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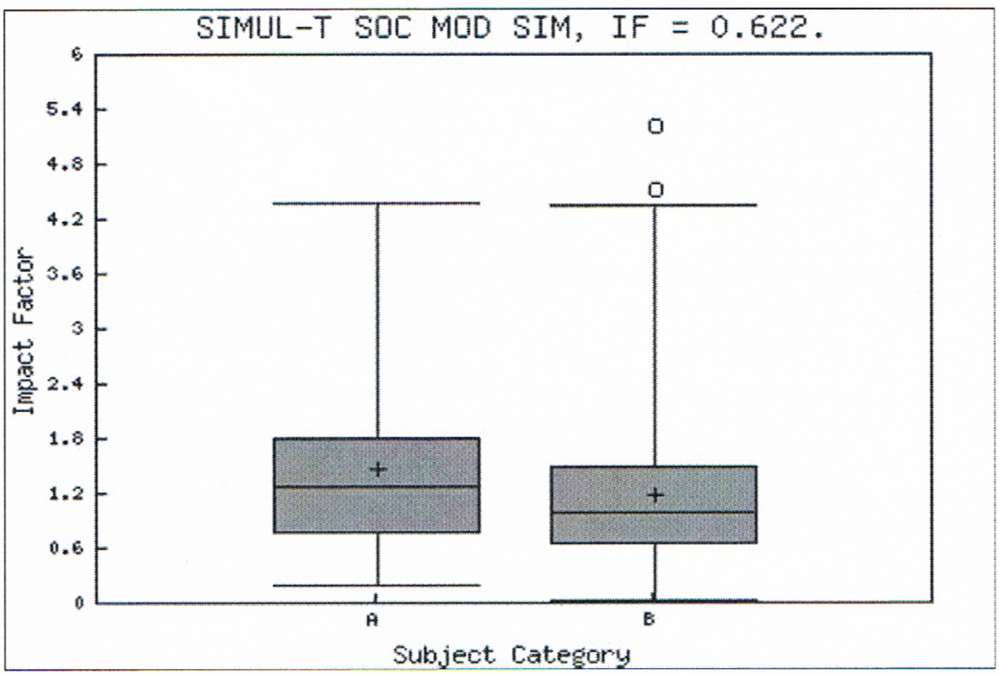

Key

A - COMPUTER SCIENCE, INTERDISCIPLINARY APPLICATIONS

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Modeling and simulation of new configuration of dynamic voltage restorer for power quality improvement

Rosli Omar[1] and Nasrudin Abdul Rahim[2]

Abstract

The dynamic voltage restorer (DVR) is a custom device that is used to maintain the voltage at the load terminals from various power quality problems from a disturbed incoming supply. In this paper, a novel control strategy is described for mitigation of voltage sags and swells on sensitive loads. The new control of the compensation voltages in the DVR based on the dqo algorithm is discussed. The MATLAB/SIMULINK SimPower System toolbox has been used to obtain simulation results in order to verify the proposed scheme. From the results, it shows that the DVR is able to compensate the voltage sag or swell at sensitive loads by injecting an appropriate voltage through the injection transformer.

Keywords

dynamic voltage restorer (DVR), power quality, sags, swells, sensitive loads, power quality, custom device

1. Introduction

The dynamic voltage restorer (DVR) is a piece of equipment used to compensate for dynamic power quality problems such as voltage sag and swell, whose core is a controllable voltage source inverter installed in the grid in series.[1]

Voltage sags are usually caused by short circuit current flowing into a fault on a transmission or distribution line (as shown in Figure 1) where the magnitude and phase of the faulted voltage sag during the sag at the point of common coupling (PCC) are determined by the fault and supply impedances using the equation

$$V_{sag} = E\frac{Z_f}{Z_f + Z_S}. \quad (1)$$

Voltage swells are not as important as voltage sags because they are less common in distribution systems. Voltage sag and swell can cause sensitive equipment (such as that found in semiconductor or chemical plants) to fail, or shutdown, as well as create a large current unbalance that could blow fuses or trip breakers. These effects can be very expensive for the customer, ranging from minor quality variations to production downtime and equipment damage.[2]

Voltage sags/swells can occur more frequently than other power quality phenomena and are known as the most important power quality problems in the power distribution system. IEEE 519–1992 and IEEE 1159–1995[3] describe the voltage sags/swells as shown in Figure 2. Sags/swells may be generated by three-phase faults, three-phase faults with ground connection, two-phase faults, two-phase faults with ground connection and single phase faults. More details about sags/swells can be found in Nielsen.[4]

