Improvement of Dynamic Voltage Restorer (DVR) Using Proportional Integral (PI)Controller for Mitigation of Voltage Sag

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ABSTRACT

Power quality is considered a pivotal issue in modern industrial and commercial applications especially for nuclear installations. Voltage sag is a common power quality problem. It has an impact on the sophisticated and sensitive electronic equipment in nuclear installations. To overcome this problem, flexible Alternating Current Transmission Systems (FACTS) are used. One of the most efficient FACTS, namely Dynamic Voltage Restorer (DVR) is used in power distribution networks to mitigate voltage sag. It is a series of connected power electronic based devices that can quickly mitigate the voltage sags and restore the load voltage to the pre-fault value. This work proposes an improvement of conventional (d-q-0) transformation of DVR using Proportional Integral (PI) controller to mitigate the voltage sag in distribution network. Our implementation of the PI controller is different than the proposed work in the literature. This allowed enhancement of the performance. Different types of faults are modeled by using MATLAB/SIMULINK to examine the improvement of the proposed technique over the conventional one.

Key words: Power Quality, Voltage Sags, FACTS, DVR, PI Controller.

INTRODUCTION

Power quality is an important issue due to its impact on electricity suppliers, equipment manufacturers and customers. Power quality is defined by the IEEE Standard 1100 “The concept of powering and grounding electronic equipment in a manner suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment”(1,2). Power quality disturbances encompass phenomena such as voltage sag, voltage swell, flicker, harmonics distortion. These disturbances are responsible for problems ranging from malfunctions or errors to plant shut down and loss of manufacturing capability(3) .

Voltage sags can occur more frequently than any other power quality phenomena in the power distribution system(4) . Voltage Sag or Voltage Dip is defined by the IEEE Standard 1159 as “The decrease in the root mean square (RMS) voltage level to 10-90% of nominal value, at the power frequency for durations of half cycle to one minute”(5). It is often caused by balanced or unbalanced faults in the distribution system or by the starting of large induction motors.

Flexible Alternating Current Transmission Systems (FACTS) are used in voltage sag mitigation, protection and control of sensitive loads, reactive power and voltage regulation, and harmonic elimination applications(6). There are many types of FACTS such as, Superconducting Magnetic Energy Storage (SMES), Static Var Compensator (SVC), Dynamic Voltage Restorers (DVR), Static Synchronous Compensator (STATCOM), and Static Synchronous Series Compensator (SSSC). Different methods are used to mitigate voltage sags such as, Solid-State Transfer Switches (SSTS), Distribution Static Compensators (D-STATCOM), and Dynamic Voltage Restorers (DVR)(2), and(6).

Dynamic Voltage Restorer (DVR) in nuclear installations is one of the prominent methods for compensating the power quality problems associated with voltage sags. Dynamic voltage restorer can provide an effective solution to mitigate voltage sag by establishing the appropriate predetermined voltage level required by the loads. It is recently being used as the active solution for voltage sag mitigation in nuclear installations(7).

In this paper, the nuclear research reactor is a case study for mitigation of voltage sags problems. The conventional (d-q-0) transformation DVR and its improvement using PI controller are presented. Different faults types are modeled using MATLAB/SIMULINK. The proposed DVR control by using an improvement of (d-q-0) transformation using PI controller is capable of compensating voltage sags effectively with reducing any distortion. The paper is devoted to discussing the basic functioning, and power circuit components of the DVR, the control strategy employed for inverter switching in the DVR, the simulation model which is developed using MATLAB/SIMULINK, and simulation results with different types of fault conditions.

DYNAMIC VOLTAGE RESTORER (DVR)

Dynamic Voltage Restorer (DVR) which is also known as a Static Voltage Booster (SVB) or a Static Series Compensator (SSC) is generally installed in distribution systems. DVR is one of the FACTS devices which is used to mitigate voltage sags. It is normally connected in series between supply and sensitive loads. DVR is intended to protect the sensitive loads at the Point of Common Coupling (PCC) from various power quality problems, which is designed to maintain a constant RMS voltage value across a sensitive load(7,8) .A DVR model, which is shown in Figure (1), consists of the following parts:

