SIMULATION VERIFICATION OF DYNAMIC VOLTAGE RESTORER USING HYSTERESIS BAND VOLTAGE CONTROL

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Abstract - *Dynamic Voltage Restorer (DVR) is one of the custom power devices that are used as an effective solution for the protection of sensitive loads against voltage disturbances in power distribution system. The efficiency of the DVR depends on the performance of the efficiency control technique involved in switching the inverters. Unlike previous approaches, this paper presents a hysteresis voltage control technique of DVR based on unipolar Pulse Width Modulation (PWM). The hysteresis voltage control has a very fast response, simple operation and variable switching frequency. To evaluate the quality of the load voltage during the operation of DVR, it is controlled by hysteresis voltage control techniques with various Hysteresis Band (HB). The validity of proposed method and achievement of desired compensation are confirmed by the results of the simulation in MATLAB/ SIMULINK.*

Key words - *Dynamic Voltage Restorer (DVR), hysteresis voltage control, Total Harmonic Distortion (THD), Hysteresis Band.*

1. Introduction

Power quality problems in industrial applications concern a wide range of disturbances, such as voltage sags and swells, flicker, interruptions, harmonic distortion. Preventing such phenomena is particularly important because of the increasing heavy automation in almost all the industrial processes. High quality in the power supply is needed, since failures due to such disturbances usually have a high impact on production costs [1-3].

Voltage sag/swell that occurs more frequently than any other power quality phenomenon is known as the most important power quality problems in the power distribution systems. IEEE 519- 1992 and IEEE 1159-1995 describe the voltage sags /swells as shown in Fig.2.

Voltage sag is defined as a sudden reduction of supply voltage down from 90% to 10% of nominal. According to the standard, a typical duration of sag is l0 ms to 1 minute. On the other hand, voltage swell is defined as a sudden increasing of supply voltage up1l0% to 180% in rms voltage at the network fundamental frequency with duration from 10 ms to 1 minute. Voltage sag/swell often caused by faults such as single line-to-ground fault, double line-to-ground fault on the power distribution system or due to starting of large induction motors or energizing a large capacitor bank. Voltage sag/swell can interrupt or lead to malfunction of any electric equipment that is sensitive to voltage variations.

The Dynamic Voltage Restorer (DVR) has been proposed to protect sensitive loads from such voltage sags/swell. The DVR is connected in series with the sensitive load or distribution feeder and is capable of injecting real and reactive power demanded by the load during voltage sag/swell compensation. The output of the DVR inverter is usually provided with an output LC filters to attenuate the harmonic contents appearing in injected voltage. The filter parameters are designed according to certain design aspects such as depth of the sag to be mitigated and the load voltage [4].

This paper presents a Hysteresis Voltage Control technique based on bipolar and unipolar PWM to improve the quality of load voltage. The hysteresis voltage control has not been investigated on DVR. The proposed method is validated through modeling in MATLAB/Simulink.

2. Dynamic Voltage Restorer (DVR)

A Dynamic Voltage Restorer (DVR) is a recently proposed series connected solid-state device that injects voltage into the system in order to regulate the load side voltage. The DVR was first installed in 1996 [5]. It is normally installed in a distribution system between the supply and the critical load feeder [6]. Its primary function is to rapidly boost up the load-side voltage in the event of a disturbance in order to avoid any power disruption to that load [7-8]. There are various circuit topologies and control schemes that can be used to implement a DVR.

In addition to voltage sags and swells compensation, DVR can also perform other tasks such as: line voltage harmonics compensation, reduction of transients in voltage and fault current limitations. The general configuration of the DVR consists of an Injection/Booster transformer, a Harmonic filter, a Voltage Source Converter (VSC), DC charging circuit and a Control and Protection system as shown in Fig. 1. In most sag correction techniques, the DVR is required to inject active power into the distribution line during the period of compensation. Hence, the capacity of the energy storage unit can become a limiting factor in the disturbance compensation process especially for sags of long duration.

