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Power Quality Improvement of Single/Two Phase Sensitive Load by a Dynamic Voltage Restorer (DVR)

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***Abstract*:- A Power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure or a mis-operation of end user equipment's. It not only relates largely to voltage but also deals with current and it is largely the corrupting effect of current disturbances upon voltage. A degradation of the power quality may lead to the presence of the voltage disturbance like sag/swells voltage, Flicker, voltage unbalanced, harmonic...etc. This study presents the application of Dynamic Voltage Restorers (DVR) on power distribution systems to improve the power quality. A DVR is a power quality (custom power) device used to correct the voltage disturbances by injecting voltage as well as power into the system. The compensation capability of a Dynamic Voltage Restorer (DVR) depends primarily on the maximum voltage injection ability and the amount of stored energy available within the restorer. Simulation results are presented to illustrate and understand the performances of DVR in supporting load voltages under voltage disturbance conditions.**

Keywords— DVR, Power Quality, Voltage Sags/Swell, FACTS, Voltage Compensation

I. INTRODUCTION

Power Quality is a technical term that has practical implications for business and equipment, when it's seeks to quantify the condition of the electrical supply. It not only relates largely to voltage but also deals with current and it is largely the corrupting effect of current disturbances upon voltage.

Power quality is yet another means of analyzing and expressing electromagnetic compatibility (EMC), but in terms of the frequency spectrum. Power quality characterizes mainly low-frequency phenomena. Perhaps because of this and because of the manner in which it affects electrical equipment, power quality has largely been dealt by engineers with electrical power experience rather than those with an EMC expertise.

Power quality is an issue of increasing importance; it has serious economic implications for customers, utilities and electrical equipment manufacturers, as the share of sensitive electronic circuits is increasing steadily in modern power systems [1, 2].

The impact of power quality problems is increasingly felt by customers-industrial, commercial and even residential. This adds to the cost of the equipment, where the equipment suppliers have to take hard decisions about including features that will tolerate (or withstand) power quality problems.

Power quality problems are associated with an enormous number of electromagnetic phenomena in power systems with broad ranges of time frames such as long duration variations, short duration variations and other disturbances. Short duration variations are mainly caused by either fault conditions or energizing of heavy loads that require high starting currents [3, 4, 5]. There are many different methods to improve the power quality, but the use of a custom power device is considered to be the most efficient one. The concept of custom power was introduced by N.G. Hingorani in 1995. Like Flexible AC Transmission Systems (FACTS) for transmission systems, the term custom power pertains to the use of power electronics controllers in a distribution system, especially, to deal with various power quality problems. Just as FACTS improves the power transfer capabilities and stability margins, custom power makes sure customers get pre-specified quality and reliability of supply. This pre-specified quality may contain a combination of specifications of the following: low phase unbalance, no power interruptions, low flicker at the load voltage, low harmonic distortion in load voltage, magnitude and duration of over-voltages and under-voltages within specified limits, acceptance of fluctuations and poor factor loads without significant effect on the terminal voltage [8]. Each of Custom Power devices has its own benefits and limitations. The most effective type of these devices is considered to be the Dynamic Voltage Restorer (DVR). Compared to the other devices, the DVR clearly provides the best economic solution for its size and capabilities.

This study introduces DVR and its operating principle. Then, analyses of the voltage compensation methods are presented. At the end, simulation results using MATLAB are illustrated and discussed.

The DVR is a Power Quality device, which can protect these industries against the bulk of these disturbances, i.e., voltage sags and swells related to remote system faults. A DVR compensates for these voltage excursions, provided that the supply grid does not get disconnected entirely through breaker trips.

II. DYNAMIC VOLTAGE RESTORER (DVR)

A DVR is a recently proposed series connected solid state device that injects voltage into the system in order to regulate the load side voltage. The DVR was first installed in 1996 [23]. It is normally installed in a distribution system between the supply and the critical load feeder. Its primary function is to rapidly boost up the load-side voltage in the event of a disturbance in order to avoid any power disruption to that load.

