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Hysteresis Voltage Control of DVR Based on Unipolar PWM

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1. Introduction

Power quality problems like voltage sag, voltage swell and harmonic are major concern of the industrial and commercial electrical consumers due to enormous loss in terms of time and money. This is due to the Advent of a large numbers of sophisticated electrical and electronic equipment, such as computers, programmable logic controllers, variable speed drives, and so forth. The use of these equipments often requires power supplies of very high quality.

Some special equipment is sensitive to voltage disturbances, especially if these take up to several periods, the circuit does not work. Therefore, these adverse effects of voltage changes necessitate the existence of effective mitigating devices. There are various solutions to these problems. One of the most effective solutions is the installation of a dynamic voltage restorer (DVR).

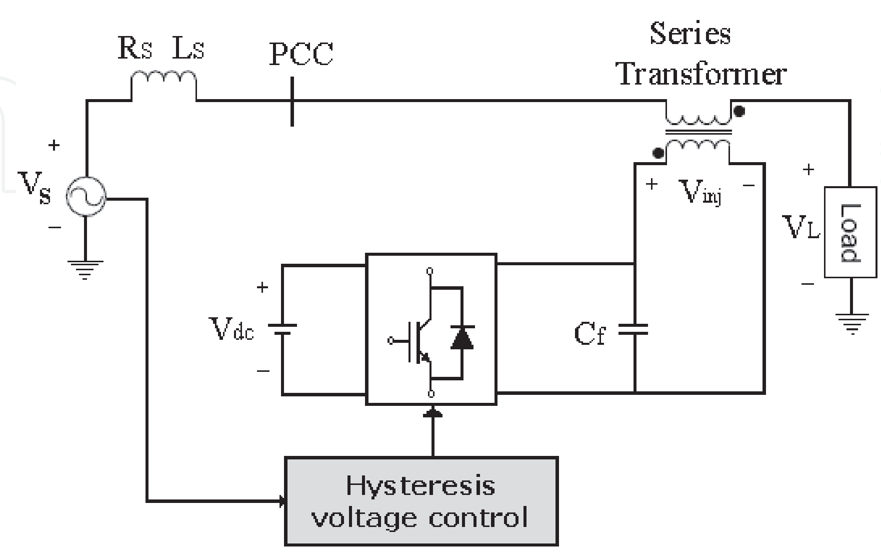


Fig. 1. Schematic diagram of a typical DVR.

DVR is the one of the custom power devices, which has excellent dynamic capabilities. It is well suited to protect sensitive loads from short duration voltage sag or swell. DVR is basically a controlled voltage source installed between the supply and a sensitive load. It injects a voltage on the system in order to compensate any disturbance affecting the load voltage. Basic operating principle of a DVR as shown in Fig. 1.
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.
Voltage sag is defined as a sudden reduction of supply voltage down 90% to 10% of nominal. According to the standard, a typical duration of sag is from l0 ms to 1 minute. On the other hand, Voltage swell is defined as a sudden increasing of supply voltage up 1l0% 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 which is sensitive to voltage variations.
IEEE 519-1992 and IEEE 1159-1995 describe the Voltage sags /swells as shown in Fig.2.

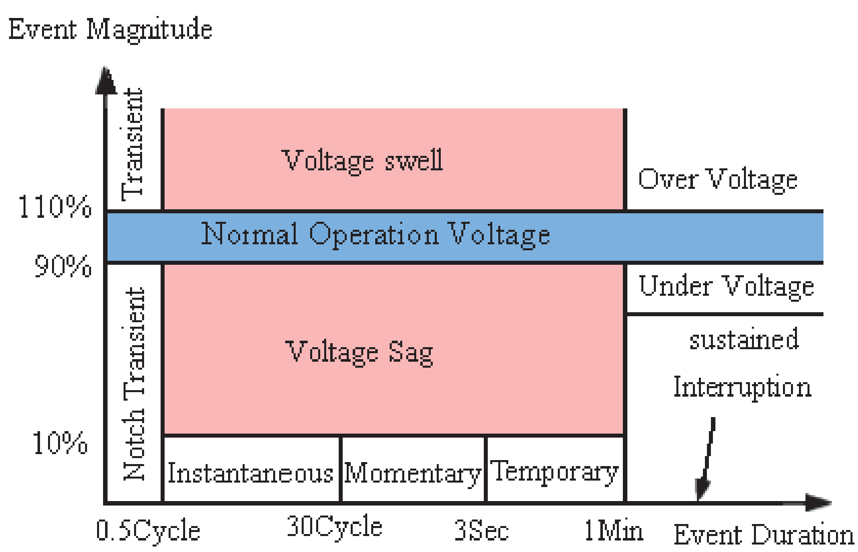


Fig. 2. Voltage Reduction Standard of IEEE Std. 1159-1995.

2. DVR power circuit

The power circuit of the DVR is shown in Fig.1. 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:

2.1 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.

2.2 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.

2.3 A Passive 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.

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

3. 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.