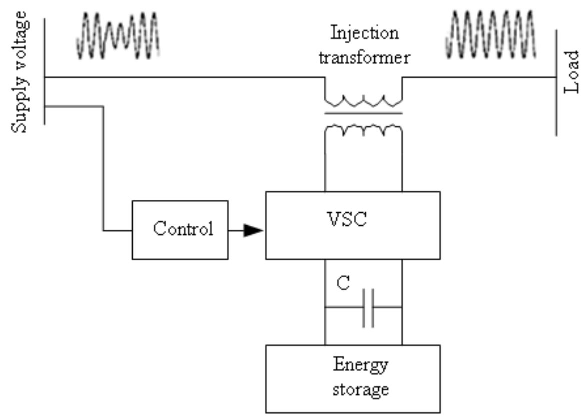


Fig. 1. Typical schematic of a power system Compensated by DVR.

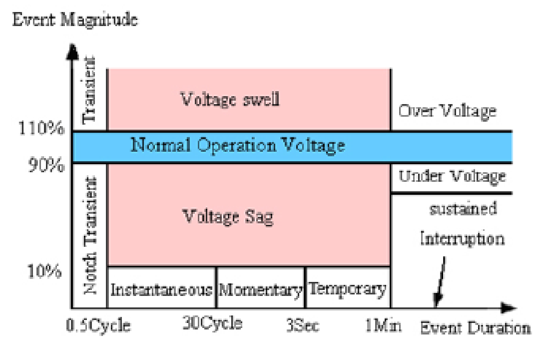


Fig.2. Voltage Reduction Standard of IEEE Std. 1159-1995.

3. DVR Power Circuit

The power circuit of the DVR is shown in Fig.3. The DVR consists of mainly a three-phase Voltage Sourced Converter (VSC), a coupling transformer, passive filter and a control system to regulate the output voltage of VSC.

3.1. Voltage Source Converter (VSC)

A voltage-source converter is a power electronic device, which can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. This converter injects a dynamically controlled voltage in series with the supply voltage through three single-phase transformers to correct the load voltage. It consists of Insulated Gate Bipolar Transistors (IGBT) as switches. The switching pulses of the IGBT are the output from the hysteresis voltage controller.

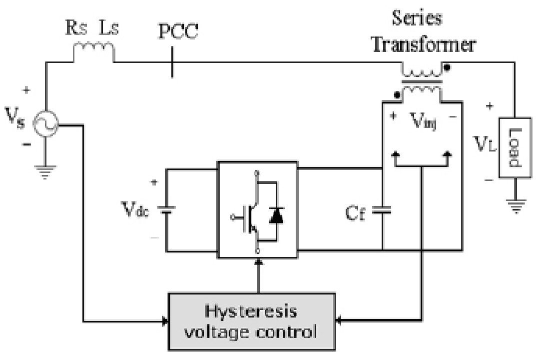


Fig.3.Power Circuit of a Typical DVR.

3.2. Coupling Transformer

Basic function is to step up and electrical isolation the ac low voltage supplied by the VSC to the required voltage. In this study single-phase injection transformer is used. For three phases DVR, three single-phase injection transformers can be used.

3.3. A C-Filter

A Passive filter consists of a capacitor that is placed at the high voltage side of coupling transformer. This filter rejects the switching harmonic components from the injected voltage.

3.4. Control Method

The aim of the control scheme is to maintain a balanced and constant load voltage at the nominal value under system disturbances. In this paper, control system is based on hysteresis voltage control.

4. Conventional Control Strategies

Several control techniques have been proposed for voltage sag compensation such as pre-sag method, in-phase method and minimal energy control.

4.1. Pre-Sag Compensation Technique

In this compensation technique, the DVR supplies the difference between the sagged and pre-sag voltage and restores the voltage magnitude and the phase angle to the nominal pre sag condition. The main defect of this technique is it requires a higher capacity energy storage device. Fig. 4(a) shows the phasor diagram for the *pre-sag control strategy.* In this diagram, Vpre-sag and VSag are voltage at the point of common coupling (PCC), respectively before and during the sag. In this case VDVR is the voltage injected by the DVR, which can be obtained as [7]:

$$V_{Pre\text{-}Sag}=V_{L},\ V_{Sag}=V_{S} \text{ and } V_{DVR}=V_{inj} \quad \text{--- (1)}$$

$$|V_{inj}| = |V_{Pre\text{-}Sag}| - |V_{Sag}| \quad \text{--- (2)}$$

$$\theta_{inj} = \tan^{-1}\left(\frac{V_{Pre-sag}\sin(\theta_{Pre-sag})}{V_{Pre-sag}\cos(\theta_{Pre-sag}) - V_{sag}\cos(\theta_{sag})}\right) \quad \text{--- (3)}$$

