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Design Requirements for a Dynamic Series Compensator for Voltage Sags Mitigation in Low Voltage Distribution System

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Abstract: Power quality issues have become an increasing concern due to an increase of sensitive loads in distribution system. A dynamic series compensator or Dynamic Voltage Restorer (DVR) is a custom device that can be used to protect sensitive loads from various power quality problems from disturbed incoming supply. The dynamic voltage restorer (DVR) has become popular as a cost effective solution for the protection of sensitive loads from voltage sags. This paper highlights a series of discussion, analysis and studies performed on the active power injection requirements for a DVR under various system and load conditions, as well as for different types of fault in both single phase and three-phase fault. The analysis and experimental results validate the effectiveness of the DVR for mitigation voltage sag in low voltage distribution system.

Keywords: Dynamic voltage restorer (DVR), voltage sag, power injected, low voltage, custom device

1. Introduction

There are many methods been used to protect equipment in low voltage distribution system from malfunction due to voltage sags. The voltage sags as defined by IEEE Standard 1159, IEEE Recommended Practice for Monitoring Electric Power Quality, is "a decrease in RMS voltage or current at the power frequency for durations from 0.5 cycles to 1 minute, reported as the remaining voltage". Typical values are between 0.1 p.u. and 0.9 p.u., and typical fault clearing times range from three to thirty cycles depending on the fault current magnitude and the type of over current detection and interruption [1].

Voltage sags are due to short duration increases in current in low voltage distribution system. The main factor causes of voltage sags are faults, motor starting, and transformer energizing. Typical end-use equipment sensitive to voltage sags are: computers, programmable logic controllers, controller power supplies, motor starter contactors, control relays and adjustable speed drives.

The most common mitigation method remains the installation of additional equipment between the power system and the equipment, either directly with the equipment terminals or at the customer-utility interface. The uninterruptable power supply (UPS) has traditionally been the method of choice for small power, single-phase equipment. For large equipment several methods are in use and under development; one of which is the dynamic series compensator, also known under the name "dynamic voltage restorer" or DVR [1, 2].

This paper studies an introduction to DVR and explains it's functions and also presents the active power injection requirements for designing of a dynamic voltage restorer in order to protect sensitive loads from any disturbances.

2. Dynamic Voltage Restorer Operations

A DVR, Dynamic Voltage Restorer is a distribution voltage DC-to-AC solid-state switching converter that injects three single phase AC output voltages in series with the distribution feeder and in synchronicity with the voltages of the distribution system. By injecting voltages of controllable amplitude, phase angle, and frequency (harmonic) into the distribution feeder in instantaneous real time via a series-injection transformer, the DVR can restore the quality of voltage at its load side terminals when the quality of the source side terminal voltage is distorted due to sensitive loads .Generally the DVR comprises of three important parts [7]:

- Voltage Source Converter (VSC)
- DC energy storage
- Control system

Figure 1 shows the basic block diagram of a DVR for single-phase representation.

A. Basic principle

The basic idea of a DVR is to inject the missing voltage cycles into the system through series injection transformer whenever voltage sags are present in the system supply voltage. As a consequence, sag is unseen by the loads. During normal operation, the capacitor receives energy from the main supply source. When voltage dip or sags are detected, the capacitor delivers dc supply to the inverter. The inverter ensures that only the missing voltage is injected to the transformer.

A relatively small capacitor is present on dc side of the PWM solid state inverter, and the voltage over this capacitor is kept constant by exchanging energy with the energy storage reservoir. The required output voltage is obtained by using pulse-width modulation switching pattern. As the controller will have to supply active as well as reactive power, some kind of energy storage is needed. In the DVRs that are commercially available now, large capacitors are used as a source of energy [8]. Other potential sources are being considered are [7]: battery banks, superconducting coils, and flywheels.

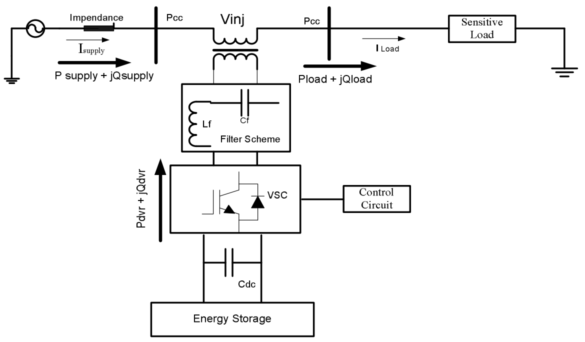


Figure 1: Typical DVR circuit topology (single-phase representation).

