Voltage Swell Compensation in an Interline Dynamic Voltage Restorer

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The Dynamic Voltage Restorer (DVR) provides an advanced and economical solution for voltage swell problems. The voltage-restoration process involves real-power injection into the distribution system. The Interline DVR (IDVR) proposed in this paper provides a way to compensate the voltage deviation caused in a feeder. The IDVR consists of several DVRs connected to different distribution feeders in the power system sharing common energy storage. Here, one DVR in the IDVR system works in voltage-swell compensation mode while the other DVR in the IDVR system operate in power-flow control mode. The single phase model of the IDVR system is illustrated which is operated by Multiple Pulse Width Modulation (PWM). Closed-loop control scheme of load voltage for a simple system is modeled and simulated using MATLAB software. The simulation results are presented to demonstrate the effectiveness of the proposed IDVR system.

Keywords: Interline Dynamic Voltage Restorer (IDVR), Multiple Pulse width modulation (PWM), Total Harmonic Distortion (THD)

Introduction

The need of the electrical power is increasing and simultaneously the problems while transmitting the power through the distribution system are also increasing. Voltage fluctuations are considered as one of the most severe power quality disturbances to be dealt with. Even a short-duration voltage fluctuation could cause a malfunction or a failure of a continuous process. There are several types of voltage fluctuations that can cause the systems to malfunction, including surges and spikes, sag, swell, harmonic distortions, and momentary disruptions. Among them, voltage sag and swell are the major power-quality problems. Voltage swell is the sudden increase of voltage to about more than 110% amplitude of the supply voltage. This is caused due to the sudden reduction of the load across that particular feeder. This increase of voltage is compensated by injecting the voltage in series with the supply from another feeder at the time of disturbances using DVR. This IDVR system is presently one of the most cost-effective and a highly efficient method to mitigate voltage swell.

The concept of Interline Dynamic Voltage Restorer (IDVR) where two or more voltage restorers are connected such that they share a common DC-link is similar to the Interline Power Flow Controller concept. In this paper, a two-line IDVR system is explained which employs two DVRs connected to two different feeders originating from two grid substations, could be of the same or different voltage level. However the DC-link of these two DVRs could be connected to a common DC-link. This would cut down the cost as sharing a common DC-link reduces the DC-link storage capacity significantly compared to that of a system whose loads are protected by clusters of DVRs with separate energy storages. When one of the DVRs compensates for voltage swell produced, the other DVR in IDVR system operates in power-flow control mode. This is to reload DC-link energy storage, which is depleted due to the power taken by the DVR working in the voltage-swell compensation mode.

The DVR is operated in such a fashion that it does not supply or absorb any active power during the steady-state operation. Control algorithm for dynamic voltage restorer (DVR) to improve voltage quality problems such as voltage sags/swells in distribution systems has been proposed. The DVR consists of three inverters sharing the same DC link via a capacitor bank. Each inverter has an individual inner control loop for generating the gate signals for the switches. The voltage-restoration process involves real-power injection into the distribution system, the capability of a particular DVR topology, especially for compensating long-duration voltage sags, depends on the energy storage capacity of the DVR. The main factor which limits capabilities of a
particular DVR in compensating long-duration voltage sags is the amount of stored energy within the restorer\(^2\). The modeling and simulation of DVR and IDVR is presented\(^6-9\). In this paper modeling and simulation of IDVR for voltage swell compensation is presented.

**Principles of operation of IDVR**

The IDVR system consists of several DVRs in different feeders, sharing a common DC-link. A two-line IDVR system employs two DVRs are connected to two different feeders where one of the DVRs compensates for voltage swell produced, the other DVR in IDVR system operates in power-flow control mode. The common capacitor connected between the two feeders act as the common DC supply.

Consider the condition when one of the DVRs in the IDVR system operates in voltage-swell compensating mode while the other DVRs operate in power-flow control mode to keep the DC-link voltage at a desired level. In order to establish the power exchange between the two systems, it is assumed that DVR\(_1\) is mitigating voltage swell appearing in that line and DVR\(_2\) is controlled to provide real power to the DC-link energy storage. As line\(_2\) is operating at its normal condition, the load voltage of line\(_2\) should be equal to the load bus voltage. Hence when there is no voltage swell, the load voltage of Feeder\(_2\) is equal to the bus voltage \(V_{b2}\). Even in swell situations, the DVR\(_2\) should be operated to meet this condition while supplying real power to the common DC-link. Hence, the locus of the \(V_{b2}\) should lie on a circle with radius equal to the desired magnitude of bus voltage \(V_{b2}\). The load voltage \(V_{l2}\) has an advance phase angle (\(\beta\)) with respect to the supply side voltage \(V_{b2}\), in order to inject power to the DC-link.

