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DYNAMIC VOLTAGE RESTORER WITH REPETITIVE CONTROLLER FOR POWER QUALITY IMPROVEMENT

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Abstract—The Dynamic Voltage Restorer (DVR) has become popular as a cost effective solution for the protection of sensitive loads from voltage sag. By providing proper control scheme the DVR can also be utilized for eliminating other power quality problem such as voltage unbalance and voltage as well as current harmonics This paper presents control system based on repetitive controller to compensate voltage sag, voltage unbalance and voltage harmonics and current harmonics The well –developed graphical facilities available in PSCAD/EMTDC are used to carry out all modeling aspects of repetitive controller.

Keywords*- Dynamic Voltage Restorer (DVR), Power Quality, repetitive control, voltage sag, harmonic distortion.*

I. INTRODUCTION

The importance of power quality has risen very considerably over last two decades, due to mark increase in number of equipment which is sensitive to adverse power quality environment, the disturbances introduced by non linear load and the proliferation of the renewable energy sources, among others.

At least 50% of all power quality disturbances are voltage quality type, where the interest is the study of any deviation of the voltage waveform from its ideal form. The best well known disturbances are voltage sag and voltage swell and voltage harmonic, interharmonic voltage for three phase system and voltage imbalance. Arguably, the most common power quality disturbance in power system is voltage sag, but other disturbances, such as harmonic voltages and voltage imbalances may also affect end user and utility equipment leading to production downtime and in some cases, equipment terminal damage.

Voltage Sag is a decrease in rms voltage between 0.1 to 0.9 per unit for duration from 0.5 cycles to 1 minute. Voltage imbalance is the ratio of maximum deviation of average three phase voltages to the average three phase voltage. Harmonics are sinusoidal voltages having frequencies that are integer multiples of the supply frequency. All these phenomenon are frequently occurring in the system and it will affect industry production

Voltage sag is normally caused by short circuit fault in the power network or by starting of induction motor of large rating. The ensuing adverse consequences are a reduction in the energy transfers of electric motors and disconnection of sensitive equipment and industrial processes bought to stand still.

Harmonics are produced by non linear equipments such as electric arc furnace, variable speed drive, large concentration of arc discharge lamp and load which use power electronic circuit. Harmonic current generated by a nonlinear device or created as a result exisisting harmonic voltages will exacerbate copper and iron losses in electrical equipment. In rotating machine they will produce pulsating torques and overheating.

Voltage imbalance is normally brought about by unbalance load or unbalance short circuit fault thus producing over heating in synchronous machine and in extreme cases, leading to load shutdowns and equipment failure.

Dynamic Voltage Restorer is essentially a voltage source converter which is connected in series with a.c. network via an interfacing transformer which was originally conceived to eliminate voltage sag. It is a power electronic converter based series compensator that can protect critical load from the supply side disturbances other than outages. This restorer is capable of generating or absorbing independently controllable real and reactive power at its output terminal. This device employs solid state devices in sinusoidal pulse width inverter structure. It injects a set of three phase a.c.output voltage in series and synchronism with the distribution feeder. The amplitude and phase angle of injected voltage are variable there by allowing control of real and reactive power exchange between device and distribution system. The main purpose of this device is to protect sensitive load from voltage sag.

The design of control law for DVR: The controller is

Normally designed with some specific aims firmly in mind, such as the kind of disturbances it should ameliorate, the velocity of time response, error in steady state etc.

Most of the published work on DVR uses a simple proportional integral controller implemented in frame of reference which rotates with the frequency of the grid voltage [1-2] This basic approach is sufficient to enable voltage sag compensation and to compensate certain kind of unbalanced voltages. However it fails when dealing with high performance application and more complex controller are required. Resonant control filters are used in together [3] with PI controller in order to eliminate harmonic voltages. One filter is required for each of harmonic to be eliminated if the system is unbalance and one half of that number is the system is balance. The perfect compensation cannot be guaranteed for every situation by using this open loop controller. Feed-forward + PI controller feedback is used [4]in order to improve the control overall performance taking into account the time delay sampled system and the DVR output filter constraints.

This work focused on design of closed loop controller for a DVR based on a repetitive controller, aiming to compensate key voltage quality disturbances normally voltage sag, harmonic voltage, harmonic currents and voltage imbalance simultaneously within the bandwidth. The control structure is quite simple and yet very robust; it contains a feed forward term to improve the transient response and feedback term to enable zero error in steady state. This could be simply implemented in digital signal processor just with time delaying.

