MITIGATION OF POWER QUALITY PROBLEMS USING DYNAMIC VOLTAGE RESTORER (DVR)

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ABSTRACT
A Power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure or a mis-operation of end use equipments. Utility distribution networks, sensitive industrial loads, and critical commercial operations all suffer from various types of outages and service interruptions which can cost significant financial loss per incident based on process down-time, lost production, idle work forces, and other factors. With the restructuring of Power Systems and with shifting trend towards Distributed and Dispersed Generation, the issue of Power Quality is going to take newer dimensions. The aim therefore, in this work, is to identify the prominent concerns in the area and thereby to recommend measures that can enhance the quality of the power, keeping in mind their economic viability and technical repercussions. In this paper electromagnetic transient studies are presented for the custom power controller dynamic voltage restorer (DVR).

Key words: Power Quality Problems, Power System Restructuring, Voltage Sag, DVR, MATLAB.

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1. INTRODUCTION

Power quality is certainly a major concern in the present era; it becomes especially important with the introduction of sophisticated devices, whose performance is very sensitive to the quality of power supply. Modern industrial processes are based on a large amount of electronic devices such as programmable logic controllers and adjustable speed drives. The electronic devices are very sensitive to disturbances [1] and thus industrial loads become less tolerant to power quality problems such as voltage dips, voltage swells, and harmonics.

Voltage dips are considered one of the most severe disturbances to the industrial equipment. A machine can be affected by disturbance of 10% voltage drop lasting for 100ms. Voltage dip of 70% (of the nominal voltage) with duration shorter than 100ms can result in material loss in the range of lakhs for the cement industries. Swells and over voltage can over heating tripping of even destruction of industrial equipment such as motor drives. Electronics equipment are very sensitive loads against harmonics because their control depends on either the peak value or the zero crossing of the supplied voltage, which are influenced by the harmonic distortion. This paper analyzes the key issues in the Power Quality problems, specially keeping in mind the present trend towards more localized generations (also termed as distributed and dispersed generation) and consequent restructuring of power transmission and distribution networks. As one of the prominent power quality problems, the origin, consequences and mitigation techniques of voltage sag problem has been discussed in detail. The study describes the techniques of correcting the supply voltage sag in a distribution system by two power electronics based devices called Dynamic Voltage Restorer (DVR) and Distribution STATCOM (D-STATCOM). A DVR voltage in series with the system voltage and a D-STATCOM injects a current into the system to correct the voltage sag[1]. The steady state performance of both DVR and D-STATCOM is studied for various levels of voltage sag levels.

Literature Review

Mr. Y. Prakash and Dr. S. Sankar[15] proposed algorithm is applied to some disturbances in load voltage caused by induction motors starting, and a three-phase short circuit fault. Also, the capability of the proposed DVR has been tested to limit the downstream fault current. The current limitation will restore the point of common coupling voltage and protect the DVR itself. The idea here is that the DVR acts as a virtual impedance with the main aim of protecting the pee voltage during downstream fault without any problem in real power injection into the DVR.

Haluk GOZDE and M.Cengiz[16] Proposed an artificial intelligence based optimization method is applied to optimize the gains of PID controller for Automatic Voltage Regulator (AVR) system. A dynamic performance of the controller which is optimized with Chaotic Particle Swarm Optimization (CPSO) algorithm is compared with the results which are obtained with standard Particle Swarm Optimization (PSO). The transient response analysis is used in order to determine the performances of the methods.

Ali O Al-Mathnani, Hussain Shareef and Azah Mohamed[17] proposed fast DVR with controller to compensate the short outage, reduced the harmonic distortion and transient voltage for balanced and unbalanced load. In-phase method with continues two vector control algorithm is used to detect and compensate $\Delta V$ and $\Delta Q$ variables during voltage sag and voltage compensation. When there is any phase angle or phase jump in supply voltage the reference voltage is adjusted to track the phase angle of the
supply voltage. A phase locked loop is used to keep the load voltage synchronized continuously and tracks the source voltage. It is shown that the proposed DVR controller improves the system power quality. Photovoltaic (PV) system with boost converter is designed to maintain the DC source voltage. Simulation was carried out using PSCAD/EMTDC.