A. Injection/Booster Transformer

The transformer is one of the high efficient devices in electrical distribution systems, which are used to convert the generated voltages to convenient voltages for the purpose of transmission and consumption.

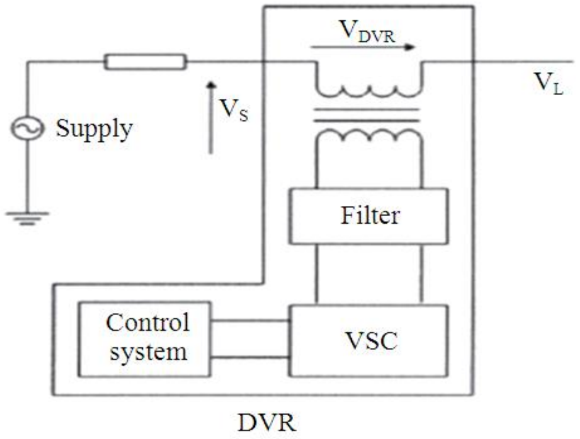

Figure 1. DVR series connected topology

The Injection/Booster transformer is a specially designed transformer that attempts to limit the coupling of noise and transient energy from the primary side to the secondary side. Its main tasks are: connects the DVR to the distribution network via the HV-windings and transforms and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage. In addition, the Injection/Booster transformer serves the purpose of isolating the load from the system (VSC and control mechanism). It is one unit three phase construction [8].

B. Harmonic Filter

The main task of harmonic filter is to keep the harmonic voltage content generated by the voltage source converters to the permissible level. It has a small rating approximately 2% of the load MVA connected to delta-connected tertiary winding of the injection transformer.

C. Voltage Source Converter

A Voltage-Source Converter (VSC) is a power electronic system consisting of a storage device and switching devices, which can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. This converter injects a dynamically controlled voltage in series with the supply voltage through three single-phase transformers to correct the load voltage. There are four main types of switching devices: Metal Oxide Semiconductor Field Effect Transistors (MOSFET), Gate Turn-Off thyristors (GTO), Insulated Gate Bipolar Transistors (IGBT) and Integrated Gate Commutated Thyristors (IGCT). Each type has its own benefits and drawbacks [7].

This model of DVR is based of principal operation of power electronics as IGBT and it's intervening of compensation through relays using the pass switches. In normal conditions the IGBT switch is off and the control system transfers the power to the load through thyristor by pass switch. When voltage disturbance occurs, the control system compensator makes the thyristor turn off and commands the IGBT to turn on and power flows through IGBT and auto transformer. Utilizing the autotransformer and the IGBT improves the output voltage maintains constant in both PWM and voltage controls.

The purpose is to supply the necessary energy to the VSC via a DC link for the generation of injected voltages. The different kinds of energy storage devices are Superconductive Magnetic Energy Storage (SMES), batteries and capacitance. The capacity of the stored energy directly determines the duration of the voltage disturbance which can be mitigating by the DVR.

D. DC Charging Circuit

The DC charging circuit has two main tasks:

The first task is to charge the energy source after a sag compensation event

The second task is to maintain DC link voltage at its nominal voltage

Different topologies are used to charge the DC-link such as an external power supply or by connecting the DC side of the DVR to the controlled or uncontrolled rectifier to maintain the DC voltage.

The other side of the rectifier can be supplied from a main power line or from an auxiliary feeder.

E. Control and Protection

The control mechanism of the general configuration typically consists of hardware with programmable logic. In past DVR development, this would normally consist of Digital Signal Processing (DSP) boards. The software on the DSP board provides the controls such as detection and correction [8].

All protective functions of the DVR should be implemented in the software. Differential current protection of the transformer, or short circuit current on the customer load side are only two examples of many protection functions possibility.

Depending on the particular fault condition, the fast control and protection may switch the DVR into bypass if it becomes inoperable, thus securing an uninterrupted energy flow to the customer's plant [10].