In this paper, the DVR which is installed between the supply and a sensitive load is discussed. A novel DVR configuration and its control based on the dqo method are proposed in order to compensate for voltage sags/swell in a low-voltage distribution system. The proposed new design and its control strategy have been

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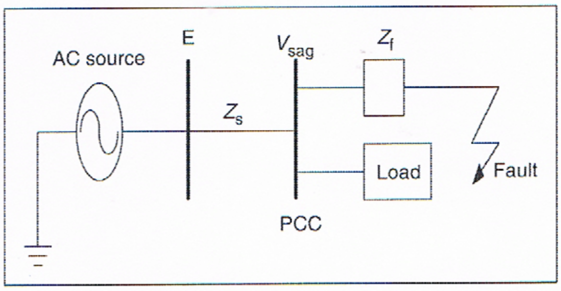

Figure 1. A simple radial circuit causing voltage sag.[2]

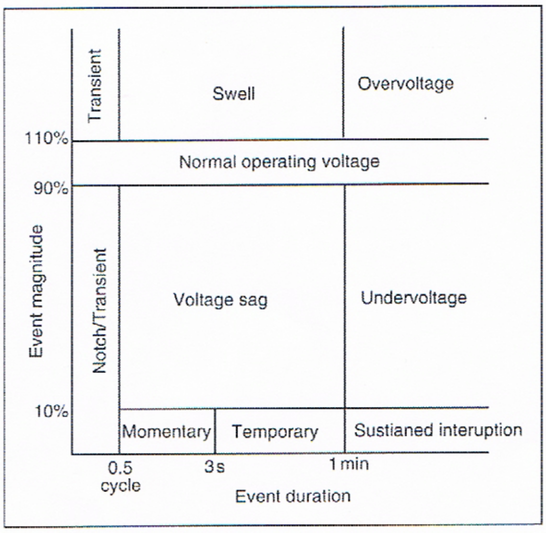

Figure 2. The voltage reduction standard of IEEE Std 1159–1995.

modeled and simulated by the MATLAB/SMLINK SimPower System toolbox. The results verify the effectiveness of the suggested control method.

2. Basic principle of DVR

A typical DVR[5,6] as shown in Figure 3 is used for voltage correction. When the supply-side voltage V_s changes, the DVR injects an appropriate voltage through a series-connected injection transformer in such a way that the desired load voltage magnitude can be maintained. The DVR considered consists of an injection or series transformer, a harmonic filter, a voltage source converter (VSC), energy storage, and a control system.

The DVR is essentially a voltage source inverter that produces an AC output voltage and injects it in series with the supply voltage. The DVR works independently of the type of fault or any event that happens in the system, provided that the whole system remains connected to the supply grid, i.e. the line breaker does not trip. For most practical cases, a more economical design can be achieved by only compensating for the positive and negative sequence components of the voltage disturbance seen at the input of the DVR. This option is considered because, for a typical distribution bus configuration, the zero sequence part of a disturbance will not pass through the step-down transformer because of infinite impedance for this component.

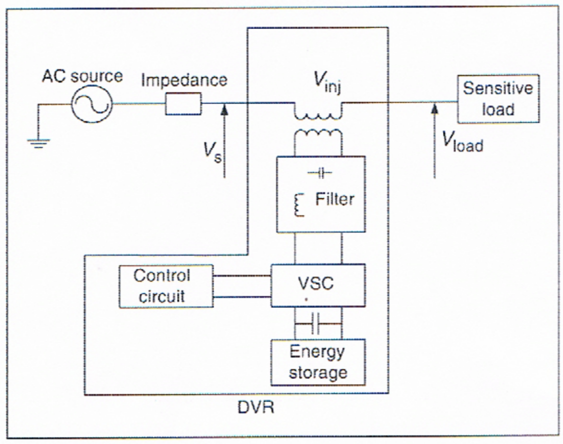

Figure 3. Schematic diagram of a conventional DVR.

