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Power conditioning using dynamic voltage restorers under different voltage sag types

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A B S T R A C T

Voltage sags can be symmetrical or unsymmetrical depending on the causes of the sag. At the present time, one of the most common procedures for mitigating voltage sags is by the use of dynamic voltage restorers (DVRs). By definition, a DVR is a controlled voltage source inserted between the network and a sensitive load through a booster transformer injecting voltage into the network in order to correct any disturbance affecting a sensitive load voltage. In this paper, modelling of DVR for voltage correction using MatLab software is presented. The performance of the device under different voltage sag types is described, where the voltage sag types are introduced using the different types of short-circuit faults included in the environment of the MatLab/Simulink package. The robustness of the proposed device is evaluated using the common voltage sag indices, while taking into account voltage and current unbalance percentages, where maintaining the total harmonic distortion percentage of the load voltage within a specified range is desired. Finally, several simulation results are shown in order to highlight that the DVR is capable of effective correction of the voltage sag while minimizing the grid voltage unbalance and distortion, regardless of the fault type.

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Introduction

Recently, much attention has been focused on the power quality domain in power system networks. Power quality measures the fitness of electric power transmitted from the utilities to the different consumers in the case of the conventional centralized generation or in some cases from the consumers to the utilities in the case of distributed generation. Voltage distortion that may occur due to power system harmonics and voltage sags is widely recognized as the most severe issue affecting power quality, because it affects both the utility company and consumers alike. Nonlinear loads create voltage and current harmonics which may have detrimental effects on consumers' equipment [1–3].

IEEE Standard 1159-1995 defines voltage sags as a root-mean-square (rms) variation with a magnitude between 10% and 90% of nominal voltage and duration typically ranging from a few milliseconds to sixty seconds [4]. Voltage sag takes

place at nearby feeders with a detrimental feeder subjected to one of the causes of voltage sag. Short circuits due to faults in the power system structure, lightning strokes, high starting currents of induction motors, and inrush currents are the common causes of voltage sags [5]. Voltage sags can be symmetrical or unsymmetrical depending on the causes of the sag. If the individual phase voltages are equal and the phase relationship is 120 degrees, the sag is symmetrical. Otherwise, the sag is unsymmetrical. A three-phase short-circuit fault can produce symmetrical sags. Single line-to-ground, phase-to-phase, or two phase-to-ground faults due to lightning, animals, accidents, and other causes, as well as energizing of large transformers, can cause unsymmetrical sags [6].

A power conditioner is a device proposed to enhance the quality of the power that is delivered to a sensitive electrical load. In addition, it can be defined as a device that acts on delivery of a voltage of the appropriate level and characteristics to facilitate the effective utilization of critical loads. At the present time, one of the power conditioners most commonly used to mitigate voltage sags is the dynamic voltage restorer (DVR). By definition, a DVR is a controlled voltage source inserted between the network and a sensitive load through a transformer injecting voltage into the network in order to correct any disturbance affecting the sensitive load voltage [2,5]. More functions can be included with the DVR such as reactive power compensation, harmonics mitigation, and fault current limitations.

DVRs' controllers have an important effect on the system dynamic response, stability and steady-state accuracy [7–14]. In the literature, there are many types of controllers that can be used in the DVR compensation practice, such as feedback and feed-forward [8], double-vector [9], proportional and integral (PI) [10], fuzzy and adaptive PI-fuzzy controllers [11,12], which are widely used in low-voltage small capacity DVR applications. Recently, a novel software phase-locked loop (SPLL) is proposed by combining the advantages of least-error-squares (LES) filters and the instantaneous symmetrical components method, which has a fast phase-lock tracking ability and guarantees no data fluctuation of the sag detection algorithm under non-sinusoidal conditions [13]. Additionally, a new strategy with the positive and the negative sequence extractions (PNSE) from the fundamental and the higher distorted harmonic orders is proposed [14], which improves the dynamic response of the DVR with an accurate steady-state compensation. Despite the valuable development added by such novel algorithms, they are mainly dedicated to high/medium-voltage applications which need large capacity dynamic voltage restorers with enhanced capability controllers, especially for the utilities that have complex non-typical industrial consumers and may considerably suffer from parameters uncertainty and/or wide range of operation circumstances, such as the grids integrated with large-scale wind and/or solar power resources.

In this paper, modelling of a DVR using PI controller for voltage correction using MatLab software is presented. The pre-sag compensation method has been used as the control strategy to maintain the voltage at the terminals of a sensitive load at its rated value. In other words, the voltage injected by the DVR will be the difference between the voltage at the point of common coupling before and during the sag [2,5].

The performance of the device under different voltage sag types is described, where the voltage sag types are introduced using the different types of short-circuit faults included in the environment of the MatLab/Simulink package. The robustness of the proposed device is evaluated using the common voltage sag indices described in [15] and the voltage and current unbalance percentages given in [16], where maintenance of the total harmonic distortion percentage of the load voltage in a specified range complying with IEEE Standard 519-1992 is desired [17]. Finally, several simulation results are shown in order to highlight the viability of the proposed device.

The proposed methodology

Dynamic voltage restorer

A dynamic voltage restorer is a solid-state power electronic switching device which is connected in series to the load voltage bus in order to inject a dynamically controlled voltage. This voltage can remove any detrimental effects of a bus fault on a sensitive load voltage.