B. Control System of a DVR

The aim of the control scheme is to maintain constant voltage magnitude at the point where a sensitive load is connected under system disturbances. The control system only measures the r.m.s voltage at the load point, i.e., no reactive power measurements are required. The VSC switching strategy is based on a space vector PWM technique which offers simplicity and good response. The control of DVR is very important and it involves detection of voltage sags (start, end and depth of the voltage sag) by appropriate detection algorithms which work in real time. The voltage sags can last from a few milliseconds to a few cycles, with typical depths ranging from 0.9 p.u to 0.5 pu of a 1-pu nominal [9].

3. A Conceptual Of the DVR Control with Symmetrical Voltage Sags Controller

A. Control Strategy

The concept of control strategies for a DVR compensating without any phase-angle jump is illustrated in Figure 2. Figure 2 shows the flow of active and reactive power with a DVR inserted. The DVR controller as shown in Figure 2 concept consists of load side voltage (V_{load}), grid or supply voltage (V_{supply}) and injection voltage from transformer (V_{inj}). The relationship between load voltage, injection voltage and supply voltage can described as:

$$\overline{V_{load}} = \overline{V_{inj}} + \overline{V_{supply}} \quad (1)$$

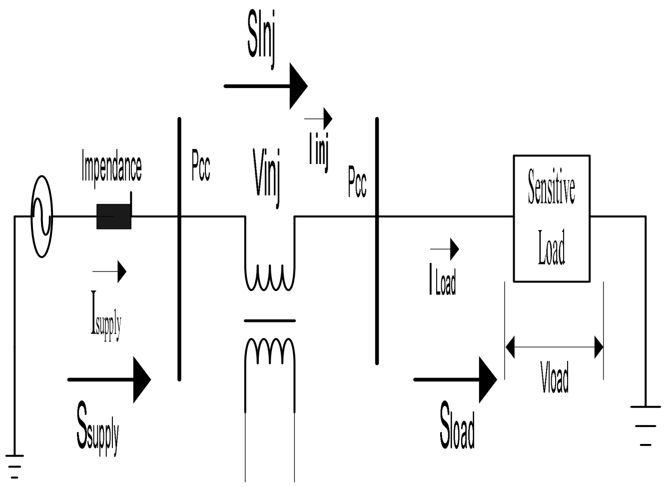


Figure 2: Circuit diagram model of power system, controller and load.

The load voltage is considered maintained at 1 p.u without any phase angle

$$\overline{V_{load}} = |V| < \beta = 1 \quad (2)$$

The voltage during sag, V_{inj} with magnitude V and phase angle α

$$\left.\begin{aligned} \overline{V_{inj}} &= |V|\angle\alpha \\ \overline{V_{inj}} &= V(\cos\alpha + \sin\alpha) \end{aligned}\right\} \quad (3)$$

The load current is equal to 1 pu, with a lagging power factor , $\cos\beta$

$$\left.\begin{aligned}\overline{I_{load}} &= |I_{load}| \angle -\beta \\ \overline{I_{load}} &= I_{load}\left[\cos\beta - j^{\sin\beta}\right]\end{aligned}\right\} \qquad (4)$$

The absorbed apparent power for S_{supply}, S_{inj} and S_{load} can be expressed as:

$$\left.\begin{aligned}S_{supply} &= P_{supply} + j^{Qsupply} \\ S_{inj} &= P_{inj} + j^{Qinj} \\ S_{load} &= P_{load} + j^{Qload}\end{aligned}\right\} \qquad (5)$$

The value of the injected power depends on the load power factor and the phase jump.

$$P_{inj} = \sqrt{3}\,|V_{inj}||I_{load}|\cos(\beta_{load} + \alpha_{inj}) \qquad (6)$$

From equation (5) the active power absorbed by the load is calculated as:

$$P_{Load} = V_{load}\, I_{load}\, \cos\beta \qquad (7)$$

In case of $V_{load} = 1$ and $I_{load} = 1$ therefore ;

$$P_{Load} = 1 \qquad (8)$$

From equation (1) and (2), the voltage injected by the controller can be determined as:

$$\overline{V_{supply}} = 1 - \overline{V_{inj}} \qquad (9)$$

The current through the controller equals the load current:

$$|I_{load}| = |I_{supply}| = \left(\cos\beta - j^{\sin\beta}\right) \qquad (10)$$

