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# Voltage Sag and Mitigation Using Algorithm for Dynamic Voltage Restorer by PQR Transformation Theory

**Prof. Shivanagouda B. Patil[1], Dr. Shekhappa. G. Ankaliki[2]**
[1]*E & E Engineering Department, Hirasugar Institute of Technology, Nidasoshi-591 236, Karnataka, India.*
[2]*E & E Engineering Department, SDM College of Engineering & Technology, Dharwad-580 002, Karnataka, India.*

***Abstract—Voltage sag is one of the power quality issue and Dynamic Voltage Restorer (DVR) is used for mitigation of voltage sag. Voltage sag is sudden reduction in voltage from nominal value, occurs in a short time which can cause damage and loss of production in industrial sector. In this paper, focus is given only on DVR using an algorithm and the related implementations to control static series compensators (SSCs). Directly sensed three-phase voltages are transformed to p-q-r co-ordinates without time delay. The controlled variables in p-q-r co-ordinates has better steady state and dynamic performance and then inversely transformed to the original a-b-c co-ordinates without time delay, generating control signals to SSCs. The control algorithm is used in DVR system. The simulated results are verified and mitigation of sag is presented in this paper.***

***Key words—Voltage Sag, Static Series Compensator (SSCs), PQR Transformation, Dynamic Voltage Restorer (DVR)***

## I. INTRODUCTION

In many recent years, power quality disturbances become most issue which makes many researchers interested to find the best solutions to solve it. There are various types of power quality disturbances in which voltage sag, voltage swell and interruption. This paper introduces DVR and its operating principle for the sensitive loads. Simple control based SPWM technique and 'pqr' transformation theory [1] is used in algorithm to compensate voltage sags/swells. A scope of work is DVR system will be simulated by using Matlab/Simulink tool box and results were presented. Due to the increasing of new technology, a lot of devices had been created and developed for mitigation of voltage sag. Voltage sag is widely recognized as one of the most important power quality disturbances [2]. Voltage sag is a short reduction in rms voltage from nominal voltage, happened in a short duration, about 10ms to seconds. The IEC 61000-4-30 defines the voltage sag (dip) as a temporary reduction of the voltage at a point of the electrical system below a threshold [3]. According to IEEE Standard 1159-1995, defines voltage sags as an rms variation with a magnitude between 10% and 90% of nominal voltage and duration between 0.5cycles and one minute [4] & [5]. Voltage sag is happened at the adjacent feeder with unhealthy feeder. This unhealthy feeder always caused by two factors which are short circuits due to faults in power system networks and starting motor which draw very high lagging current. Both of these factors are the main factor creating voltage sag as power quality problem in power system. Voltage sags are the most common power disturbance which certainly gives affecting especially in industrial and large commercial customers such as the damage of the sensitivity equipments and loss of daily productions and finances. An example of the sensitivity equipments are programmable logic controller (PLC), adjustable speed drive (ASD) and chiller control. There are many ways in order to mitigate voltage sag problem. One of them is minimizing short circuits caused by utility directly which can be done such as with avoid feeder or cable overloading by correct configuration. The control of the compensation voltages in DVR based on dqo algorithm is discussed in [6]. DVR is a power electronic controller that can protect sensitive loads from disturbances in supply system. Dynamic voltage restorers (DVR) can provide the most commercial solution to mitigation voltage sag by injecting voltage as well as power into the system. The mitigation capability of these devices is mainly influenced by the maximum load; power factor and maximum voltage dip to be compensated [7]. In [12-17] Voltage Sag Mitigation Using Dynamic Voltage Restorer System are discussed under fault condition and dynamic conditions.

