Mitigation of Voltage Sag and Swell Using Dynamic Voltage Restorer

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***Abstract*—The fast developments in power electronic technology have made it possible to mitigate voltage disturbances in power system. Among the voltage disturbances challenging the industry, the voltage sags are considered the most important problem to the sensitive loads. Dynamic voltage restorer (DVR) is a series connected power electronic based device that can quickly mitigate the voltage sags in the system and restore the load voltage to the prefault value. DVR is recognized to be the best effective solution to overcome this problem. The primary advantage of the DVR is keeping the users always on-line with high quality constant voltage maintaining the continuity of production. In this paper, the usefulness of including DVR in distribution system for the purpose of voltage sag and swell mitigation is described. The DVR presented here is based on the concept of dqo. The proposed control method is found very efficient for detecting and clearing any power quality disturbance in distribution systems. Results of simulation using Matlab-Simulink are demonstrated to prove the usefulness of this scheme.**

Keywords—Dynamic Voltage Restorer, Voltage sag, Voltage swell, dqo technique.

I. INTRODUCTION

Nowadays, Power quality is identified as one of the very serious issues in electric power transmission and distribution, because of its bad impact on electricity suppliers, manufacturers and users. Generally we can define power quality as the deviation of voltage, current and frequency from its standard values in a power system [1]. Presently, most of the industries use power electronics conversion and switching for manufacturing and processing. These technologies are in need of high quality and reliable power supply. Not only the industries, but also the electric power utilities and customers are becoming increasingly anxious about the electric power quality. Sensitive loads such as digital computers, programmable logic controllers (PLC), consumer electronics and variable frequency motor drives need high quality power supplies. Good quality of electric power is necessary for right functioning of industrial processes as well as protection to the industrial machines and its long usage. The frequently occurring power quality issues are voltage unbalance, voltage sag and swell, transients, flickers and harmonic distortions. These power quality issues can cause serious malfunctions and lost production in industries [2].

Out of these power quality issues, voltage sag or swell causes more serious problems in power system, both at transmission and distribution level. Faults on electrical power system like short circuit due to insulation breakdown at heavy load conditions can cause voltage sag. The voltage sag can be defined as decrease in rms value of voltage below the nominal voltage ranging from 0.1 to 0.9 pu and that lasts for half a cycle to one minute. Depending on the type of fault, the voltage sag could be either balanced or unbalanced and they could have magnitudes that cannot be predicted. Voltage swell, in contrast, can be defined as a rapid increase in rms voltage above the nominal value ranging from 1.1 to 1.8 pu and that lasts for half a cycle to 1 minute. Switching off of large loads, energization of capacitor banks etc can be considered as the common causes of voltage swell. Voltage sag occurrence is more common than voltage swell in distribution power system. Sensitive electronic and electrical equipments may be subjected to failure, complete shutdown or generate a large inrush current that results in blown fuses and tripped circuit breakers due to voltage sag and swell. [3].

Out of the different methods for voltage sag and swell compensation, the installation of custom power device in distribution system is regarded as the most accomplished one. The custom Power concept was put forward by N.G. Hingorani in the year 1995. Flexible AC Transmission Systems (FACTS) deals with various power problems in transmission systems like improvement in power transfer capabilities and stability margins, whereas the custom power devices involves the utilization of power electronics controllers in a distribution system and deals with various power quality problems and it make sure that the users get a good quality and trustworthy supply. By good quality, it means: low phase unbalance, less flicker in load voltage, less deformation in load voltage due to harmonics, level and extent of overvoltage and undervoltage within specific limits and no power interruptions.

Some examples of Custom power devices are as follows: Battery Energy Storage System (BESS), Distribution STATic synchronous COMpensator (DSTATCOM), Dynamic Voltage Restorer (DVR), Surge Arrester (SA), Super-conducting Magnetic Energy Storage (SMES), Solid-State Transfer switch (SSTS), Static Var Compensator (SVC), Uninterruptible Power Supply (UPS) etc [4].

