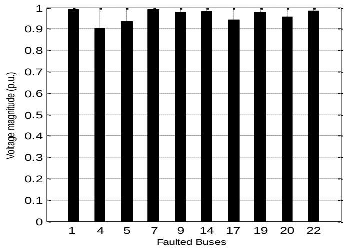
Figure 7. Double phase sag magnitude.

D. *Line-to-line Fault*

Line-to-line fault are simulated without DVR and then sag simulation repeated with the DVR connected. The results are illustrated in Fig. 8 (a) and (b).



(a) Without DVR



(b) With DVR

Figure 8. Line-to-line sag magnitude.

From Fig. 8, it can be seen the effect of a DVR that improves voltage magnitude for line-to-line fault. The connected DVR injects reactive power when the sag voltage is below pre-fault value at, so most of the voltages all close system buses are smoothened.

It can be seen that the overall improvement of bus voltage magnitude ranging from 0% to 35% depending on distance of the bus from DVR and rating of DVR. From the simulation results it can conclude that DVR can restores the voltage magnitude in the system network and all so the whole network.The amount of injection of active power and reactive power is depends on the severity of the fault in system network.

The cost of DVR depends on the power rating, if less real power, than the cost of DVR will be cheaper but less effective than the bigger real power used. Therefore total cost of the solution and voltage profile requirements at the bus and whole network should be taken into account when deciding DVR.

VI. CONCLUSION

In this paper, the operation and capability of DVR used in system network is introduced. Detailed components and working principles of DVR were explained. Methods of control strategies for voltage compensation for three different types of control systems were illustrated in detail. Calculations of DVR were derived in order to minimize the input of real power. Based on the calculation, the magnitude of injection of voltage and current (real power and reactive power) by DVR can be obtained. The capability of the simulation with and without DVR, were demonstrated on 30-bus generic distribution system. The efficiency of the mitigation devices can be seen from the results obtained with and without DVR.

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