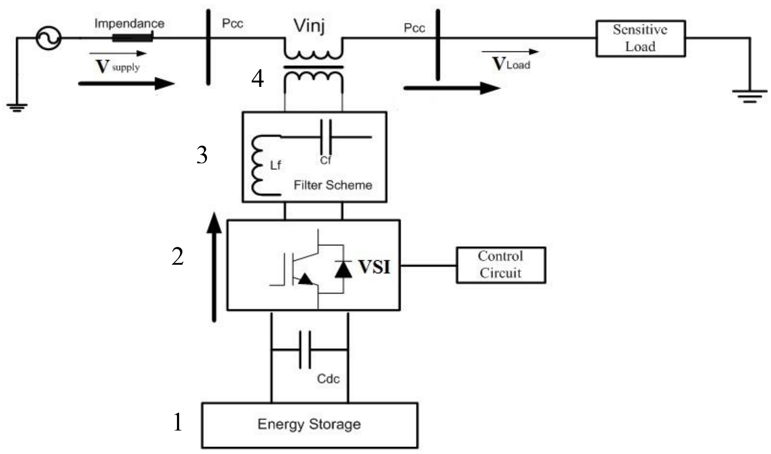

Fig. (1): Schematic diagram of DVR

1. Energy storage device, which supplies the required power for compensation of load voltage during voltage sag period(9). Various systems can be used for this purpose like flywheel, lead acid batteries, superconducting Magnetic Energy Storage systems (SMES)(7), and(10).
2. Voltage Source Inverter (VSI), which basically, consists of switching devices. It converts the DC input to sinusoidal voltage of desired phase angle and magnitude. There are four main types of switching devices: MOSFET, GTO, IGBT and IGCT. Highly sophisticated converter design with IGBT's is used which allows the DVR to compensate large voltage dips(7).

3. LC filter, eliminates the unwanted harmonic components produced by the voltage source inverter. The ratings of the inductance and capacitance are related to the maximum injection limit of the DVR(6).

4. Injection transformer, the three single phase transformers connect the DVR to the distribution network via the high voltage windings. They transform and couple the injected compensating voltages generated by the VSI to the incoming supply voltage. Transformer can be connected in star/star or delta/star configuration(7).The transformer winding ratio is determined according to the voltage requirement in its secondary side. The rating of the transformer is an important factor to determine the performance of a DVR as it limits the maximum compensation ability of the DVR(9).

DVR CONTROL

The basic functions of DVR controller are the detection of voltage sag events in the system, computation of the correcting voltage, generation of trigger pulses to the sinusoidal PWM based DC-AC inverter, correction of any anomalies in the series voltage injection and termination of the trigger pulses when the event has passed(11). There are two functions control; the conventional (d-q-0) transformation control and Improvement of (d-q-0) using PI controller.

A. CONVENTIONAL (d-q-0) TRANSFORMATION

The conventional (d-q-0) transformation control scheme of DVR is shown in Figure (2). In this figure, the supply voltage is connected to a transformation block that converts the stationary (a-b-c) frame to (d-q-0) transformation frame, which detects the phase and changes the axis of supply voltage. The reference voltage is connected to anther transformation block, which converts the reference voltage from (a-b-c) frame to (d-q-o) reference. Equations 1 to 3 define the transformation from three phase voltage system (Va, Vb, Vc) to (Vd, Vq, V0) transformation voltage frame(12,13) .

$$Vd = \frac{2}{3}\left[Va * \sin(wt) + Vb * \sin\left(wt - \frac{2\pi}{3}\right) + Vc * \sin\left(wt + \frac{2\pi}{3}\right)\right] \quad (1)$$

$$Vq = \frac{2}{3}\left[Va * \cos(wt) + Vb * \cos\left(wt - \frac{2\pi}{3}\right) + Vc * \cos\left(wt + \frac{2\pi}{3}\right)\right] \quad (2)$$

$$V0 = \frac{1}{3}\left[Va + Vb + Vc\right] \quad (3)$$

If the voltage sag occurs, the injection voltage is generated by difference between the reference voltages and the supply voltage. The injection voltage is applied to the voltage source inverter to produce the preferred voltage through PWM. The Phase Locked Loop (PLL) block is used to generate a unit sinusoidal wave in phase.