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All of the above mentioned devices have their own advantages and disadvantages. Among the custom power devices, we can consider Dynamic Voltage Restorer (DVR) as the most economic and efficient solution for various power quality issues. Some of the reasons for this conclusion are as follows: When DVR is compared with SVC, SVC lacks the active power flow control capability. Therefore DVR is preferred over SVC. When DVR is compared with UPS, UPS is not only costly but also it requires high battery maintenance and replacement due to leak. When compared with SMES, DVR has lower cost and higher energy capacity. When compared with DSTATCOM, DVR is smaller in size and lower in cost. Considering these reasons, DVR can be regarded as the most effective custom power device for voltage sag and swell compensation in distribution systems. Additional DVR features are harmonics and power factor correction. The first DVR installation was in North America in the year 1996 on a 12.47 kV system located in Anderson, South Carolina. Since then and till now, DVRs have been useful in distribution systems to protect sensitive loads in industries from various power quality issues [5].

In this paper, a brief overview of the DVR, its functions and configurations, its basic components, modes of operation, voltage compensation methods and control of the DVR output voltage are reviewed and simulation results using MATLAB are illustrated.

II. DVR BASICS

A Dynamic Voltage Restorer is a lately proposed series connected solid state device that injects missing voltage waveform into the system for regulating the voltage at the load end. Its location in the distribution system is between supply and sensitive load. It continuously and quickly regulate the load side voltage in case of any power quality issues like voltage sag or swell thus preventing any power interruption to the sensitive load. There are different methodologies and control techniques by which a DVR can be implemented. [3].

A. Operating Principle

The fundamental principle behind DVR operation is that it injects a voltage waveform through an injection transformer that is the difference between pre-sag and sagged voltage. This is demonstrated in Fig. 1. This is made possible by the supply of required real/active power from an energy storage device along with reactive power. The injection transformer ratio and ratings of the energy storage device can put limitations on the maximum injection capability of DVR.

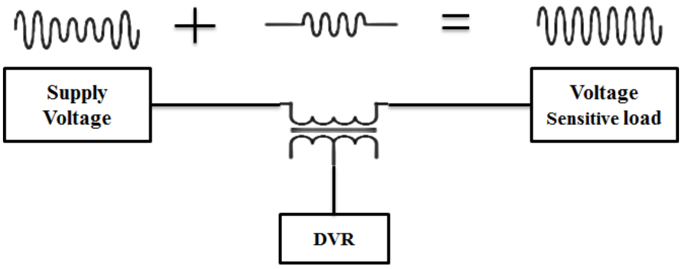

Fig. 1 Operation of DVR

Separate control over the magnitude of injected voltage is usually done for a three single phase DVRs.

B. Fundamental Components of DVR

The fundamental components of DVR are [6]:

1. Injection or Booster transformer
2. Harmonic filter.
3. Voltage Source Inverter (VSI)
4. DC Energy Storage Device and charging circuit.
5. Control system.

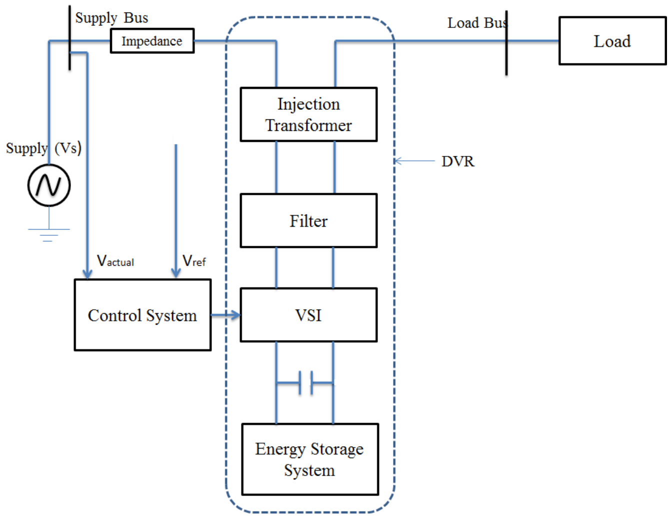

Fig. 2 DVR block diagram

C. Equation Related to DVR

The equivalent circuit of DVR is shown in Fig. 3. On detection of any reduction in the supply voltage V_{source} from any set value, the DVR injects a voltage, V_{DVR}, in series through the injection transformer such that the desired load voltage, V_{load} can be maintained at the load end.

