Role of a Dynamic Voltage Restorer in Mitigation of Power Quality Problems

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Abstract

Interest in Power Quality has been explicitly seen in Electrical Power Engineering since past decade, even though Utilities all over the world have for decades worked on the improvement of voltage quality, what is now known as power quality. There are numerous types of power quality issues and power problems each of which might have varying and diverse causes. Typical power problems include voltage sag, harmonics, notching, transients like surge, swell, etc. Control of power quality problems involves cooperation between network operator (utility), customer and equipment manufacturer. A Dynamic Voltage Restorer (DVR) is a distribution voltage DC-to-AC solid-state switching converter that injects three single phase AC output voltages in series with the distribution feeder and in synchronism with the voltages of the distribution system. A DVR is an interface equipment between utility and customer connected in series between the supply and load to mitigate the three major power quality problems, namely, the voltage sags, swells, and interruptions. The equations are formulated for calculating the voltages and power injected (inverter rating) from each of the three DVR phases (3-phase DVR). The results are presented, considering an example system.

Key Words

DVR, Power Quality, Mitigation Methods, Voltage Quality, Missing Cycles

1.0 Introduction

Background:

Power quality may be defined as any power problems manifested in voltage, current or frequency deviations that results in failure or mis-operation of customers equipment. Both electric utilities and end users of electrical power are becoming increasingly concerned about the quality of electric power. Power quality is an umbrella concept for multitude of individual types of power system disturbances. The issues that fall under this umbrella are not necessarily new. What is new is that engineers are now attempting to deal with these issues with a systems approach rather than as individual problems. One important and noticeable change seen is that the quality of electricity supplied is now subject to legislation which considers it to be no different from other goods and services. Quality of Supply may be categorized as below:

Quality of Supply

- Reliability
- Power Quality
- Customer Service

Just a few years ago, momentary power outages, sags, swells, surges had relatively little effect on most industrial processes. Today, manufacturing systems, sensitive telemetry, and precision electronic equipment can be disturbed, halted, or even damaged by voltage sag of two or three electrical cycles [1]. Production losses can soar. Power Quality problems evidence themselves in a variety of ways [2] such as: Computer shut down, malfunction of errors, PLC (Programmable Logic Controller) malfunction or errors, variable speed drives tripping out, racing or blinking digital clocks, etc. These can give problems ranging from inconvenience to loss of manufacturing capability with substantial loss in income [3]. Understanding Power Quality and the range of associated problems becomes very important to mitigate the problems. The ideal power supply to a low voltage customer is 240 / 415 V at 50 Hz with a sinusoidal waveshape. The electricity supplier through his local network can not keep the supply exactly at the ideal due to a range of disturbances outside its control and attempts to maintain its voltage within specified ranges. Power
Quality problems arise when these ranges are exceeded and this can occur in three ways [2]:

a) Frequency events: change of the supply frequency outside of the normal range
b) Voltage events: change of the voltage amplitude outside its normal range (may occur for very short periods or be sustained)
c) Waveform events: distortion of the voltage waveform outside the normal range.

Actual voltage varies from the normal range because of disturbances on the supply system, within customer’s plant and / or within nearby plants. These disturbances can [2]:

i. Damage sensitive data processing, control and instrumentation equipment
ii. Interrupt supply
iii. Trip out variable speed drives
iv. Cause data processing, control and instrumentation equipment to malfunction
v. Cause capacitors, transformers and induction motors to overheat
vi. Cause annoying light flicker

While the electricity supplier (local network operator) has the responsibility of keeping the power supply voltage within specified limits, Customers have two basic responsibilities:

1) To ensure that their equipment is able to tolerate the normal range of supply disturbances (in accordance with the regulations)
2) To ensure that their equipment does not cause disturbances which will propagate into supply system at an excessive level (this is very important aspect of power quality)

Frequency, Voltage and Waveform events are the basic types of power quality disturbances. The frequency of a power system [2] is established by the rotational speed of the power station generators and it is very rare that this frequency is significantly varied and it is not further discussed in this paper. Waveform events result in distortion of the normal sinusoidal wave shapes of the mains voltage. Harmonics, Inter-harmonics, notching, transients, noise disturbance etc. [2] and these are mostly caused by the consumers of electricity due to their equipment, particularly power electronic related equipment and induction motors. These are also not further discussed in this paper. The third type of power quality disturbance, viz, Voltage events are considered in this paper. The role and certain deign aspects of Dynamic Voltage Restorer (DVR) to mitigate the power quality problems related with the voltage events are presented here.