Normally there are two modes of operation in the DVR, the standby mode and the boost mode. If the injection voltage ($V_{inj} = 0$) from the injection transformer is equal to zero, the DVR is assumed to be in the standby mode. In this mode the low voltage winding of the injection transformer is shorted. The switching of the semiconductor does not occur due to the individual converter legs. The connecter legs are triggered so as to establish a short circuit path for the transformer connection. When the injection voltage is greater than zero ($V_{in} > 0$), the DVR is in boost mode and it will inject a missing voltage into the network through the injection transformer when the controller detects any disturbance in the supply voltage.[7]

Figure 4 shows the equivalent circuit of the DVR. When the source voltage drops or increases, the DVR injects a series voltage V_{inj} through the injection transformer so that the desired load voltage magnitude V_L can be maintained. The series voltage injection of the DVR can be written as

$$V_{inj} = V_{load} + V_s \tag{2}$$

where V_{load} is the desired load voltage magnitude, V_s is the source voltage during the sag/swell condition and the load current I_{load} is given by

$$I_{load} = \left(\frac{(P_{load} \pm j \times Q_{load})}{V_{load}}\right) \quad \phi = \tan^{-1}\frac{Q_{load}}{P_{load}}. \tag{3}$$

V_{load} is also considered as a reference.

3. Proposed new configuration circuit of the DVR

3.1. New configurations of the proposed circuit

Figure 5 illustrates a new configuration model of the DVR system. The system consists of a DC voltage source (V_{dc}), a three-phase voltage source Pulse Width Modulation (PWM) inverter, an inductance - Capacitance (L-C) output filter, and a load (R). In this proposed designed of the DVR, special attention must be paid to the filtering scheme as it is related to the system dynamic response. The filtering system of the DVR can be placed either on the high-voltage or the low-voltage side of the injection transformer, referred to as the line-side filter[8–10] and the inverter-side filter,[11–13] respectively. In the proposed filtering system as shown in Figure 5, the filtering scheme is installed for both the low and high voltages. The filter inductor, capacitor, and resistor (L_{fa}, L_{fb}, L_{fc}, C_{fa}, C_{fb}, C_{fc} and R_a, R_b, R_c) are installed on the low-voltage side between the series converter and the transformer and the high-voltage side (C_1, C_2 and C_3). When they are placed on the low-voltage side, high-order harmonics from the three-phase voltage source PWM inverter is bypassed by the filtering scheme and its impact on the injection current rating can be ignored. A ripple filter (R_aC_a, R_bC_b, R_cC_c) is used to reduce the high-frequency ripple voltage due to the switching current of the VSC of the DVR. When the filtering scheme is placed on the high-voltage side in this case, high-order harmonic currents will penetrate through the injection and carry the harmonic voltages. In order to eliminate zero sequence components in the system, a split capacitor (C_{dc1} and C_{dc2}) inverter has been used as can be seen in Figure 5.

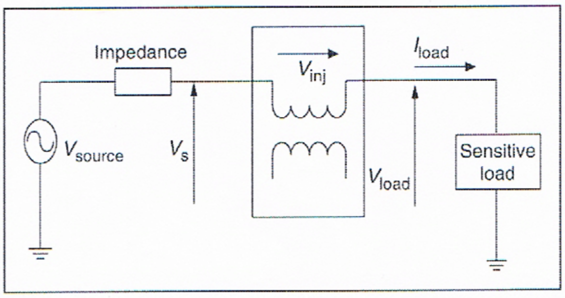

Figure 4. Existing equivalent circuit of the DVR.

3.2. Control method of the proposed scheme

There are several control schemes reported in the literature for control of the DVR such as instantaneous reactive power theory, power balanced theory,