3.1 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.3 (a) shows the phasor diagram for the pre-sag control strategy.
In this diagram, $V_{pre\text{-}sag}$ and V_{Sag} are voltage at the point of common coupling (PCC), respectively before and during the sag. In this case V_{DVR} is the voltage injected by the DVR, which can be obtained as:

$$|V_{inj}| = |V_{pre\text{-}sag}| - |V_{Sag}| \tag{1}$$

$$\theta_{inj} = \tan^{-1}\left(\frac{V_{pre\text{-}sag}\sin(\theta_{pre\text{-}sag})}{V_{pre\text{-}sag}\cos(\theta_{pre\text{-}sag}) - V_{Sag}\cos(\theta_{Sag})}\right) \tag{2}$$

3.2 In-phase compensation technique
In this technique, only the voltage magnitude is compensated. V_{DVR} 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.3 (b) shows phase diagram for the in-phase compensation technique

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

$$|V_{inj}| = |V_{pre\text{-}sag}| - |V_{Sag}| \tag{3}$$

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

3.3 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.3 (c) 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 chapter, the control strategy adopted is Pre-sag compensation to maintain load voltage to pre-fault value.

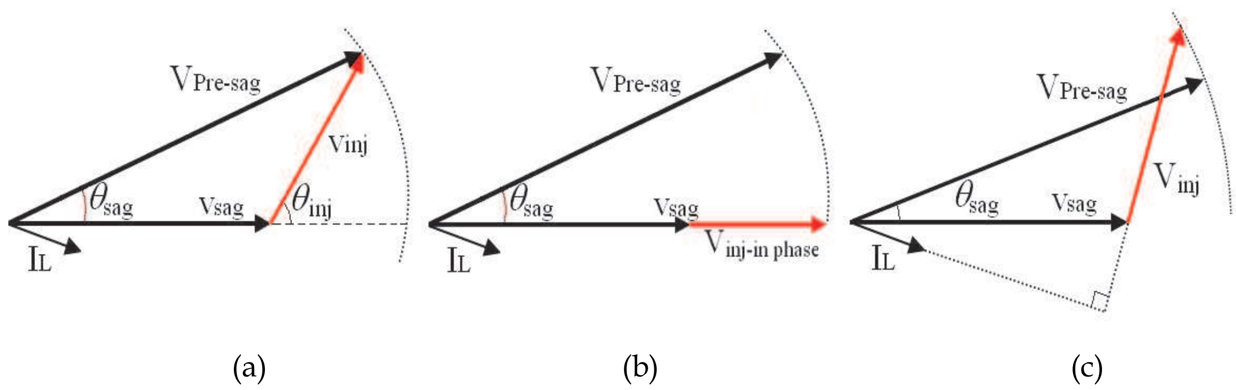


Fig. 3. Conventional control strategies. (a) Pre-sag compensation technique, (b) In-phase compensation technique, (c) Energy optimized compensation technique.

This chapter presents a hysteresis voltage control technique based on unipolar PWM to improve the quality of output voltage. The hysteresis voltage control of DVR has not been studied in our knowledge. The proposed method is validated through modeling in MATLAB SIMULINK.

This is chapter organized as follows: in next section, the power circuit of DVR is described briefly. Then we introduce conventional strategies for control. In next section, we state about control of the DVR and present our method to this end. Finally, experimental results are presented.

4. Control of the DVR

4.1 Detection of sag / swell in the supply voltage

The main stages of the control system of a DVR are as follows: detection of the start and finish of the sag, voltage reference generation, injection voltage generation, and protection of the system.

In Ref [9], several detection techniques have been analyzed and compared. In this chapter, monitoring of V_d and V_q is used to return the magnitude and phase load voltage to the magnitude and phase reference load voltage. The control system is presented in Fig. 4.

The three-phase supply voltage is connected to a transformation block that convert to rotating frame (d q) with using a software based Phase – Lock Loop (PLL). Three-phase voltage is transformed by using Park transform, from a-b-c to o-d-q frame:

$$\begin{bmatrix} v_d \\ v_q \\ v_o \end{bmatrix} = p \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{2}$$

$$p = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{4\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{3}$$

$$\theta = \theta_0 - \int_0^t \omega t \, dt$$

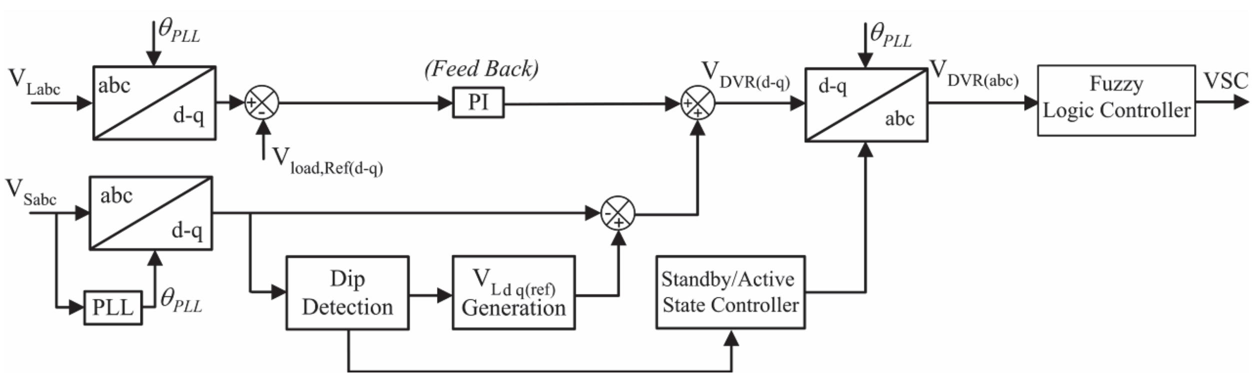


Fig. 4. Control structure of DVR

If voltage sag/swell occurs, the detection block generates the reference load voltage. The sag detection strategy is based on Root Means Square (rms) for the error vector which can be used for symmetrical and non symmetrical sags with any associated phase jump. Load voltage feedback is also added, and it is implemented in the odq frame to minimize any steady state error in the fundamental component.