Fig. 1 shows a schematic diagram of a typical DVR structure which is used for voltage recovery. It consists of the following units:

(i) Energy storage unit: This is DC storage energy with a proper capacity which supplies the DVR during compensation by the required real power. It can be simply a capacitor or a battery. Recently, super capacitors, fly wheels, and super-magnet conductors are emerging as energy storage devices with a fast response. Unfortunately, difficult maintenance and the high cost of these facilities compared with conventional facilities have been noted in the power quality markets, delaying their widespread deployment in a broad sense.

(ii) Injection transformer: The DVR transfers the voltage which is required for the compensation from the voltage source converter to the distribution network through the injection transformer [18]. The high voltage side is normally connected in series with the distribution network while its low voltage side is connected to the power circuit of the DVR.

(iii) Voltage source converter (VSC): This is a power electronic configuration which is used to generate a sinusoidal voltage with the required magnitude, phase, and frequency. Its dc input is the energy storage unit.
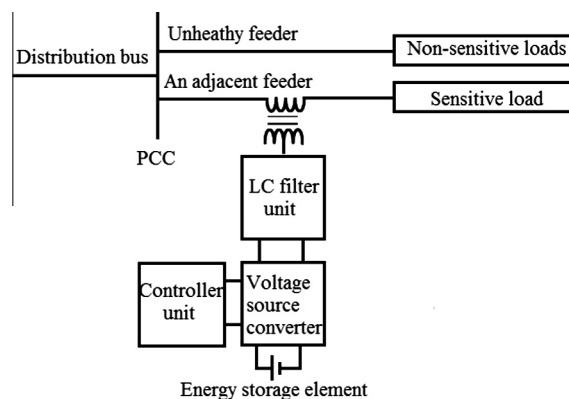

Fig. 1 Schematic diagram of a typical DVR structure.

(iv) LC passive filter: A simple output filter composed of passive elements such as a resistance R, inductance L, and a capacitance C. It is used to reduce the undesired harmonic components of the waveform generated by the converter to their permissible limit. Its output is a sinusoidal waveform with low total harmonic distortion.

(v) Bypass switch: This is used to isolate the DVR from the system in case of high currents [19].

(vi) Control unit: This is used to detect the presence of voltage sags in the system. In other words, it is considered as a monitor of the load-bus voltage. If a sag voltage is sensed, the controller will be initiated in order to inject the missing voltage after determination of its magnitude and phase [20–22].

The DVR has two main modes of operation, which are as follows:

Standby mode: This is the monitoring action of the load-bus voltage. No voltage is injected and the transformer low-voltage side is shorted through the converter.

Injection mode: The DVR in this mode injects the required voltage to the system to correct the sag [20].

Consequentially, one can say that the DVR is a series-connected device between the source and a sensitive load that injects a dynamically controlled voltage and protects voltage-sensitive equipment from sags. On the other hand, uninterruptible power supplies (UPSs), static voltage compensators (SVCs), distributed static compensators (DSTATCOMs), and super-magnetic energy storage (SMES) are other approaches that can handle the case. Unfortunately, large size, difficult maintenance, and the higher cost of these facilities compared with the DVR facility have been noted in the markets. Thus, the simplest and cheapest device for voltage sag correction is the DVR.

Voltage sag calculation

Fig. 2a shows a simplified equivalent circuit of a Thevenin source system represented by voltage source V_S and source reactance X_S. It is feeding two equal loads represented by Z_1 and Z_2 through two feeders F_1 and F_2, where Z represents the load impedance and X_F the magnitude of feeder reactance. I_S is the supply current. In normal operation, the pre-sag voltage at the point of common coupling ($V_{Pre-sag}$) and the supply current are given as follows:

$$V_{Pre-sag} = V_S - I_S X_S \tag{1}$$

$$I_S = I_1 + I_2 = \frac{V_{Pre-sag}}{Z_1 + X_{F1}} + \frac{V_{Pre-sag}}{Z_2 + X_{F2}} \tag{2}$$

When a fault occurs on F_1 (the unhealthy feeder), a high current will flow through it as well as the supply current. During such a case, the supply current $I_{S,fault}$ and the voltage at the point of common coupling during sag (V_{Sag}) will be given as follows:

$$V_{Sag} = V_S - I_{S,fault} X_S \tag{3}$$

$$I_{S,fault} = \frac{V_{Sag}}{X_{F1}} + \frac{V_{Sag}}{Z_2 + X_{F2}} \tag{4}$$

Accordingly, the voltage across the adjacent feeder F_2 will be reduced due to the excessive voltage drop that will appear across the source reactance X_S. This voltage drop will be defined as voltage sag [5]. Hence, a DVR represented by a controlled voltage source V_{DVR} will be inserted between the point of common coupling and the sensitive load Z_2, as shown in Fig. 2b.
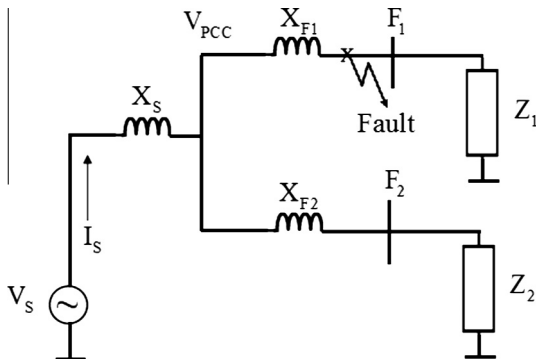
Description of the system under study