The complex power injected by the controller is obtained from (9) and (10):

$$\overline{S}_{supply} = \left(1 - \overline{V_{DVR}}\right) \qquad (11)$$

The active power injected to the load is calculated as:

$$P_{supply} = \sqrt{3}\,|V_{inj}||I_{load}|(\cos\beta_{load}) \qquad (12)$$

The power factor of the load determines how much power from the supply can be increased. The increase in active power ΔP is calculated as[10]:

$$\Delta P = P_{supply\ max} - P_{supply\ pre\text{-}sag}$$

$$\Delta P = P_{supply} = \sqrt{3}\,|V_{supply}||I_{load}| \times (\cos(\beta_{load})) \qquad (13)$$

4. Single Line Of Voltage Sag In Low Voltage Distribution System

Figure 3, 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:

$$V_{sag} = \frac{Z_F}{Z_F + Z_s} \qquad (14)$$

Where ;

$\overline{Z_F}$ is the impedance between the fault and the point-of-common coupling (pcc) of the fault and the load.

$\overline{Z_S}$ is the source impedance at the pcc, the pre-event voltage is considered equal to 1 pu, and all load is assumed to be of the constant-impedance type[3,4].

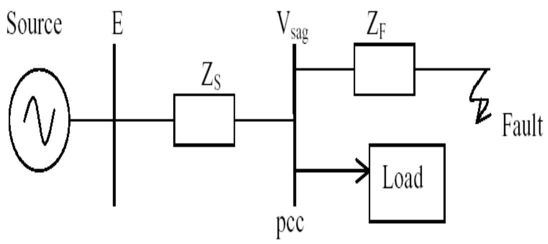


Figure 3: A simple radial circuit of Voltage Sag[3]

$$V_{sag} = \frac{\mu}{\mu + e^{j\varphi}} \qquad (15)$$

Where $\mu = \left|\frac{\overline{Z_F}}{\overline{Z_S}}\right|$ and $\varphi = \arg\left\{\frac{\overline{Z_F}}{\overline{Z_S}}\right\}$

The voltage-divider model gives the so-called "characteristic voltage" for the voltages in the three phases. The model can be applied directly to study the effect of voltage sags on three-phase equipment [4, 5, 6].

A. Three-Phase Unbalance Voltage Sag

Due to different kinds of faults in power systems, different types of voltage sag can be produced most faults in power systems are single phase or three phases. Different types of faults lead to different types of voltage sags. Normally, voltage sag is characterized by a magnitude and duration. In some cases phase-angle jumps are also included. Voltage sags are divided in to seven groups as type A, B, C, D, E, F and G as shown in table (1).Type A is symmetrical and the other types are known as unsymmetrical voltage sag.

B. Balance Voltage Sags

Balance voltage sags are due to three phases and three phase to ground faults. All three-phase voltage magnitudes are equal and lower than the sag threshold with no phase shift.

Table 1 The equations of different voltage sags [1]

TYPE A $\overline{V_a} = V$ $\overline{V_b} = -\frac{1}{2}V - \frac{1}{2}jV\sqrt{3}$ $\overline{V_c} = -\frac{1}{2}V + \frac{1}{2}jV\sqrt{3}$	TYPE B $\overline{V_a} = V$ $\overline{V_b} = -\frac{1}{2}V - \frac{1}{2}j\sqrt{3}$ $\overline{V_c} = -\frac{1}{2}V + \frac{1}{2}j\sqrt{3}$
TYPE C $\overline{V_a} = 1$ $\overline{V_b} = -\frac{1}{2}V - \frac{1}{2}jV\sqrt{3}$ $\overline{V_c} = -\frac{1}{2}V + \frac{1}{2}jV\sqrt{3}$	TYPE D $\overline{V_a} = V$ $\overline{V_b} = -\frac{1}{2}V - \frac{1}{2}j\sqrt{3}$ $\overline{V_c} = -\frac{1}{2}V + \frac{1}{2}j\sqrt{3}$
TYPE E $\overline{V_a} = 1$ $\overline{V_b} = -\frac{1}{2}V - \frac{1}{2}jV\sqrt{3}$ $\overline{V_c} = -\frac{1}{2}V + \frac{1}{2}jV\sqrt{3}$	TYPE F $\overline{V_a} = V$ $\overline{V_b} = -\frac{1}{2}V - \frac{1}{2}j\left(\frac{2}{2} + \frac{1}{2}V\right)\sqrt{3}$ $\overline{V_b} = -\frac{1}{2}V + \frac{1}{2}j\left(\frac{2}{2} + \frac{1}{2}V\right)\sqrt{3}$
TYPE G $\overline{V_a} = \frac{2}{3} + \frac{1}{2}V$ $\overline{V_b} = -\frac{1}{2}\left(\frac{2}{3} + \frac{1}{2}V\right)V - \frac{1}{2}jV\sqrt{3}$ $\overline{V_b} = -\frac{1}{2}\left(\frac{2}{3} + \frac{1}{2}V\right)V + \frac{1}{2}jV\sqrt{3}$	

