Compensation of Voltage Sags and Swells During Abnormal Conditions in Distribution Systems by Dynamic Voltage Restorer (DVR)

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INTRODUCTION

Power quality is certainly a major concern in the present era; it becomes especially important with the introduction of sophisticated devices, whose performance is very sensitive to the quality of power supply. Modern industrial processes are based a large amount of electronic devices such as programmable logic controllers and adjustable speed drives. The electronic devices are very sensitive to disturbances and thus industrial loads become less tolerant to power quality problems such as voltage dips, voltage swells, and harmonics.

Voltage dips are considered one of the most severe disturbances to the industrial equipment. A paper machine can be affected by disturbances of 10% voltage drop lasting for 100ms. A voltage dip of 75% (of the nominal voltage) with duration shorter than 100ms can result in material loss in the range of thousands of US dollars for the semiconductors industry. Swells and over voltages can cause over heating tripping or even destruction of industrial equipment such as motor drives. Electronic equipments are very sensitive loads against harmonics because their control depends on either the peak value or the zero crossing of the supplied voltage, which are all influenced by the harmonic distortion. This paper analyzes the key issues in the Power Quality problems, specially keeping in mind the present trend towards more localized generations (also termed as distributed and dispersed generation) and consequent restructuring of power transmission and distribution networks. As one of the prominent power quality problems, the origin, consequences and mitigation techniques of voltage sag problem has been discussed in detail. The study describes the technique of correcting the supply voltage sag in a distribution system by power electronics based device called Dynamic Voltage Restorer (DVR). Dynamic voltage restorer (DVR) is a series-connected flexible ac transmission systems (FACTS) controller used to compensate voltage sags and swells during abnormal conditions in distribution systems.

VOLTAGE DIPS & HARMONICS

Introduction to Voltage Dips

A Voltage dip is a short-term reduction in, or complete loss of, RMS voltage. It is specified in terms of duration and retained voltage, usually expressed as the percentage of nominal RMS voltage remaining at the lowest point during the dip. A voltage dip means that the required energy is not being delivered to the load and this can have serious consequences depending on the type of load involved. Voltage sags - longer-term reductions in voltage – are usually caused by a deliberate reduction of voltage by the supplier to reduce the load at times of maximum demand or by an unusually weak supply in relation to the load.

Motor drives, including variable speed drives, are particularly susceptible because the load still requires energy that is no longer available except from the inertia of the drive. In processes where several drives are involved individual motor control units may sense the loss of voltage and shut down the drive at a different voltage level from its peers and at a different rate of deceleration resulting in complete loss of process control. Data processing and control equipment is also very sensitive to voltage dips and can suffer from data loss and extended downtime. The cost implications are very serious and are discussed in Section 2. There are two main causes of voltage dips; starting of large loads either on the affected site or by a consumer on the same circuit and faults on other branches of the network.

Dips caused by large loads

When heavy loads are started, such as large drives, the starting current can be many times the normal running current. Since the supply and the cabling of the installation are dimensioned for normal running current the high initial current causes a voltage drop in both the supply network and the installation. The magnitude of the effect depends on how 'strong' the network is, that is, how low the impedance is at the point of common coupling (PCC) and on the impedance of the installation cabling. Dips caused by starting currents are characterized by being less deep and much longer than those caused by network faults –typically from one to several seconds or tens of seconds, rather than less than one second. On-site problems, caused by too high resistance in the internal cabling, are easily dealt with. Large loads should be wired directly back to the origin of the appropriate voltage level – either the PCC or the secondary of the supply transformer. If the problem is caused by the impedance of the PCC – i.e. the supply is too 'weak'– then further action is required. One solution, if applicable to the equipment in question, is to fit a soft starter so that the starting current is limited to a lower value but is required for rather longer. Another solution is to negotiate with the supply company for a lower impedance connection – but this may be expensive depending on the geography of the network in the area.

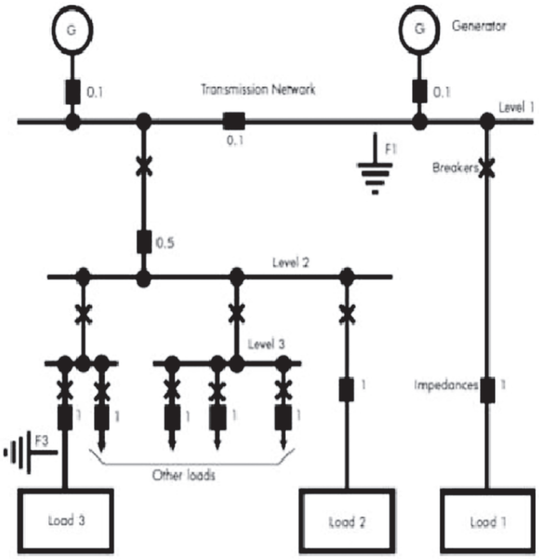

Fig. 2.1 The cause of voltage dips

What is a Harmonic?