III. BASIC PRINCIPLE OF DVR

The basic idea of a DVR is to dynamically control and inject the missing voltage Vinj(t) into the system through series injection transformer whenever the defaults of voltage are present in the system supply voltage. There are three single-phase transformers connected to a three-phase converter with energy storage system and control circuit. The amplitudes of the three injected phase voltages are controlled so as to eliminate any detrimental effects of a bus fault to the load voltage VL(t). This means that any differential voltage caused by transient disturbances in the AC feeder will be compensated by an equivalent voltage generated by the converter and injected on the medium voltage level through the booster transformer [8, 11].

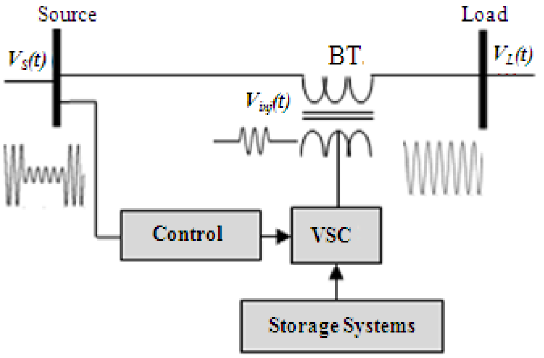

Figure 2. Schematic diagram of DVR system

As a consequence, the voltage disturbance is unseen by the loads. In normal situation without short circuit in power system, a capacitor between rectifier and inverter (Fig. 2) will be charged. When voltage fault happened, this capacitor will discharge to maintain load voltage supply. Nominal voltage will be compared with disturbed voltage in order to get a difference voltage that will be injected by DVR system to maintain load voltage supply VL(t). PWM technique is used to control this variable voltage. To quantify Voltage Disturbance (VD) in radial distribution system, the voltage divider model, shown in Fig. 3, can be used on the assumption that the fault current is much larger than the load current during faults. The Point of Common Coupling (PCC) is the point from which both the fault and the load are connected [4, 13]. From figure. 3, the voltage at the PCC and phase angle jump can be obtained by:

$$V_D = \frac{Z_F}{Z_S + Z_F} E \qquad (1)$$

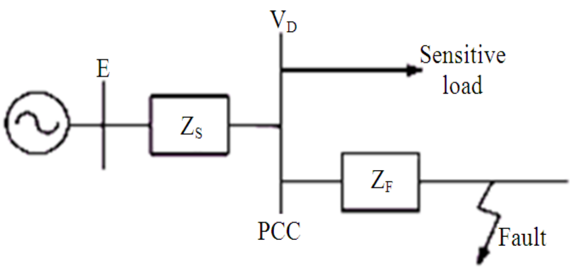

Figure 3. Voltage divider model

$$\Delta\varphi = \arg(\bar{V}_D)\arctan\left(\frac{X_F}{R_F}\right) - \arctan\left(\frac{X_S + X_F}{R_S + R_F}\right) \qquad (2)$$

The DVR is able to compensate the disturbed voltage especially at sensitive loads by injecting an appropriate voltage through an injection transformer. An equivalent circuit diagram of the DVR and the principle of series injection for sag compensation are depicted in figure 4.

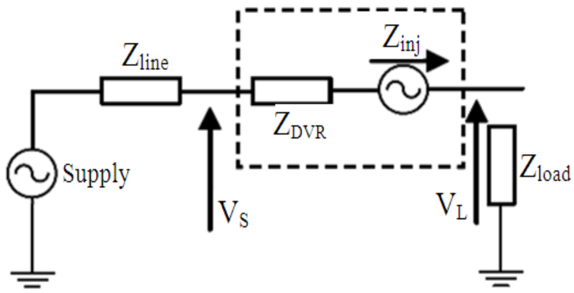

Figure 4. Equivalent circuit of DVR

Mathematically expressed, the injection satisfies:

$$V_L(t) = V_S(t) + V_{inj}(t) \qquad (3)$$

where, VL(t) is the load voltage, VS(t) is sagged supply voltage and Vinj(t) is the voltage injected by the mitigation device as shown in Fig. 5. Under nominal voltage conditions, the load power on each phase is given by (4):

$$S_L = V_L I_L^* = P_L - JQ_L \qquad (4)$$

where, IL is the load current and PLand QL are the active and reactive powers taken by the load respectively during a voltage disturbance. When the mitigation device is active and restores the voltages back to normal, the following applies to each phase:

$$S_L = P_L - JQ_L = (P_S - JQ_S) + (P_{inj} - JQ_{inj}) \qquad (5)$$

Where voltage fault subscripted refers to the sagged supply quantities. The inject subscript refers to quantities injected by the mitigation device

