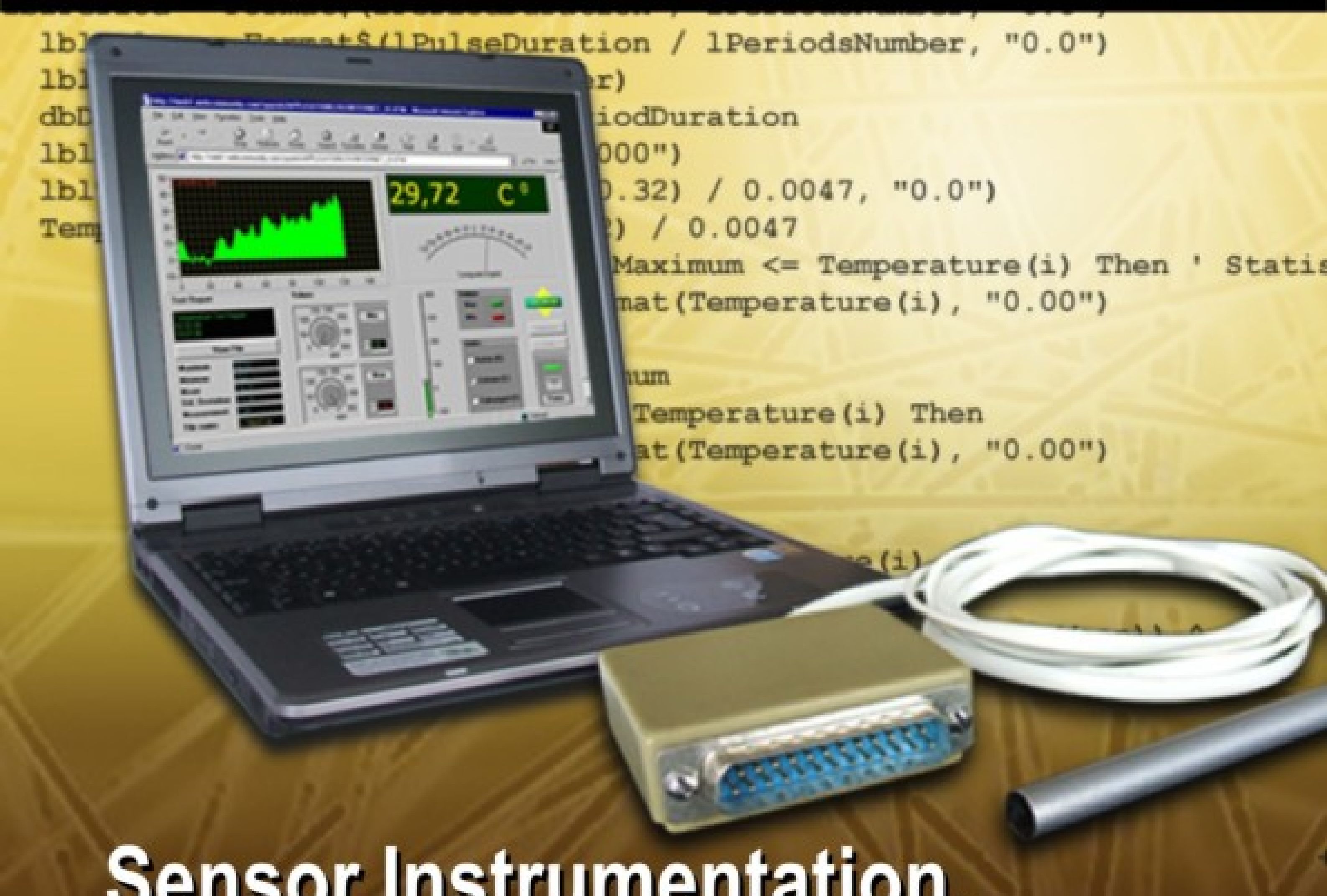
ISSN 1726-5749

SENSORS & TRANSDUCERS

1 /08 vol. 87



Sensor Instrumentation, DAQ and Virtual Instruments

International Frequency Sensor Association Publishing

Sensors & Transducers

Volume 87
Issue 1
January 2008

www.sensorsportal.com

ISSN 1726-5479

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA). Available in electronic and CD-ROM.