The typical definition for a harmonic is "a sinusoidal component of a periodic wave or\ quantity having a frequency that is an integral multiple of the fundamental frequency." Some references refer to "clean" or "pure" power as those without any harmonics.

The frequency of the harmonics is different, depending on the fundamental frequency. For example, the 2nd harmonic on a 60 Hz system is 2*60 or 120 Hz. At 50Hz, the second harmonic is 2* 50 or 100Hz.

300Hz is the 5th harmonic in a 60 Hz system, or the 6th harmonic in a 50 Hz system. Figure 2.6 shows how a signal with two harmonics would appear on an oscilloscope-type display, which some power quality analyzers provide.

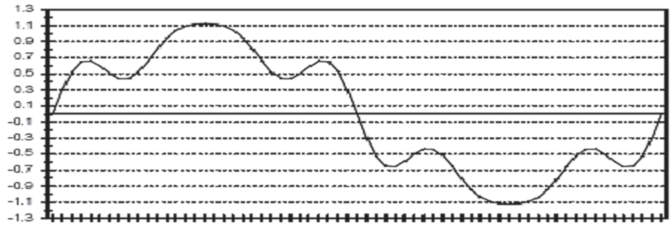

Fig 2.2 Fundamental with two harmonics

In order to be able to analyze complex signals that have many different frequencies present, a number of mathematical methods were developed. One of the more popular is called the Fourier Transform. However, duplicating the mathematical steps required in a microprocessor or computer-based instrument is quite difficult. So more compatible processes, called the FFT for Fast Fourier transform, or DFT for Discrete Fourier Transform, are used.

Problems due to Harmonics:

The presence of harmonics does not mean that the factory or office cannot run properly. Like other power quality phenomena, it depends on the "stiffness" of the power distribution system and the susceptibility of the equipment. As shown below, there are a number of different types of equipment that can have mis operations or failures due to high harmonic voltage and/or current levels. In addition, one factory may be the source of high harmonics but able to run properly. This harmonic pollution is often carried back onto the electric utility distribution system, and may affect facilities on the same system which are more susceptible.

Some typical types of equipment susceptible to harmonic pollution include: - Excessive neutral current, resulting in overheated neutrals. The odd triplen harmonics in three phase wye circuits are actually additive in the neutral. This is because the harmonic number multiplied by the 120 degree phase shift between phases is a integer multiple of 360 degrees. This puts the harmonics from each of the three phase legs "in-phase" with each other in the neutral, as shown in Figure 2.4.

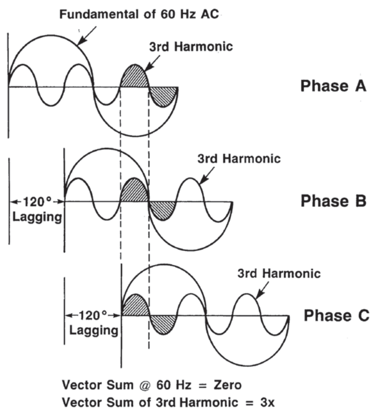

Fig 2.4 Additive Third Harmonics

Preventive Measures for Harmonics

Care should be undertaken to make sure that the corrective action taken to minimize the harmonic problems don't actually make the system worse. This can be the result of resonance between harmonic filters, PF correcting capacitors and the system impedance. Isolating harmonic pollution devices on separate circuits with or without the use of harmonic filters are typical ways of mitigating the effects of such. Loads can be relocated to try to balance the system better. Neutral conductors should be properly sized according to the latest NEC-1996 requirements covering such. Whereas the neutral may have been undersized in the past, it may now be necessary to run a second neutral wire that is the same size as the phase conductors. This is particularly important with some modular office partition-type walls, which can exhibit high impedance values. The operating limits of transformers and motors should be derated, in accordance with industry standards from IEEE, ANSI and NEMA on such. Use of higher pulse converters, such as 24-pulse rectifiers, can eliminate lower harmonic values, but at the expense of creating higher harmonic values.