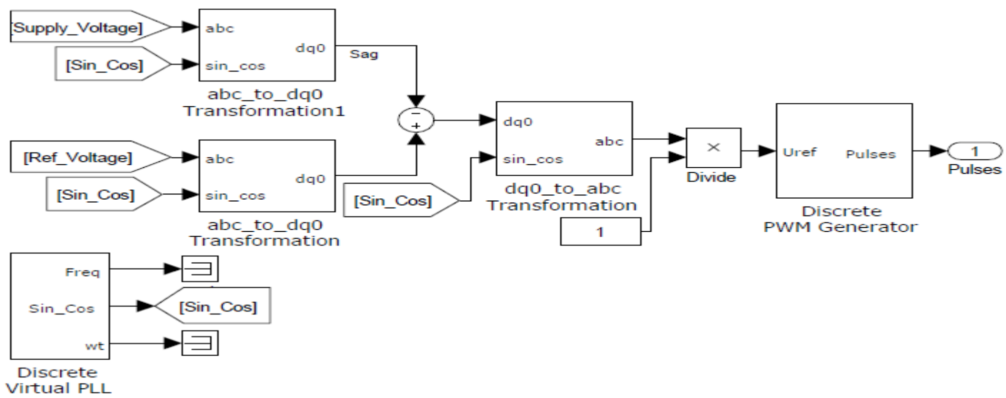

Fig. (2): Conventional (d-q-0) transformation control

B.IMPROVEMENT OF (d-q-0) USING PI CONTROLLER:

The output of the conventional (d-q-0) transformation is the injection voltage carrying error signal, which obtained from the difference between reference voltage and supply voltage. Such error is processed by a PI controller then the output is provided to the PWM signal generator that controls the DVR inverter to generate the required injected voltage. The reason behind the extensive use of proportional integral (PI) controller is its effectiveness in the control of steady state error of a control system[(13)]. The implementation of the (PI) Controller with DVR is shown in Figure (3).

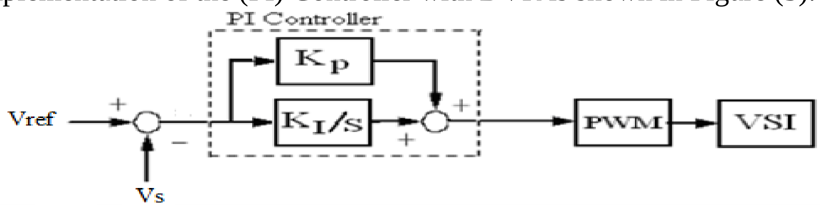

Fig.(3):PI Controller

There are three (PI) controllers for d-component, q-component, and 0-component, as shown in Figure (4). The inputs of PI controller block for these components are an actuating signal which is the difference between the reference voltage and supply voltage.

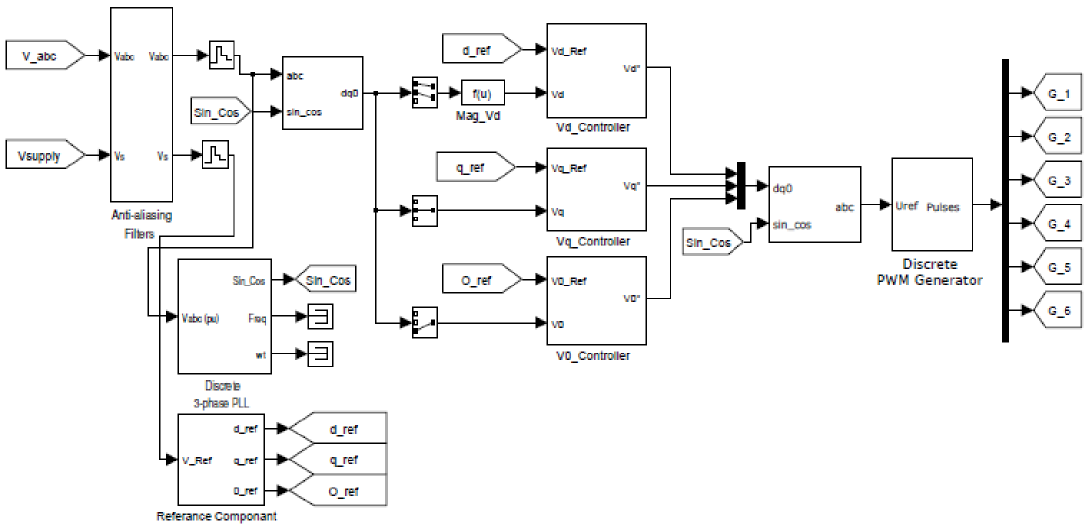

Fig. (4): Improvement of (d-q-0) using PI controller

Outputs of the controller block are of the form of an angle (θ), which introduces additional phase-lag/lead in the three-phase voltages. These outputs are converted to three phase stationary voltage (a-b-c) frame by using (d-q-0 to a-b-c transformation block). Equations 4 to 6 defines the transformation from (Vd, Vq, V0) transformation voltage frame to three phase voltage system (Va, Vb, Vc) [(10)] .