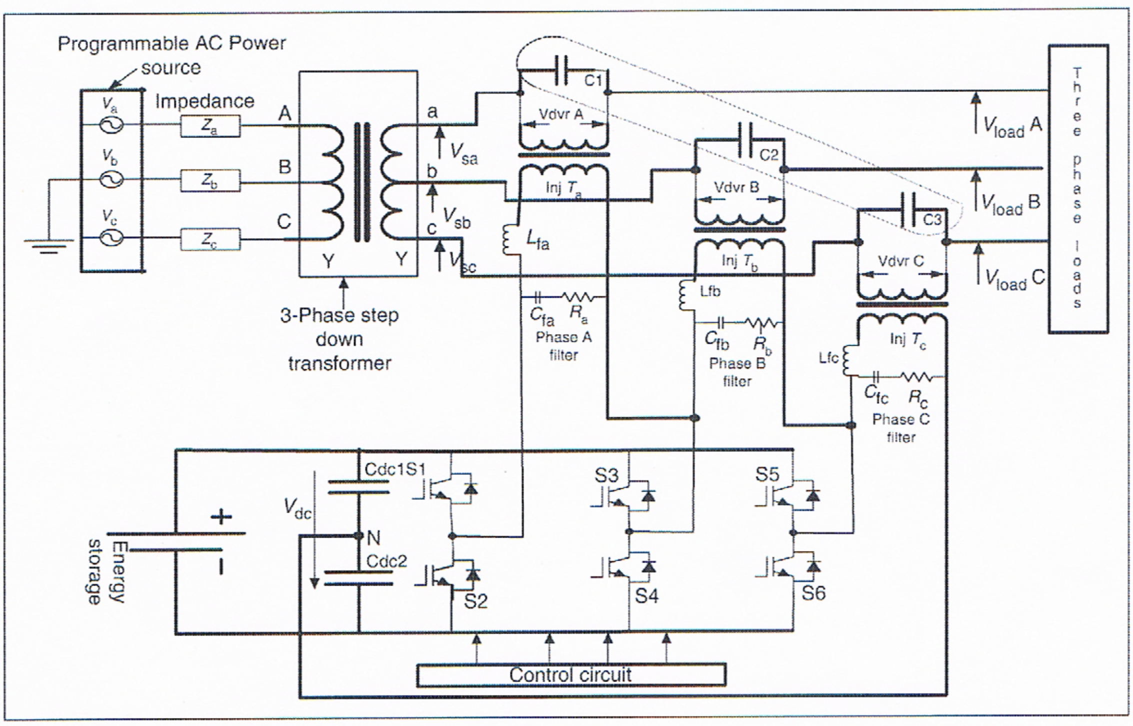

Figure 5. Line diagram of the new configuration for the DVR.

synchronous reference frame theory, etc.[14] In this paper, a new control method for the DVR system is proposed by using the dqo transformation or Park's transformation for sag/swell detection. The dqo method gives the sag depth and phase shift information with start and end times. The main aspects of the control system are shown in Figure 6 and they include the following blocks:

- Block 1 is used to convert the three-phase load voltages (V_{La}, V_{Lb}, V_{Lc}) into the α-β-o coordinates as in

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_o \end{bmatrix} = Q \begin{bmatrix} V_{La} \\ V_{Lb} \\ V_{Lc} \end{bmatrix}. \quad (4)$$

where

$$Q = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix}.$$

- Block 2 is the α-β-o to d-q-o transformation block used to convert the three-phase load voltage reference components $V_{\alpha\text{-ref}}$, $V_{\alpha\text{-ref}}$ and $V_{o\text{-ref}}$ to $V_{d\text{-ref}}$, $V_{q\text{-ref}}$ and $V_{o\text{-ref}}$ by using the following equations:

$$V_d = \frac{2}{3}\left[V_a \cos\theta \;\; V_b \cos\left(\theta - \frac{2\pi}{3}\right) \;\; V_c \cos\left(\theta + \frac{2\pi}{3}\right)\right] \quad (5)$$

$$V_q = \frac{2}{3}\left[-V_a \sin\theta - V_b \sin\left(\theta - \frac{2\pi}{3}\right) - V_c \sin\left(\theta + \frac{2\pi}{3}\right)\right] \quad (6)$$

$$V_o = \frac{1}{3}[V_a + V_b + V_c] \quad (7)$$

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix}. \quad (9)$$

- Block 3 is considered as a source voltage (V_{sa}, V_{sb}, V_{sc}). The amplitude of AC voltage at the source (V_{source}) can be calculated as follows:

$$V_{source} = \sqrt{\frac{2}{3}}\left(\sqrt{(V_{sa})^2 + (V_{sb})^2 + (V_{sc})^2}\right) \quad (10)$$

- Block 4 is a three-phase phase-locked loop (PLL). The angle θ of the source voltage can be obtained using three-phase PLL. The information extracted from the PLL is used for detection and reference voltage generation.
- Block 5 is the detection scheme for the voltage sag/swell compensator. From Figure 5, it can be shown that the synchronous frame variables, V_d and V_q, are used as inputs for low-pass filters to generate voltage references in the synchronous frame.