SOLUTION TO POWER QUALITY PROBLEMS

Introduction

There are two approaches to the mitigation of power quality problems. The solution to the power quality can be done from customer side or from utility side. First approach is called load conditioning, which ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install line conditioning systems that suppress or counteracts the power system disturbances. A flexible and versatile solution to voltage quality problems is offered by active power filters. Currently they are based on PWM converters and connect to low and medium voltage distribution system in shunt or in series. Series active power filters must operate in conjunction with shunt passive filters in order to compensate load current harmonics. Shunt active power filters operate as a controllable current source and series active power filters operates as a controllable voltage source. Both schemes are implemented preferable with voltage source PWM inverters , with a dc bus having a reactive element such as a capacitor. Active power filters can perform one or more of the functions required to compensate power systems and improving power quality. Their performance also depends on the power rating and the speed of response. However, with the restructuring of power sector and with shifting trend towards distributed and dispersed generation, the line conditioning systems or utility side solutions will play a major role in improving the inherent supply quality; some of the effective and economic measures can be identified as following:

FACTS Devices

The use of Flexible AC Transmission System (FACTS) controllers in power transmission system have led to many applications of these controllers not only to improve the stability of the existing power network resources but also provide operating flexibility to the power system. In addition, with relatively low investment compared to new transmission or generation facilities, these FACTS technology allows the industries to better utilize the existing transmission and generation reserves, while enhancing the power system performance. They clearly enhance power system performance, improve quality of supply and also provide an optimal utilization of the existing resources [6]. FACTS devices are a family of high-speed electronic devices, which can significantly increase the power system performance by delivering or absorbing real and/or reactive power. There are many types of FACTS controllers available in real power System and some are under research. Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Thyristor-Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) are popular FACTS devices [6]. They can be connected to power system at any appropriate location, in series, in shunt or in a combination of series and shunt. The SVC and STATCOM are connected in shunt, whereas TCSC and SSSC are connected in series. UPFC is connected in a combination of both shunt and series. Application of FACTS to enhance power system stability is an important issue. The problems that are to be faced in the planning stage are appropriate type, location, size and setting for these controllers for various applications. In order to address this problem, an effort is made in this paper to study technical issues of FACTS controllers in types, capacity and placement, and other pertinent information relating to power system in developing nations.

DYNAMIC VOLTAGE RESTORER (DVR)

Introduction

The major objectives are to increase the capacity utilization of distribution feeders (by minimizing the rms values of the line currents for a specified power demand), reduce the losses and improve power quality at the load bus. The major assumption was to neglect the variations in the source voltages. This essentially implies that the dynamics of the source voltage is much slower than the load dynamics. When the fast variations in the source voltage cannot be ignored, these can affect the performance of critical loads such as (a) semiconductor fabrication plants (b) paper mills (c) food processing plants and (d) automotive assembly plants. The most common disturbances in the source voltages are the voltage sags or swells that can be due to (i) disturbances arising in the transmission system, (ii) adjacent feeder faults and (iii) fuse or breaker operation. Voltage sags of even 10% lasting for 5-10 cycles can result in costly damage in critical loads. The voltage sags can arise due to symmetrical or unsymmetrical faults. In the latter case, negative and zero sequence components are also present. Uncompensated nonlinear loads in the distribution system can cause harmonic components in the supply voltages. To mitigate the problems caused by poor quality of power supply, series connected compensators are used. These are called as Dynamic Voltage Restorer (DVR) in the literature as their primary application is to compensate for voltage sags and swells. Their configuration is similar to that of SSSC. However, the control techniques are different.

Modeling of DVR

The configuration of the DVR, proposed in this paper, is shown in Fig. 7.1. The shunt converter connected to the load side is uncontrolled rectifier, which has uncontrollable dc output voltage V_{dc1}. The uncontrolled rectifier is connected to the load bus through a step down transformer. The dc output voltage of the rectifier Vdc1 is the input voltage of the dc-to-dc step up converter. The output voltage of the step up converter V_{dc2} is the input dc voltage of the V_{SC} of the DVR. Although, with this configuration, the uncontrolled rectifier draws non-linear current, the DVR is able to eliminate all harmonics associated with the load voltage. In this paper, two loads are considered;