The voltage is normally held in the range of ±6% [4]. Voltage variations can be divided into several categories:

i. Long term variations lasting more than 1 minute, called as undervoltages (if less than 90% of nominal voltage) or overvoltages (if greater than 110% of nominal voltage).

ii. Short term variations of duration less than 1 minute, called sags (voltages between 10% and 90% of nominal) or swells (voltage greater than 110% of nominal). These are shown in Figure1[5].

iii. Voltage unbalance where the voltage on each phase conductor is different.

iv. Continuous or random fluctuations that are observed as light flicker as shown in Figure 2 [5].

v. Interruptions where supply is lost completely

vi. Neutral-ground voltage rises that are usually associated with poor grounding/earthing practices.

Power quality problems can originate at the supply system, or the customer’s plant or even a neighboring installation which could propagate via the supply. Some effects of power quality disturbances for the voltage events [2] are shown in the following Table

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over voltage</td>
<td>Overstress insulation</td>
</tr>
<tr>
<td>Under voltage</td>
<td>Excessive motor current</td>
</tr>
<tr>
<td>Unbalance</td>
<td>Motor heating</td>
</tr>
<tr>
<td>Neutral-ground voltage</td>
<td>Digital device malfunction</td>
</tr>
<tr>
<td>Interruption</td>
<td>Complete shut down</td>
</tr>
<tr>
<td>Sag</td>
<td>Variable speed drive &amp; computer trip-out</td>
</tr>
<tr>
<td>Swell</td>
<td>Overstress insulation</td>
</tr>
<tr>
<td>Fluctuations</td>
<td>Light flicker</td>
</tr>
</tbody>
</table>

Mitigation of Power Quality Problems:

Power quality problems can be mitigated with the following practices:

- Proper Earthing and its verification, Uninterruptible Power supplies (UPS), Local or embedded generation (such as diesel generators, microturbines, fuel cells,
stirling engines, etc), Transfer switches, Static breakers, Active filters, Static VAR compensators (SVC), Passive filters, Energy storage systems, Ferro-resonant transformers, DVRs etc.

The interface between the system and the equipment is the most common place to mitigate sags and interruptions. A DVR is one of such utility-customer interface equipment designed to mitigate the power quality problems associated with voltage sags, swells and interruptions.

The next section gives an introduction to DVR and explains its functioning and suitable locations. It also presents a basic block diagram of DVR and explains the three major components of a DVR. Most of the mitigation techniques are based on the injection of active power, thus compensating the loss of active power supplied by the system. All modern techniques are based on power electronic devices, with voltage source converters being the main building block. Section 3 presents the equations for calculating the injection voltages and rating of a DVR to mitigate voltage sags for a 3-phase DVR. An example system is also given in the same section along with the results obtained. Nomenclature used for the equation formulation is given in appendix A.

The conclusions are given in section 4.

2.0 Dynamic Voltage Restorer

A DVR, Dynamic Voltage Restorer is a distribution voltage DC-to-AC solid-state switching converter that injects three single phase AC output voltages in series with the distribution feeder, and in synchronism with the voltages of the distribution system. By injecting voltages of controllable amplitude, phase angle, and frequency (harmonic) into the distribution feeder in instantaneous real time via a series-injection transformer, the DVR can restore the quality of voltage at its load side terminals when the quality of the source side terminal voltage is significantly out of specification for sensitive load equipment.

It is designed to mitigate voltage sags and swells on lines feeding sensitive equipment. A viable alternative to uninterruptible power systems (UPS) and other utilization solutions to the voltage sag problem, the DVR is specially designed for large loads of the order of 2 MVA to 10 MVA served at distribution voltage. A DVR typically requires less than one-third the nominal power rating of the UPS [6]. DVR can also be used to mitigate troublesome harmonic voltages on the distribution system.