Fig. 2c shows a single line diagram of the system configuration under study. It is composed of a 13 kV, 50 Hz generation system feeding two transmission lines through a three-winding transformer connected in $Y_g/\Delta/\Delta$, 13/66/66 kV. Such transmission lines feed two distribution networks through two transformers connected in Δ/Y_g, 66/0.38 kV. Bus-A represents the unhealthy feeder in which different faults will occur at point X, while bus-B represents the adjacent feeder connected to sensitive loads. To validate the performance of the DVR for voltage correction, balancing, and harmonics mitigation, different fault types will be applied at point X for the duration of 135 ms. The DVR is simulated to be in operation only for the duration of the fault [5].

The following indices regarding the goodness of the system quality after compensation are taken into consideration:

Voltage total harmonic distortion (THDV)

Harmonic distortion is a good indication of the quality of the system output voltage. According to IEEE 519-1992, THDV for a voltage level up to 69 kV is less than or equal to 5.0%

Fig. 2a   Simplified equivalent circuit for voltage sag calculation.
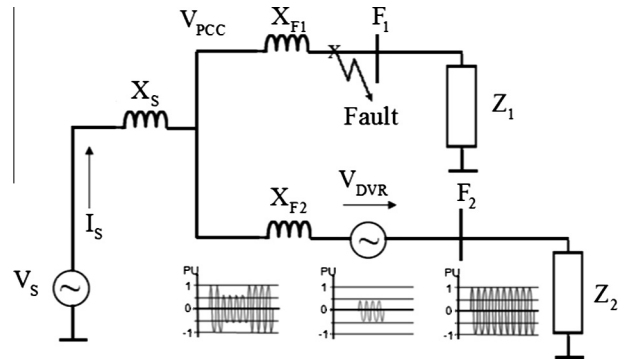
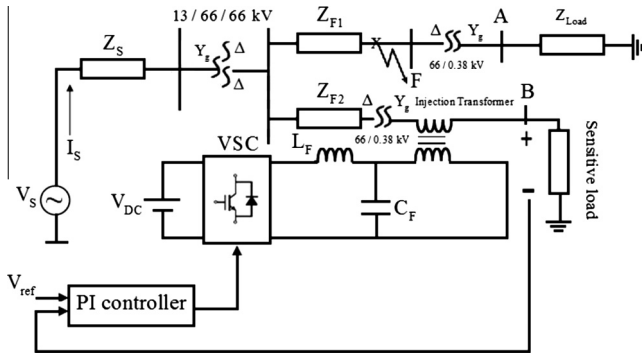**Fig. 2b**   Simplified equivalent circuit for the DVR voltage injection.

Fig. 2c Single line diagram of the system under study.

of the fundamental. The maximum individual frequency voltage harmonic is limited to 3% for a system without a major parallel resonance at one of the injected harmonic frequencies [17]. The expression of the THDV measured at the point of common coupling can be written as follows, where h is the harmonic number presented and p is the phase order so that $p = a, b, c$ [23,24]:

$$THDV = \frac{THDV_a + THDV_b + THDV_b}{3} \tag{5}$$

$$THDV_p = \frac{\sqrt{\sum_{h \geqslant 2} V_{ph}^2}}{V_{p1}} \cdot 100 \tag{6}$$

Voltage sag indices

Sag indices are indicators that describe the quality of voltage sag or voltage recovery. These indices are sensitive for any disturbance; hence they can give accurate feedback on the system performance. The following indices are discussed in the simulated system results:

Detroit Edison Sag Score (SS)

This is the first voltage sag index that is used in contracts between utilities and consumers. The Detroit Edison Sag Score (SS) is defined as follows [15]:

$$SS = 1 - \frac{V_a + V_b + V_b}{3} \tag{7}$$

where V_a, V_b, and V_c are the root-mean-square (rms) values of the phase voltages per unit. An SS value closer to 0 indicates a good recovered voltage after compensation.

Voltage sag lost energy index (VSLEI)

During voltage sag, the voltage is below normal for some period of time, which reduces the energy delivered to the loads. This index gives the lost energy W during a sag event, which is defined as follows:

$$W = \sum_{p=a,b,c} W_p = \sum_{p=a,b,c} T_p * \left(1 - \frac{V_p}{V_{nominal}}\right)^{3.14} \tag{8}$$

where V_p is a phase voltage per unit with respect to the nominal voltage $V_{nominal}$ during the sag event, and T_p is the sag duration in milliseconds for each phase [15,16]. It is obvious

that for three-phase calculation, the lost energy is added for all three phases.

Phase unbalance rate

The IEEE definition [25] of voltage unbalance, known as the phase voltage unbalance rate (PVUR), is given by

$$PVUR = \frac{Maximum(V_d)}{V_{avg}} \cdot 100 \tag{9}$$

where V_d represents phase voltage deviation from the average phase voltage (V_{avg}).