Sensors & Transducers Journal

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January 2008

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Modeling & Simulation of Dynamic Voltage Restorer (DVR) for Enhancing Voltage Sag

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Received: 3 November 2007 /Accepted: 21 January 2008 /Published: 28 January 2008

Abstract: The aim of this paper is to summaries the fundamental aspects of voltage sag production and their effects on power quality as well as enhancing this power quality in distribution network, using FACTS (Flexible AC Transmission System) Devices i.e. Dynamic Voltage Restorer (DVR). DVR is a powerful custom power device for short duration voltage compensation, which is connected in series with the load & hence it possesses some advantages. (In this paper detailed modeling and simulation and analysis of the DVR device is presented). *Copyright © 2008 IFSA.*

Keywords: Dynamic voltage restorer (DVR), Voltage sag, Power quality, FACTS

1. Introduction

Voltage Sag (Fig.1) is a momentary decrease in the root mean square voltage between 0.1 to 0.9 per unit, with a duration ranging from half cycle up to 1 min .In other word it is defined as a sudden reduction of supply voltage down 90% to10% of nominal and followed by a recovery after short period of time. A normal duration of sag according to standards is, 10 ms to 1 minute. It is considered as the most serious problem of power quality. It is caused by fault in power system or by starting of large induction motor. It can interrupts or malfunction any electronic or electrical equipment which is sensitive to load. Therefore huge losses result, due to voltage sag problem at customer load end.

Fig. 1. Sag or dip.

Dynamic Voltage Restorer (DVR) and Static compensator (STATCOM) have been recently used as active solution for voltage sag mitigation. It is a device that injects a Dynamic controlled voltage in series to the bus voltage by means of a booster transformer. DVR installed in front of a critical load will appropriately provide correction to the load only.

2. Dynamic Voltage Restorer

The Dynamic Voltage Restorer (DVR), Fig.2, is designed to mitigate voltage sags on lines feeding sensitive equipment. A viable alternative to uninterruptible power systems (UPS's) and other utilization voltage solutions to the voltage sag problem, the DVR is specifically designed for large loads (2 MVA and up) served at distribution voltage. A DVR is expected to be a lower cost alternative to UPS for applications at distribution voltage. A DVR typically requires less than one-third the nominal power rating of the UPS. Also, the DVR can be used to mitigate troublesome harmonic voltages on the distribution system. The DVR is available in 2 MVA increment sizes up to 10 MVA.

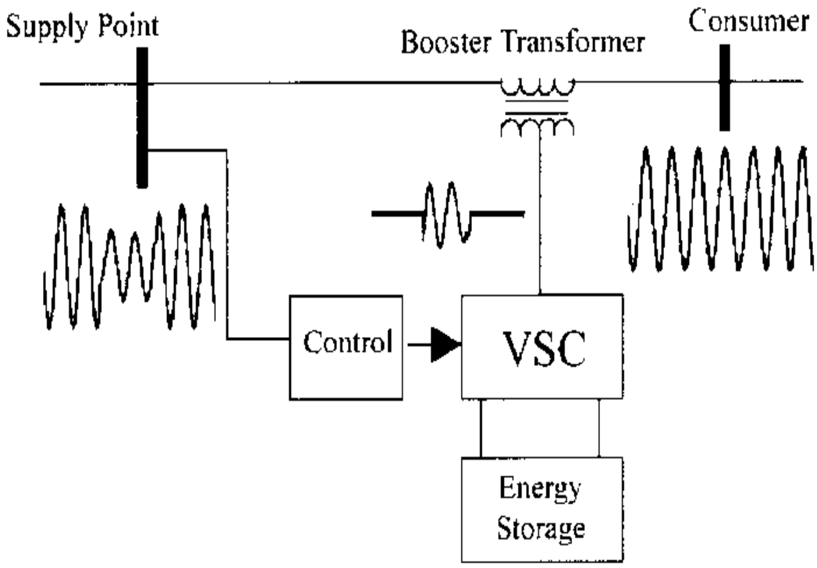

Fig. 2. Schematic diagram of DVR System.