DVR comprises of three main parts:
1. Inverter
2. DC energy storage
3. Control system

The basic block diagram of a DVR is shown in Figure 3 [7].

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**Figure 3: DVR Block Diagram**

**Basic Principle**

The basic idea of a DVR is to inject the missing voltage cycles into the system through series injection transformer whenever voltage sags are present in the system supply voltage. As a consequence, sag is unseen by the loads. During normal operation, the capacitor receives energy from the main supply source. When voltage dip or sags are detected, the capacitor delivers dc supply to the inverter. The inverter ensures that only the missing voltage is injected to the transformer.

A relatively small capacitor is present on dc side of the PWM solid state inverter and the voltage over this capacitor is kept constant, by exchanging energy with the energy storage reservoir. The required output voltage is obtained by using pulse-width modulation switching pattern. As the controller will have to supply active as well as reactive power, some kind of energy storage is needed. In the DVRs that are commercially available now large capacitors are used as a source of energy [8]. Other potential sources are being considered are [7]: battery banks, superconducting coils, and flywheels

**Control Techniques**

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 p.u to 0.5 pu of a 1-pu nominal [9]. Several sag detection algorithms along with control techniques are discussed in detail elsewhere [9]. The effectiveness of the sag detection algorithm and the controller lag play an important role in mitigating the short duration reductions in the rms supply voltage (sag) in real time.
DVR Operation:

The reactive power exchanged between the DVR and the distribution system is internally generated by the DVR without any AV passive reactive components, i.e. reactors and capacitors. For deep sags (large variations) in the source voltage, the DVR supplies partial power to the load from a rechargeable energy source attached to the DVR dc terminal. The DVR with its three single phase independent control and inverter design is able to restore line voltage of critical loads during sags caused by unsymmetrical line to ground, line to line, double line to ground faults, as well as symmetrical three phase faults on adjacent feeders or disturbances that may originate many kilometers away on the higher voltage interconnected transmission. During normal line voltage conditions following sag, the energy storage device is recharged from ac supply system by the DVR. Even without stored energy the DVR can compensate for the variations of terminal voltage due to load variations by injecting a lagging voltage in quadrature with the load current thus providing continuously variable series capacitive line compensation. The DVR can also limit fault currents by injecting voltage vector during the fault that opposes the source voltage and maintains the fault current to an arbitrary low value.

Voltage dips or sags can originate with faults at customer site, the local distribution system, or the transmission system. Studies have shown that transmission faults, while relatively rare in the basis of faults per mile of transmission, can cause widespread sags that may constitute source of process interruptions for very long distances from the faulted point [8]. Distribution faults are considerably more common but the resulting sags are more geographically limited.

Typical Digital simulation results for a single phase and three phase Dynamic Voltage Restorer developed using PSCAD/EMTDC program [10] are shown in Figures 4 and 5.

A DVR is primarily for use at the distribution level, where the basic principle is to inject a voltage in series with the supply when an upstream fault is detected. Loads connected downstream of the DVR are thus protected from any voltage sags caused by faults elsewhere on the network. Typical location of a DVR in a power network [9] is shown in Figure 6. Such a location eliminates the need to control the zero sequence in a 3-phase distribution system.

The Dynamic Voltage Restorer (DVR) is a promising and effective device for power quality enhancement due to its quick response and high reliability. Associated with the DVR is its energy-saving compensation control method which is considered to be attractive. It necessitates the injected voltage to effect a phase angle adjustment in the load-side voltage so as to maximize the use of the stored energy of the DVR. [11].
3.0 Voltage Injection and Active Power

The voltage injection from each phase may be calculated from the following equations.