DVR control algorithm

The control algorithm produces a three-phase reference voltage to the series converter that seeks to keep the load voltage at its reference value. In this paper, the well known dq_0 transformation (Park's transformation) is used to control the DVR as shown in (10), where ω is the angular frequency in radians per second. Hence, the three-phase system is simplified and can be easily controlled after transformation of the three phase abc voltage into the two voltage components V_d and V_q. For simplicity, zero phase sequence components are ignored. The control block diagram with a phase-locked loop (PLL) is illustrated in Fig. 2d. Basically, the PLL circuit is used to generate a unit sinusoidal wave in phase with the main voltage [20].

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2\sin\omega t & 2\sin\left(\omega t - \frac{2\pi}{3}\right) & 2\sin\left(\omega t + \frac{2\pi}{3}\right) \\ 2\cos\omega t & 2\cos\left(\omega t - \frac{2\pi}{3}\right) & 2\cos\left(\omega t + \frac{2\pi}{3}\right) \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{10}$$

In order to maintain simplicity, the control algorithm can be summarized as follows [10]:

- The DVR controller monitors the load-bus voltage. Consequentially, this voltage is transformed to its corresponding dq components. The components of the load voltage are compared with the reference voltage dq components.
- If a sag voltage is sensed, an error signal will be generated due to the difference between the measured and reference voltage values and the controller will be initiated in order to inject the missing voltage. This error signal drives a PI (proportional and integral) controller which controls the system depending on the actuating error signal. It should be noted that the output signal generated from the PI
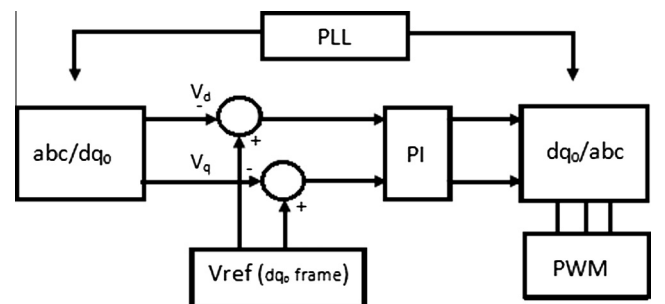

Fig. 2d Control scheme of the dynamic voltage restorer.

controller is transformed back to three phase *abc* voltage before it is forwarded to the Pulse Width Modulation (PWM) generator, as shown in Fig. 2d.

- For getting smooth and sinusoidal output voltage, a simple output filter composed of passive elements is needed at the output of the converter. The input to the filter is high frequency modulated 50 Hz AC input. The switching signal that modulates the 50 Hz signal is taken to be 5.5 kHz for the proposed case. Accordingly, a low pass LC filter that suppresses most of the generated harmonic frequencies, is proposed. This will result in a nearly sinusoidal output voltage. Sizing of the filter parameters is given in Table 1 [27].
- The Pulse Width Modulation (PWM) control technique is applied for inverter switching so as to generate a three-phase 50 cycles-per-second sinusoidal voltage at the terminals of the load. Consequentially, its output signal controls the pulses for the inverter. In other words, the PWM generator will generate pulses to trigger the PWM inverter with the desired firing sequence. IGBT is the switching device that is used with the VSC for the DVR operation because a freewheeling diode is connected in antiparallel with each IGBT, thus bringing more flexibility to the proposed device with a compromise among conducting and switching losses [26].

Simulation results and discussion

Three cases of an industrial plant (Table 1) were simulated using MatLab software Simulink. The numerical data were taken from an example in an existing publication [20]. The cases under study can be summarized as follows:

- **Case I**: A three-phase to ground fault is applied. Therefore, the system is under type A sag voltage. The voltage during this event is equal in the three phases. This type of sag is considered a balanced sag regardless of the transformer or the load connection.
- **Case II**: A double line to ground fault is applied. Basically, types E, F, and G are only expected if the fault is a double line to ground fault. However, the transformer between the faulted point and the considered bus is a D/Y_g transformer. This means that the system is under type F sag voltage.

- **Case III**: A single line to ground fault is applied. Basically, types B, C, and D are only expected if the fault is a single line to ground fault. The healthy phases show the same magnitude and direction in their voltage change. In this case, the system is under type C sag voltage.

Each fault is applied on the unhealthy feeder for a duration of 0.05–0.185 s (135 ms), respectively. Thus a sag voltage will be sensed on the sensitive feeder.

Table 2 shows the uncompensated system results to be defined and compared with the DVR compensation results.

Table 3 shows the compensated system results after using the proposed device. It is obvious that the THDV percentages are consistent with the total harmonic distortion limit of the IEEE Standard 519-1992, for all cases under study. Besides, it is notable, as shown in Table 3, that the phase voltage unbalance rate percentages have met the IEEE recommendations defined in [25].

Even when the sag score was high as shown in Case I (50%) or moderate as in Case II (24.2%), or only a slight action for voltage correction and regulation was needed as in Case III (1.85%), the proposed device was able to achieve the required goals while minimizing voltage harmonic distortion, sag lost energy, and voltage unbalance rate.