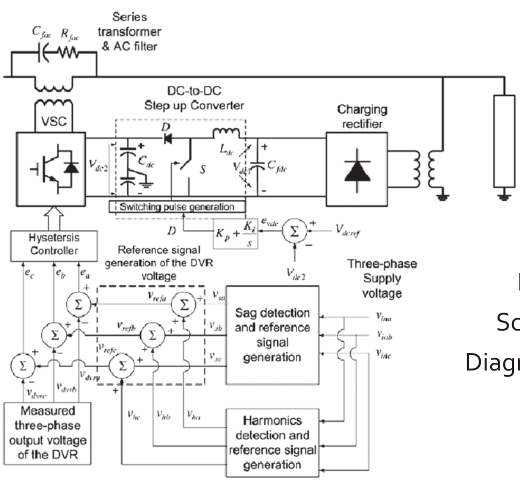

Fig 4.2 Schematic Diagram of DVR

DESIGN OF DVR COMPONENTS

In this section, the dc capacitor C_{fdc} of the uncontrolled rectifier, the dc capacitor C_{dc} and the inductor Ldc of the dc-to-dc step up converter are designed based on single-phase voltage sag which induces a voltage fluctuation with twice the line frequency of the dc capacitor [14]. The parameters of the series and shunt transformers are the default parameters of the transformer model in SIMULINK/MATLAB. The voltage sag factor K_{sag} is defined as

$$K_{sag} = V_{ssag} / V_{spre-sag} \quad (4.1)$$

where V_{ssag} is the sag load voltage and $V_{spre-sag}$ is the pre-sag load voltage. The magnitude of the voltage sag factor $|K_{sag}|$is equal to the depth of the voltage sag D_{sag}; that is

$$D_{sag} = | K_{sag} | \quad (4.2)$$

The power ratings of the series PWM and the shunt uncontrolled (passive) converters in per unit of the load power are given as [3]

$$S_{shunt} = S_{series} = (1-K_{sag})/K_{sag} \quad (4.3)$$

where Sshunt is the pu power rating of the shunt converter and Sseries is the pu power rating of the series converter. Fig. 4.10 shows the relation between the total converters rating (Sseries & Sshunt) and the voltage sag. It has to be mentioned that the DVR with load-side-connected passive converter has the highest size among the other topologies [3].

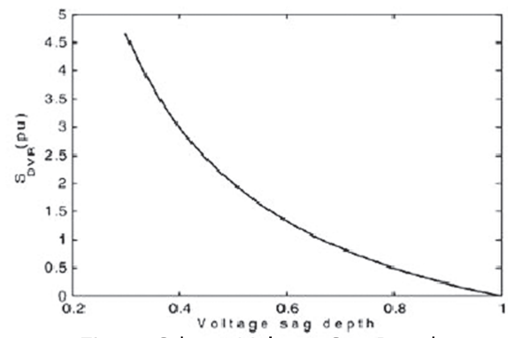

Fig 4.3 Sdvr vs Voltage Sag Depth

Sizing the dc capacitor Cfdc The required capacitance of the dc capacitor C_{fdc} is given as follows [14]:

$$C_{fdc} = (D_{sag} V_{sL-L} [\cos \varphi])/2 \sqrt{3}\, w\varepsilon\, V_{sL-L} (2-D_{sag}) \quad (4.4)$$

where VsL-L is the line-to-line rated load voltage, IL is the rated load current, cosΦ is the power factor of the load, w is the angular speed (w=2πf), ε is the allowable dc voltage fluctuation ($\varepsilon = \Delta V_{dc1}/ V_{dc1}$) and Vdc1 is the dc voltage of the uncontrolled rectifier. The dc voltage of the uncontrolled rectifier (V_{dc1}) is almost equal to the magnitude of line-to-line load voltage ($V_{dc1} = V_{sL\_L}$) as shown in [3]. Therefore (4.4) can be rewritten as

$$C_{fdc} = (D_{sag} I_L [\cos \varphi])/2\sqrt{3}\, w\varepsilon\, V_{sL-L}\,(2-D_{sag}) \quad (4.5)$$

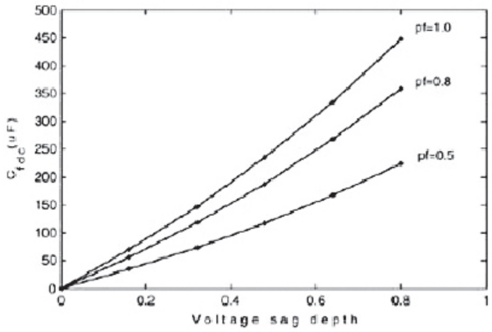

Fig 4.4 C_{fdc} vs Voltage Sag Depth

Fig. 4.4 shows the relation between the size of the dc capacitor C_{fdc} and the voltage sag depth Dsag for various values of the power factor (cos Φ).