2. POWER QUALITY PROBLEMS
The distortion in the quality of supply power can be introduced /enhanced at various stages; however, some of the primary sources of distortion [3] can be identified by 1) Power Electronics Device 2) Arcing Devices 3) IT and Office Equipments 4) Load Switching 5) Embedded Generation 6) Large Motor Starting 7) Electromagnetic Radiations and Cables 8) Storm and Environment Related Causes etc.

While power disturbances occur on all electrical systems, the sensitivity of today’s sophisticated electronic devices makes them more susceptible to the quality of power supply. For some sensitive devices, a momentary disturbance can cause scrambled data, interrupted communications, a frozen mouse, system crashes and equipment failure etc. A power voltage spike can damage valuable components. Some of the common power quality issues and their prominent impact are summarized in the table below:

<table>
<thead>
<tr>
<th>Problem</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volgate Sags</td>
<td>Devices/process drowntime, effect on product quality, failure/malfunction of customer equipments(such as tripping of large industrial devices) and associated scrap cost, clean up cost, maintenance and repair cost etc.</td>
</tr>
<tr>
<td>transients</td>
<td>tripping component failures, flashover of instrument insulation, hardware rebooting, software ‘glitches’, poor production quality etc.</td>
</tr>
<tr>
<td>harmonics</td>
<td>excessive losses and heating in motors, capacitors and transformers connected to the system, insulation failure due to overheating and over voltages, loss of conductor life and possible risk of fire due to overheating, malfunctioning of sophisticated electronic equipments cores, interfaces with adjacent communication networks, audio hum, video ‘flutter’. power supply failure etc.</td>
</tr>
<tr>
<td>flicker</td>
<td>visual irritation introduction of many harmonic components in the supply power and their associated ill effects</td>
</tr>
</tbody>
</table>

3. SOLUTION FOR POWER QUALITY PROBLEMS
There are two approaches to the mitigation of power quality problems. The solution to the power quality can be done from customer side or from utility side [4]. First approach is called load conditioning, which ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install line conditioning systems that suppress or counteracts the power system disturbances. A flexible and versatile solution to voltage quality problems is offered by active power filters. Currently they are based on PWM
Mitigation of Power Quality Problems Using Dynamic Voltage Restorer (DVR) converters and connect to low and medium voltage distribution system in shunt or in series. Series active power filters must operate in conjunction with shunt passive filters in order to compensate load current harmonics. Shunt active power filters operate as a controllable current source and series active power filters operates as a controllable voltage source. Both schemes are implemented preferable with voltage source PWM inverters [5], with a dc bus having a reactive element such as a capacitor. Active power filters can perform one or more of the functions required to compensate power systems and improving power quality. Their performance also depends on the power rating and the speed of response.

However, with the restructuring of power sector and with shifting trend towards distributed and dispersed generation, the line conditioning systems or utility side solutions will play a major role in improving the inherent supply quality; some of the effective and economic measures can be identified as following:

A. Lightening and Surge Arresters
Arresters are designed for lightening protection of transformers, but are not sufficiently voltage limiting for protecting sensitive electronic control circuits from voltage surges.

B. Thyristor Based Static Switches
The static switch is a versatile device for switching a new element into the circuit when the voltage support is needed. It has a dynamic response time of about one cycle. To correct quickly for voltage spikes, sags or interruptions, the static switch can used to switch one or more of devices such as capacitor, filter, alternate power line, energy storage systems etc. The static switch can be used in the alternate power line applications. This scheme requires two independent power lines from the utility or could be from utility and localized power generation like those in case of distributed generating systems [4]. Such a scheme can protect up to about 85 % of interruptions and voltage sags.

C. Energy Storage Systems
Storage systems can be used to protect sensitive production equipments from shutdowns caused by voltage sags or momentary interruptions. These are usually DC storage systems such as UPS, batteries, superconducting magnet energy storage (SMES), storage capacitors or even fly wheels driving DC generators [6]. The output of these devices can be supplied to the system through an inverter on a momentary basis by a fast acting electronic switch. Enough energy is fed to the system to compensate for the energy that would be lost by the voltage sag or interruption. In case of utility supply backed by a localized generation this can be even better accomplished.