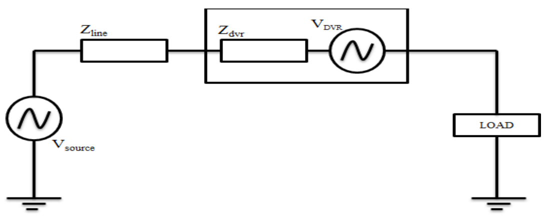

Fig. 3 Equivalent circuit of DVR

The DVR injection voltage is as written as in equation (1):

$$V_{DVR} = V_{load} + Z_{line} I_{load} - V_{source} \quad (1)$$

Where
V_{load} = Desired load voltage
Z_{line} = Line impedance
I_{load} = Load current
V_{source} = System voltage during any fault condition
V_{DVR} = DVR injected voltage

Incase if the supply voltage is not sagged or swelled, then the V_{load} will be equal to V_{source} and the DVR injected voltage will be a very small quantity (Z_{line} I_{load}) which is required to compensate for the line voltage drop

D. Operating Modes of DVR

The operating modes of DVR can be classified into three as below:

1. Protection mode:

In case of short circuit fault on load and high inrush current, the over current on the load side exceeds an allowable limit. Then the DVR will get cut off from the systems by using the bypass switches and providing alternate path for current flow.

2. Standby mode:

Switching of semiconductors of VSI will not occur in this mode and the full load current will pass through the primary winding of injection transformer. The low voltage winding of the injection transformer is shorted through the converter in this mode.

3. Injection mode:

DVR injects voltage through the injection transformer to compensate for any disturbance detected in the supply voltage. [6].

E. Voltage Compensation methods of DVR

Compensation is achieved via real power and reactive power injection. Based on the compensation level required by the load, there are three types of compensation methods as discussed below:

1. Presag compensation:

Non linear loads need both magnitude as well as phase angle compensation. In presag compensation technique, DVR supplies the difference between pre-sag and sag voltage thus restoring the voltage magnitude as well as the phase angle to that of the pre-sag value. Therefore this method is suited for nonlinear loads. However this technique needs a higher rated energy storage device and voltage injection transformers.

2. InPhase compensation:

The DVR compensates only for the voltage magnitude in this particular compensation method, i.e. the compensated voltage has the same phase as that of sagged voltage and it only compensates for the voltage magnitude. Therefore this technique minimizes the voltage injected by the DVR. Hence it is suited for the linear loads, which do not need phase angle compensation.

3. Energy-Optimization technique:

In this particular control technique the use of real power is minimized (or made equal to zero) by injecting the required voltage by the DVR at a 90° phase angle to the load current. However in this technique the injected voltage will become higher than that of the in-phase compensation technique. Hence this technique needs a higher rated transformer and an inverter, compared with the earlier cases. Further the compensated voltage is equal in magnitude to the pre sag voltage, but with a phase shift [5].

III. Proposed Control Scheme

The control scheme implemented here is with the help of dqo transformation. Once a voltage disturbance occurs, the output of the inverter can be adjusted in phase with the incoming ac source while the load voltage is regulated. The output of inverter is equipped with inductors and capacitors for filtering purpose. The role of DVR controller is the recognition of voltage sag/swell issues in the power system; calculation of the compensating voltage, trigger pulse creation for the sinusoidal PWM inverter, correction of any errors in the series voltage injection and extinction of the trigger pulses once the fault is cleared.

The simulation block diagram based on the dqo transformation technique is shown in Fig. 4 below.