Seeking a clear demonstration of the proposed device, Figs. 3–5 show waveforms of the faulty feeder voltage, the uncompensated sensitive feeder voltage, and the compensated load voltage for all cases under study, respectively. The significant sag voltage recovery in the load voltage waveforms after compensation is obvious.

Case I: Three-phase to ground fault.
Case II: Double line to ground fault.
Case III: Single line to ground fault.

Fig. 6a shows the voltage total harmonic distortion percentages generated after compensation with respect to changing

Table 1 System and DVR parameters.

Parameter	Value
Line resistance (Ω)	1.0
Line inductance (mH)	5.0
Line frequency (Hz)	50
Load phase voltage (V)	220
Load power per phase (W)	100
Load inductive reactive power per phase (kvar)	0.2
Load capacitive reactive power per phase (kvar)	0.5
Injection transformer turns ratio	1:1
Saw-tooth carrier wave frequency (*Hz*)	5500
DC supply voltage (V)	200
Filter series inductance (mH)	80
Filter series resistance (Ω)	0.1
Filter shunt capacitance (μF)	6.0
Filter shunt resistance (Ω)	60

Table 2 Uncompensated system results in the three cases.

Parameters and cases	Case I	Case II	Case III
$THDV_a$ (%)	4.11	3.16	0.93
$THDV_b$ (%)	8.08	8.13	0.96
$THDV_c$ (%)	8.56	2.84	0.41
THDV (%)	6.92	4.71	0.77
PVUR (%)	8.10	16.3	1.46
SS (%)	50	24.2	1.85
VSLEI (J)	47.45	17.2	0.01

Table 3 Compensated system results in the three cases.

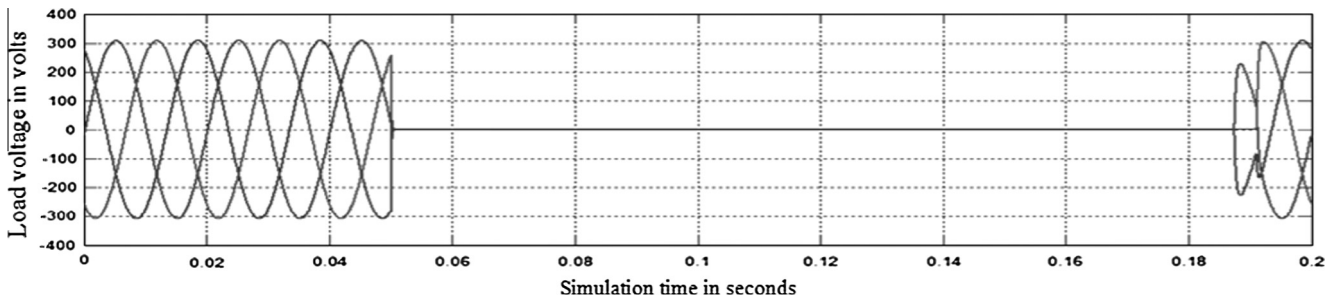| Parameters and cases	Case I	Case II	Case III
$THDV_a$ (%)	0.46	0.98	0.55
$THDV_b$ (%)	1.75	1.6	0.54
$THDV_c$ (%)	1.7	1.1	0.01
THDV (%)	1.30	1.23	0.37
PVUR (%)	0.5	0.69	0.02
SS (%)	2.00	0.7	0.22
VSLEI (J)	0.002	0.00032	0.000002

Fig. 3a   Faulty feeder voltage in volts versus time in seconds, Case I.
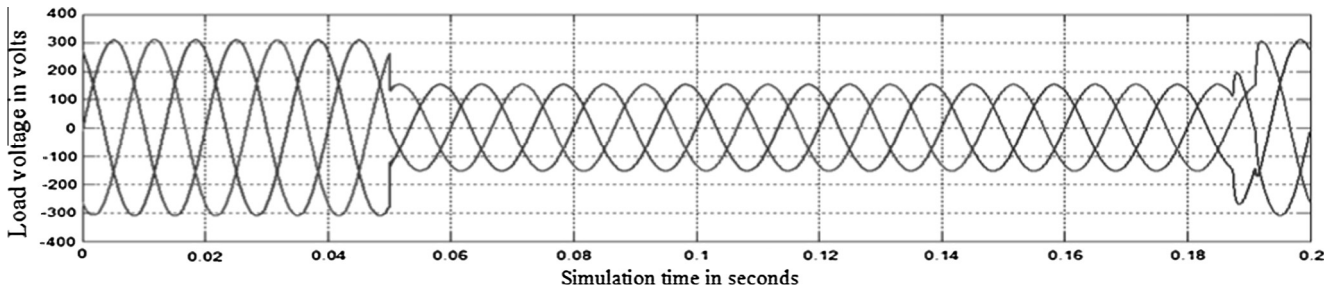