D. Electronic tap changing transformer
A voltage-regulating transformer with an electronic load tap changer can be used with a single line from the utility. It can regulate the voltage drops up to 50% and requires a stiff system (short circuit power to load ratio of 10:1 or better). It can have the provision of coarse or smooth steps intended for occasional voltage variations.
E. Harmonic Filters
Filters are used in some instances to effectively reduce or eliminate certain harmonics [7]. If possible, it is always preferable to use a 12-pluse or higher transformer connection, rather than a filter. Tuned harmonic filters should be used with caution and avoided when possible. Usually, multiple filters are needed, each tuned to a separate harmonic. Each filter causes a parallel resonance as well as a series resonance, and each filter slightly changes the resonances of other filters.

F. Constant-Voltage Transformers
For many power quality studies, it is possible to greatly improve the sag and momentary interruption tolerance of a facility by protecting control circuits. Constant voltage transformer (CVTs) can be used [6] on control circuits to provide constant voltage with three cycle ride through, or relays and ac contactors can be provided with electronic coil hold-in devices to prevent mis-operation from either low or interrupted voltage.

G. Digital-Electronic and Intelligent Controllers for Load-Frequency Control
Frequency of the supply power is one of the major determinants of power quality, which affects the equipment performance very drastically. Even the major system components such as Turbine life and interconnected-grid control are directly affected by power frequency. Load frequency controller used specifically for governing power frequency under varying loads must be fast enough to make adjustments against any deviation. In countries like India and other countries of developing world, still use the controllers which are based either or mechanical or electrical devices with inherent dead time and delays and at times also suffer from ageing and associated effects. In future perspective, such controllers can be replaced by their Digital-electronic counterparts.

4. USE OF DYNAMIC VOLTAGE RESTORER TO IMPROVE POWER QUALITY
In order to overcome the problems such as the ones mentioned above, the concept of custom power devices is introduced recently; custom power is a strategy, which is designed primarily to meet the requirements of industrial and commercial customer. The concept of custom power is to use power electronic or static controllers in the medium voltage distribution system aiming to supply reliable and high quality power to sensitive users [1]. Power electronic valves are the basis of those custom power devices such as the static transfer switch, active filters and converter-based devices. Converter based power electronics devices can be divided into two groups: shunt-connected and series-connected devices. The shunt connected devices is known as the DSTATCOM and the series device is known as the Static Series Compensator (SSC), commercially known as DVR. It has also been reported in literature that both the SSC and DSTATCOM have been used to mitigate the majority the power system disturbances such as voltage dips, sags, flicker unbalance and harmonics.

For lower voltage sags, the load voltage magnitude can be corrected by injecting only reactive power into the system. However, for higher voltage sags, injection of active power, in addition to reactive power, is essential to correct the voltage magnitude [8]. Both DVR and D-STATCOM are capable of generating or absorbing reactive power but the active power injection of the device must be provided by an
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external energy source or energy storage system. The response time of both DVR and D-STATCOM is very short and is limited by the power electronics devices. The expected response time is about 25 ms, and which is much less than some of the traditional methods of voltage correction such as tap-changing transformers.

5. REAL MODAL OF DYNAMIC VOLTAGE RESTORER

A. DVR Basic Configuration and Components

Fig 1 shows the schematic diagram of DVR. It consists of an Injection transformer, Harmonic filter, Storage Devices, a Voltage Source Converter (VSC), and DC charging circuit and Control and Protection system.

![Figure 1 Schematic diagram of DVR](image)

1. Energy Storage Unit

![Figure 2 DVR with supply rectified energy](image)

During voltage sag, the DVR injects a voltage to restore the load supply voltages. The DVR needs a source for this energy. Two types of system are considered; one using stored energy to supply the delivered power as shown in Figure 2, and the other having no internal energy storage, where energy is taken from the incoming supply through a shunt converter as Shown in Figure 2.

2. Inverter Circuit

The Voltage Source Inverter (VSI) or simply the inverter converts the dc voltage from the energy storage unit (or the dc link) to a controllable three phase ac voltage. The inverter Switches are normally fired using a sinusoidal Pulse Width Modulation (PWM) scheme. Since the vast majority of voltage sags seen on utility systems are unbalanced, the VSI will often operate with unbalanced switching functions for the
three phases, and must therefore treat each phase independently. Moreover, sag on one phase may result in a swell on another phase, so the VSI must be capable of handling both sags and swells simultaneously. Another topology of the DVR is the use of multi-inverter system in cascade. This topology will add the voltage of the single cascaded inverters in series in order to obtain the desired inverter voltage. This method gets rid of the injection transformer used in the basic configuration of the DVR.