The injected voltage is also generated according to difference between the reference load voltage and supply voltage and it is applied to the VSC to produce the preferred voltage using hysteresis voltage control.

4.2 Hysteresis voltage control

In this chapter, Hysteresis Band Voltage control is used to control load voltage and determine switching signals for inverter switches.

There are bands above and under the reference voltage. If 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.4.

In this method, the following relation is applied Where *HB* and f_c are Hysteresis band and switching frequency, respectively.

$$T_1 + T_2 = T_c = 1/f_c \tag{5}$$

Fig.5 shows a single phase diagram of a full bridge inverter that is connected in series with a sensitive load. The inverter can be controlled in unipolar or bipolar PWM methods.

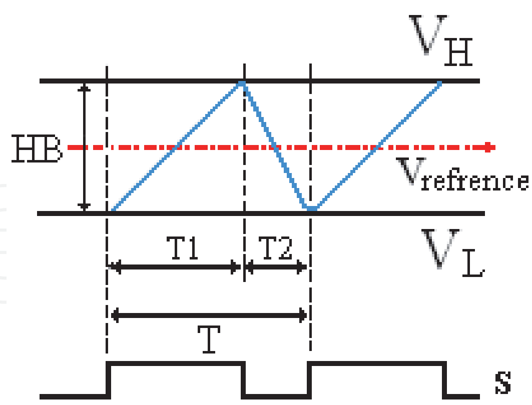


Fig. 5. Hysteresis band voltage control.

The HB that has inverse proportional relation with switching frequency is defined as the difference between V_H and V_L ($HB=V_H-V_L$) [19-20].
In present chapter, for pulse switching generation for DVR, random hysteresis voltage control is analyzed. The biopolar modulation is base of this analyze.
In bipolar switching scheme, as shown in Fig.6, there are two bands and the controller turns on and turns off the switch pairs (S_1, S_3 or S_2, S_4) at the same time to generate $+V_{dc}$ or -Vdc at the output of inverter.

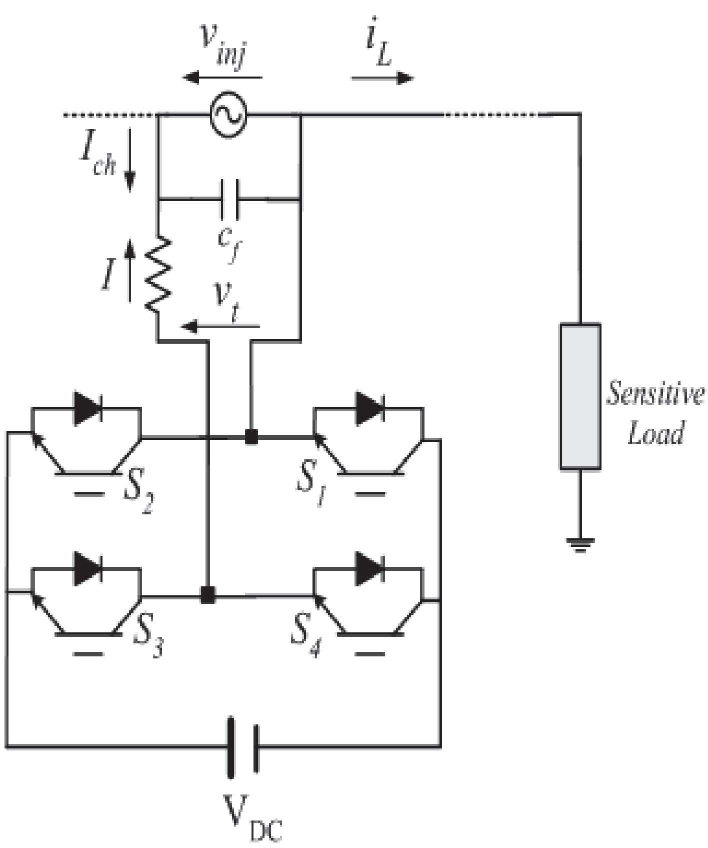
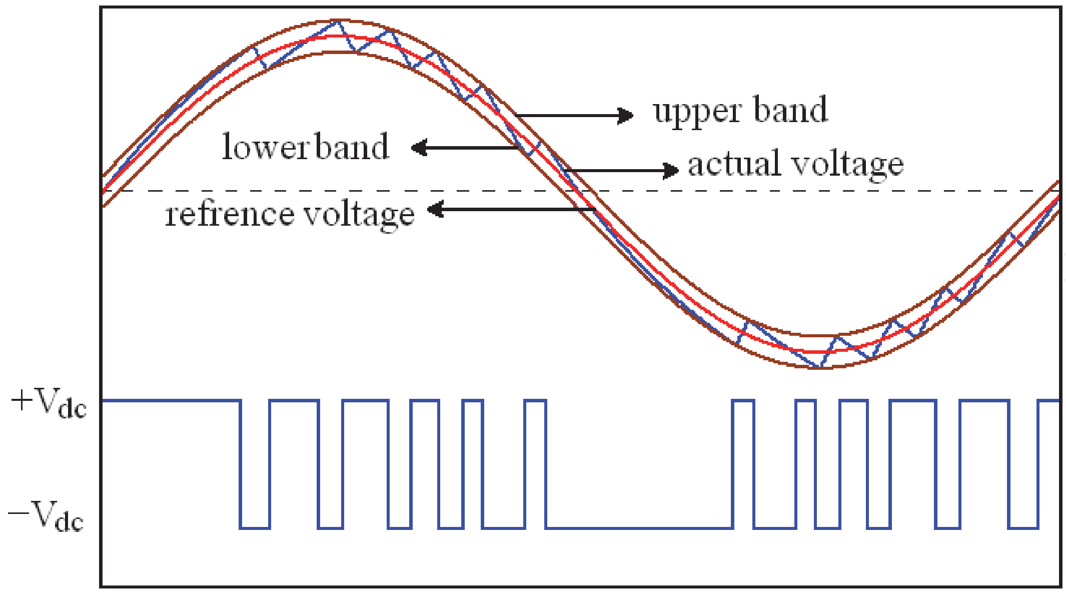
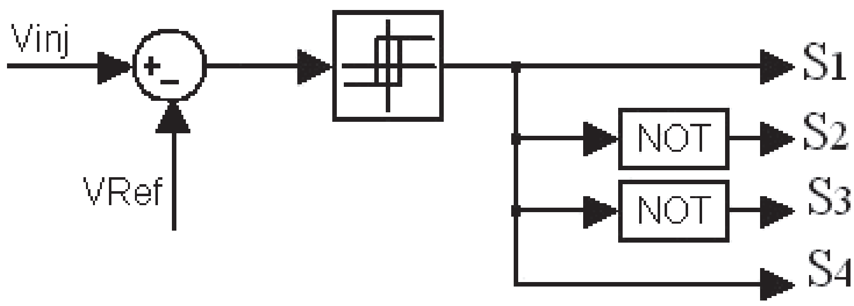