Fig. 3b   Uncompensated sensitive feeder voltage in volts versus time in seconds, Case I.
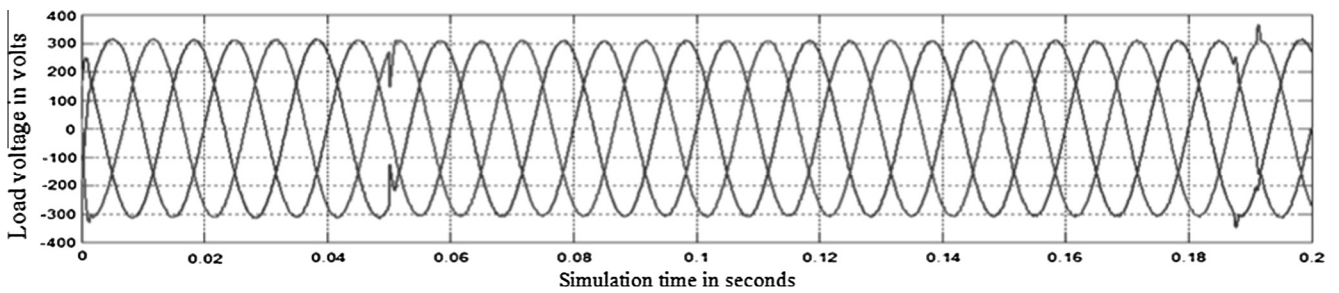

Fig. 3c   Compensated load voltage in volts versus time in seconds, Case I.
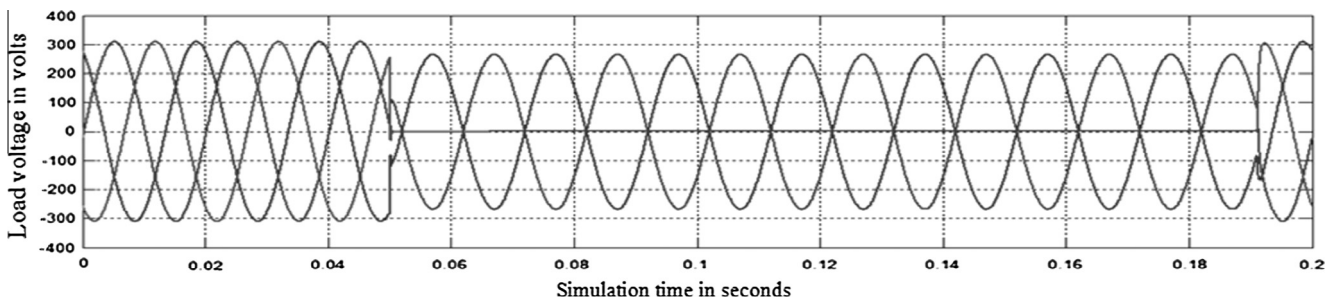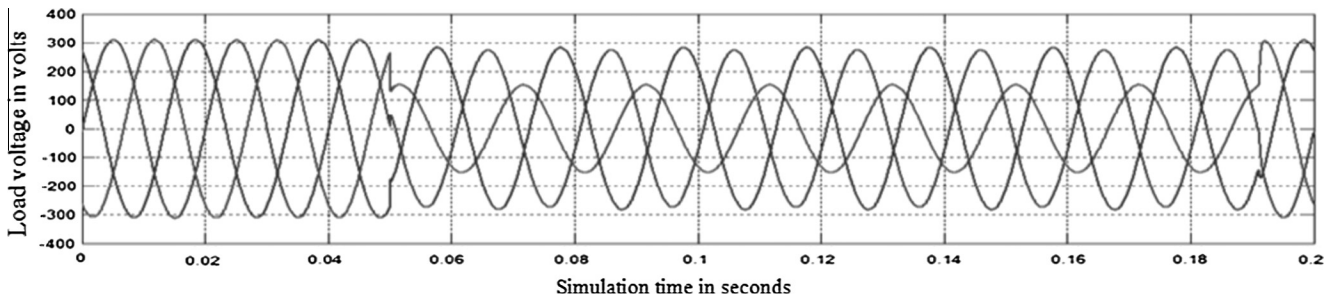

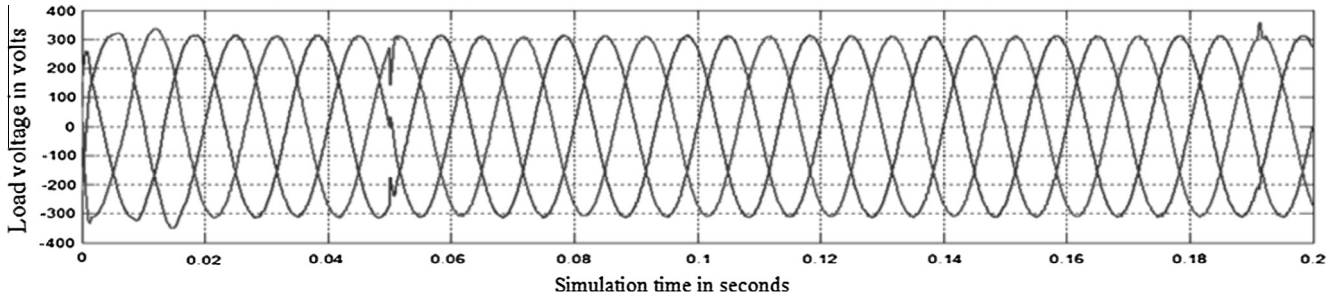**Fig. 4a**   Faulty feeder voltage in volts versus time in seconds, Case II.

the energy storage capacity. It is obvious that 200 V_{DC} is the optimal value that achieves the lowest voltage harmonic distortion percentage. Fig. 6b shows the variation of the sag score percentage (%SS) with respect to changing the energy storage capacity. Once more, it is obvious that 200 V_{DC} was an appropriate choice which achieves a low sag score percentage. Additionally, Fig. 6c shows variation of the phase voltage unbalance rate (%PVUR) with respect to changing the energy

storage capacity. It is clearly obvious that 130 V_{DC} is the lowest voltage capable of complying with IEEE Standard 112-1991 recommendations with a phase unbalance rate less than 2%.