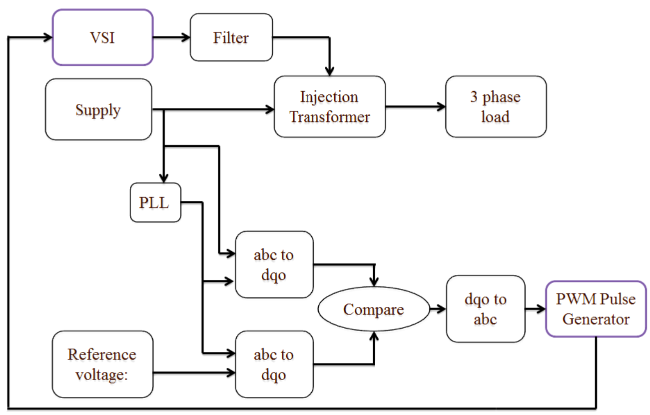

Fig. 4 Simulation block diagram

The dqo transformation or otherwise called Park's transformation is implemented here in the DVR controller. The dqo technique provides the magnitude of sag and details of phase shift with their beginning and finishing times. The quantities are expressed as the instantaneous space vectors. The voltage is converted from a-b-c reference frame to d-q-o reference. We ignore zero sequence components for simplicity. The control is implemented by comparing a set reference voltage and the measured load phase voltage (V_a, V_b, V_c).

The error signal formed by the above comparison is used as a control signal that generates a commutation sequence pattern for the power switches of the VSI using Sinusoidal Pulse Width Modulation technique (SPWM); voltages are controlled by modulation. The PLL (Phase Locked Loop) circuit is used for the generation of a unit sinusoidal wave in phase with mains supply voltage.

The equation that transforms the three phase a-b-c system to stationary dqo frame is given below equation (2).

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & 1 \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \quad (2)$$

The abc to dqo Transformation computes the direct axis, quadratic axis, and zero sequence quantities in a two-axis rotating reference frame for a three-phase sinusoidal signal. In this transformation, phase A is aligned to the d-axis that is in quadrature with the q-axis. The theta (θ) is defined by the angle between phase A and the d-axis.

IV. Simulation Study and Results

A detailed simulation of the above DVR control system is performed using MATLAB/SIMULINK program to verify its operation under sag and swell conditions. The SIMULINK model is shown in Fig. 5.

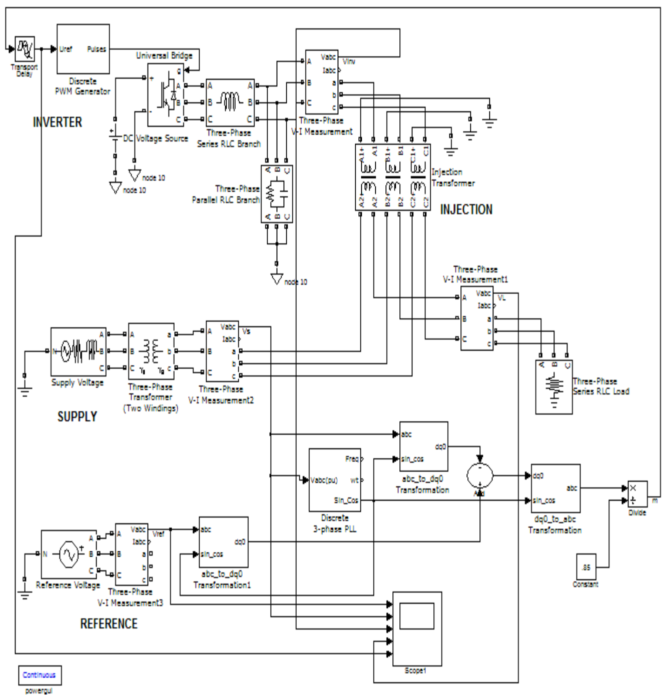

Fig. 5 DVR Simulink model

The system data information used in the Simulink model above is listed in Table 1 below.