3. Filter Unit

![DVR with load side filter](image)

Figure 3 DVR with load side filter

The nonlinear characteristics of semiconductor devices cause distorted waveforms associated with high frequency harmonics at the inverter output. To overcome this problem and provide high quality energy supply, a harmonic filtering unit is used. These filters can be placed either in the inverter side as shown in Figure 2 or in the line side as shown in Figure 3.

4. Series Injection Transformer

Three single-phase injection transformers are used to inject the missing voltage to the system at the load bus. To integrate the injection transformer correctly into the DVR, the MVA rating, the primary winding voltage and current ratings, the turn-ratio and the short-circuit impedance values of transformers are required. The existence of the transformers allow for the design of the DVR in a lower voltage level, depending upon the stepping up ratio.

6. CONTROL TECHNIQUES

A. Linear Controllers

The three main voltage controllers, which have been proposed in literature, are feed forward (open loop), Feedback (closed loop) and Multi-loop controller [13-18]. The feed-forward voltage controller is the primary choice for the DVR, because of its simplicity and fastness. The supply voltage is continuously monitored and compared with a reference voltage; if the difference exceeds a certain tolerance, the DVR injects the required voltage. The drawback of the open loop controller is the high steady state error. In the feedback control, the load voltage is measured and compared with the reference voltage; the missing voltage is supplied by the DVR at the supply bus in a feedback loop. This controller has the advantage of accurate response, but it is complex and time-delayed. Multi-loop control is used with an outer voltage loop to Control the DVR voltage and an inner loop to control the load current. This method
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has the strengths of feed-forward and feedback control strategies, on the expense of complexity and time delay.

B. Non-linear Controllers

It appears that the nonlinear controller is more suitable than the linear type since the DVR is truly a non-linear system due to the presence of power semiconductor switches in the inverter bridge. The most non-linear controllers are the Artificial Neural Networks (ANN), Fuzzy Logic (FL) and Space Vector Pulse Width Modulation (SVPWM) [19-24].

ANN control method has adaptive and self-organization capacity. The ANN has inherent learning capability that can give improved precision by interpolation. FL controllers are an attractive choice when precise mathematical formulations are not possible. When a FL controller is used, the tracking error and transient overshoots of PWM can be considerably reduced. SVPWM control strategy is to adopt a space vector of the inverter voltage to get better performance of the exchange is gained in low switching frequency conditions.

7. MODELING OF DVR AND SIMULATION RESULTS

As mentioned in the previous section that custom power devices could be the effective means to overcome some of the major power quality problems by the way of injecting active and/or reactive power(s) into the system [9]-[11]. This section of the paper deals with the modeling of DVR. Consequently some case studies will be taken up for analysis and performance of these devices. The modeling approach adopted in the paper is graphical in nature, as opposed to mathematical models embedded in code using a high-level computer language. The well-developed graphic facilities available in an industry standard power system package, namely, MATLAB (/Simulink) [12], is used to conduct all aspects of model implementation and to carry out extensive simulation studies.

The control scheme for these devices is shown in Fig. 1. The controller input is an error signal obtained from the reference voltage and the value rms of the terminal voltage measured. Such error is processed by a PI controller and the output is the angle $\delta$, which is provided to the PWM signal generator. The PWM generator then generates the pulse signals to the IGBT gates of voltage source converter [10].

![Figure 1 The PI Controller](image)

In order to show the performance of the DVR in voltage sags mitigation, a simple radial distribution network is simulated using MATLAB/SIMULNK, and shown in fig 7. The parameters of the main components are listed in the Table
A Three-phase 15 kV, 50Hz programmable voltage source is connected to a feeder and it is step down to 415V, 50 Hz through 15kV/415V transformer at Point of Common Coupling (PCC).

The DVR is connected in series between PCC and the nonlinear load with the help of an injection transformer. The primary side of injection transformer is connected in series with the load and secondary side is connected in delta to the DVR. A three phase fault is applied to the system in order to see the voltage sag. The DVR uses self-commutating IGBT solid-state power electronic switches to mitigate voltage sags in the system. The voltage controlled three single-phase full bridges PWM inverters are used to produce compensating voltage. These inverters are connected to the common DC voltage source. The DC voltage source is an external source of supplying DC voltage to the inverter for AC voltage generation.