In order to check the control robustness against harmonic distortion, simulation results of the system with an additional three-phase diode rectifier type (a typical non-linear load) which is connected in parallel with the sensitive load, are
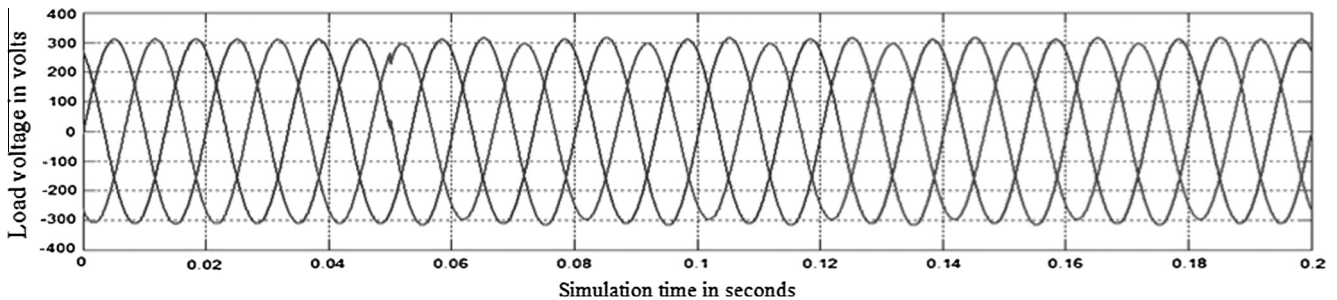
Fig. 4b Uncompensated sensitive feeder voltage in volts versus time in seconds, Case II.

Fig. 4c Compensated load voltage in volts versus time in seconds, Case II.
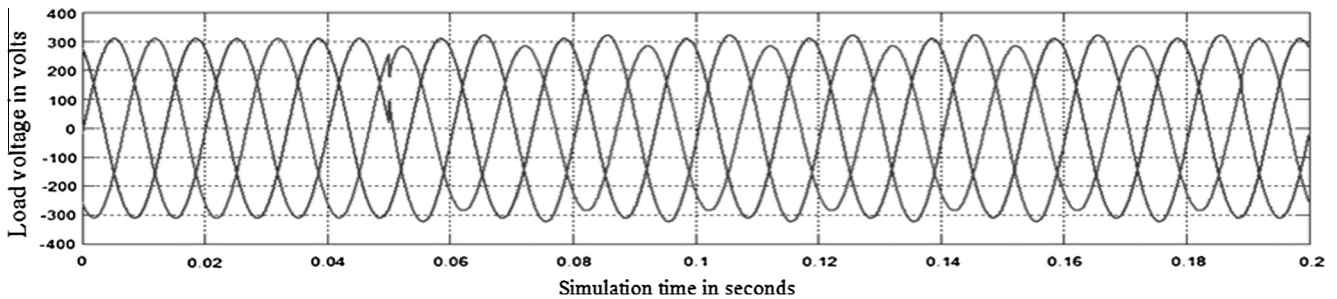
Fig. 5a Faulty feeder voltage in volts versus time in seconds, Case III.

Fig. 5b Uncompensated sensitive feeder voltage in volts versus time in seconds, Case III.