Sizing the inductor L_{dc} and the dc capacitor C_{dc}:

The inductor Ldc and the capacitor C_{dc} of the dc-to-dc step up converter are given by [12]

$$L_{dc} = V_{dc1}\, D / \Delta I_{dcz} f_s \quad (4.6)$$

$$C_{dc} = I_{dcz}\, D / \Delta V_{dcz} f_s \quad (4.7)$$

where D is the duty cycle of the dc-to-dc step up converter, fs is the switching frequency of the switch (MOSFET) of the dc-to-dc step up converter (fs= 20 kHz), ΔI_{dc2} is the dc output current ripple of the dc-to-dc step up converter (ΔI_{dc2} = 0.02%), I_{dc2} is the dc output current of the dc-to-dc step up converter and ΔVdc2 is the ripple dc output voltage of the dc-to-dc step up converter (ΔV_{dc2} =0.02%). It can be depicted from (4.6) that the inductor Ldc is directly proportional to the duty cycle D and the dc voltage of the uncontrolled converter V_{dc1}. Since Vdc1 = V_{sL-L} as shown in [3] and by setting D= D_{max}, (4.6) can be rewritten as

$$L_{dc} = (V_{sL-L}\, D_{max}) / \Delta I_{dcz} f_s \quad (4.8)$$

The maximum duty cycle Dmax is given by

$$D_{max} = (V_{dcz} - V_{dc1min}) / V_{dcz} \quad (4.9)$$

Where Vdc2 is the dc output voltage of the dc-to-dc converter (V_{dc2} =500 V) and Vdc1min is the minimum dc voltage of the uncontrolled rectifier. The minimum dc voltage of the uncontrolled (Vdc1min) corresponds to the maximum voltage sag occurred in the distribution system. Therefore V_{dc1min} can be given by

$$V_{dc1min} = 1 - D_{sag} V_{sL-L} \quad (4.10)$$

By substituting (4.10) into (4.9) and then the result is substituted in (4.8), the value of the inductor L_{dc} can be given by

$$L_{dc} = V_{sL-L}\,(V_{dcz} + D_{sag} V_{sL-L} - 1) / \Delta I_{dcz} f_s V_{dcz} \quad (4.11)$$

It can be seen from Fig. 4.12 that as the Dsag increases the value of the inductor Ldc has to be increased. Since D_{sag}= 0.5 is selected in designing C_{fdc}, the value of the inductor L_{dc},