$$Va = [Vd * \sin(wt + \theta) + Vq * \cos(wt + \theta) + V0] \quad (4)$$

$$Vb = [Vd * \sin\left(wt + \theta - \frac{2\pi}{3}\right) + Vq * \cos\left(wt + \theta - \frac{2\pi}{3}\right) + V0] \quad (5)$$

$$Vc = [Vd * \sin\left(wt + \theta + \frac{2\pi}{3}\right) + Vq * \cos\left(wt + \theta + \frac{2\pi}{3}\right) + V0] \quad (6)$$

This three phase voltage is used as a modulation signal that allows to generate six gates of commutation pattern for the power switches (IGBT's) constituting the voltage source inverter. The commutation pattern is generated utilizing the Sinusoidal Pulse Width Modulation(SPWM) technique. The PLL block is used to generate a unit sinusoidal wave in phase with the supply voltage.

DVR TEST SYSTEM

The simulation test system is shown in Figure (5), where a radial distribution feeder in medium voltage feeding two types of loads through two transformers. One of them is sensitive load, which is connected to DVR and the other is normal load. It is assumed that the voltage magnitude is maintained at 1 pu during the voltage sags condition. Table 1 presents the data of test system.

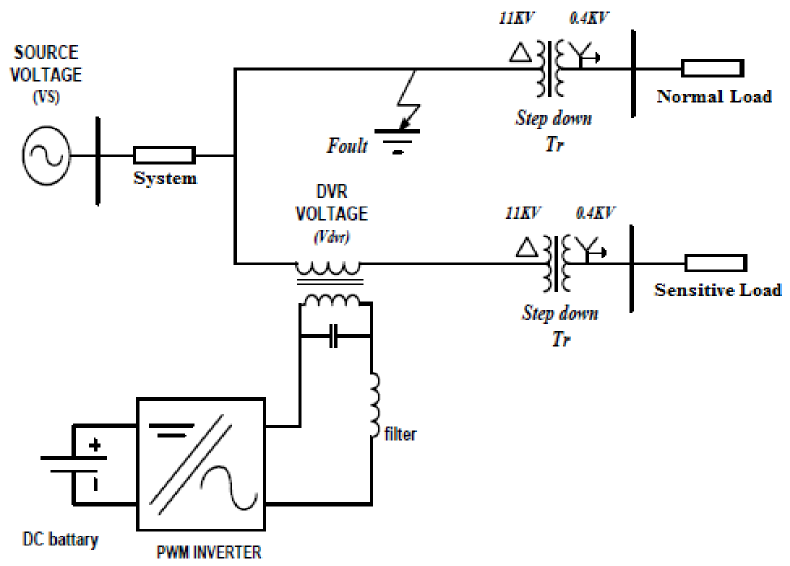

Fig. (5): DVR test system

Table (1): System Parameters

System Parameters	Value
Supply Feeder Voltage (rms)	11KV
Fundamental Frequency	50 Hz
DC Battery	10KV
DC capacitor	1000 µF
Injection transformer turns ratio	1:1
Filter inductance	1mH
Filter capacitance	1µF
Rating Sensitive Load Power	400 KVA
Power Factor (lagging)	0.95

Simulation Results

To explain the improvement in voltage sag mitigation achieved with implementing the PI controller with DVR, the MATLAB/SIMULINK model is shown in Figure (6).