The majority of voltage sags are within 40% of the nominal voltage. Therefore, by designing drives and other critical loads, capable of riding through sags, with magnitude of up to 40%, interruption of processes can be reduced significantly. The DVR can correct sags resulting from faults in either the transmission or the distribution system.

3. Modeling of DVR

Power quality has a significant influence on high-technology equipments related to communication, advanced control, automation, precise manufacturing technique and on-line service. For example, voltage sag can have a bad influence on the products of semiconductor fabrication with considerable financial losses. Power quality problems include transients, sags, interruptions and other distortions to the sinusoidal waveform. One of the most important power quality issues is voltage sag that is a sudden short duration reduction in voltage magnitude between 10 and 90% compared to nominal voltage. Voltage sag is deemed as a momentary decrease in the rms voltage, with duration ranging from half a cycle up to one minute. Deep voltage sags, even of relatively short duration, can have significant costs because of the proliferation of voltage-sensitive computer-based and variable speed drive loads. The fraction of load that is sensitive to low voltage is expected to grow rapidly in the coming decades. Studies have shown that transmission faults, while relatively rare, can cause widespread sags that may constitute a major source of process interruptions for very long distances from the faulted point. Distribution faults are considerably more common but the resulting sags are more limited in geographic extent. The majority of voltage sags are within 40%of the nominal voltage. Therefore, by designing drives and other critical loads capable of riding through sags with magnitude of up to 40%, interruption of processes can be reduced significantly. The DVR can correct sags resulting from faults in either the transmission or the distribution system.

4. Simulation of DVR

To quantify voltage sag 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 fed. Voltage sag is mostly unbalanced and accompanied by phase angle jump.

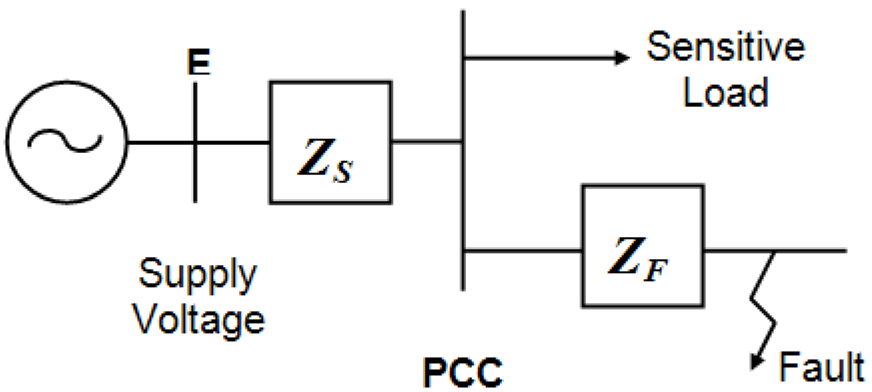

Fig.3. Voltage divider model for Voltage Sag.

From Fig. 3, the voltage at the PCC and phase angle jump can be obtained by

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} E = \frac{Z_F}{Z_S + Z_F}$$

$$\Delta\phi = \arg(\bar{V}_{sag}) = \arctan\left(\frac{X_F}{R_F}\right) - \arctan\left(\frac{X_S + X_F}{R_S + R_F}\right)$$

The design of the DVR allows real and reactive power to be either supplied or absorbed when operating. If a small fault occurs on the protected system, then the DVR can correct it using only reactive power generated internally. For correction of larger faults, the DVR may be required to develop real power. To enable the development of real power an energy storage device must be used; currently the DVR design uses a capacitor bank. Once the fault has been corrected and the supply is operating under normal conditions, the DVR replenishes the energy expended from the healthy system. The rating (in terms of energy storage capabilities) of the capacitor bank is dependent upon system factors such as the rating of the load that protects and the duration and depth of anticipated sags. When correcting large sag (using real power), the power electronics are fed from the capacitor bank via a DC-DC voltage conversion circuit.