Fig. 6. Single phase full bridge inverter



(a)



(b)

Fig. 6. Bipolar hysteresis voltage control (a) out put voltage with lower and higher bands (b) switching signals.

5. Proposed method

We are now in position to introduce our proposed method named Hysteresis voltage control based on unipolar switching Technique as shown in Fig 7.
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 (HB_1) are used when the output current is changed between (+V_{dc} & 0) or (-V_{dc} or 0) and the second upper and lower bands (HB_2) are used to change the current level Fig 7(a).
There are four switching states for switches (S_1, S_2) and (S_3, S_4) as shown in Fig.7(b) As a result, three levels are generated +V_{dc}, -V_{dc} or 0 at the output of inverter. In comparison with other PWM methods, the hysteresis voltage control has a variable switching frequency, very fast response and simple operation [13].
The switching functions of both B and C phases are determined similarly using corresponding reference and measured voltage band (HB) [13].

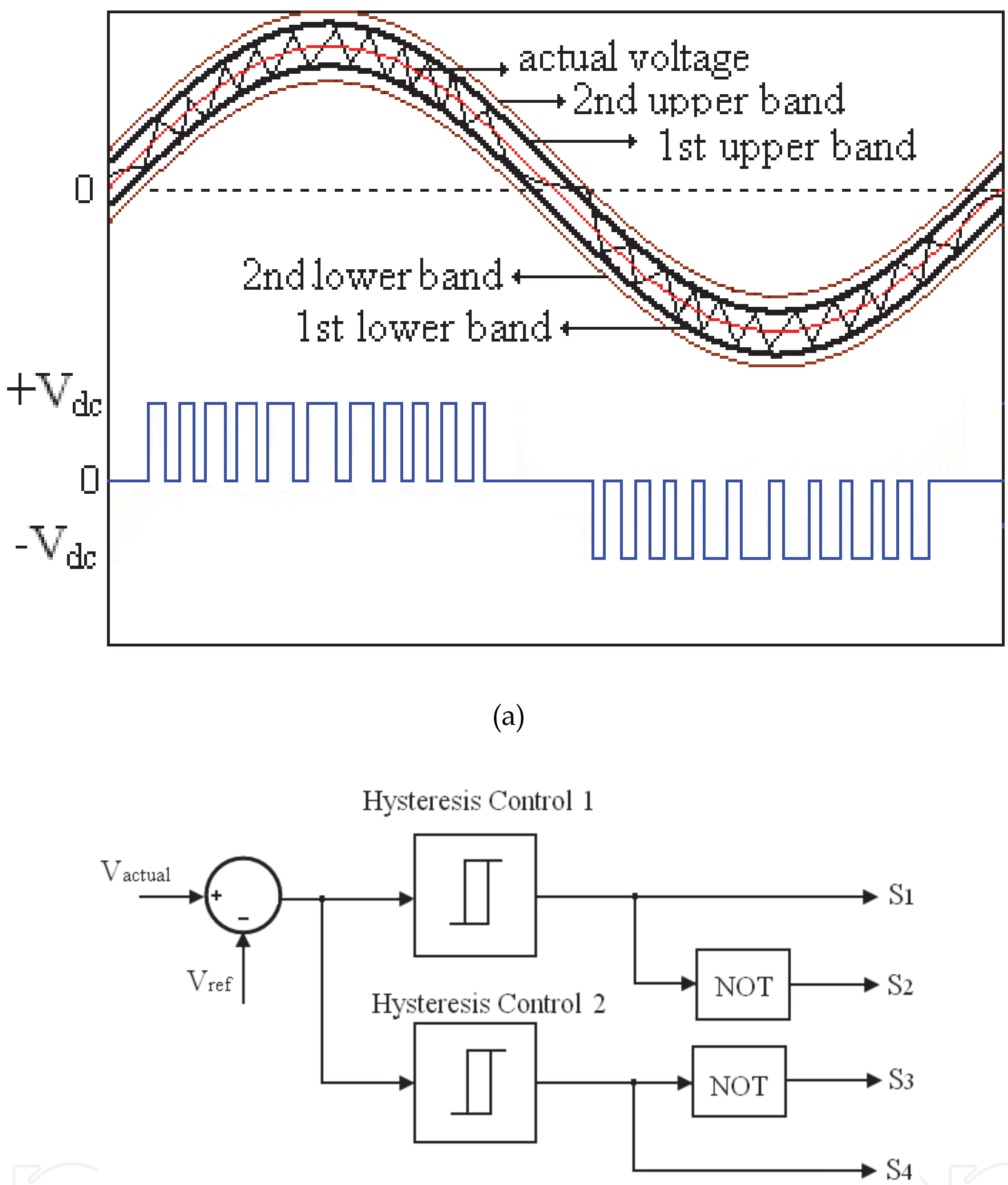


Fig. 7. Unipolar hysteresis voltage control (a) out put voltage with lower and higher bands (b) switching signals

6. Simulation results

The proposed method is validated by simulation results of MATLAB. Simulation parameters are shown in table 1. DVR with unioplar voltage control is applied to compensate load voltage. In order to demonstrate the performance of the DVR using unioplar switchin technique to control, a Simulink diagram is proposed as shown in Fig.8.
To have a fair comparison, in this simulation it has been considered same situation as mentioned in Ref [12].

Parameter	Value
Supply voltage (V_{L-L})	415V
V_{dc} ,C_F	120V, 500uF
Series Transformer(V_{Ph-Ph})	96V / 240V
Z_{Trans}	0.004 + *j* 0.008
R_{Load}, L_{Load}	31.84 *Ω*, 0.139 *H*