Repetitive control was first introduced in [5] to eliminate periodic disturbances and to track periodic reference signals with zero tracking error. The repetitive control was originally applied to eliminate speed fluctuation in electric motors but it has since been adopted in a wide range of power electronic applications. In [6] a repetitive controller is applied to obtain an output voltage with low distortion in a constant voltage, constant frequency three phase PWM inverter. In[7]a repetitive controller is also used to achieve zero tracking error in the output current of a three phase rectifier in order to improve power factor. More recently in [8] repetitive controller is used in a parallel active filter to cancel out harmonic produced by non linear load. The repetitive controller presented in this work has a wider range of applicability; it used in a DVR system to compensate voltage sag, voltage harmonics, current harmonics and voltage imbalance within a band width. Unlike other schemes, which also have a comparable range of applicability, only one controller is needed to cancel all three disturbances simultaneously. The control structure contains a grid voltage feed forward term to improve the system transient response, and closed loop control which comprises a feedback of the load voltage with repetitive controller in order to warrant zero tracking error in steady state

This paper is organized as follows model of DVR is presented in Section II. DVR with repetitive control scheme is presented in section III. The modeling of study case with repetitive controller using the well developed graphical facilities available in PSCAD/EMTDC and simulation results are presented in section IV. The main conclusion is presented in section V.

II. MODEL FOR A DVR APPLICATION

A system, incorporating a DVR, is depicted in Fig.1. Various kinds of loads are connected at the point of common coupling (PCC), including a linear load, a nonlinear load, and a sensitive load. The series connection of the voltage-source converter (VSC) making up the DVR with the ac system is achieved by means of a coupling transformer whose primary is connected in series between the mains and the load. Although a passive LC filter is normally used to obtain a switching-ripple-free DVR voltage, in this paper, this filter is not considered in order to fully assess the harmonic cancelling properties of the repetitive controller.

Fig. 2 shows the equivalent circuit for the DVR, where V*s*, is the supply voltage, *Zs* is the line impedance, i_S is the current supplied by the source, which splits at the PCC into a current injected into the sensitive load *i* and a current injected into other loads i_r..The voltage V_{pcc} is the measured voltage at the PCC; *u* is the voltage representing the DVR, which is modeled as an ideal voltage source. Also, *R* and *L* are the resistance and inductance of the coupling transformer, respectively, and *v* is the measured voltage across the sensitive load. The sensitive-load voltage can be obtained as