## II. DVR SYSTEM

Dynamic voltage restorer (DVR) is a series compensator which is able to protect a sensitive load from the distortion in the supply side during fault or overloaded in power system. The basic principle of a series compensator is simple, by inserting a voltage of required magnitude and frequency, the series compensator can restore the load side voltage to the desired amplitude and waveform even when the source voltage is unbalanced or distorted [8]. This DVR device employs gate turn off thyristor (GTO) solid state power electronic switches in a pulse width modulated (PWM) inverter structure. The DVR can generate or absorb independently controllable real and reactive power at the load side. The DVR also is made of a solid state dc to ac switching power converter that injects a set of three phase ac output voltages in series and synchronism with the distribution feeder voltages [8]. The amplitude and phase angle of the injected voltages are variable thereby allowing control of the real and reactive power exchange between the DVR and the distribution system [8]. The dc input terminal of a DVR is connected to an energy source or an energy storage device of appropriate capacity. The reactive power exchange between the DVR and the distribution system is internally generated by the DVR without ac passive reactive components. The real power exchanged at the DVR output ac terminals is provided by the DVR input dc terminal by an external energy source or energy storage system. DVR structure comprises rectifier, inverter, filter and coupling transformer shown in Fig.1. Besides, pulse width modulated (PWM) technique is using to control variable voltage. Filter is using for elimination harmonic generated from high switching frequency in PWM technique. In power system network, DVR system is connected in series with the distribution feeder that supplies a sensitive load shown in Fig. 2. There are two main factors relating to the capability and performance of DVR working against voltage sags in a certain power system: the sag severity level and the Total Harmonic Distortion (THD). Both of these in turn are mainly decided by the DC source [9]

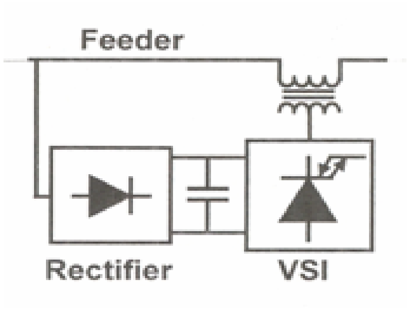


***Fig. 1 DVR Structure***

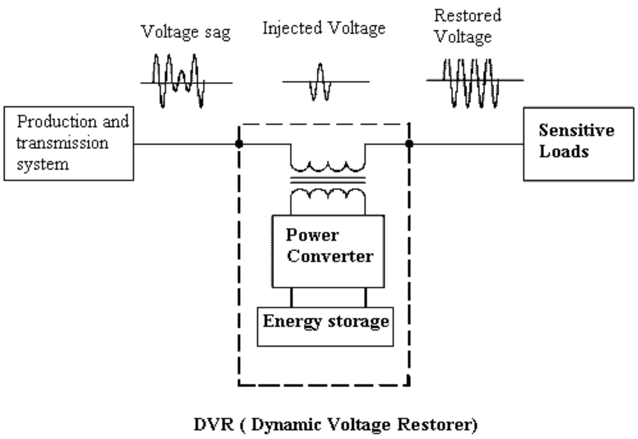


***Fig. 2 DVR System in Power System***

**The Principle Operation of DVR System**

In normal situation without short circuit in power system, a capacitor between rectifier and inverter (Fig. 1) will be charging. When voltage sag happened, this capacitor will discharge to maintain load voltage supply. Nominal voltage will be compared with voltage sag in order to get a difference voltage that will be injected by DVR system to maintain load voltage supply. PWM technique is using to control this variable voltage. In order to maintain load voltage supply, reactive power must be injected by DVR system. Practically, the capability of injection voltage by DVR system is 50% of nominal voltage. It is sufficient for mitigation voltage sag because from statistic shown that many voltage sag cases in power system involving less than 0.5 p.u. voltage drop.

**Mathematical Model for Voltage Sag Calculation**

In this principle the assumption is that the fault current is larger than the load current. The point of common coupling is the point from which both fault and load are fed. Upon the occurrence of the fault which may be a line-line ground fault, a short circuit current flow which leads to reduction in the voltage magnitude at the point of common coupling (PCC) shown in Fig. 3. This voltage sag may be unbalanced and may be accompanied with a phase jump.