Table 1. Case study parameters

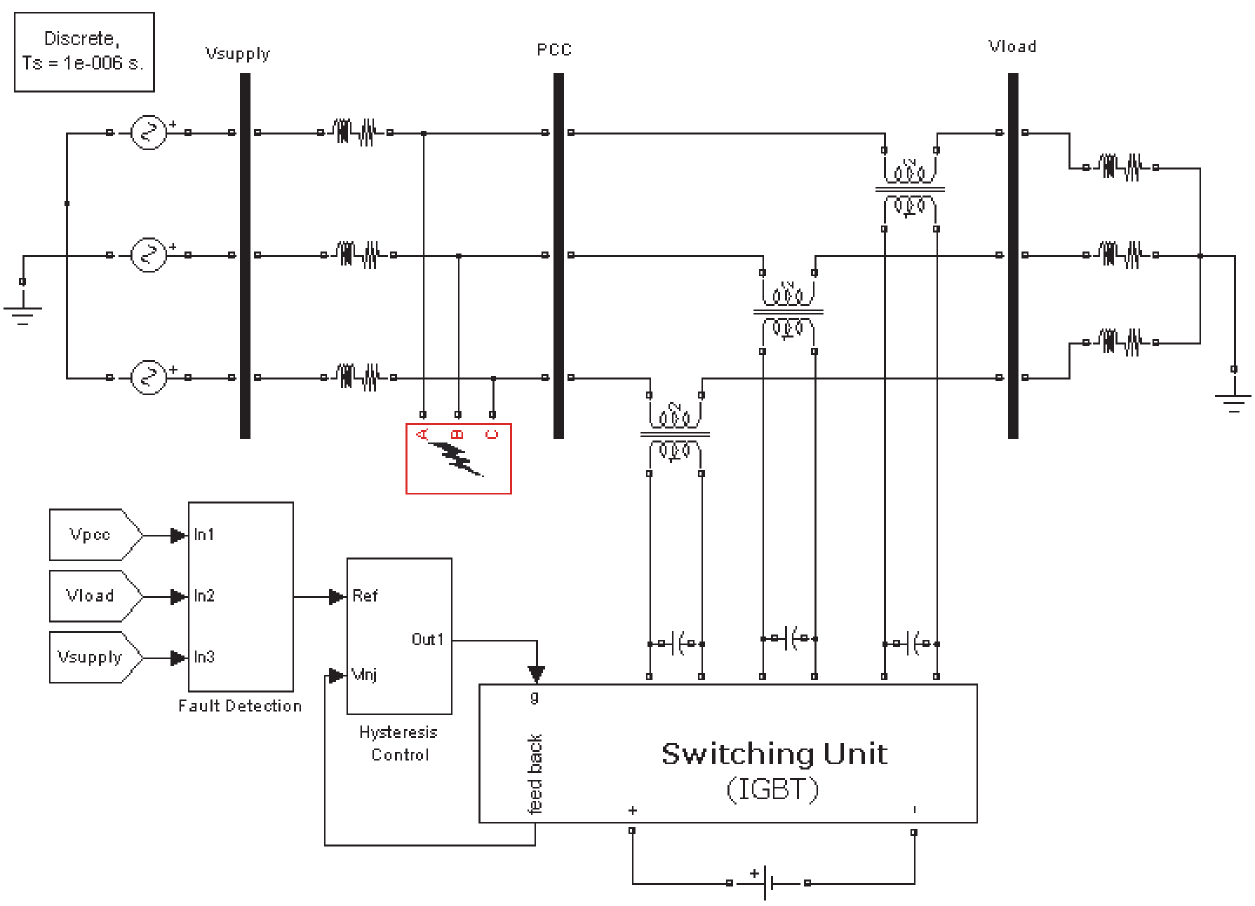
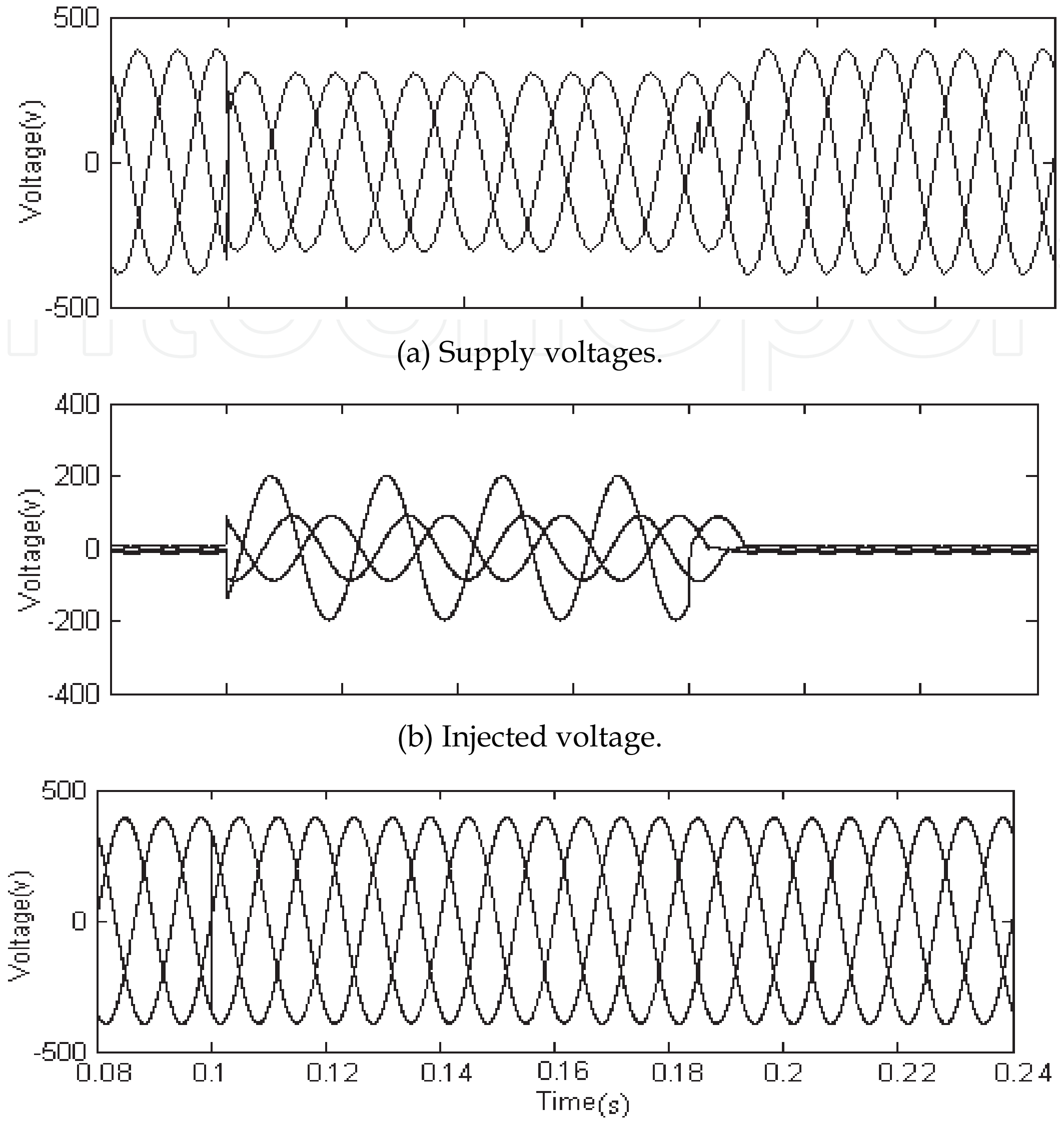


Fig. 8. Simulation model of DVR in MATLAB.

A. Voltage sags

In the first 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 results for HB_1=0.005 and HB_2=0.007 are shown in Fig .9.

Fig .9 (b) and (c) show the series of voltage components injected by the DVR and compensated load voltage, respectively.