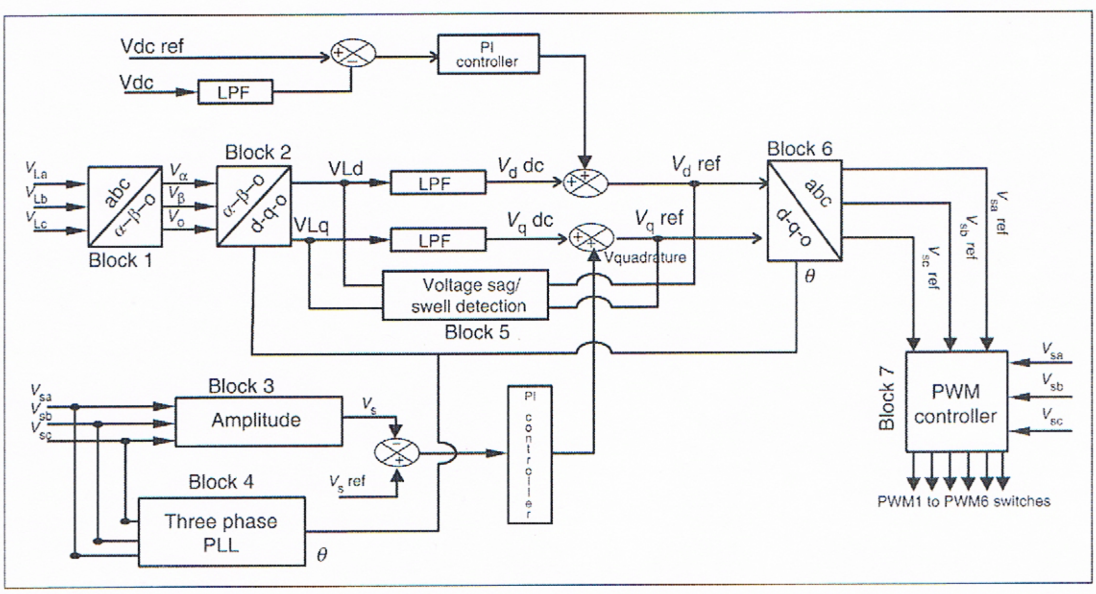

Figure 6. Block diagram of the proposed control scheme for the DVR for voltage sag/swell detection.

- Block 6 receives the components of the load voltage vectors $V_{d\text{-ref}}$ and $V_{q\text{-ref}}$ and transforms them to three-phase coordinates using Equation (9) where the generation voltages are used as the voltage reference. The DC link error in Figure 5 is used to get the optimized controller output signal because the energy on the DC link will be changed during the sag/swell.
- Block 7 is the PWM block. This block provides the firing for the inverter switches (PWM1 to PWM6). The injection voltage is generated according to the difference between the reference load voltage, and the injection voltage is generated according to the difference between the reference load voltage and the supply voltage and is then applied to the VSC.

The control scheme for the proposed system is based on a comparison of the load voltage (reference voltage) and the measured terminal voltage (V_{sa}, V_{sb}, V_{sc}). According to the IEEE-1159–1995 standard, voltage sag is defined as a sudden reduction in rms voltage within 10% to 90% of its nominal voltage. So, in this case, voltage sag is detected when the supply voltage drops below 90% of its nominal voltage. On the other hand, voltage swell is known as a sudden increase of the supply voltage up to 110% to 180% of the rms voltage at the network. The detection of voltage swell occurs when the supply voltage increases to up to 25% of its nominal voltage. Based on this study, the wide band to encounter sag and swell varies between 10% and 25%.

4. Simulation results and discussion

The proposed control scheme for the DVR is validated in this section via the MATLAB/SIMULINK SimPower System Toolbox. In this paper, the load is represented by a series equivalent rated at 240 V, with 5 KVA at 0.9 load power factor. A simulation model has been developed in MATLAB/SIMULINK as shown in Figure 7. The simulation parameters are given in Table 1. The performance of the DVR for different supply disturbances was tested under various operating conditions. Several simulations of the DVR with the proposed controller scheme and the new configuration have been made. It was assumed that the voltage magnitude of the load bus is maintained at nominal value *e* during the voltage sag/swell condition. The results of the most important simulations are represented in Figures 8–11.

In the case of three-phase balance voltage sags, 50% voltage sags of the supply voltage can be created through the MATLAB simulation. The generated balance voltage sags were observed and they are illustrated in Figure 8(a). This figure shows that the voltage sag occurs at 0.25 s and is continuous until 0.45 s, after which it recovers back to its nominal value. The total duration of the voltage sag was 0.2 s. The injection voltage response of the DVR can be seen in Figure 8(b) whereas Figure 8(c) illustrates the compensation load voltage to its nominal value. The performance of the DVR under unbalanced voltage conditions is also investigated through simulation. Unbalanced three-phase voltage sags occur when one of the phases drops down to 50% of the other phases as shown in Figure 9(a). Figure 9(b) shows that the DVR recovered the unbalanced voltage by injecting an appropriate missing voltage into the network through the injection transformer. The immediate action taken by the DVR to protect the sensitive loads from the unbalanced voltage sag can be seen in Figure 9(c). This figure shows the compensation method which keeps the load at a constant value or returns it to its nominal value.