**Table I TEST SYSTEM PARAMETERS**

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Parameter</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Supply Voltage</td>
<td>15kV</td>
</tr>
<tr>
<td>2</td>
<td>Load transformer rating</td>
<td>6.6KVA</td>
</tr>
<tr>
<td>3</td>
<td>DC Bus battery Amplitude</td>
<td>2600V</td>
</tr>
<tr>
<td>4</td>
<td>Filter inductance</td>
<td>0.0225H</td>
</tr>
<tr>
<td>5</td>
<td>Filter capacitance</td>
<td>0.02F</td>
</tr>
<tr>
<td>6</td>
<td>Load resistance</td>
<td>0.001Ohms</td>
</tr>
<tr>
<td>7</td>
<td>Load inductance</td>
<td>0.002H</td>
</tr>
</tbody>
</table>
The basic function of the DVR is to inject a dynamically controlled voltage into the bus voltage by means of an voltage injection 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 disturbances in the ac feeder will be compensated by an equivalent voltage. The DVR works independently to any of the type of fault or any event that happens in the system.

Highly inductive load are applied to the test system to analyse the performance of DVR. Such faults are applied to the system during 50-150ms. Due to this voltage sag will occur.

Fig 5.1(a) shows the load voltage without DVR when a highly inductive load is applied and it is observed that 85% Voltage sag is initiated at 0.05s and it is kept until 0.15s, with total voltage sag duration of 0.1s. Fig 5.1(b) shows the RMS Voltage without DVR. Due to the condition.

![Figure 5.1 (a) Load Voltage DVR](image)

5.1(b) RMS Voltage without DVR

Now DVR with the proposed controls scheme is connected to the system. Fig 5.2 (a) shows the injected voltage by the DVR with PI controller during 0.2ms to 0.25ms to the system with the help of injection transformer in order to maintain the load voltage constant.

![Magnitude of 3-Phase supply with SAG](image)
The amplitude index is kept fixed at 1pu, in order to obtain the highest fundamental voltage component at the controller output.

\[ k = \frac{V_{\text{Control}}}{V_{\text{Trin}}} = \text{1pu} \]

\( V_{\text{Control}} \) is the peak amplitude of the control signal
\( V_{\text{Trin}} \) is the peak amplitude of the triangular signal

The switching frequency is set at 1035Hz. The frequency modulation index is given by,

\[ mf = \frac{f_2}{f_1} = \frac{1035}{50} = 20.7 \]

Where \( f_1 \) is the fundamental frequency?

The modulating angle is applied to the PWM generators in phase A. The angles for phases B and C are shifted by 1200 and 2400, respectively [10-11]. It can be seen that the control implementation is kept very simple by using only voltage measurements as the feedback variable in the control scheme. The speed of response and robustness of the control scheme are clearly shown in the simulation results. Fig 5.3 Pulses generated by Discrete PWM Generator. Fig 5.4 shows that the input of PI controller

Figure 5.3 Pulses generated by Discrete PWM Generator

Figure 5.4 Input of PI controller
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Fig 5.4(a) shows the load Voltage after compensation with PI controller... Here the load voltage is 98% of the supply voltage. Fig 5.4(b) shows the load RMS Voltage after compensation using PI controller. Here RMS voltage is maintained to 98% at the sensitive load point. From the below figures it is concluded that using PI controller performance of DVR is more satisfactory then the conventional method

![Figure 5.4 (a) Load Voltage after compensation with DVR.](image)

![Figure 5.4(a) RMS Voltage after compensation with DVR.](image)

8. CONCLUSION

In this paper the main objectives for the utilization of the studied equipment to mitigate the voltage sag. In order to protect critical loads from more sever fault in distribution network. The facility available in MATLAB/SIMULINK is used to carry out extensive simulation study. Supply voltage is compared with reference voltage to get error signal which is given to the gate pulse generation circuit as a reference sine wave which is compared with carrier signal to get pulses for inverter. Voltage sag values are major factors in estimating the DC storage value. 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.

REFERENCES