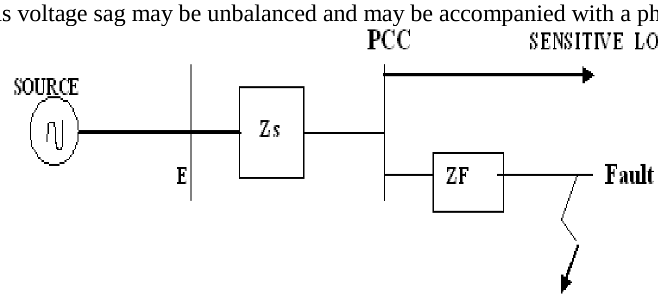


***Fig. 3 Calculation for voltage sag***

$$I_F = \frac{E}{Z_s + Z_F} \quad (1)$$

$$V_{sag} = I_F Z_F \quad (2)$$

$$\Delta\phi = \tan^{-1}\left(\frac{X_F}{R_F}\right) - \tan^{-1}\left(\frac{X_S + X_F}{R_S + R_F}\right) \quad (3)$$

Where

$Z_S = R_S + jX_S$, is the source impedance, $Z_F = R_F + jX_F$, is the impedance between the PCC and the fault, and $E = 1p.u$ is the source voltage. The missing voltage which is the voltage difference between pre-sag condition and sagged (faulted) condition which is given by equation (4) and vectorial representation is shown in Fig. 4.

$$V_{missing} = V_{presag} - V_{sag} \quad (4)$$

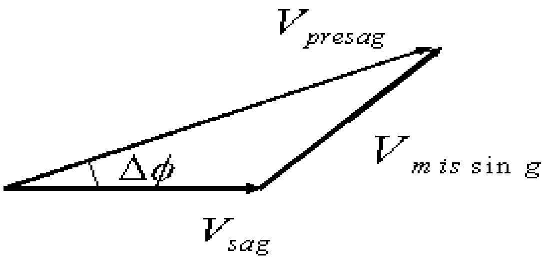


***Fig. 4 Vector Diagram Showing Voltage Sag***

The missing voltage has to be provided by sag compensating device like Dynamic Voltage Restorer (DVR) which is injected in series with the supply voltages to bring the voltages to pre-sag condition.

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## III. PROPOSED APPROACH

The objective of this paper is to implement DVR in series with a sensitive load. It is a series compensating device which injects a set of controllable three-phase AC output voltages, in series and synchronism with the distribution feeder voltages. The DVR employs solid state switching devices in a pulse width modulated inverter (PWMI), the magnitude and phase angle of the injecting voltages can be controlled independently. In this work directly sensed three phase voltages are transformed to p-q-r co-ordinates without time delay [1]. The controlled variables p-q-r co-ordinates have better steady state and dynamic performance. Later these are inversely transformed to the original a-b-c co-ordinates without time delay. It must able to respond quickly and experience no voltage sags to the end users of sensitive equipment shown in Fig. 3.

## IV. BASIC CONTROL STRATEGIES OF DVR

The type of the control strategy mainly depends upon the type of the sensitive or critical load, i.e. it depends on the sensitivity of the load to changes in magnitude, phase shift and wave shape of the voltage wave form. The control techniques adopted should consider the limitations of the DVR like voltage injection capability and energy limit. Voltage sag compensation can be done by DVR using real and reactive power transfer. Reactive power solely will not meet the requirements of dynamic compensation of disturbances that require real power transfer.

The three basic control strategies are,

a) Pre-sag Compensation
b) In-phase Compensation
c) Energy Optimal Compensation

**a) Pre-sag Compensation**

In this technique, the DVR compensates for the difference between the sagged and the presag voltages by restoring the instantaneous voltages to the same phase and magnitude as the nominal pre-sag voltages. In this method, in case there is sag associated with phase shift, full phase compensation is provided so that the load is undisturbed as far as the phase angle and magnitude are concerned. But there is no control of energy injected into the line and often exhausts the rating of the DVR. The vector diagram for pre-sag compensation is shown in Fig. 5.