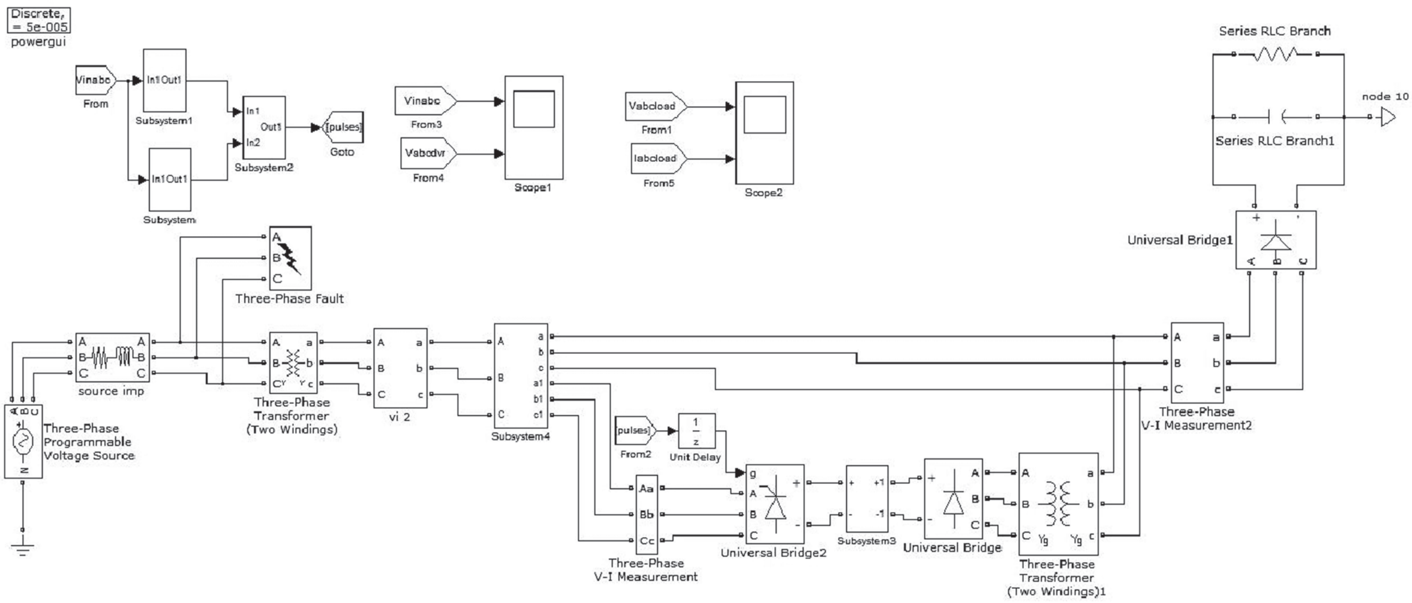

Fig 4.5 Simulink diagram for mitigation of voltage dip using DVR for linear load

Fig 4.6 Simulink diagram for mitigation of voltage dip using DVR for non linear load which corresponds to the same voltage sag depth, is selected to be L_{dc}=12 mH. Following the same procedure, the dc capacitor of the dc to- dc step converter Cdc can be given by

$$C_{dc} = I_{dcz}(V_{dcz}+D_{sag}V_{sL-L} - 1) / \Delta V_{dcz} f_s V_{dcz} \quad (4.12)$$

The active power injected by the DVR during the voltage sag, ignoring the losses in the PWM converter, is given [14] by

$$P_{inj} = D_{sag}(V_{sL-L}/\sqrt{3}) I_L \cos\varphi = V_{dc2} I_{dc2} \quad (4.13)$$

The expression of the dc output current from the dc-to dc converter I_{dc2} can be obtained from (4.13) and then substituted in (4.12). Thus, the dc capacitor C_{dc} can be given by

$$C_{dc} = \frac{D_{sag}V_{sL-L} I_L \cos\varphi \, [D_{sag}V_{sL-L} - 1] = V_{dc2} I_{dc2}}{\sqrt{3}\Delta V_{dcz} f_s V^2_{dcz}} \quad (4.14)$$

RESULTS

5.1. System Response because of 3-phase 60% voltage sag and +280 phase jump(Linear Load):

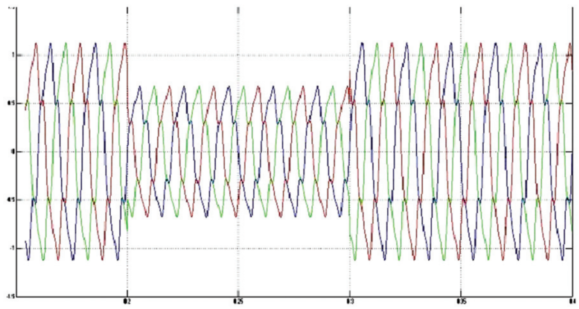

Fig 5.1.1 Three Phase Supply Voltage

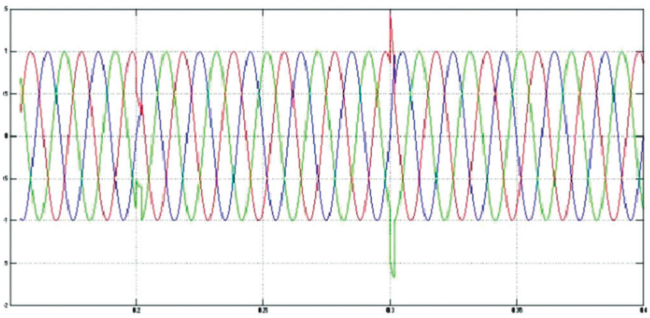

Fig 5.1.2 Three Phase Load Voltage

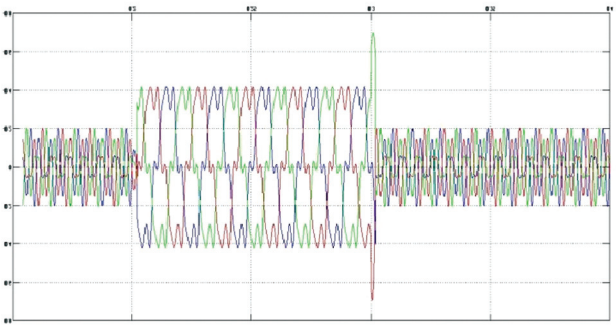

Fig 5.1.3 Three phase DVR voltage

System Response because of 3-phase 60% voltage sag and +280 phase jump (Non-Linear Load)