$$v(t) = Vpcc(t) + u(t) - Ri(t) - L\frac{di}{dt} \qquad (1)$$

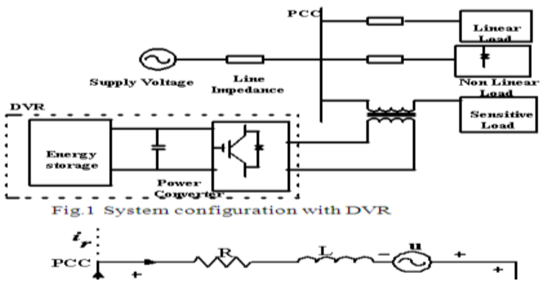

Fig.1 System configuration with DVR

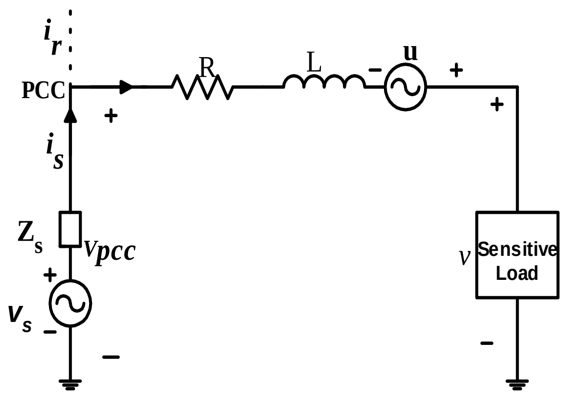

Fig.2 Single phase equivalent circuit of DVR

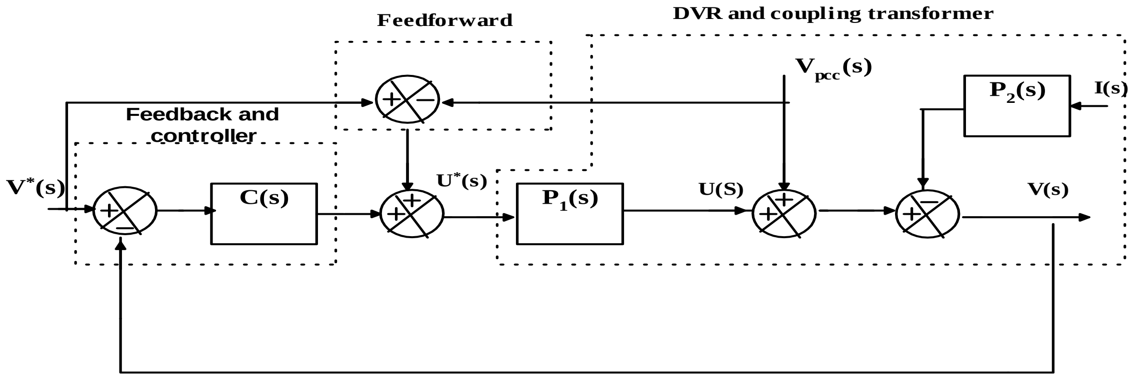

Fig.3 Closed-loop control scheme

II. DVR WITH REPETITIVE CONTROL SCHEME

The aim of control scheme is to regulate load voltage in the presence of various kinds of disturbances. The control structure proposed in this paper is based on the use of feed forward term of the voltage at PCC to obtain fast transient response and a feedback term of load voltage to ensure zero error in the steady state. The continuous time of the whole control system is depicted in fig. 3 where C(s) represents the controller. If the switching frequency is high enough the DVR can be modeled as a linear amplifier with a pure delay $P_1(s)= e^{-t_o s}$ [4].This delay is the sum of one sample period plus the time delay of the inverter due to PWM switching. The former applies in case of microprocessor based implementation [10] and latter can be taken half the switching period [4]. The transfer function $P_2(s)$ is equal to Ls +R,V *(s) is the reference voltage for the load. U*(s) is the control output, whereas U(s) is the output voltage of the DVR and V(s) is the load voltage. The inputs $V_{pcc}(s)$ and I(s) stand for grid voltage and current through the load, respectively. Both inputs are assumed to be measurable. The model may be extended with ease to three phase application.

The load voltage is

$$V(s) = F(s)V^*(s) + F_w(s)V_{pcc}(s)+F_i(s)I(s \quad (2)$$

Where

$$F(s) = \frac{[1 + C(s)]P_1(s)}{1+ C(s)P_1(s)} \quad (3)$$

$$F_w(s) = \frac{1 - P_1(s)}{1+ C(s)P_1(s)} \quad (4)$$

$$F_i(s) = \frac{-P_2(s)}{1+ C(s)P_1(s)} \quad (5)$$

As first approximation, as described in conventional repetitive control theory [5], the controller C(s) can be Written as

$$C(s) = \frac{M(s)}{1- e^{\frac{-2\pi}{\omega_1}}} \quad (6)$$

Where M(s) is a transfer function chosen so that closed –loop stability is always fulfilled and ω_1 is the fundamental frequency at the mains.

The substitution of (6) into (3) – (5) yields

$$F(s) = \frac{[1 - e^{-2\pi/\omega_1 s} + M(s)]P_1(s)}{1 - e^{-2\pi/\omega_1 s} + M(S)P_1(s)} \quad (7)$$

$$F_w(s) = \frac{[1 - P_1(s)][1 - e^{-2\pi/\omega_1 s}]}{1 - e^{-2\pi/\omega_1 s} + M(S)P_1(s)} \quad (8)$$

$$F_i(s) = \frac{-[1 - e^{-2\pi/\omega_1 s}]P_2(s)}{1 - e^{-2\pi/\omega_1 s} + M(s)P_1(s)} \quad (9)$$

In order to calculate the frequency response of (7) - (9), the

Variable s is substituted by jω . It should be noticed that the term ($1 - e^{(-2\pi)/(\omega_1) j\omega}$) is always zero whenever ω is an integer multiple of the frequency ω_1.Hence the frequency response shows that $F(j\omega_h) = 1$, $F_w(j\omega_h)=0$ and $F_i(j\omega_h) = 0$ for frequencies $\omega_h = h\omega_1$ with $h = 0,1,2$ - - - - - - -- ∞. Therefore if the closed loop system is stable, the error in the steady state is zero for sinusoidal reference inputs or sinusoidal disturbance inputs of frequency ω_h..