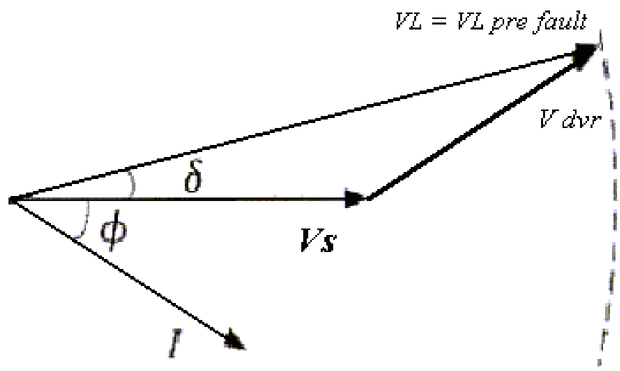



***Fig. 5 Vector Diagram of Pre-sag Compensation***

**b) In-phase Compensation**

In this method, the restored voltages are in-phase with the depressed source side voltages regardless of load current and presag voltages, thus minimizing the magnitude of the injected voltage. Fig.4 shows phase compensation is not provided but has got better performance in compensating a broader range of voltage sags. The vector diagram for inphase compensation is shown in Fig. 6.

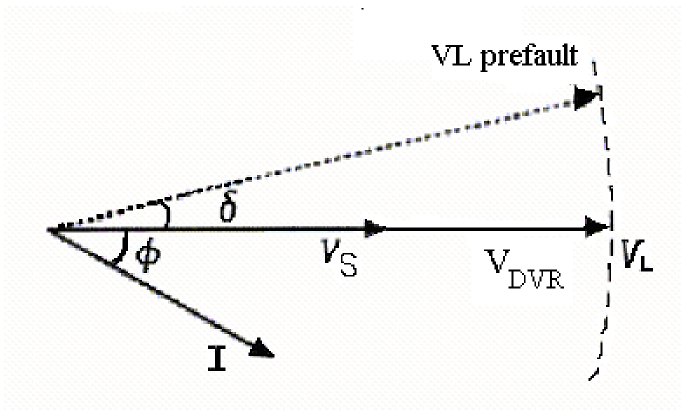



***Fig. 6 Vector Diagram for Inphase Compensation***

**c) Energy Optimal Compensation**

Voltages are injected at an angle that will minimize the use of real power since voltage restoration is the only requirement. That means the DVR voltage is injected perpendicular to the load current but the current will change the phase according to the new voltage applied to it and energy will be drawn from DVR. The vector diagram for optimal compensation is shown in Fig.7.

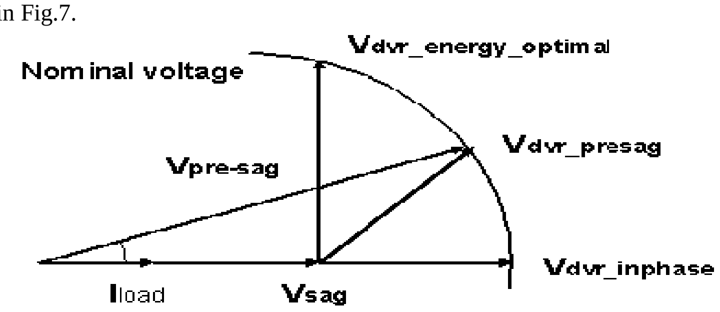



***Fig. 7 Vector Diagram for Optimal Compensation***

## V. COMPUTATION OF COMPENSATING VOLTAGES

There are many methods to calculate the compensating reference voltage waveforms for dynamic voltage restorers. One of those methods is “PQR power theory”. An effective algorithm based on “PQR power theory” is used to calculate reference compensating voltages. In this algorithm, the directly sensed three phase voltages are converted into p-q-r coordinates instantaneously without any time delay. Then the reference voltages in p-q-r domain have simple forms - DC values. The controller in p-q-r domain is very simple and clear, has better dynamic and steady state performance than conventional controllers. The algorithm based on PQR power theory is used to get the reference compensation voltages in p-q-r domain and transformed back to $0\alpha\beta$ domain to drive the space vector modulator to generate the firing signals for inverter.