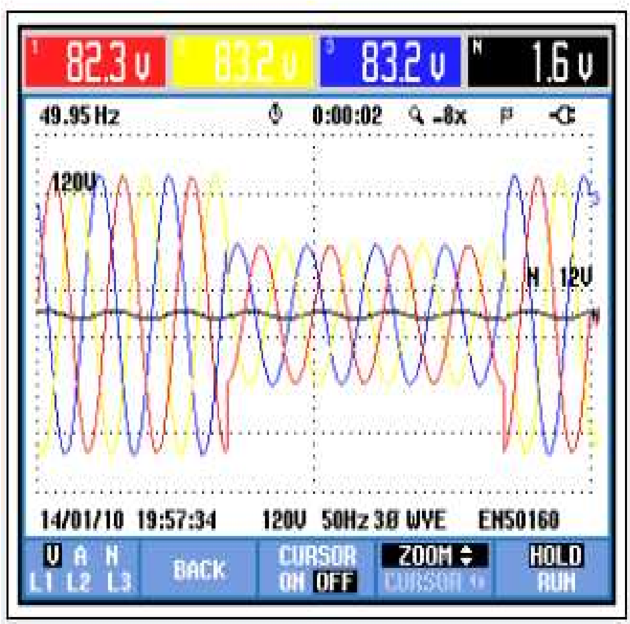
5. Experimental Results

A small scale prototype DVR has been built based on schematic in Figure 1, in order to verify the effectiveness of the DVR operation principles. The experimental results obtained are based on type A, B and E of voltage sags.

The prototype is rated to protect a 5KVA load a 40% voltage sags. Balanced voltage sag is created immediately after a fault as shown in Figure 4(a). The performance during 40% balance voltage sag is illustrated in Figure 4(a).

Figure 4(b) shows the injection voltages produced by the DVR in order to inject missing voltages due to balanced fault from the supply voltages. Restoration voltages on the loads are shown in Figure 4(c).

Figure 5(a) shows experimental waveforms for the source voltages based on type B of voltage sags. One phase voltage magnitude is lower than two other phase voltage .Figure 5(b) shows the DVR compensated for the type B of voltage sags. Load terminal voltages are restored through the compensation by DVR. As can be seen from Figure 5(c), the load voltage is kept at the nominal value with the help of the DVR. Next, the performance of DVR for two phases to ground fault is also investigated. Figure 6(a) shows the series of voltages components for unbalanced conditions two phase to ground fault. Similar to the case of voltage sag for this type, the DVR reacts very fast to inject the appropriate voltage in order to correct the supply voltage as shown in Figure 6(b). The DVR load voltages are shown in figure 6(b). From the results, it shows that the sagged load terminal voltage is restored and help to maintain a balanced and constant load voltage.



(a)