TABLE 1. DVR SYSTEM DATA

Supply Voltage and frequency	415V, 3phase, 50 Hz
Injection transformer turns ratio	1:2
DC link Voltage	240 V
Filter Inductance	500 µH
Filter capacitance	4.7µF

A. Voltage sag

The simulation result of 50% three-phase voltage sag and 50% single phase (phase A) voltage sag in supply voltage is shown in Fig. 6 and Fig. 8 respectively. All the voltages are measured in p.u quantities. The nominal voltage is taken as 415V. The sagged supply voltage demonstrated here is 207.5V. We could observe satisfactory sag compensation in Fig. 6(d). Also the dqo conversion of supply and reference voltage and its difference which is being converted to a-b-c quantities is demonstrated clearly in the Fig. 7.

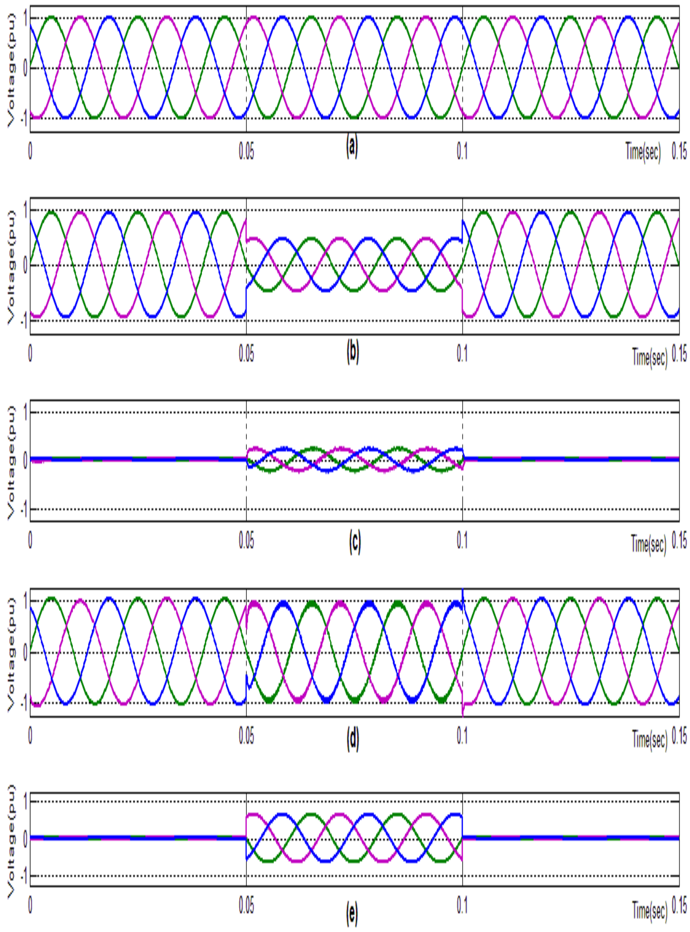

Fig. 6. Three phase voltage sag compensation. (a).Reference Voltage. (b) 3 phase Sagged supply Voltage. (c) Inverter injection voltage. (d) Compensated load voltage. (e) Modulation signal.

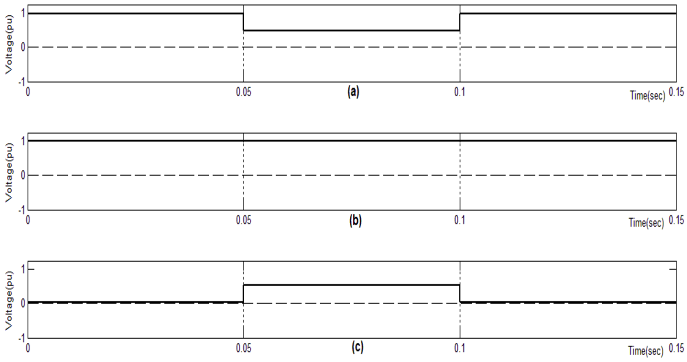

Fig. 7. (a) dqo converted supply voltage. (b) dqo converted reference voltage. (c) Difference between the reference and supply.