***PQR Transformation Theory***

The 3-phase voltages of three-phase a-b-c coordinates can be transformed to $o-\alpha-\beta$ coordinates as given below,

$$\begin{bmatrix} V_o \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{5}$$

If sinusoidal balanced voltages $v_{aREF}$ , $v_{bREF}$ and $v_{cREF}$ are selected for the reference waves in the a-b-c coordinates, the reference waves in $o-\alpha-\beta$ coordinates can becalculated and shown below,

$$V^{REF} = \begin{pmatrix} v_{\alpha REF} \\ v_{\beta REF} \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} v_{aREF} \\ v_{bREF} \\ v_{cREF} \end{pmatrix} \tag{6}$$

Since the reference waves $v_{aREF}$ , $v_{bREF}$ and $v_{cREF}$ are sinusoidal balanced, the 0-axis component voltage $v_{oREF}$ does not exist and the reference wave $v_{\alpha REF}$ $v_{\beta REF}$ become sinusoidal and orthogonal on the $\alpha-\beta$ plane.

Using the reference waves $v_{\alpha REF}$ $v_{\beta REF}$ in the $o-\alpha-\beta$ coordinates in a mapping matrix, the voltages in $o-\alpha-\beta$ coordinates can be transformed to p-q-r coordinates as given by (2).

$$\begin{pmatrix} v_p \\ v_q \\ v_r \end{pmatrix} = \begin{pmatrix} 0 & \frac{v_{\alpha REF}}{v_{\alpha\beta REF}} & \frac{v_{\beta REF}}{v_{\alpha\beta REF}} \\ 0 & -\frac{v_{\beta REF}}{v_{\alpha\beta REF}} & \frac{v_{\alpha REF}}{v_{\alpha\beta REF}} \\ 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} v_o \\ v_\alpha \\ v_\beta \end{pmatrix} \tag{7}$$

Where

$$v_{\alpha\beta REF} = \sqrt{v_{\alpha REF}{}^2 + v_{\beta REF}{}^2} \tag{8}$$

Combining (5) and (7) the voltages in a-b-c coordinates can be transformed to p-q-r coordinates as shown below,

Where $C = C_1 C_2$

$$C_1 = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{9}$$

$$C_2 = \begin{pmatrix} 0 & \frac{v_{\alpha REF}}{v_{\alpha\beta REF}} & \frac{v_{\beta REF}}{v_{\alpha\beta REF}} \\ 0 & -\frac{v_{\beta REF}}{v_{\alpha\beta REF}} & \frac{v_{\alpha REF}}{v_{\alpha\beta REF}} \\ 1 & 0 & 0 \end{pmatrix} \quad (10)$$

From p-q-r domain to a-b-c domain can be achieved by taking inverse of C,

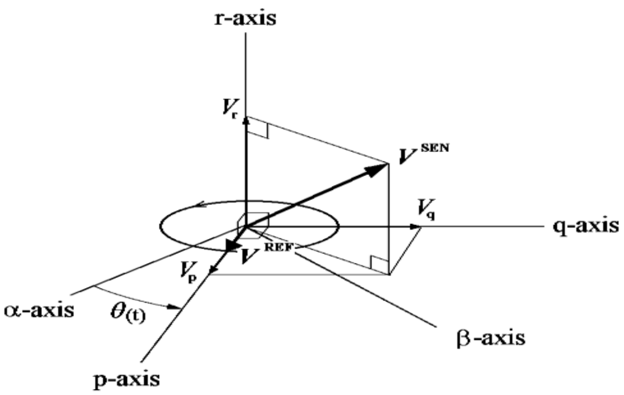
$$\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} = (C)^{-1} \begin{pmatrix} v_p \\ v_q \\ v_r \end{pmatrix} \quad (11)$$