The core element in DVR design is the three-phase voltage converter. This inverter utilizes solid-state power electronics (insulated gate bipolar transistors, IGBTs) to convert DC to AC and back again during operation. The DVR connects in series with the distribution line through an injection transformer, actually three single-phase transformers. The primary side (connected into the line) must be sized to carry the full line current. The primary voltage rating is the maximum voltage the DVR can inject into the line for a given application. The DVR rating (per phase), is the maximum injection voltage times the primary current. The bridge outputs on the secondary are filtered before being applied to the injection transformer. The bridges are independently controllable to allow each phase to be compensated separately. The output voltage wave shapes are generated by pulse-width modulated switching. When voltage sag reaches a value below the limit for correction using zero energy, the energy storage system within the DVR has to be used to aid voltage correction.

The ideal restoration is to make load voltages unchanged. When DVR restores large voltage disturbances, active power or energy should be injected from DVR to distribution system. If the capability of energy storage of DVR were infinite, DVR could maintain load voltage unchanged ideally during any kind of faults. However, the stored energy in DVR is limited practically by the limit of DC link capacity of DVR. Namely, DVR cannot restore the load voltage constantly when the voltage across the DC link has gone down and stored energy has run out eventually during deep voltage sag with long duration. Therefore, it is necessary to minimize energy injection from DVR.

There are several methods how to inject DVR mitigating voltage to distribution system: pre-sag compensation, in-phase compensation, and phase advance.

5. Conventional DVR Voltage Injection Methods

The possibility of compensating voltage sag can be limited by a number of factors including finite DVR power rating, different load conditions, and different types of voltage sag. Some loads are very sensitive to phase angle jump and others are tolerant to phase angle jump. Therefore, the control strategy depends on the type of load characteristics. There are three distinguishing methods to inject DVR compensating voltage, that is, pre-sag compensation method, in-phase compensation method, and phase advance method.

Pre-sag compensation methods are to track supply voltage continuously and compensate load voltage during fault to pre-fault condition. Fig. 4 shows the single-phase vector diagram of the pre-sag compensation. In this method, the load voltage can be restored ideally, but injected active power cannot be controlled and is determined by external conditions such as the type of faults and load condition.

In in-phase compensation shown in Fig. 5 the injected DVR voltage is in phase with measured supply voltage regardless of the load current and the pre-fault voltage. The advantage of this method is that magnitude of injected DVR voltage is minimized for constant load voltage magnitude.

Pre-sag compensation and in-phase compensation must inject active power to loads almost all the time. However, the amount of possible injection active power is confined to the stored energy in DC link, which is one of the most expensive components in DVR. Due to the limit of energy storage capacity of DC link, the DVR restoration time and performance are confined in these methods. For the sake of controlling injection energy, phase advance method was proposed (Fig. 6).

The injection active power is made zero by means of having the injection voltage phasor perpendicular to the load current phasor. This method can reduce the consumption of energy stored in DC link by injecting reactive power instead of active power. Reducing energy consumption means that ride-through ability is increased when the energy storage capacity is fixed. On the other hand, the injection voltage magnitude of phase advance method is larger than those of pre-sag or in-phase method and the voltage phase shift can cause voltage waveform discontinuity, inaccurate zero crossing, and load power swing. Therefore, phase advance method should be adjusted to the load that is tolerant to phase angle jump, or transition period should be taken while phase angle is moved from pre-fault angle to advance angle:

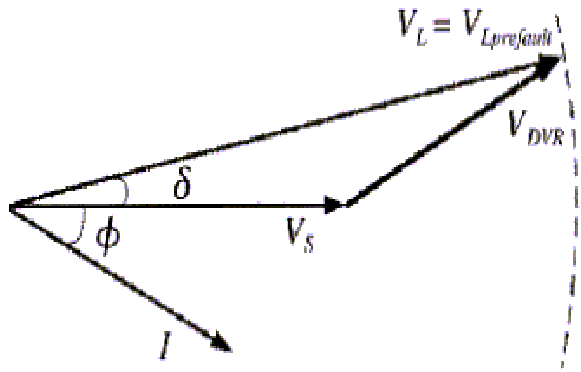

Fig. 4. Vector diagram of pre-sag compensation.