(dark line(__): d component; dotted line(----): q component)

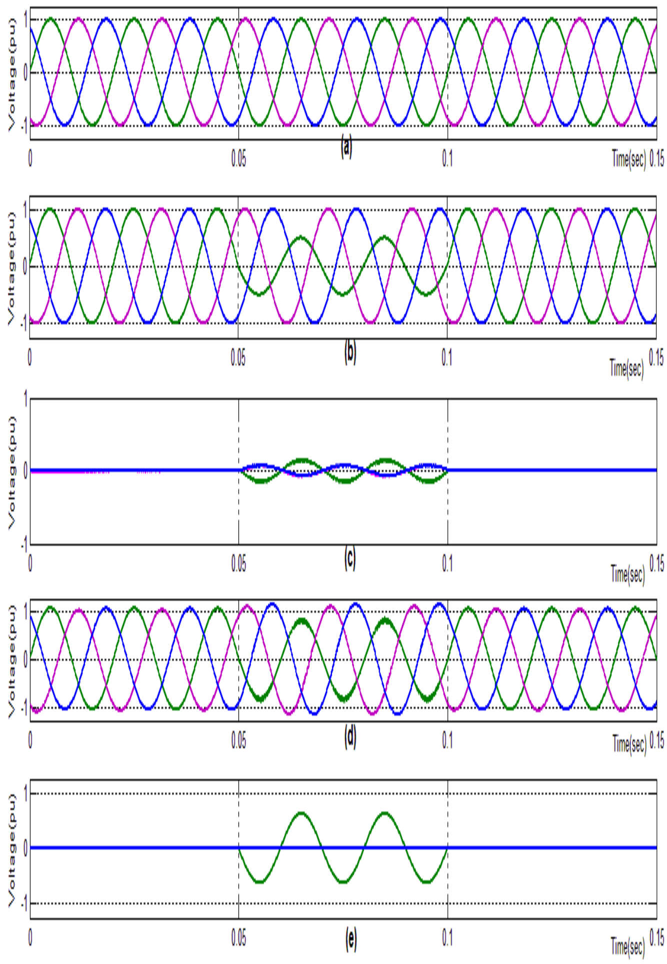

Fig. 8. Single phase voltage sag compensation:(a).Reference Voltage. (b) Single phase Sagged supply Voltage. (c) Inverter injection voltage. (d) Compensated load voltage. (e) Modulation signal.

B. Voltage swell

The simulation result of 50% three-phase voltage swell and 50% single phase (phase A) voltage swell in supply voltage is shown in Fig. 9 and Fig. 11 respectively. All the voltages are measured in p.u quantities. The nominal voltage is taken as 415V. The swelled supply voltage demonstrated here is 622.5 V. We could observe satisfactory swell compensation in Fig. 9(d). Also the dqo conversion of supply and reference voltage and its difference which is being converted to a-b-c quantities is demonstrated clearly in the Fig. 10.

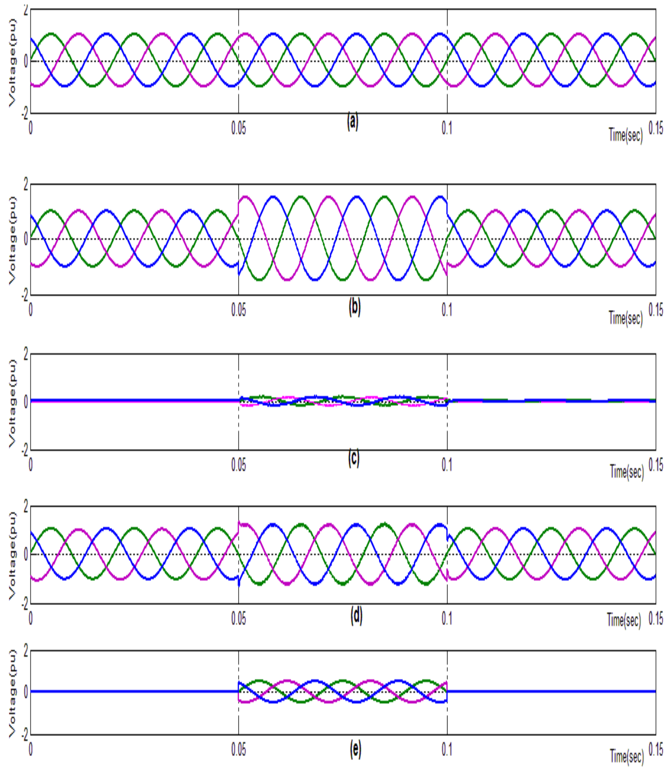

Fig. 9. Three phase voltage swell compensation. (a).Reference Voltage. (b) Swelled supply Voltage. (c) Inverter injection voltage. (d) Compensated load voltage. (e) Modulation signal.