4.2. In-phase compensation technique

In this technique, only the voltage magnitude is compensated. VDVR is in-phase with the left hand side voltage of DVR. This method minimizes the voltage injected by the DVR, unlike in the pre-sag compensation. Fig. 4(b) shows phase diagram for the *in-phase compensation technique.*

$$V_{DVR}=V_{inj}$$

$$|V_{inj}| = |V_{Pre-sag}| - |V_{sag}| \quad \text{--(4)}$$

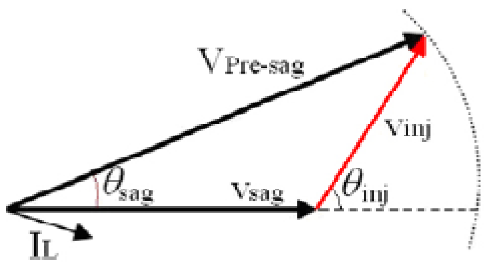
$$\angle V_{inj} = \theta_{inj} = \theta_{S}$$

4.3. Energy optimization technique

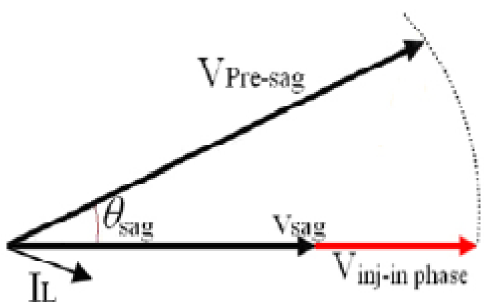
Pre-sag compensation and in-phase compensation must inject active power to loads almost all the time. Due to the limit of energy storage capacity of

DC link, the DVR restoration time and performance are confined in these methods. The fundamental idea of energy optimization method is to make injection active power zero. In order to minimize the use of real power the voltages are injected at 90° phase angle to the supply current. Fig.4 shows a phasor diagram to describe the Energy optimization Control method.

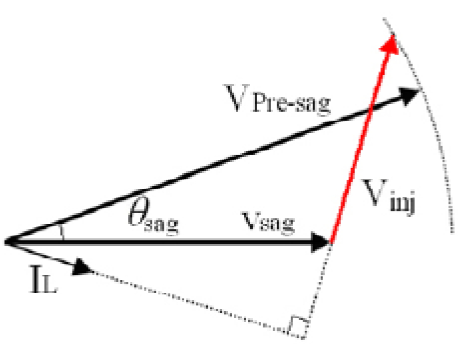
The selection of one of these strategies influences the design of the parameters of DVR. In this paper, the control strategy adopted is Pre-sag compensation to maintain load voltage to pre fault value.



(a) Pre-sag compensation technique.



(b) In-phase compensation technique.



(c) Energy optimized compensation technique.

Fig.4. Conventional control strategies.

5. Hysteresis Voltage Control

In this paper, hysteresis voltage control is used to improve the load voltage and determine switching signals for inverters gates. A basic of the hysteresis voltage control is based on an error signal between an injection voltage (Vinj) and a reference voltage of DVR (Vref), which produces proper control signals. There is Hysteresis Band (HB) above and under the reference voltage and when the difference between the reference and inverter voltage reaches to the upper (lower) limit, the voltage is forced to decrease (increase) as shown in Fig.5.

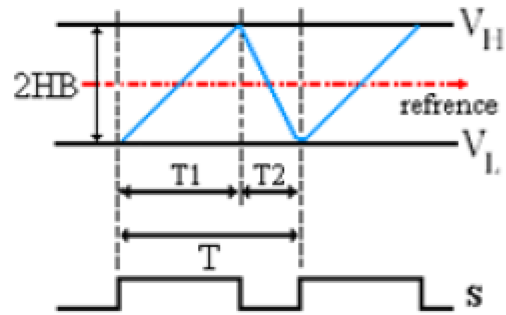


Fig.5.Hysteresis band voltage control.