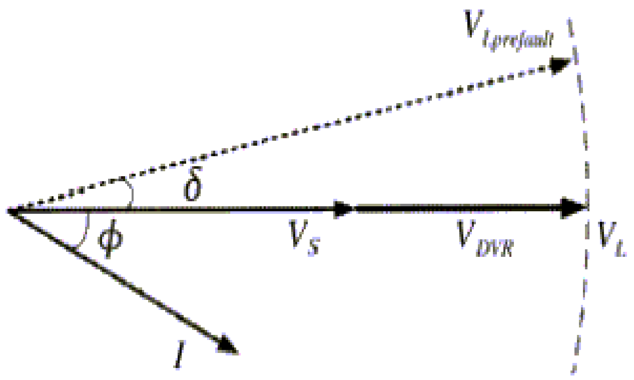

Fig. 5. Vector diagram of in-phase compensation.

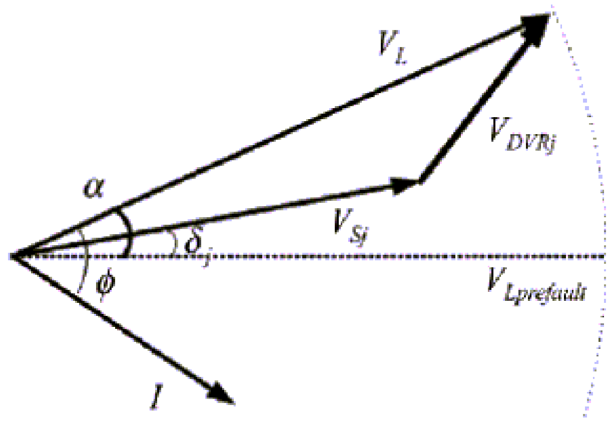

Fig. 6. Vector diagram of phase advance method.

6. A Three Phase DVR and its Control

A sample three phase DVR capable of maintaining the load voltage balanced and of constant amplitude against flicker, harmonics, sags, swells and unbalance in supply and unbalance in load is discussed below.

The three phase inverter is made by three single phase inverters connected to star connected primary of interface transformer. The secondaries are connected in series with the lines. The three phase inverter rating is 10kVA and the transformer has a turn's ratio of 1:5. This means that the inverter can inject up to 20% of rated voltage in series with the supply. Inverter modulator will saturate after that and clip the injected voltage at around 65V peak (assuming 320V peak phase voltage). The maximum load in the supply line is assumed to be around 50kVA. The inverter uses sinusoidal PWM (unipolar switching) at 20 kHz switching frequency. The control strategy is explained with reference to the diagram (Fig. 7) that follows.