The real power exchanged between line\(_2\) and the DC-link energy storage can be written as follows:

\[
P_{ex} = 3V_{b2}I_2 \cos (\Phi_2 - \beta) - 3V_2I_2 \cos (\Phi_2) ...
\]  

Equation (1)

Where \(I_2\), \(V_{b2}\), \(V_2\), \(\Phi_2\) and \(\beta\) are load current, load bus voltage, load voltage, load power factor angle, and load voltage advance angle of line\(_2\), respectively.

As the magnitude of the load voltage should be equal to the load bus voltage, Equation (1) can be written in terms of load apparent power as shown in equation (2):

\[
P_{ex} = S_2 (\cos (\Phi_2 - \beta) - pf_2) ...
\]  

Equation (2)

Where \(S_2 = 3V_{b2}I_2\) is line\(_2\) load apparent power and \(pf_2\) is line\(_2\) load power factor.

The DVR in the healthy feeder acts to reload the DC-link energy storage. Therefore, the converters that link the two feeders should be operated in power flow control mode. The required real power is transferred from line\(_2\) to line\(_1\) through a common DC-link capacitor within the allowable power transfer limit. Therefore, the real power exchanged can be controlled by controlling the DC-link voltage. The IDVR system is operated in closed loop control and the real and reactive powers is analyzed.

**Results of voltage compensation in a two feeder IDVR system**

The voltage swell in a two-feeder IDVR system is caused due to sudden decrease of the load across a feeder. Considering that the DVR\(_1\) in the IDVR system operates in voltage-swell compensating mode while the DVR\(_2\) operates in power-flow control mode to keep the DC-link voltage at a desired level. When there is no voltage disturbance, the load voltage of Feeder\(_1\) is equal to the bus voltage. During voltage swell, the DVR\(_2\) should be operated to meet this condition while supplying real power to the common DC link. The modelling and simulation of the closed loop controlled IDVR for voltage swell compensation is presented. For a closed loop control, the output voltage from the load across the load is rectified to give a DC voltage. This DC voltage is controlled via PI controller. The error is used and the driving pulse is generated. This pulse is fed to the rectifier which therefore yields in the injection of voltage.

The AC voltage is converted to DC voltage and controlled by a PI controller and the error is used to generate the driving pulse. The general requirement of such control scheme is to obtain an AC waveform with low Total Harmonic Distortion (THD) and good dynamic response against supply and load disturbance whether the DVR in the IDVR system operates in voltage swell compensation or power flow control mode. The AC voltage from Feeder\(_2\) is converted to DC voltage and then back to AC voltage which is fed to Feeder\(_1\). Here, the Multiple Pulse Width Modulation (PWM) technique is used to create pulses, which is given to both the rectifier and inverter. Filters are added to reduce harmonics. The capacitance present between the rectifier and the inverter acts as a common DC-link source between the two DVRs.

The Fig.1 shows the response of voltage swell compensation in a closed loop control of two feeder IDVR system. The swell produced due to the sudden decrease of the load is about 20%. Hence this sudden increase in the voltage is compensated by supplying
Out-of-phase voltage from the healthy Feeder$_2$ to the Feeder$_1$. This compensated output voltage is also shown in Figure 1c.

The input voltage is subjected to a swell of 20% magnitude. The voltage is injected out-of-phase from feeder$_2$ and as a result the load voltage is maintained at the same value throughout the simulation, including the voltage swell period. Fig. 2 shows the real and reactive power obtained across Feeder$_1$. Both the real and reactive power is decreased when there is an decrease in the load. Compared to that of the open loop control, the real and reactive power in a closed loop control is greater with comparatively less disturbances.

The line spectrum for the compensated voltage is taken to determine the Total Harmonic Distortion (THD) present in the waveform. The Fig 3 shows that the Total Harmonic Distortion (THD) which is 5.27% for a 20% voltage swell. The distortions produced in the voltage waveform for a closed loop control is comparatively lesser.

**Conclusion**

The IDVR consists of several DVRs connected to different distribution feeders in the power system sharing common energy storage. IDVR is useful for voltage sag/swell compensation. Closed-loop control scheme of IDVR for a voltage swell compensation system is modeled and simulated using MATLAB.
software. The model for 20% of the voltage swell is compensated using IDVR. The simulation results are presented to demonstrate the effectiveness of the proposed IDVR system.

References