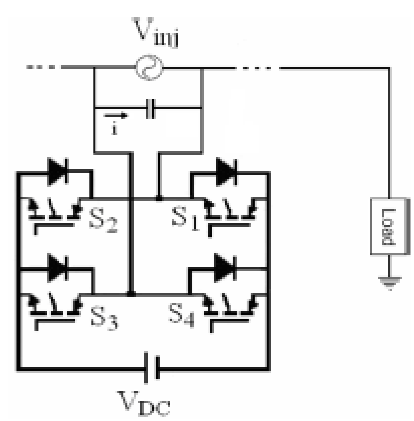


Fig.6. Single-phase full bridge inverter.

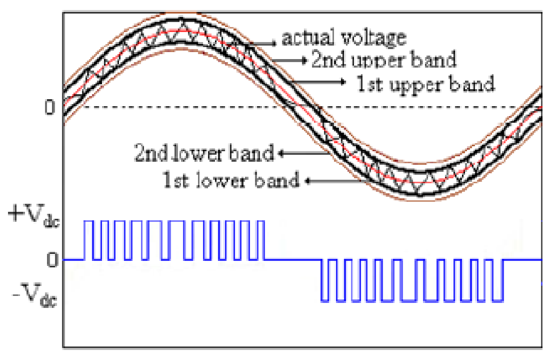
$T_1+T_2=T_c=1/f_c$ ------(5)

Where HB and *fc* are Hysteresis Band and switching frequency respectively. The HB that has inversely proportional relation to switching frequency is defined as the difference between VH and VL (HB=VH-VL).

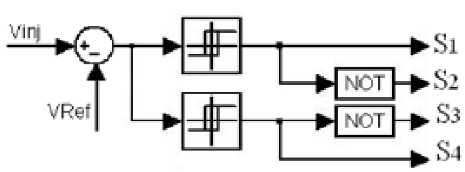
In comparison with the other PWM methods, the hysteresis voltage control has a very fast response, a simple operation and a variable switching frequency.

Fig.6 shows a single-phase full bridge inverter that is connected in series to a sensitive load. The inverter can be controlled in unipolar or bipolar PWM method [9-10].

In the unipolar modulation, four voltage bands are used to achieve proper switching states to control the load voltage. The first upper and lower bands (HB1) are used when the output current is changed between (+Vdc & 0) or (-Vdc or 0). The second upper and lower bands (HB2) are used to change the current level Fig.7 (a). There are four switching states for switches (S1, S2) and (S3, S4) as shown in Fig.7 (b). The switching functions of both B and C phases in bipolar and unipolar Hysteresis voltage control are determined similarly using corresponding reference and measured voltage band (HB).



(a) Output voltage with two lower and higher bands.



(b) Switching Signals.

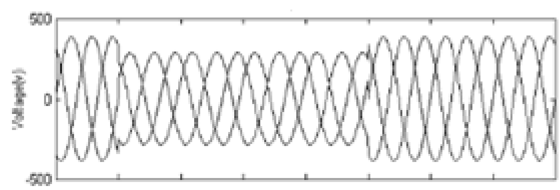
Fig.7. Unipolar Hysteresis Voltage Control.

6. Simulation Results

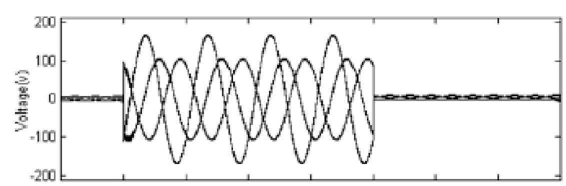
The proposed method is validated by simulation results of MATLAB/Simulink. The system parameters are given in the Appendix. DVR with hysteresis voltage control is applied to compensate load voltage. Here we consider two different cases. In Case 1, the unbalanced voltage sag is simulated. To demonstrate the performance of the proposed method we assumed voltage swell condition in Case 2.