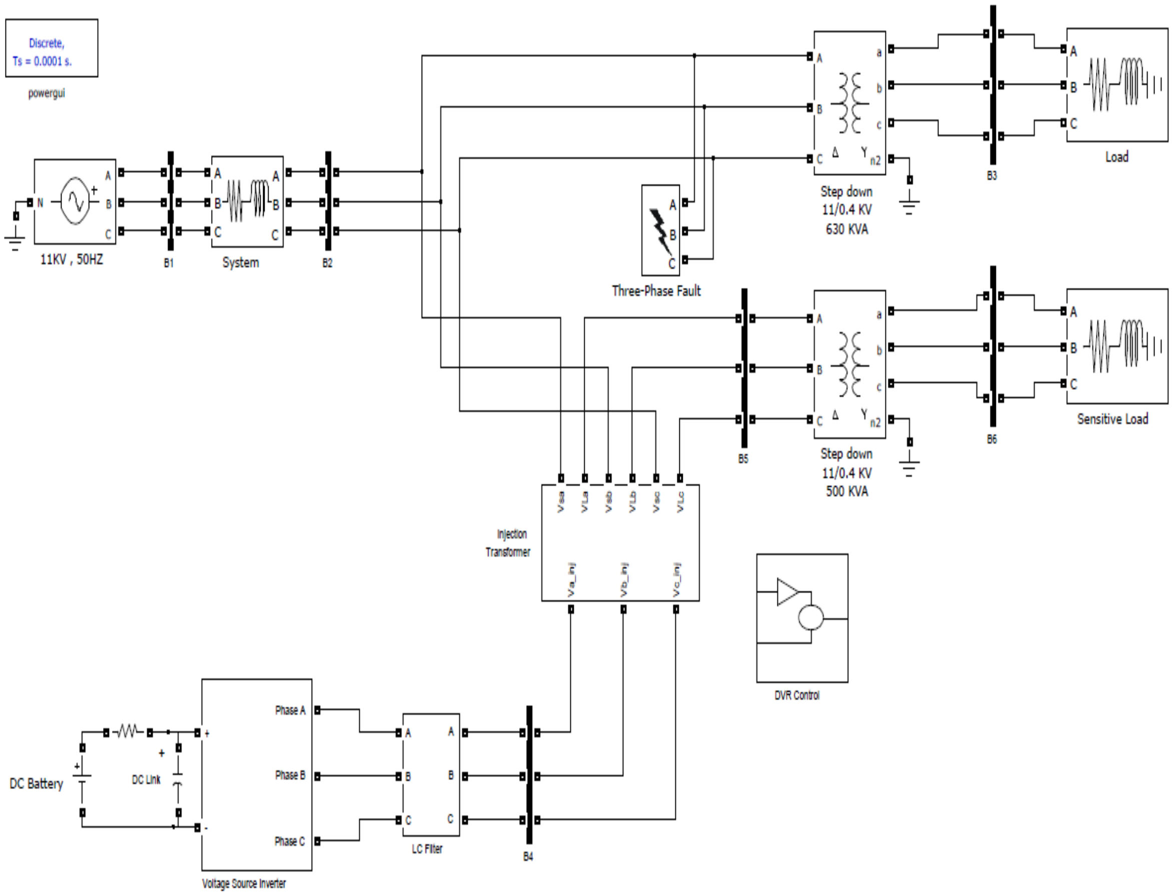

Fig. (6): Circuit model of DVR in Matlab/Simulink

The simulation comprises two types of control, which are the conventional (d-q-0) transformation control and Improvement of (d-q-0) using PI controller. The following are the simulation results for balanced voltage sag and unbalanced voltage sag by applying the different cases of fault to study the impact of DVR in distribution system. All the following figures will be divided into three plots (a) Source voltage, (b) Injected voltage, and (c) Sensitive load voltage.

A. CONVENTIONAL (d-q-0) TRANSFORMATION:

Three phase balanced sag Three Phase Faults: The voltage will be decreased to 50% of its normal value, for duration of 80 ms from t = 40 ms till t =120 ms, as shown in Figure (7).

Three phase unbalanced sag Single-Line-To-Ground Faults (SLGF): Phase A will be sagged to 50% for 80 ms from t = 40 ms till t =120 ms, as shown in Figure (8).

Three phase unbalanced sag Double-Line-Ground Faults (DLGF): Phases B, C will be sagged to 60% for 80 ms from t = 40 ms till t =120 ms, as shown in Figure (9).

B. IMPROVEMENT OF (d-q-0) USING PI CONTROLLER

Three phase balanced sag: The voltage will be decreased to 50% of its normal value, for duration of 80 ms from t = 40 ms till t =120 ms, as shown in Figure (10).

Three phase unbalanced sag Single-Line-To-Ground Faults (SLGF): Phase A will be sagged to 50% for 80 ms from t = 40 ms till t =120 ms, as shown in Figure (11).

Three phase unbalanced sag Double-Line-Ground Faults (DLGF): Phases B, C will be sagged to 60% for 80 ms from t = 40 ms till t =120 ms, as shown in Figure (12).