\[ V_{LR} = \sqrt{2} |V_{LR}| \sin \omega t \]  \hspace{1cm} (1)

\[ I_R = \sqrt{2} \frac{|V_{LR}|}{Z} \sin(\omega t) \]  \hspace{1cm} (2)

\[ P_{LR} = |V_{LR}|I_{LR} \cos \phi = \frac{|V_{LR}|^2}{Z} \cos \phi \]  \hspace{1cm} (3)

\[ V_{SR} = \sqrt{2} |V_{SR}| \sin(\omega t - \alpha) \]  \hspace{1cm} (4)

\[ P_{SR} = \frac{|V_{SR}|V_{LR}}{Z} \cos(\phi - \alpha) \]  \hspace{1cm} (5)

\[ P_D = \frac{1}{Z} \left[ \left( |V_{LR}|^2 + |V_{LY}|^2 + |V_{LB}|^2 \right) \cos \phi - \left( |V_{SR}| |V_{LR}| + |V_{SR}| |V_{LY}| + |V_{SR}| |V_{LB}| \right) \cos(\phi - \beta) \right] \]  \hspace{1cm} (6)

\[ \alpha = \phi - \cos^{-1} \left( \frac{\left( |V_{LR}|^2 + |V_{LY}|^2 + |V_{LB}|^2 \right) \cos \phi}{|V_{SR}| |V_{LR}| + |V_{SR}| |V_{LY}| + |V_{SR}| |V_{LB}|} \right) \]  \hspace{1cm} (7)

\[ V_{DR} = V_{LR} - V_{SR} = \sqrt{2} \left( |V_{LR}| \cos \alpha \sin \omega t - \frac{1}{2} |V_{SR}| \sin \alpha \cos \omega t \right) \]  \hspace{1cm} (8)

If \( V_{DR} \) is defined as equal to \( |V_{DR}| \sin (\omega t - \beta) \)

\[ |V_{DR}|^2 = |V_{LR}|^2 + |V_{SR}|^2 - 2 |V_{LR}| |V_{SR}| \cos \alpha \]  \hspace{1cm} (9)

\[ \beta = \tan^{-1} \left( \frac{|V_{SR}| \sin \alpha}{|V_{LR}| - |V_{SR}| \cos \alpha} \right) \]  \hspace{1cm} (10)

Nomenclature used is given in appendix A

Appendix A

Consider a single phase dip to zero volts on R phase of a plant power system with the following:

System load = 8300 kVA, system voltage of 11 kV
Load impedance = 14.58 \( \Omega \)
Maximum voltage that can be injected onto the line by the plant specification DVR= 3113 V

For two power factors (pf) of 0.707 and 0.95, the voltages (volts) and power (MW) injected from DVR are given in Table 1.

<table>
<thead>
<tr>
<th>pf</th>
<th>( V_{DR} )</th>
<th>( V_{DY} )</th>
<th>( V_{DB} )</th>
<th>( P_{DR} )</th>
<th>( P_{DY} )</th>
<th>( P_{DB} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.707</td>
<td>3113</td>
<td>817</td>
<td>817</td>
<td>0.47</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.95</td>
<td>3113</td>
<td>2008</td>
<td>2008</td>
<td>0.631</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

4.0 Conclusion

The Dynamic Voltage Restorer (DVR) is a promising and effective device for power quality enhancement due to its quick response and high reliability. The conclusion is that the DVR is an effective apparatus to protect sensitive loads from short duration voltage dips. The DVR can be inserted both at the low voltage level and at medium voltage level. The series connection with the existing supply voltages makes it effective at locations where voltage dips are the primary problem. However, the series connection makes the protection equipment more complex as well as the continuous conduction losses and voltage drop.

The role of a DVR in mitigating the power quality problems in terms of voltage sag, swell and interruptions is explained. The equations for calculating the voltages and power injected from each of the three DVR phases are given. The results obtained for a single phase dip to zero volts on the red phase are presented to design the PWM Inverter rating of the DVR.

Example System:

V – voltage
I – current
P – active power delivered to the load
Cos \( \phi \) - power factor of the load
Subscribe S – source side voltage
Subscribe L – load side voltage
Subscribe D – voltages injected by DVR
Subscribe R, Y, B – the three phases
\[ | | \] - scalar quantities, otherwise voltages and currents are vectors
Assumptions: neglects harmonics and ideal distribution line and transformer.
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References

4. IEE Wiring Regulations, 2004 Edition