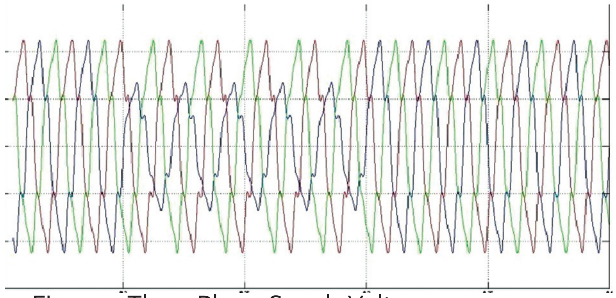

Fig 5.2.1 Three Phase Supply Voltage

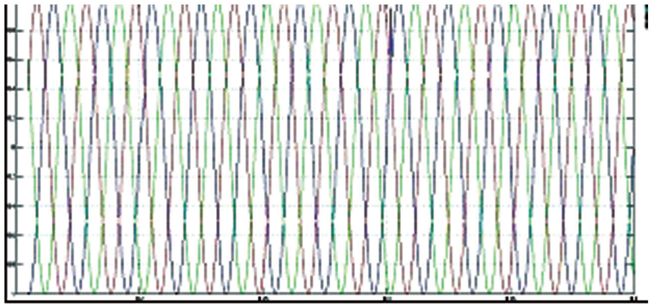

Fig 5.2.2 Three Phase Load Voltage

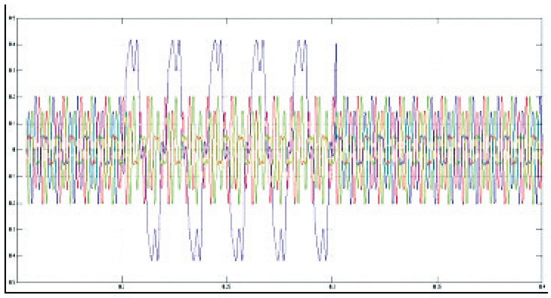

Fig 5.2.3 Three Phase Supply Voltage

Steady State Harmonic Compensation (linear load)