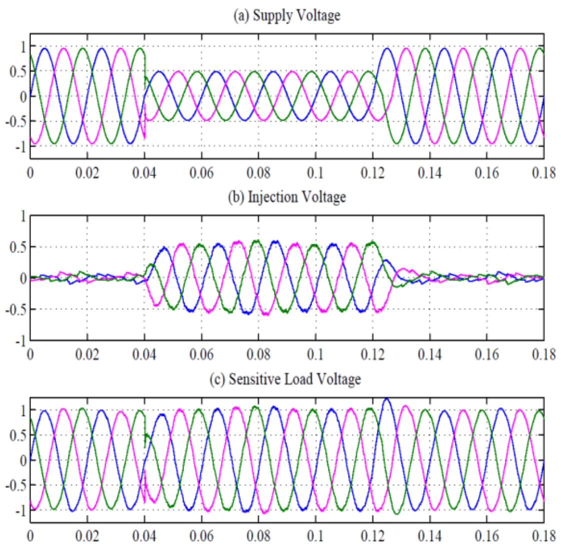

Fig. (7): Three-phase voltage sag (a) Source voltage, (b) Injected voltage, and (c) Sensitive load voltage.

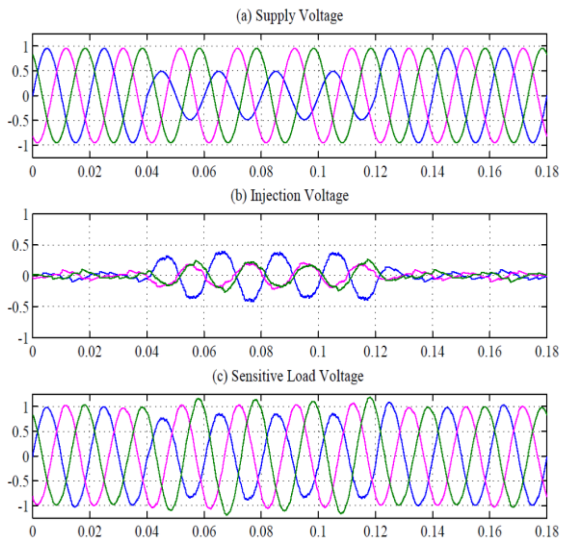

Fig.(8): Three phase unbalanced sag (SLGF) (a) Source voltage, (b) Injected voltage, and (c) Sensitive load voltage**.**

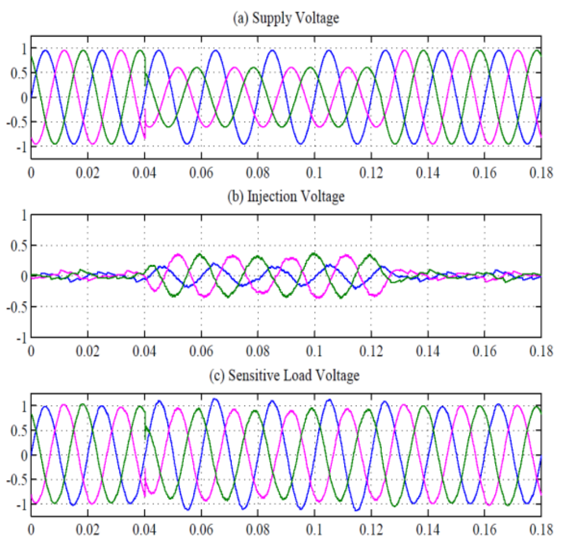

Fig.(9): Three phase unbalanced sag (DLGF) (a) Source voltage, (b) Injected voltage, and (c) Sensitive load voltage.

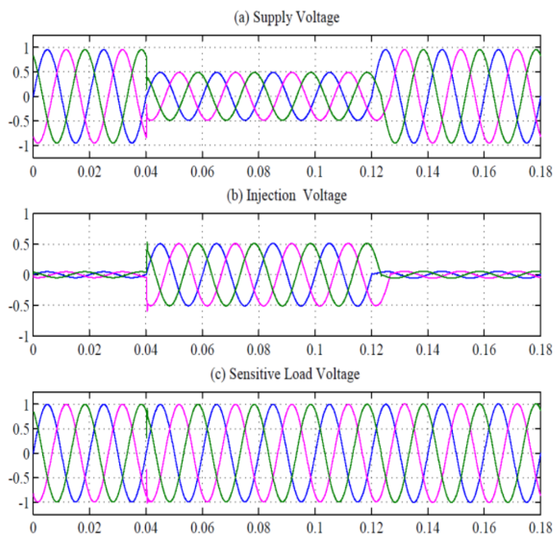

Fig.(10): Three-phase voltage sag (a) Line voltage, (b) Injected voltage, and (c) Sensitive load voltage.