Where $C^{-1} = (C_1 C_2)^{-1} = C_2^{-1} C_1^{-1}$

$$C_1^{-1} = \sqrt{\frac{2}{3}} \begin{pmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \quad (12)$$

$$C_2^{-1} = \begin{pmatrix} 0 & 0 & 1 \\ \frac{v_{\alpha REF}}{v_{\alpha\beta REF}} & -\frac{v_{\beta REF}}{v_{\alpha\beta REF}} & 0 \\ \frac{v_{\beta REF}}{v_{\alpha\beta REF}} & \frac{v_{\alpha REF}}{v_{\alpha\beta REF}} & 0 \end{pmatrix} \quad (13)$$

**PQR Transformation**




When three-phase voltages are sinusoidal and balanced, the locus of the sensed voltage space vector $V_{SEN}$ is a circle on the $\alpha - \beta$ plane. If the three-phase voltages are in-phase with the three-phase reference waves, the sensed voltage space vector $V_{SEN}$ becomes aligned with the reference wave space vector $V_{REF}$. In this case $v_q$ and $v_r$ do not exist while $v_p$ comprises only a dc component that is equal to $|V_{SEN}|$. This condition will be a target for the voltage sag compensation by a DVR.

**DVR *Model Description***

The block diagram of overall control flow is shown in Fig. 9. Here open loop feed forward control technique is adopted. Upon the occurrence of sag, there is a reduction in the phase voltages on the downstream of the DVR. The data is acquired by data acquisition system and detected. The speed with which the sag is detected depends upon the sensors and sag detection algorithms. Then the three phase voltages are processed using PQR algorithm. The reference compensating voltages are generated in PQR domain and transformed back to alpha-beta domain. The alpha and beta axis reference voltages are given as inputs to drive the space vector modulator. The generated firing pulses are used to fire the switches of the voltage Source Inverter (VSI). The topology of the VSI used is conventional 2-level, three-leg inverter and three-level (multi-level configuration) diode clamped inverter. Depending upon the topology of the inverter, the number of firing pulses may be 6/12.