DVR performance in mitigating voltage swells in the network can also be created and investigated through MATLAB simulation. Normally voltage swell is caused by line to ground faults. In this investigation the voltage swell of the supply voltage is created through simulation and its waveform can be seen in Figure 10(a). As observed from this figure, two-phase supply voltages increase to 20–25% above their nominal voltage. When the voltage swells starts, voltage injection occurs and power flows from the DVR to the system because the voltage swells is detected. The DVR will inject a different voltage into the system so that the voltage swell does not affect the sensitive load. The injection and the load voltages can be seen in Figures 10(b) and 10(c), respectively. The results show the effectiveness of the DVR in mitigating voltage swell in order to maintain load voltage at its nominal value. In the case of unbalanced voltage swell, two of the three phases are higher by 20–25% than the third phase as shown in Figure 11(a). As soon as the unbalance voltage swell begins, the DVR detects the voltage swell and injects an appropriate voltage to recover the load voltage to its nominal value. The injected voltage is produced by the DVR so as to correct the load voltage and the voltage maintained at a constant value as shown in Figures 11(b) and (c), respectively.

When compensating for the voltage sag/swell at the critical load, the DVR produces a harmonic distortion fed from the series transformer as an injection voltage to the critical load. Using a fast Fourier transform (FFT) analyzer, the voltage total harmonic distortion (VTHD) of 1.4% of the filtering scheme is shown in Figure 12 later and this satisfies the IEEE-519 standard harmonic voltage limit.