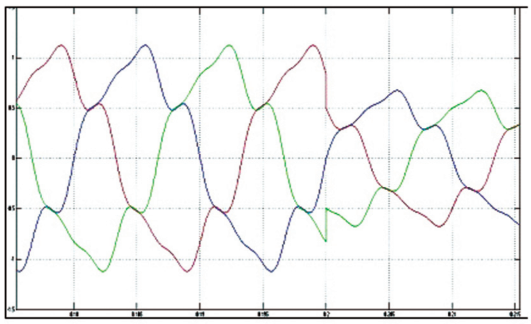

Fig 5.3.1 Three Phase Supply Voltage

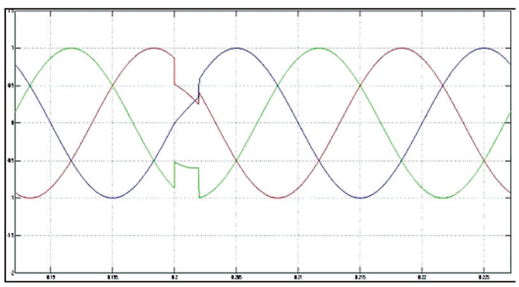

Fig 5.3.2 Three Phase Load Voltage

5.4 Steady State Harmonic Compensation (Non-linear load):

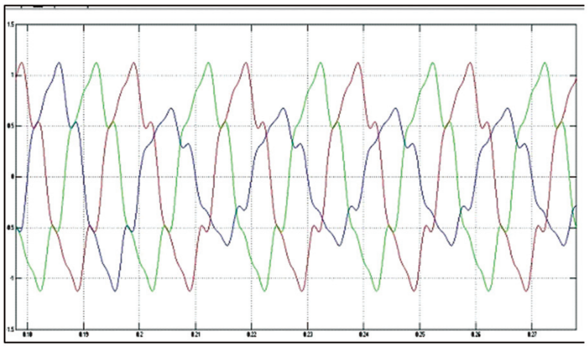

Fig 5.4.1 Three Phase Supply Voltage

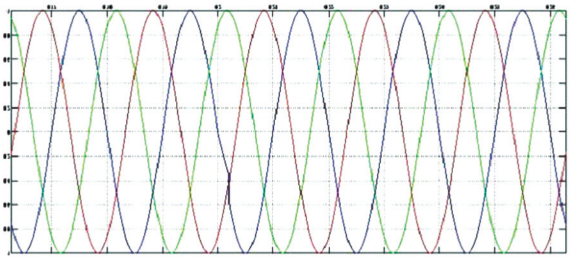

Fig 5.4.2 Three Phase Load Voltage

CONCLUSIONS

This paper has proposed a DVR that can compensate deep and long duration voltage sag and, simultaneously, compensate steady-state harmonics. The DVR is based on a shunt rectifier fed series inverter through dc-to-dc step up converter. A method of incorporating harmonic compensation capability to the DVR has been proposed using hysteresis voltage control. The design of the components of the DVR has been presented. The influence of the power factor of the load and the depth of the voltage sag on the size of the dc capacitor of the shunt rectifier and the inductor and dc capacitor of the dc to- dc step up converter has been analyzed. It has been shown that higher power factor loads require higher dc capacitor size for both; the shunt rectifier and the dc-to-dc step up converter. In addition, it has been shown that as the depth of the voltage sag increases, the size of dc capacitors of shunt rectifier and the dc-to dc step up converter as well as the size of the inductor of the dc to- dc step up converter have to be increased. Time domain simulations of the DVR, under different conditions including distorted supply voltage and distorted voltage sags, have validated the operation of the proposed DVR.

REFERENCES

[1] WOODLEY N.H., SUNDARAM A., COULTER B., MORRIS D.: 'Dynamic voltage restorer demonstration paper experience'. Presented at the Proc. 12th Conf. Elect. Power Supply Ind., Pattaya, Thailand, 1998

[2] WOODLEY N.H., MORGAN L., SUNDARAM A.: 'Experience with an inverter-based dynamic voltage restorer', IEEE Trans. Power Deliv., 1999, 14, (3), pp. 549–557

[3] NIELSEN J.G., BLAABJERG F.: 'A detailed comparison system topologies for dynamic voltage restorers', IEEE Trans. Ind. Appl., 2005, 41, (5), pp. 1272–1280

[4] NIELSEN J.G., BLAABJERG F., MOHAN N.: 'Control strategies for dynamic voltage restorer compensating voltage sags with phase jumps'. Proc. IEEE APEC'01, 2001, vol. 2, pp. 1267–1273

[5] WEI LI Y., MAHINDAV., BLAABJERGF., CHIANG LOHP.: 'A robust control scheme for medium-voltage-level dvr implementation', IEEE Trans. Ind. Electron., 2007, 54, (4), pp. 2249–2261

[6] GHOSH A., JINDAL A.K., JOSHI A.: 'Design of a capacitor supported dynamic voltage restorer (DVR) for unbalanced and distorted loads', IEEE Trans. Power Deliv., 2004, 19, (1), pp. 405–413

[7] HO C.N.-M., CHUNG H.S.H., AU K.T.K.: 'Design and implementation of a fast dynamic control scheme for capacitor-supported dynamic voltage restorers', IEEE Trans. Power Electron., 2008, 23, (1), pp. 237–251

[8] SINGH B., JAYAPRAKASH P., KOTHARI D.P., CHANDRA A., AL-HADDAD K.: 'Indirect control of capacitor supported DVR for power quality improvement in distribution system'. Conversion and Delivery of Electrical Energy in the 21st Century, Power and Energy Society General Meeting, July 2008, pp. 1–7

[9] NEWMAN M.J., HOLMES D.G., NIELSEN J.G., BLAABJERG F.: 'A dynamic voltage restorer (DVR) with selective harmonic compensation at medium voltage level', IEEE Trans. Ind. Appl., 2005, 41, (6), pp. 1744–1753

[10] ZHAN C., FITZER C., RAMACHANDARAMURTHY V.K., ARULAMPALAM A.,BARNS M., JENKINS N.: 'Software phase-locked loop applied to dynamic voltage restorer (DVR)'. IEEE Power Engineering Society Winter Meeting 2001, 2001, vol. 3, pp. 1033–1038

[11] SEN K.K., KERI A.J.F.: 'Comparison of field results and digital simulation results of voltage-sourced converter-based FACTS controllers', IEEE Trans. Power Deliv., 2003, 18, (1), pp. 300–306

[12] RASHID M.H.: 'Power electronics, circuits, devices, and applications' (Prentice-Hall, 1993, 2nd edn.) [13] ASIMINOAEI L., BLAABJERG F., HANSEN S.: 'Detection is key harmonic detection methods for active power filter applications', IEEE Ind. Appl. Mag., 2007, 13, pp. 22–33

[14] TAKUSHI J., HIDEAKI F., HIROFUMI A.: 'Design and experimentation of a dynamic voltage restorer capable of significantly reducing an energy-storage element', IEEE Trans. Ind. Appl., 2008, 44, (3), pp. 817–825