A. Case 1

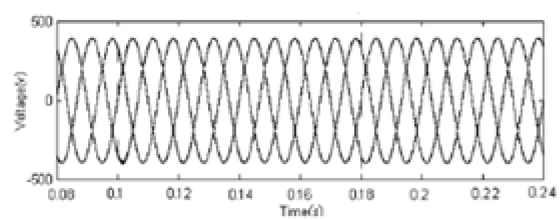
In this case, we assume that there is a 30% three-phase voltage sag with +30° phase jump in phase-a in supply voltage that is initiated at 0.1s and it is kept until 1.8 s. The outcome of voltage sag compensation considering hystersis voltage control based on unipolar switching for HB1=0.005 and HB2=0.007 is demonstrated in Fig.8. Fig.8 (b) shows the serial injected voltage components. Moreover, the compensated load voltage is shown Fig.8 (c). As it can be seen from the results, the DVR is able to produce the required voltage components for different phases rapidly and help to maintain a balanced and constant load voltage at the nominal value (400 V).



(a) Supply voltages.



(b) Injected voltage, VDVR.

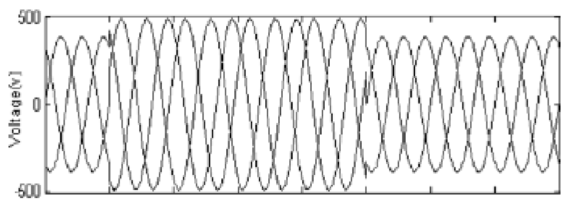


(c) Load voltage, VL.

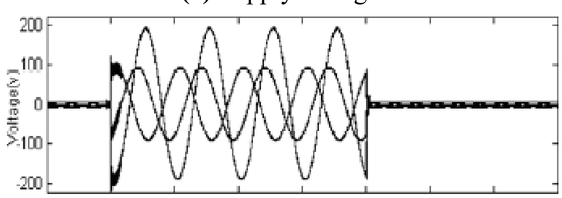
Fig.8. Simulation result of DVR response to unbalance voltage sag (HB1=0.005, HB2=0.007).

B. Case 2

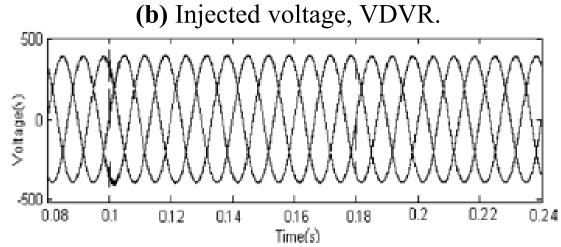
In the second case, performance of DVR for a voltage swell condition is investigated. Here, an unbalance voltage swell with 30% three-phase voltage swell with +30° phase jump in phase-a which starts at 0.1s and ends at 1.8s is considered. Fig.9 shows the result of voltage swell compensation considering hysteresis voltage control based on unipolar switching for HB1=0.005 and HB2=0.007. The injected voltage that is produced by DVR to correct the load voltage is shown in Fig.9 (b). As it can be seen from Fig.9, DVR is able to correct the voltage swell by injecting negative three phase voltage components.



(a) Supply voltages.



(b) Injected voltage, VDVR.



(c) Load voltage, VL.

Fig.9. Simulation result of DVR response to unbalance voltage swell (HB1=0.005, HB2=0.007).

7. Conclusion

This paper has been successfully demonstrated a hysteresis voltage control technique based unipolar Pulse Width Modulation (PWM) For Dynamic Voltage Restorer to improve the quality of load voltage. The validity of proposed method is approved by results of the simulation in MATLAB/ Simulink. The result simulation shows that DVR can compensate Voltage Sag and Swell of the distribution system.

8.Appendix

Table.1: Case Study Parameters.

PARAMETERS	VALUE
SUPPLY VOLTAGE	400V
V_{DC},C_F	200V,500MF
SERIES TRANSFORMER	96V/240V
Z_{TRANS}	0.004+J0.008
R_{LOAD},L_{LOAD}	31.84Ω,0.139H

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