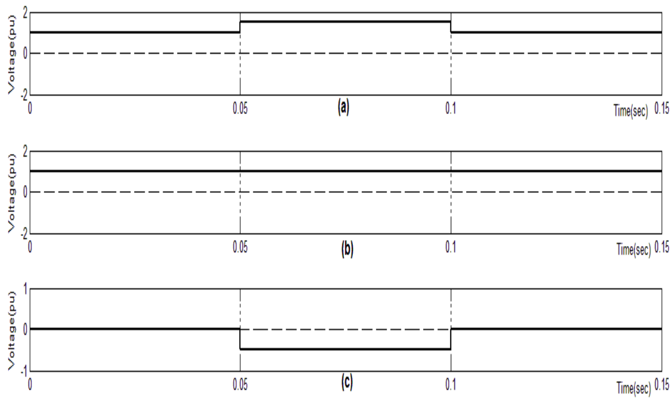

Fig. 10. (a) dqo converted supply voltage. (b) dqo converted reference voltage. (c) Difference between the reference and supply.
(dark line(__): d component; dotted line(----): q component)

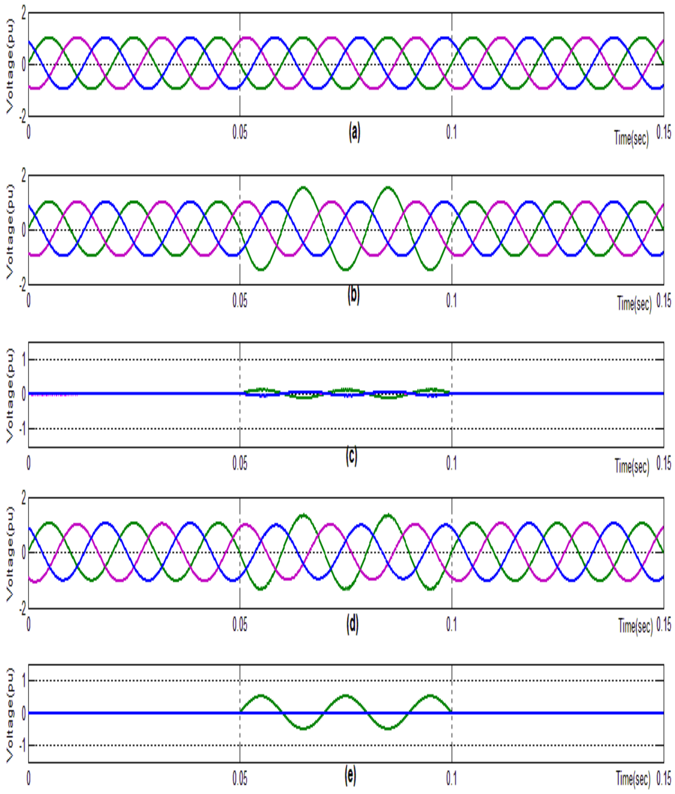

Fig. 11. Single phase voltage swell compensation:(a).Reference Voltage. (b) Single phase swelled supply Voltage. (c) Inverter injection voltage. (d) Compensated load voltage. (e) Modulation signal.

V. CONCLUSION

In this paper, the modeling and simulation of a DVR with Sinusoidal PWM based controller for 3Φ 415V, 50 Hz distribution system has been developed by using Matlab/Simulink. The simulation results show that the DVR compensates the sag and swell effectively and provides excellent voltage regulation. The control system implemented here is based on dqo technique which is a scaled error between supply side of the DVR and its set reference value.

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