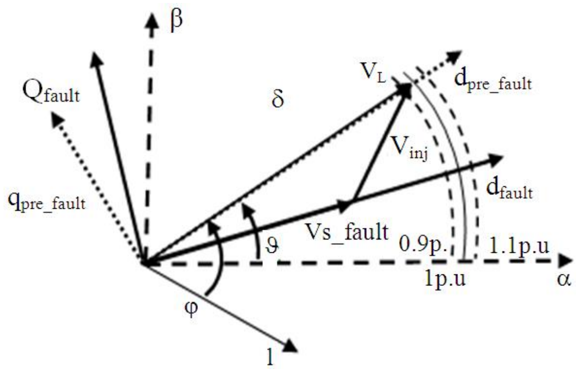

Figure 5. Compensation strategy of DVR for voltage faults

IV. SIMULATION

In order to understand the performance of the DVR in voltage disturbance, a simple distribution network is simulated using MATLAB/SIMULINK (Fig. 2). A DVR is connected to the system through a series transformer with a transformation rate equal to 1:1.

The DVR is based on three phase voltages PWM inverter with LC output filter to remove high frequency voltage components. An RL load (R = 10Ω, L = 10-5H) is considered.

A. *Voltage Sags*

A case of voltage sags is simulated by connecting a three-phase reactance to the busbar. The results are shown in figure. 6.

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Figure 6 (a) shows that 25 % voltage sag is initiated at 0.08s and it is kept until 0.16s. Figures 6 (b) shows the injection voltages produced by the DVR in order to inject the missing voltages due to balanced fault from the supply voltages and figure 6 (c) shows the compensated load voltage. As a result of DVR use, the load voltage is kept at 220 Vrms throughout the simulation, including the voltage sag period. One can observe that during normal operation, the DVR is doing nothing. It quickly injects necessary voltage components to smooth the load voltage upon detecting voltage sag.

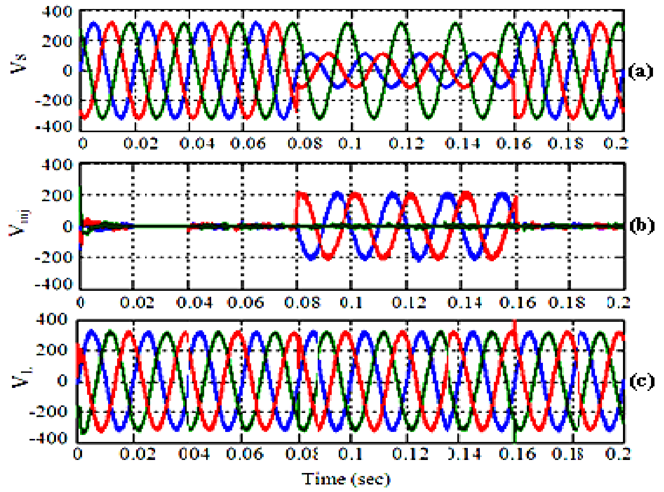

Figure 6. Simulation result of DVR response to balanced voltage sag with connection load: (a) supply voltage, (b) DVR injected voltage, (c) load voltage