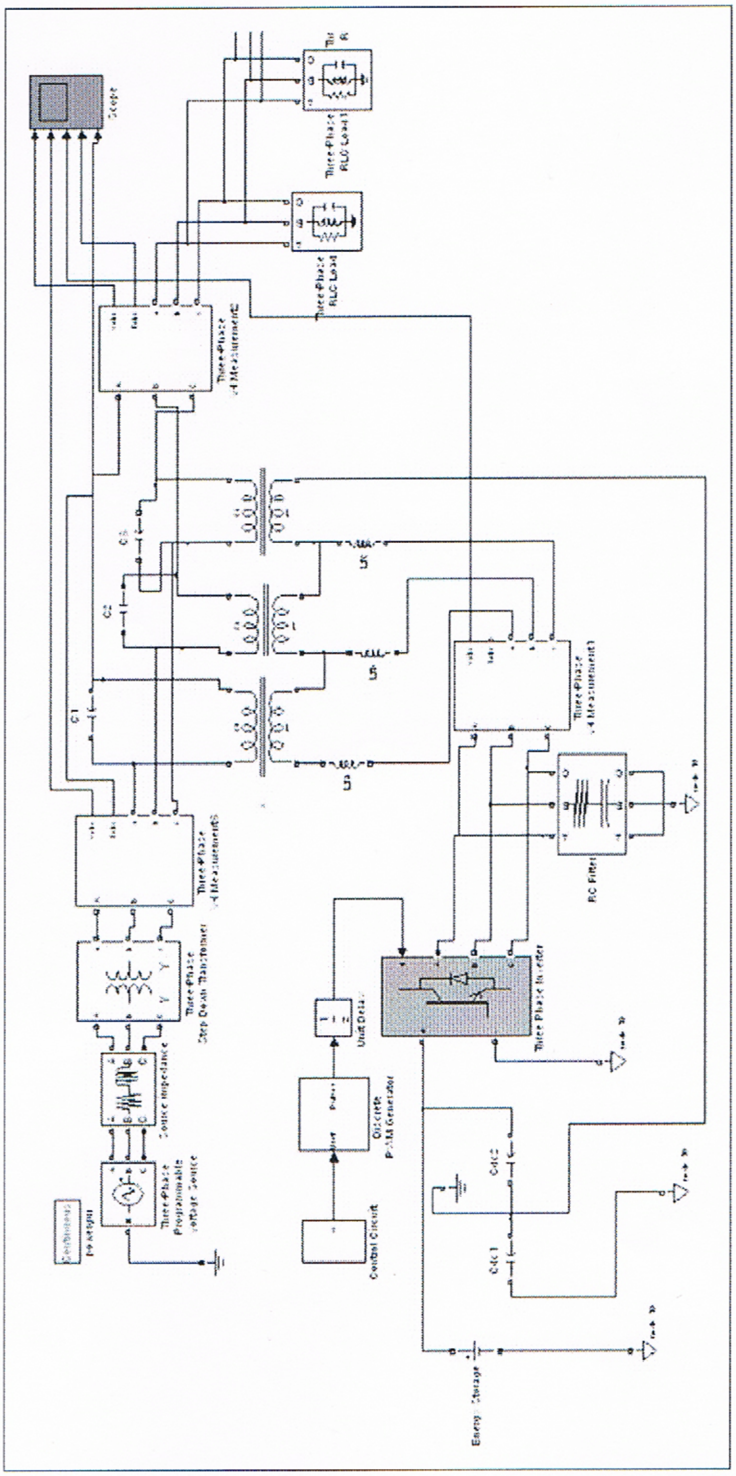

Figure 7. Simulink model development of the DVR for voltage sag/swell detection.

Table 1. System parameters and constant values

Main supply voltage per phase	240 V
Line impedance	$L_s = 0.6$ mH, $R_s = 0.2\ \Omega$
Series transformer turns ratio	1 : 1
DC bus voltage	120 V
Filter inductance	5 mH
Filter capacitance	1 uF
Load resistance	100 Ω
Load inductance	60 mH
Switching frequency	5 kHz
Line frequency	50 Hz

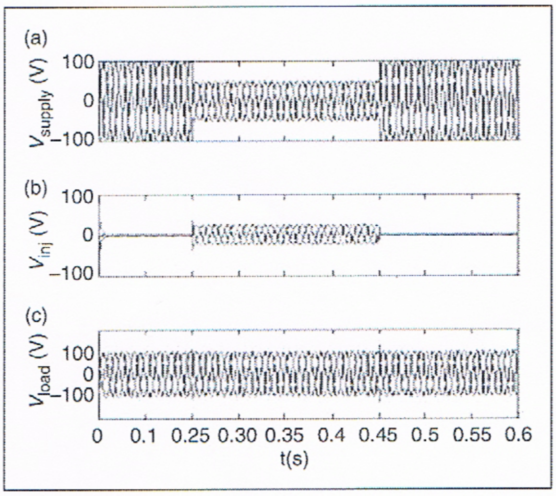

Figure 8. Compensation of the balanced supply voltage sag using the DVR.

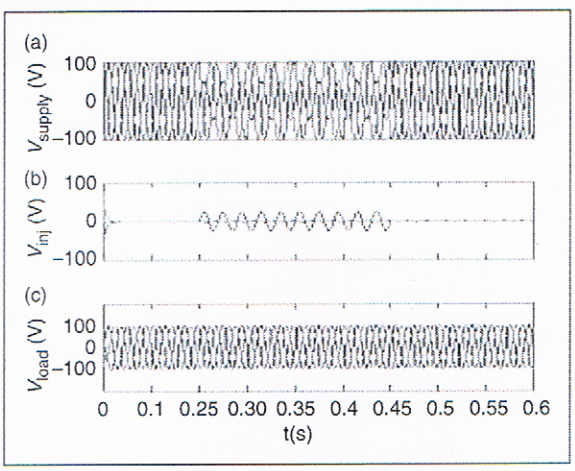

Figure 9. Compensation of single-phase fault supply voltage sag using the DVR.

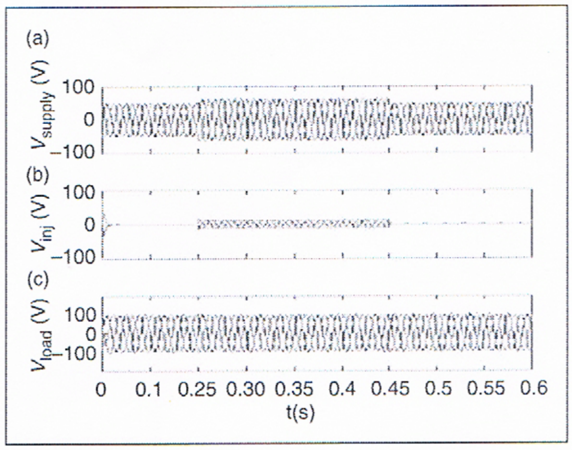

Figure 10. Compensation of the supply voltage balanced swell using the DVR.