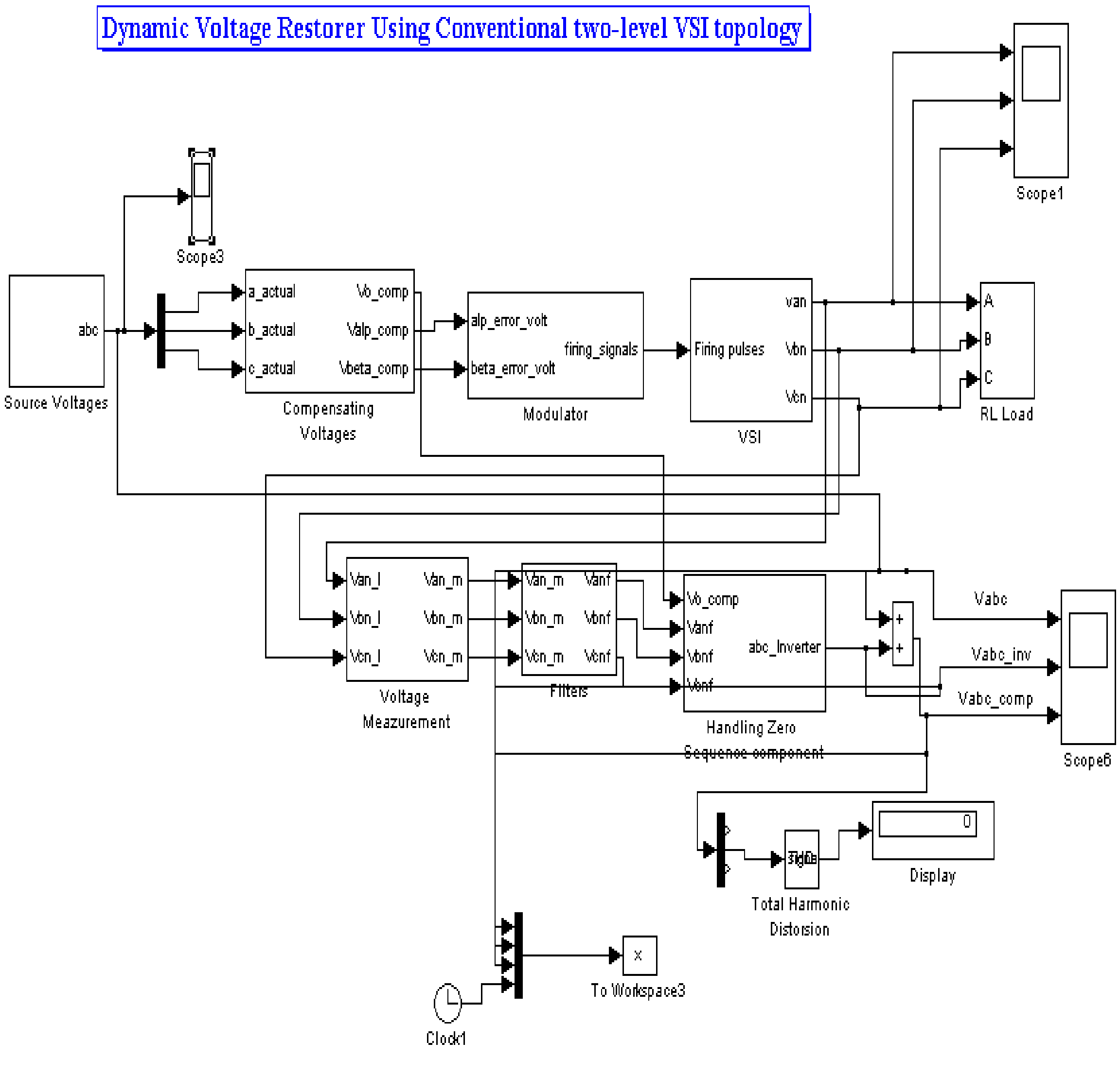



***Fig. 9 Simulation Model of Dynamic Voltage***

## VI. SIMULATION RESULTS

The simulation results carried out using Matlab/Simulink tool box for conventional two-level inverter using space vector modulation scheme is presented.

The data used for simulation is,

$V_{sa} = 230\angle 0°$; $V_{sb} = 230\angle -120°$; $V_{sc} = 230\angle 120°$; $V_{ab} = 350$ V

The three phase output voltages generated by the VSI can be controlled both in magnitude and phase individually. Finally the 3-phase voltages are filtered out by a low pass filter before injecting into the line via booster transformer. All the simulations are carried out using MATLAB/SIMULINK tool box. The phase and line voltages in conventional two-level inverter are shown in Fig.10. The sag compensation by DVR for double line to ground fault is shown in Fig.11. There is voltage sag in phase 'b' and phase 'c'. The DVR provides full magnitude and phase compensation instantaneously.