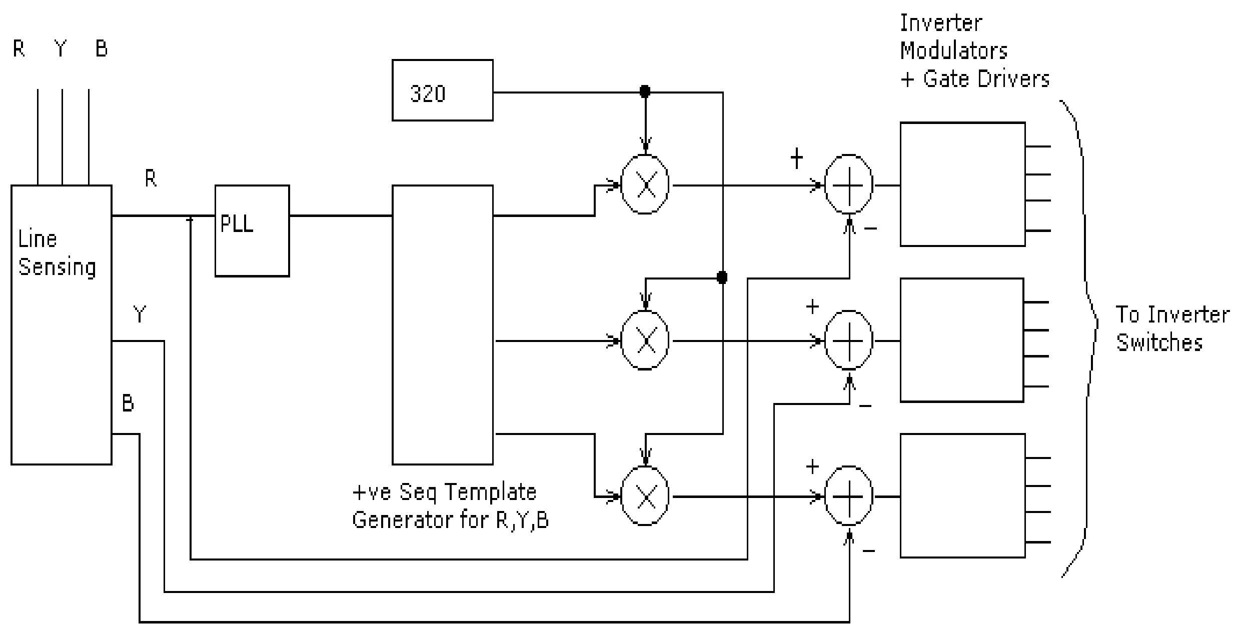

Fig. 7. Block Diagram of Control Strategy for a DVR.

The load voltage is stepped down using PTs and a PLL is locked onto R phase. The pure sinewave phase synchronized to R phase goes into a Positive Sequence Constructor circuit (all pass filters based) which generates unit amplitude positive sequence waves. These templates are multiplied by the desired amplitude (320V) to form the desired load voltage. The actual load voltage from the sensing circuit is subtracted from this to form the reference signals into Inverter Modulator. The inverter injects the required voltage. The control strategy is feed-forward and hence is fast, but suffers from the disadvantage of not having any feedback. The DC Side is assumed to be a power source like a battery or an AC-DC converter running from same bus. Correction strategy is inphase and hence active power flow is involved.

The control of DVR is not a very complex problem and in fact field experience justifies feedforward control. However providing a suitable DC Side energy source to handle long periods of sag or swell or flicker throughout the day (like arc furnace) will be a problem. If it is a Battery it requires a charger. Some researchers have proposed drawing charging power from the line using the same inverter during periods which sag or swell is little and can be handled by 90-degree voltage injection. But that makes the control pretty complex. If it is a AC-DC Diode Rectifier, the DVR can handle only sags and not swells since during swells the inverter will absorb power (in the 'inphase injection strategy' considered here) and dump it on the DC Side. So, then it has to be a Bilaterlal Converter based AC-DC Converter and then we get very close to what they call a 'Unified Power Quality Conditioner' – then it is no more a DVR alone, but can easily become a UPQC.

7. The Simulation Results

The simulation results are shown below in Figures 8, 9 and 10.