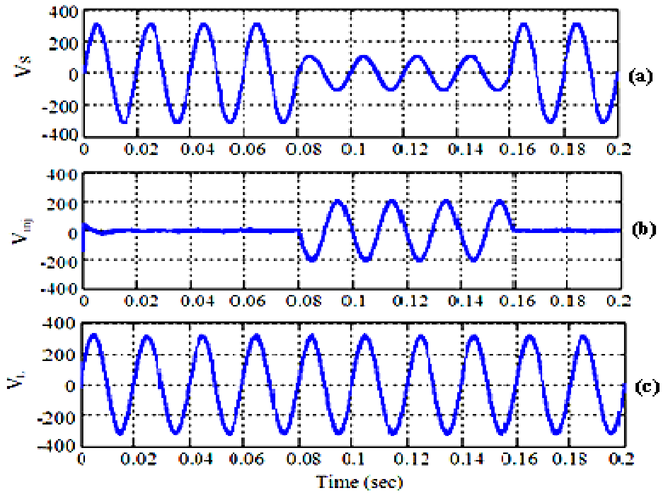

Figure 7. Single-phase voltage sag: a)-Source voltage, b)-Injected voltage, c)-Load voltage

In order to understand the performance of the DVR under unbalanced conditions, Single-phase voltage sag at supply bus bar is simulated and the results are shown in figure 7. The supply voltage with one phase voltage dropped down to 25% is shown in figure 7 (a).

The DVR injected voltage and the load voltage are shown in figure 7 (b) and c, respectively. As it can be seen from the results, the DVR is able to produce the required voltage components for different phases rapidly and help to maintain a balanced and constant load voltage at 220Vrms.

B. Over Voltage

Next, the performance of DVR for a voltage swell condition is investigated.

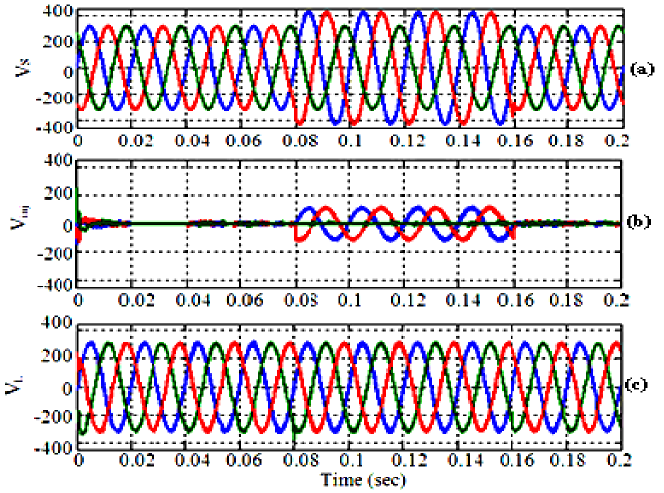

Figure 8. Two-phase voltages swell: (a)-Source voltage, (b)-Injected voltage, (c)-Load voltage

In this case, two of the three phases are higher by 30% than the third phase as shown in figure 8 (a). The voltage amplitude is increased about l30% of nominal voltage.

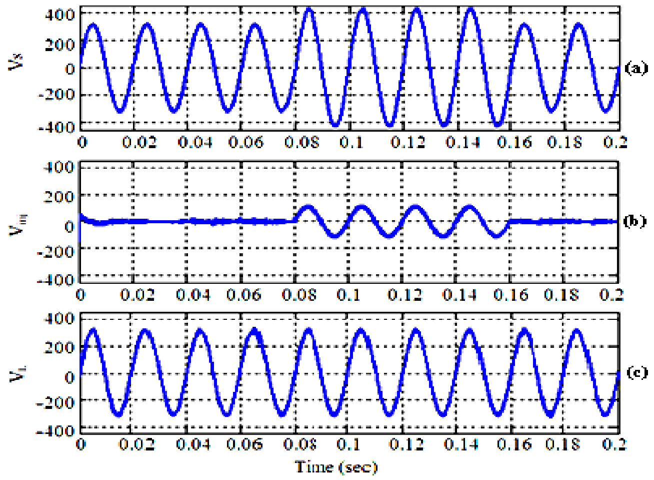

Figure 9. Single-phase voltages swell: (a)-Source voltage, (b)-Injected voltage, (c)-Load voltage.