shown in Tables 4 and 5 for the uncompensated and compensated systems, respectively. Even with the more harmonic-distorted system due to the connection of the non-linear load, it is notable that the THDV percentages for the compensated system are consistent with the total harmonic distortion limit of the IEEE Standard 519-1992, for all cases under study. Besides, it is notable, as shown in Table 5, that the phase voltage unbalance rate percentages have met the IEEE recommendations (less than 2%). Thus, the proposed device with the presented control scheme was able to achieve the required goals of voltage recovery while minimizing voltage harmonic distortion, sag lost energy, and voltage unbalance rate. This is mainly because the DVR has similar structure and principle of operation to series active filters [26]; accordingly, it operates
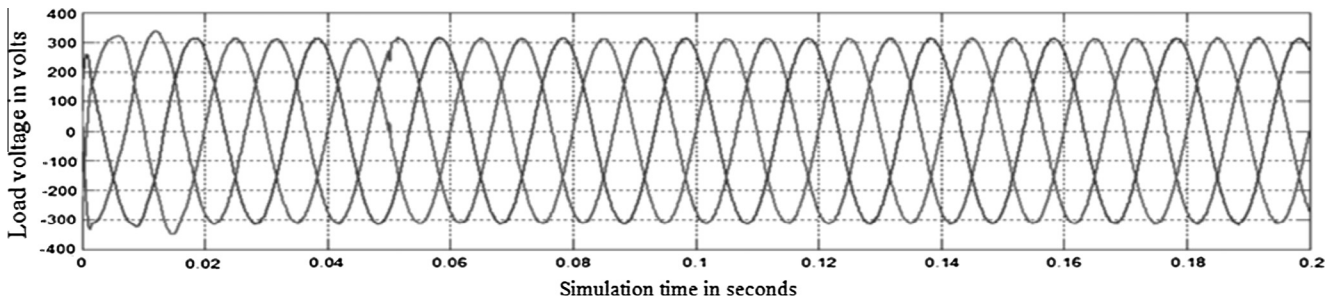
Fig. 5c   Compensated load voltage in volts versus time in seconds, Case III.
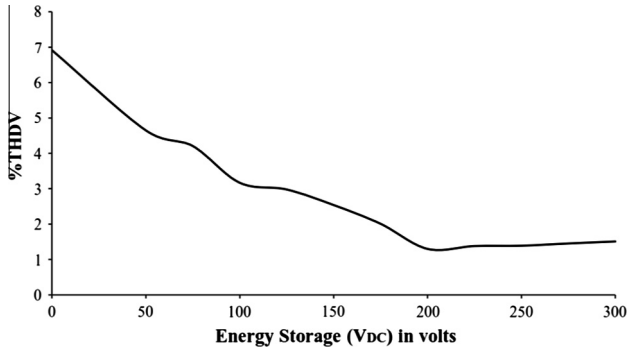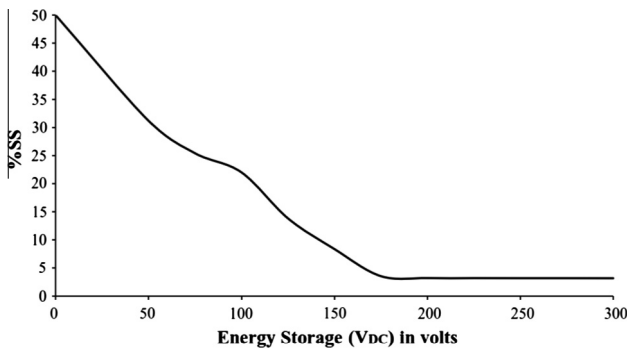

Fig. 6a   %THDV variation versus the energy storage unit.

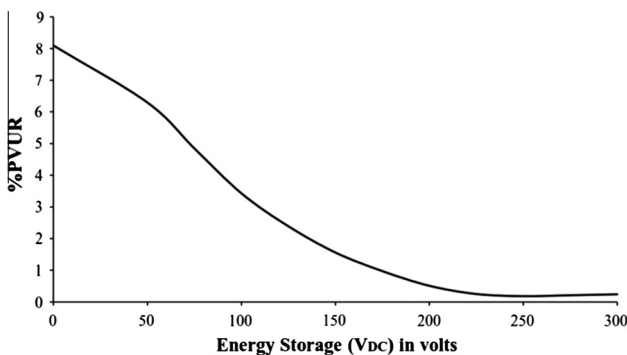**Fig. 6b**   %SS variation versus the energy storage unit.

Table 4   Uncompensated system results with linear and non-linear loads in the three cases.

Parameters and cases	Case I	Case II	Case III
THDV$_a$ (%)	5.47	3.95	4.40
THDV$_b$ (%)	7.47	9.66	5.64
THDV$_c$ (%)	9.59	3.34	5.55
THDV (%)	7.51	5.65	5.20
PVUR (%)	7.89	14.56	1.23
SS (%)	50.61	30.98	12.00
VSLEI (J)	47.72	18.55	0.55

Table 5   Compensated system results with linear and non-linear loads in the three cases.

Parameters and cases	Case I	Case II	Case III
THDV$_a$ (%)	0.81	2.40	1.18
THDV$_b$ (%)	1.84	3.03	1.08
THDV$_c$ (%)	1.97	1.29	1.65
THDV (%)	1.54	2.24	1.30
PVUR (%)	0.52	1.36	0.12
SS (%)	2.05	2.21	0.31
VSLEI (J)	0.002	0.007	0.000

well in harmonics mitigation. Finally, many controllers can be used for the DVR. Each controller has its own advantages and disadvantages. For example, choosing appropriate controller for the DVR is greatly affected by the percentage of load distortion; if it is small, the PI controllers may be the most appropriate scenario because of their simplicity; if it is moderate; the fuzzy or adaptive PI controllers can be a good choice; if it is high, then the controllers previously reported [13,14] are the best because of their effectiveness in operating under non-sinusoidal conditions. Accordingly, more simulation results should be done to determine which controller can considerably enhance the DVR's dynamic response with a reasonable efficiency and without decreasing accuracy, while taking into account the various power quality factors. The findings of this research will be presented in a future paper.

Conclusions

Voltage sag detection is the first step in enabling a proper solution to many disturbances affecting a power system network. In this paper, modelling of DVR for voltage correction using

Fig. 6c   %PVUR variation versus the energy storage unit.

MatLab software is presented. The performance of the device under different voltage sag types is described. Various power quality indices are used to evaluate the performance of the grid with the proposed device. Several simulation results are introduced to validate that the proposed DVR operation scheme fulfils the required goals. It is obvious that the DVR is capable of effective correction of the voltage sag while minimizing the grid voltage unbalance and harmonics distortion, regardless of the fault type.

Conflict of interest

The authors have declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

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