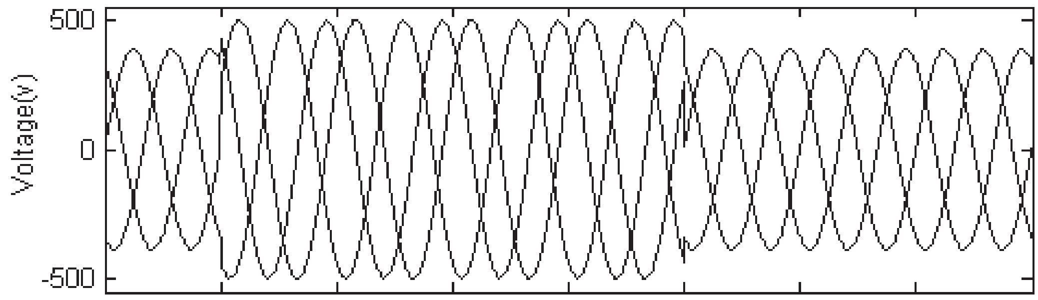


(c) Load voltage, V_L.

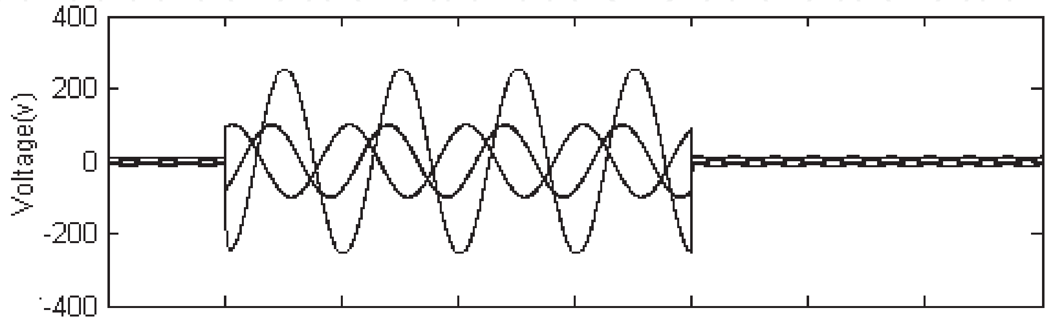
Fig. 9. Simulation result of DVR response to a balance voltage sag (HB1=0.005, HB2=0.007).

B. Voltage swell

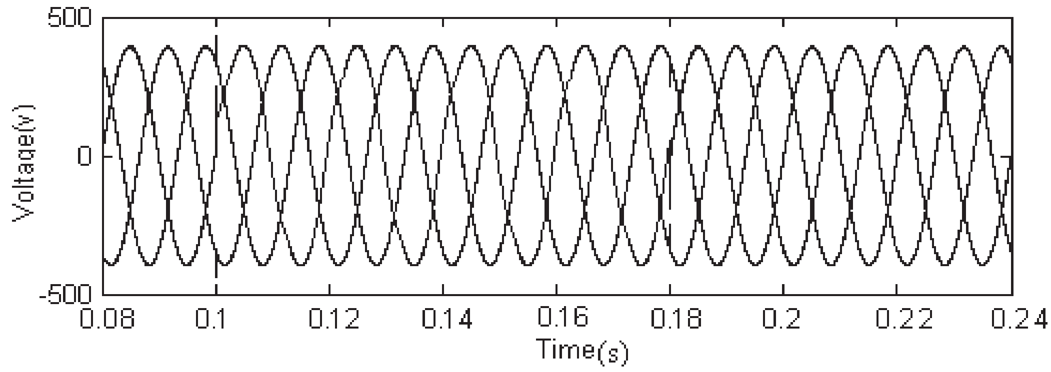
In the second case, performance of DVR for a voltage swell condition is investigated. Here, a voltage swell with 30% three-phase voltage swell with +30 phase jump in phase-a starts at 0.1s and ends at 1.8 s is considered. The injected voltage that is produced by DVR in order to correct the load voltage and the load voltage for HB_1=0.005 and HB_2=0.007 are shown in Fig. 10(b) and (c), respectively.
To evaluate the quality of the load voltage during the operation of DVR, Total Harmonic Distortion (THD) is calculated with various HB.
Table 1 shows the obtained results for each HB_1 and HB_2.
Table 2 summarizes the THD values for the constant HB_1 and various HB_2.
For further study on the control scheme performance, the results obtained in Table 2, 3 is plotted in Fig. 11 and Fig.12.



(a) Supply voltages.



(b) Injected voltage, V_{DVR}.



(c) Lad voltage, V_L.

Fig. 10. Simulation result of DVR response to a Balance voltage Swell (HB_1=0.005, HB_2=0.007).

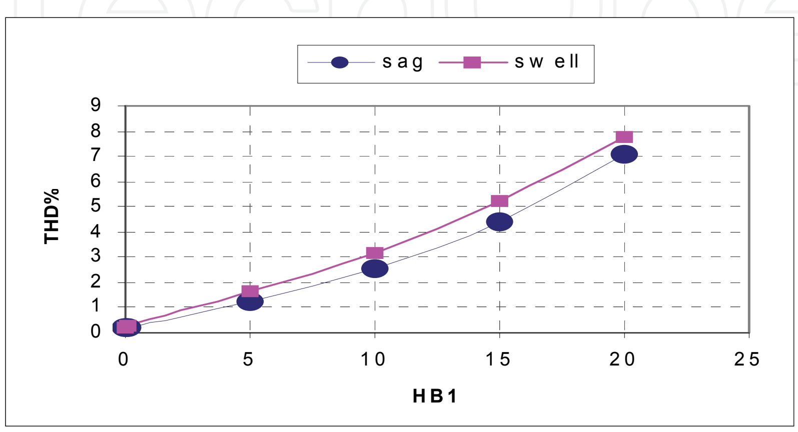


Fig. 11. Increase of THD with various HB_1 and HB_2.