The injected voltage that is produced by DVR in order to correct the load voltage and this former are shown in Fig.8b and c, respectively. As it can be seen from the results, the load voltage is kept at the nominal value.

Similar to the case of voltage sag, the DVR reacts quickly to inject the appropriate voltage component (anti phase with the supply voltage or negative voltage magnitude) to correct the supply voltage.

C. Voltage Unbalance

Electrical networks are normally three-phase. They supply three-phase loads but also a large number of single-phase loads. The currents absorbed on the three phases are thus of different amplitude, which results in voltage unbalances.

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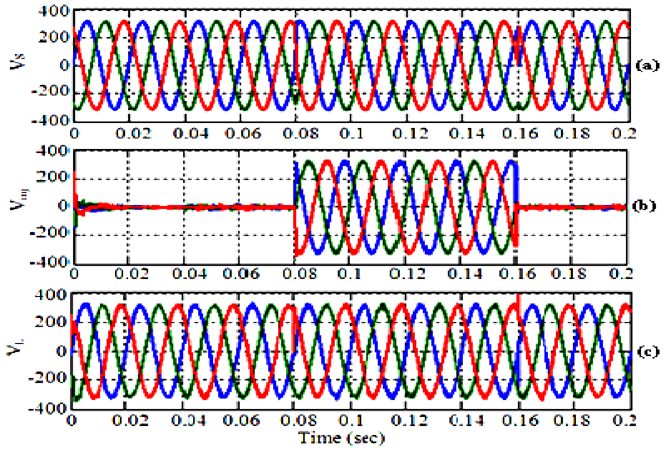

Figure 10. Voltage unbalance: (a)-Source voltage, (b)-DVR Injected voltage, (c)-Load voltage

There are also a few disturbances of much higher/much lower amplitude, these are mainly caused by short-circuits close to the point of measurement. Unsymmetrical short-circuits severely disturb the voltage balance of the three-phase power system and thus create large under- or overvoltage.

This case is shown in figure 10 (a), the typical length of such rare events is about 80 ms. The injected voltage that is produced by DVR in order to correct the load voltage and this former are shown in figure 10 (b) and (c), respectively. As it can be seen from the results, the load voltage is kept at the nominal value.

These voltage unbalances generate negative sequence components that mainly lead to unwanted braking torques and temperature rises in AC motors.

D. Voltage Variations and Fluctuations

Voltage variations are variations in the rms value or the peak value with amplitude. Voltage fluctuations are a series of voltage changes or cyclical or random variations in the voltage envelope which are characterized by the frequency of variation and the magnitude.

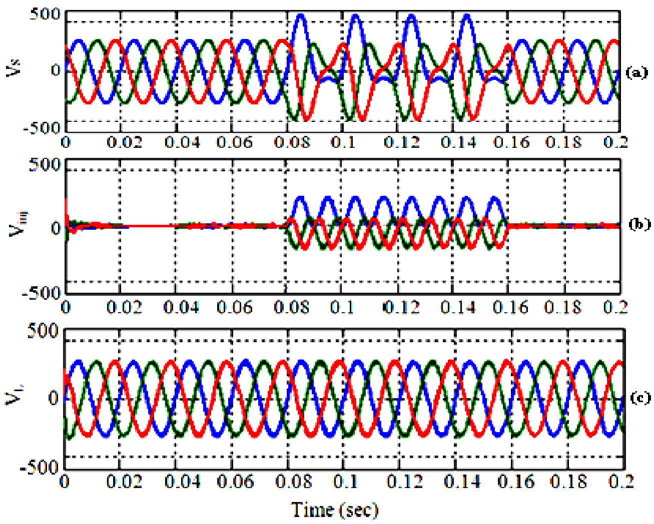

Figure 11. Simulation result of DVR response to variation and fluctuation voltage deformation with connection load: (a) supply voltage, (b) DVR injected voltage, (c) load voltage

Slow voltage variations are caused by the slow variation of loads connected to the network and voltage fluctuations are mainly due to rapid variationof industrial loads such as welding machines, arc furnaces or rolling mills.