Figure 4(a): Three phase fault Supply Voltages

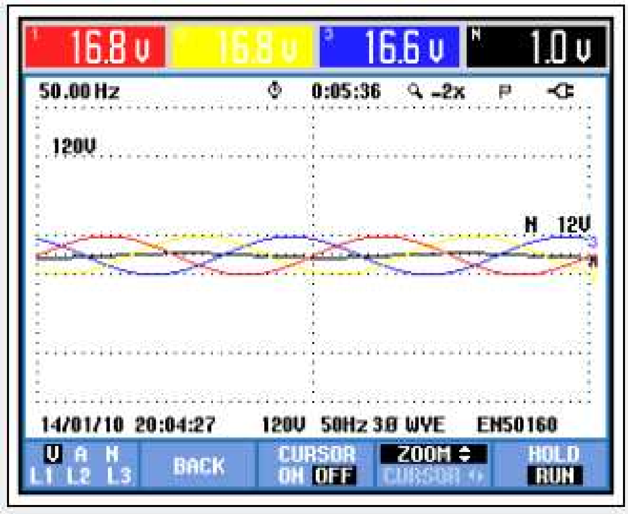


Figure 4(b): Injection Voltage by DVR

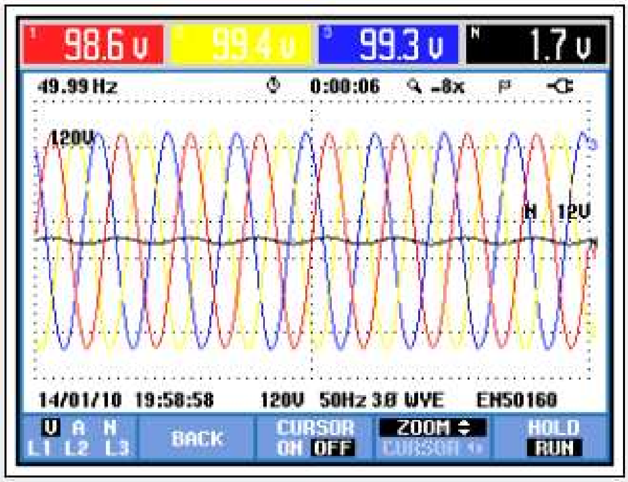


Figure 4(c): Load Voltages Restoration

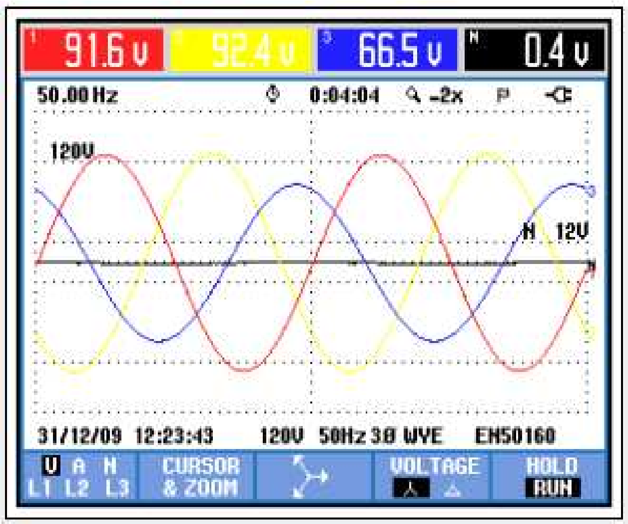


Figure 5(a): Single phase fault Supply Voltages

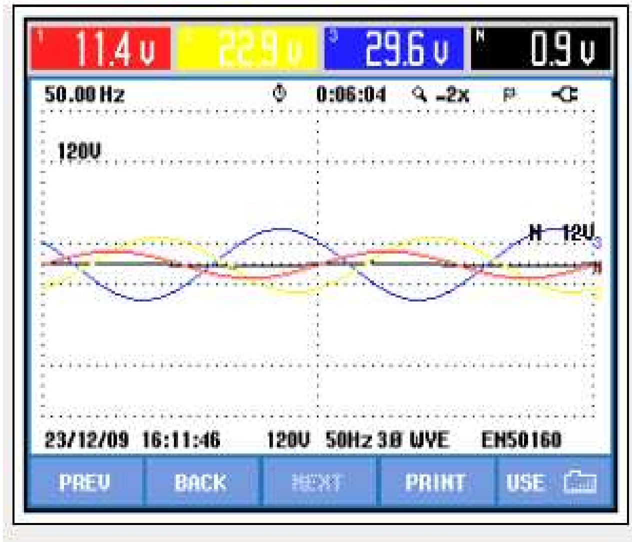


Figure 5(b): Injection Voltages by DVR

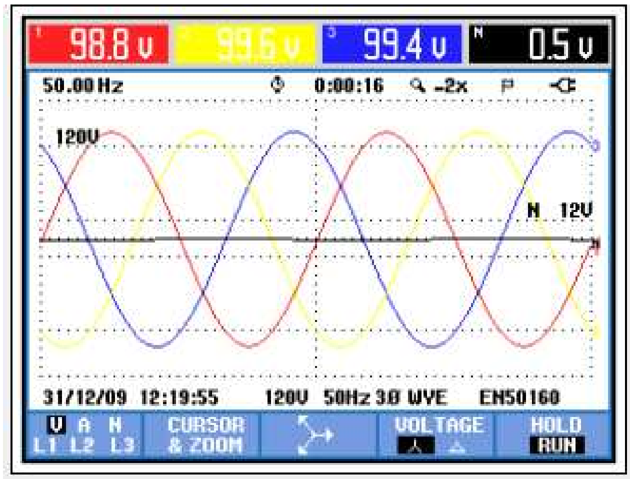


Figure 5(c): Load Voltages Restoration

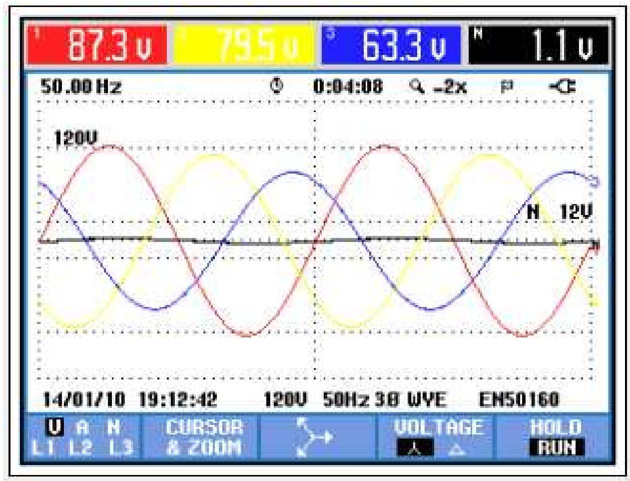


Figure 6(a): Two phases fault Supply Voltages

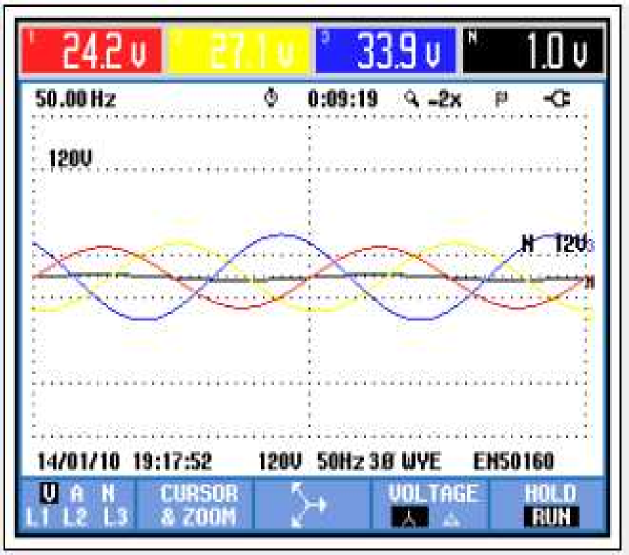


Figure 6(b): Injection Voltages by DVR

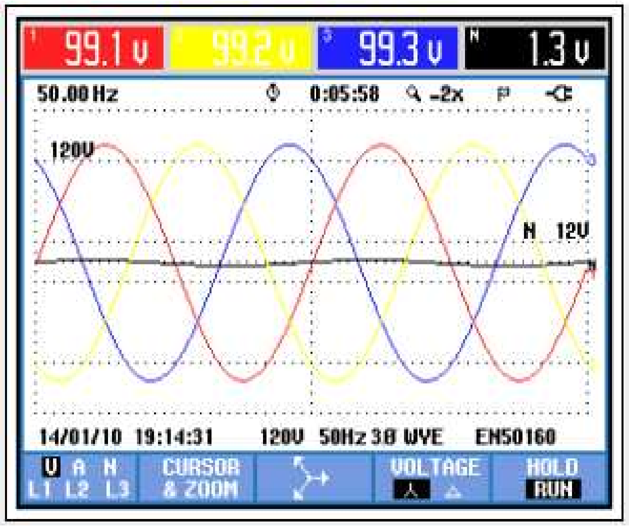


Figure 6(c): Load Voltages restoration

6. Conclusion

This paper analyzes the compensation technique of a DVR for mitigating type A, B and E voltages sags in low voltage distribution system. The Dynamic Voltage Restorer (DVR) is a promising and effective device for power quality enhancement due to its quick response and high reliability. The conclusion is that the DVR is an effective apparatus to protect sensitive loads from short duration voltage sags. The DVR can be inserted both at the low voltage and medium voltage level. The proposed theory has been verified by an experimental DVR system that shows very good performance as predicted by the analysis.

It is shown that the active power requirements of a DVR depend on magnitude and phase-angle jump of the sag as well as on the power factor of the load.

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