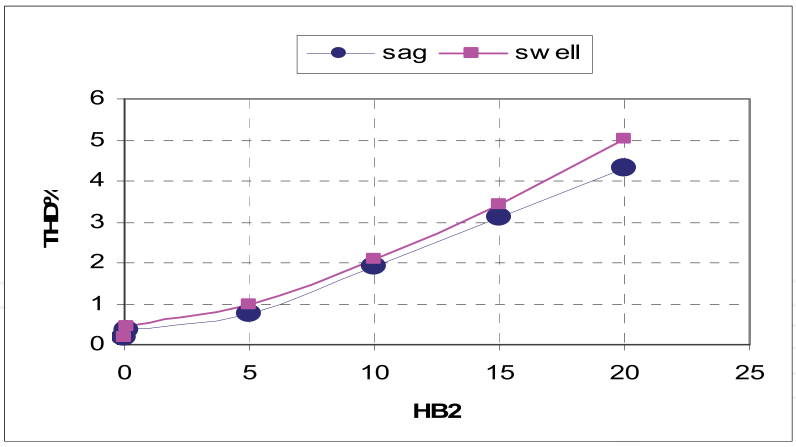


Fig. 12. Increase of THD with constant HB_1 and various HB_2.

Hysteresis Band		THD (%)	
HB_1	**HB_2**	**Sag**	**swell**
0.005	0.007	0.187	0.199
0.1	0.12	0.213	0.243
5	7	1.251	1.623
10	12	2.564	3.157
15	17	4.387	5.217
20	22	7.06	7.74

Table 2. THD for Load voltage for various values of HB1 and HB2.

Hysteresis Band		THD (%)	
HB_1	**HB_2**	**Sag**	**swell**
0.005	0.007	0.187	0.199
0.005	0.1	0.34	045
0.005	5	0.75	0.98
0.005	10	1.91	2.13
0.005	15	3.23	3.42
0.005	20	4.35	5.01

Table 3. THD for Load voltage for the constant values HB1 and various values HB2 for 30% voltage sag and swell.

As it can be seen, with growth of the $HB_1$and HB_2, THD of the load voltage correspondingly raises but the effect of increasing the HB on THD of the load voltage under voltage swell is more than THD of the voltage sag. It is obvious that the THD value varies when ever HB_1 and HB_2 value vary or when HB_1 is contented and HB_2 value varies. But THD of the load voltage under the voltage swell is greater than the voltage sag case. Therefore HB value has to be selected based on the voltage sag test.

With comparison of the obtained results in this chapter and Ref [12] in the voltage sag case, it can be observed that calculated THD in unipolar control is lower than bipolar control. In the other word, quality voltage in unipolar control is more than bipolar control. Fig 13.

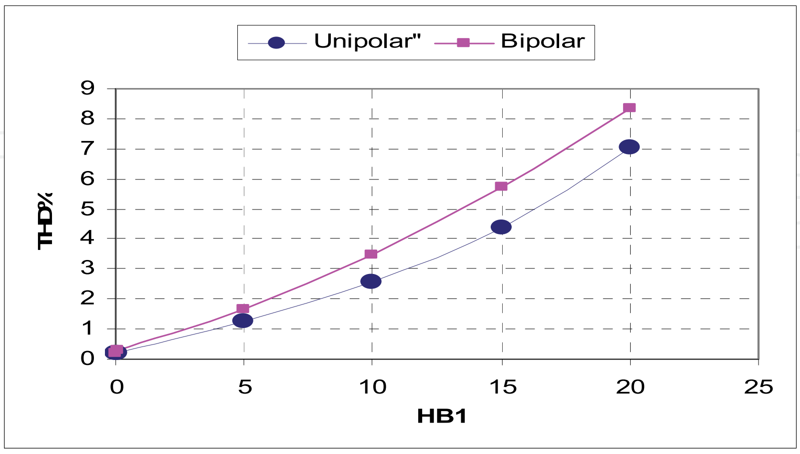


Fig. 13. Comparison of the in unipolar control and bipolar control.

This chapter introduces a hysteresis voltage control technique based on unipolar Pulse Width Modulation (PWM) For Dynamic Voltage Restorer to improve the quality of load voltage. The validity of recommended method is testified by results of the simulation in MATLAB SIMULINK.

To evaluate the quality of the load voltage during the operation of DVR, THD is calculated. The simulation result shows that increasing the HB, in swell condition THD of the load voltage is more than this THD amount in sag condition. The HB value can be found through the voltage sag test procedure by try and error.

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The book consists of 24 chapters illustrating a wide range of areas where MATLAB tools are applied. These areas include mathematics, physics, chemistry and chemical engineering, mechanical engineering, biological (molecular biology) and medical sciences, communication and control systems, digital signal, image and video processing, system modeling and simulation. Many interesting problems have been included throughout the book, and its contents will be beneficial for students and professionals in wide areas of interest.