The performance of the DVR with an unbalanced voltage deformation is shown in figure 11 The compensating voltage injected by the DVR is shown in figure 11 (b) and the load voltage is given in figure 11 (c). Notice the constant and balanced voltage across the load.

E. Harmonic

In a DVR, there are two main considerations in its working performance: the compensation capability and the output voltage quality. It is revealed by simulation that the value of the DC source voltage has also some side-effect as distortion to the output waveform. In addition, the severity of sag decides whether or not the DVR with that set value of DC voltage is capable of compensating.

In other words, the main factor relating to the capability and performance of DVR is the Total Harmonic Distortion (THD) introduced to protected load. This factor is mainly decided by the DC source.

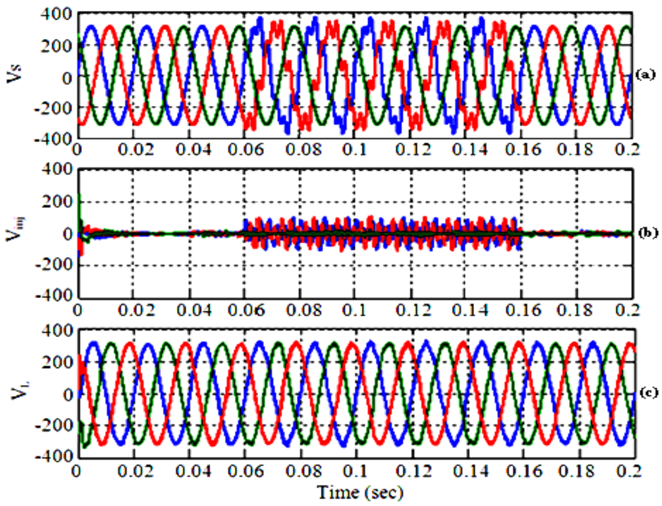

Figure 12. Degradation of network voltage caused by a non-linear load: (a)-Voltage harmonics in two phase of source voltage, (b)- Injected voltage, (c)-Load voltage

The corresponding phase voltage waveforms are shown in figure 12 (a), where the voltage supply has amplitude the 220Vrms and a THD equalized to 10.61%. In this case, our system is polluted. The performance of DVR is shown in Fig. 12b when the amount of harmonics injected into the network to clean up fueled voltage sensitive load. It can be seen that during normal operation, the average value of harmonic distortion in voltage waveform is within the limit, the THD equals to 1.84% (Figure 12c).

The DVR is capable to compensate the voltage harmonics, because the switching frequency is much high than the line frequency, the size of both input filter and output filter are highly reduced. By using the designed output filter, the harmonic voltage is eliminated and the sinusoidal compensation voltage is obtained.

V. CONCLUSION

In this study, performance of DVR in power quality is demonstrated via the obtained results under MATLAB / SIMULINK. A forced commutated voltage sources converter is considered in the DVR along with energy storage to maintain the capacitor voltage.

The DVR handles both balanced and unbalanced situations without any difficulties and injects the appropriate voltage component to correct any anomaly in the supply voltage to keep the load voltage balanced and constant at the nominal value.

In the case of voltage sag, which is a condition of a temporary reduction in supply voltage, the DVR injects an equal positive voltage component in all three phases, which are in phase with the supply voltage to correct it. On the other hand, for a voltage swell case, which is a condition of a temporary increase in supply voltage, the DVR injects an equal negative voltage in all three phases, which are anti-phase with the supply voltage. For unbalanced conditions, the DVR injects an appropriate unbalanced three-phase voltage components positive or negative depending on whether the condition of unbalanced.

In this part, the DVR robustness is tested in the critical condition due to the load current prompt variations. Finally, the study of DVR capability and quality performance was examined thoroughly.

This discusses appropriate ways to configure DVR so that it can deal with all types and levels of voltage disturbance. This addresses the harmonic distortion problem that DVR produces in the power system.

DVR is considered to be an efficient solution due to its low cost, small size and fast dynamic response. It presents excellent performance to protect critical loads against balanced voltage disturbance.

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