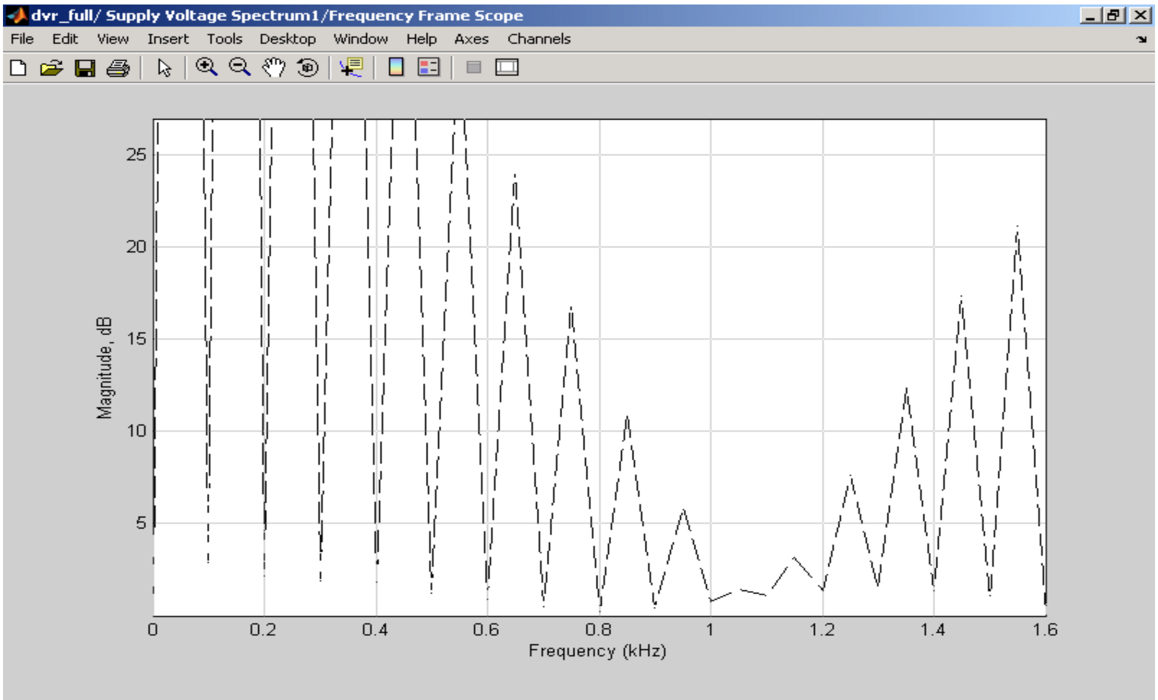

Fig. 8. DVR_Full/Supply Voltage Spectrum 1/Frequency Frame Scope.

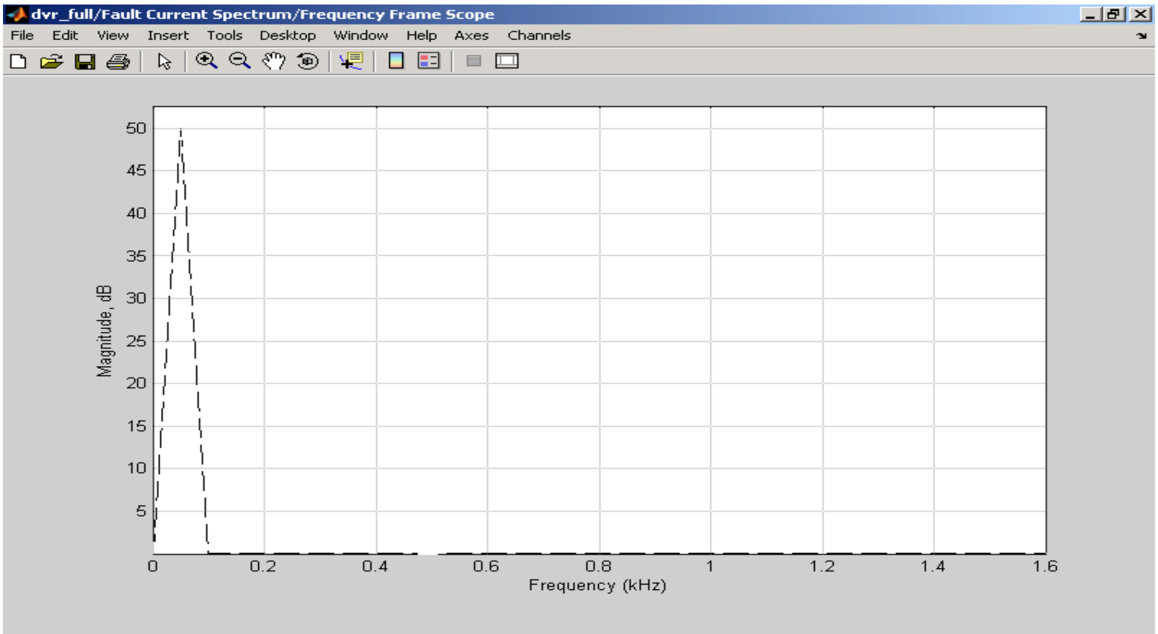

Fig. 9. DVR_full/Fault Current Spectrum/Frequency Frame Scope.