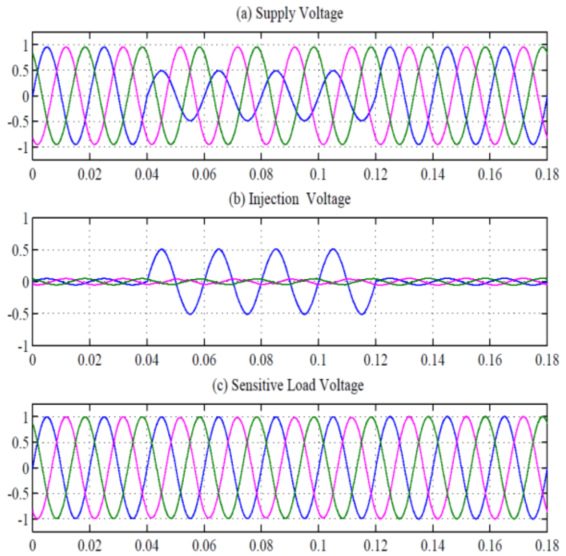

Fig.(11): Three phase unbalanced sag (SLGF) (a) Source voltage, (b) Injected voltage, and (c) Sensitive load voltage.

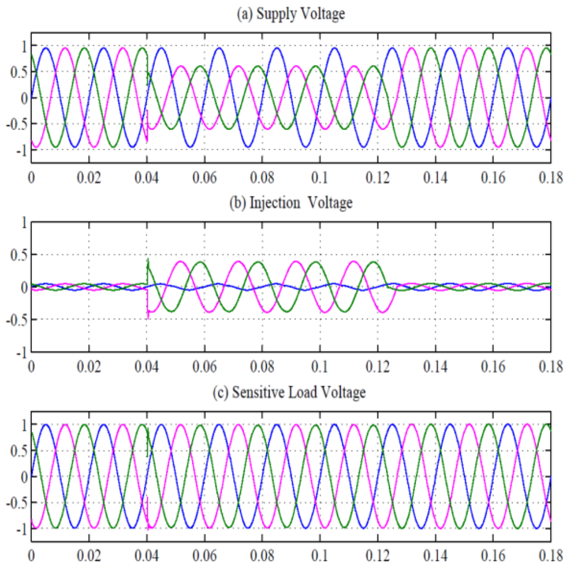

Fig. (12): Three phase unbalanced sag (DLGF) (a) Source voltage, (b) Injected voltage, and (c) Sensitive load voltage.

The above results show the comparison between two controls under different types of fault. It was found that the injection voltage is clear when using an improvement of (d-q-0) transformation using PI controller and removes any distortion from sensitive load voltage and makes it smooth.

Table (2) shows the comparison of the output voltage due to voltage injection from DVR controlled by conventional (d-q-0) transformation control and improvement of (d-q-0) using PI controller for each phase in different type of fault. It can be seen that improvement of (d-q-0) using PI controller gave an optimum performance and have the ability to improve the source voltage back to 1 p.u before deliver it to the load in balanced and unbalanced fault condition.

Table (2): The comparison of the output injection voltage

Type of Fault	Before Injection (%)			Injection DVR (Conventional (d-q-0)) (%)			Injection DVR ((d-q-0) with PI Controller) (%)		
	A	B	C	A	B	C	A	B	C
3-PHF	48.49	48.71	48.7	99.25	99.41	99.95	100.3	100.1	100.2
SLGF	48.78	95.1	95.08	84.44	101.2	112.5	100	100.2	100.1
DLGF	95.03	60.44	60.43	112.9	92.73	95.28	100.4	100	100.1

CONCLUSIONS

In this paper, we introduced the dynamic voltage restorer (DVR) as one of the FACTS, which is considered efficient and effective solution for voltage sag mitigation. An improvement of conventional (d-q-0) transformation DVR using PI controller to mitigate the voltage sags in distribution network are presented. Different types of faults are modeled by using MATLAB/SIMULINK. The proposed technique is effective to restore the sensitive load voltage to the pre-fault value and makes it smooth under different cases of faults.

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