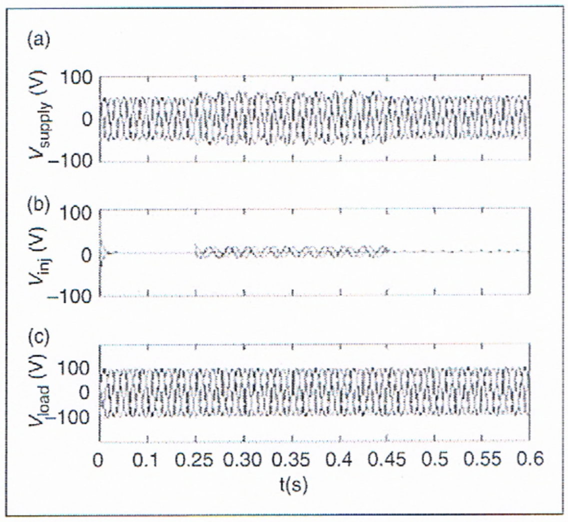

Figure. 11. Compensation of the supply voltage unbalanced swell using the DVR.

5. Conclusion

This study has focused on power quality problems such as voltage sags and swells in a low-voltage distribution system. The modeling and simulation of a DVR using MATLAB/SIMULINK has been presented. A control system based on the dqo technique has been proposed. The simulation shows that the DVR performance is satisfactory in mitigating voltage sags/swells.

It is very important to note that the designed DVR through simulation can detect voltage sags/swells very fast in the network in order to maintain voltage for a sensitive load to its nominal voltage. The controller of

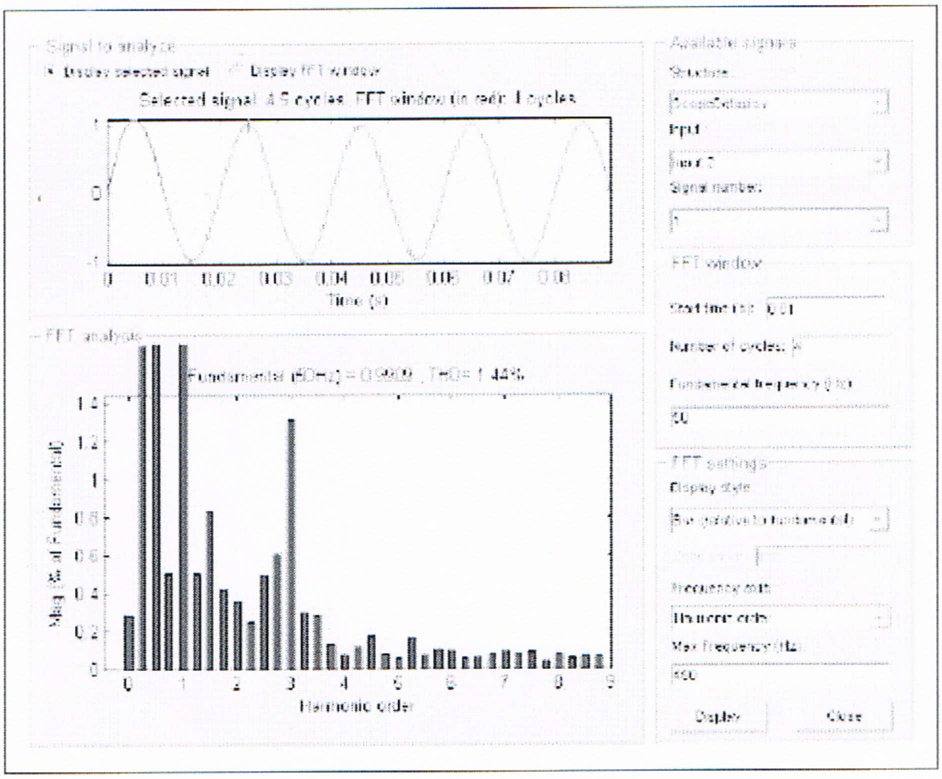

Figure 12. THD for the voltage of the proposed scheme.

the DVR can handle both balanced and unbalanced voltage sags/swells by injecting an appropriate missing voltage through the injection transformer. As a result, the load voltage is protected from any disturbance.

The proposed controller can mitigate for long duration voltage sags/swells effectively. The new configuration of the suggested DVR can reduce costs. Laboratory experiments will also be included in future work in order to make a comparison between simulation and experiment.

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