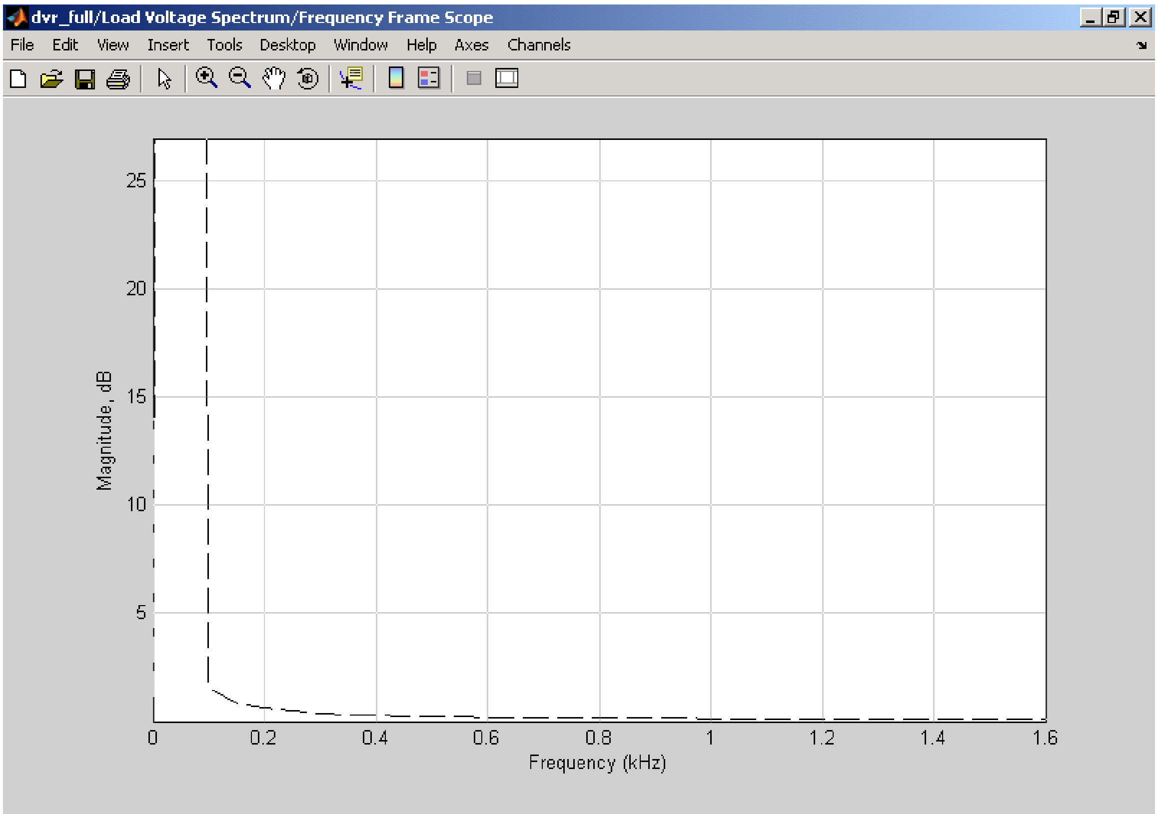

Fig.10. DVR_full/Load Voltage Spectrum/Frequency Frame Scope.

Conclusions

Many aspects of voltage sag mitigation have been studied. First A DVR with its mathematical aspects has been studied and then also examined for its performance against critical load. DVR has excellent performance to protect critical loads. It can deal with all levels of sag severity- shadow, severe and worst. The whole study was mainly involved with DVR control and Protection. DVR was specially designed to mitigate the voltage sag up to 20% of its nominal voltage. Performance of a DVR in mitigating voltage sags/swells is demonstrated with the help of MATLAB. A forced commutated voltage sources converter is considered in the DVR along with energy storage to maintain the capacitor voltage.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

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