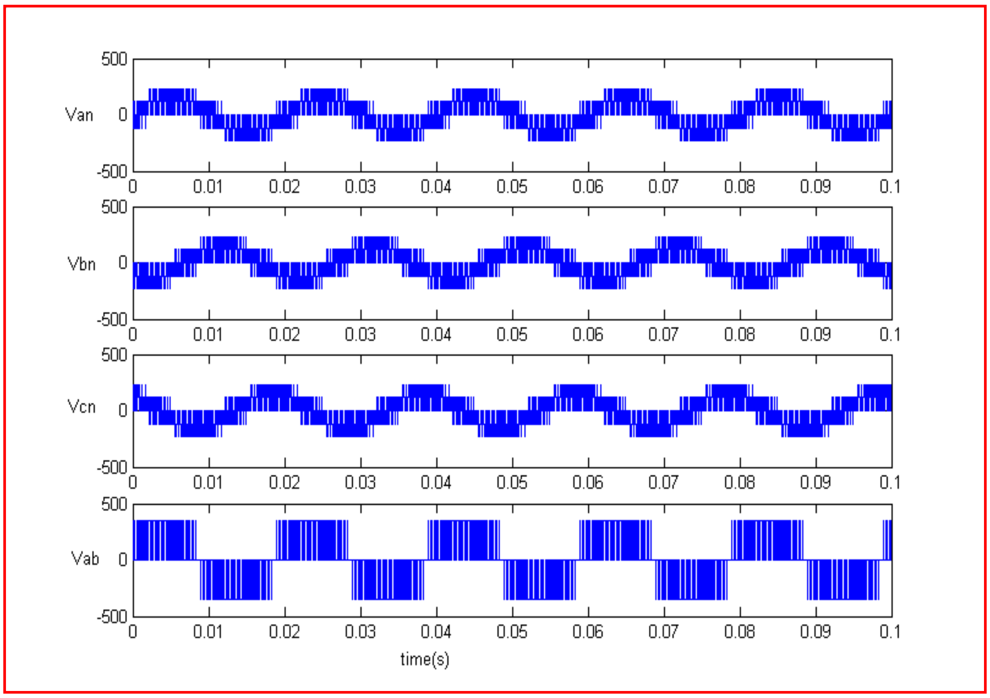



***Fig. 10 Phase and Line Voltages in Conventional Two Level Inverter***

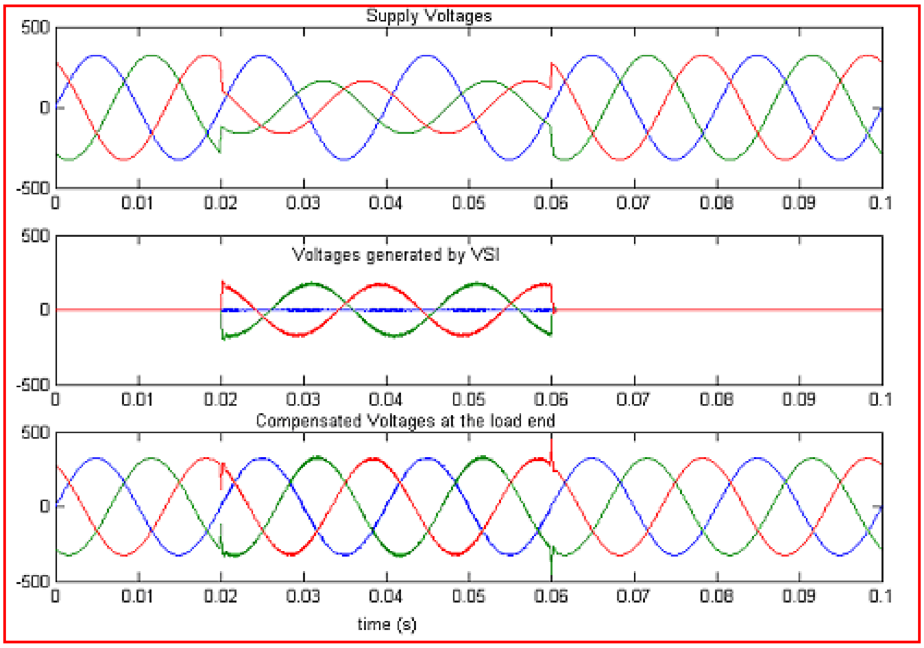



***Fig.11 Compensation of Sag by DVR for Phase b and c.***

## VII. CONCLUSION

In this paper, a complete simulated DVR system has been developed by using MATLAB/SIMULINK tool box. The proposed scheme for DVR uses the PQR algorithm to generate the reference compensation voltages without time delay applied to space vector modulator to drive the conventional two-level topology which generates the required compensation voltages. It is shown that the simulated DVR developed, works successfully without lacks in its performance when applied to a simulated power system network. By introducing DVR in the power network, it can help to improve power quality. It is important to have a good delivery power quality in electrical power systems especially to the critical areas, such as in the industrial sectors, in order to ensure the smoothness of the daily operations.

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