To solve the problems which may arise due to some factors such as modeling errors ,inverter time delay,or dead time effects in the converter switches the controller based on (6) is modified as

$$C(s) = \frac{Q(s)e^{-(T-\hat{to})s}}{1-Q(s)e^{-TS}} \quad (10)$$

Where Q(s) is the transfer function of a low pass filter [10]

$\hat{to}$ is the estimated value for the DVR delay , with $T=2\pi/\omega_1 - \beta$ and β is design parameter which is smaller than the period of grid voltage ($\beta < (2\pi)/(\omega_1)$).

Substituting (10) in (3) – (5)

$$F(s) = \frac{e^{-tos} + Q(s)\, e^{-Ts} [\, e^{-\delta s} - e^{-tos} \,]}{1 + Q(s)\, e^{-Ts} (\, e^{-\delta s} - 1)} \quad (11)$$

$$F_w(s) = \frac{[\, 1 - e^{-tos} \,][\, 1 - Q(s)\, e^{-Ts} \,]}{1 + Q(s)\, e^{-Ts} (e^{-\delta s} - 1)} \quad (12)$$

$$F_i(s) = \frac{[1 - Q(s)\, e^{-Ts}\,]\; P_2(s)}{1 + Q(s)\, e^{-Ts} (\, e^{-\delta s} - 1)} \quad (13)$$

The Characteristic equation of resulting loop system is

$$\frac{G(s)}{1 + Q(s)\, e^{-Ts} (\, e^{-\delta s} - 1)} \quad (14)$$

To ensure the stability the term G(s) in (14) must satisfy the Nyquist criteria: if the number of unstable poles of open loop system G(s) is equal to zero (P=0), then the number of counterclockwise encirclement of the point (-1,0) of the term G(jω) must be zero (N=0) with $-\infty < \omega < \infty$. A low-pass filter which is approximated by a constant time delay ($Q(j\omega) \approx 1e^{-j\beta_Q}$) within its pass band can be designed with β_Q being the time delay of filter. For continuous time system Bessel filter can be used because they can be approximated by constant time delay [11] .The transfer function of second order low pass filter is

$$Q(s) = \frac{3\omega_c^2}{S^2 + 3s\omega_c + 3\omega_c^2} \quad (15)$$

Where ω_c is the cut off frequency of the low pass filter. In order to obtain $F(j\omega_h)=1$, $F_w(j\omega_h)=0$ and $F_i(j\omega_h)=0$, the time delay of the term $Q(s)e^{-(2\pi/\omega_1-\beta)s}$ must be $2\pi/\omega_1$.

Since the delay is equal to $\beta_Q + 2\pi/\omega_1 - \beta$ within filter pass band the parameter β is chosen to cancel out filter time delay ($\beta = \beta_Q$) under such condition the closed loop system frequency response will satisfy $F(j\omega_h)=1$, $F_w(j\omega_h)=0$ and $F_i(j\omega_h)=0$, while approximation of constant time delay is valid

IV STUDY CASE

The power system depicted in fig. 1and the controller shown in fig. 3 has been implemented in PSCAD/EMTDC. The test system is comprised of a 400-V, 50-Hz source which feeds three different loads i)a Squirrel cage induction machine, 2) a non linear load which consist of an uncontrolled three –phase rectifier with an inductive –resistive load, and 3) a three phase sensitive load which consist of a star made up of a resistance connected in Series with an inductance in each phase. A two level DVR is connected between PCC and the sensitive load by means of a 20 kVA coupling transformer with unity turns ratio and star connected secondary winding. The voltage of the dc storage device is 400V.

A. System Parameter

The system parameter are summarized in Table I

TABLE I
PARAMETERS OF THE SYSTEM

Parameter	Value
RMS line-line voltage	400 V
Resistance and inductance of the line	R_s=10mΩ,L_s=750 μH
Motor Connection inductance	L_1= 50 μH
Nonlinear-load connection inductance	L_2= 50 μH
Mechanical power of the motor	P_m=46kW
DC load :resistance and inductance	R_{dc}=10Ω,L_{dc}= 0.4H
Sensitive load: resistance and inductance	R_{sl}=3Ω,L_{sl}= 50 mH
Transformer: inductance	L= 0.01(p.u)
Transformer no load losses	P_o=0.02 p.u.
Transformer cu losses	P_w=0.02 p.u.

TABLE I
PARAMETERS OF CONTROLLER

Parameter	Value
Fundamental frequency f_1	50 H_z
Switching frequency f_s	6.45 kH_z
Frequency modulation Index	129
t_o	1/2 f_s
δ	0.2 t_o
Amplitude modulation index	0.8
Cut off frequency of Bessel filter	5 kH_z
Constant time delay of Bessel filter	551.33 μs

B .Controller parameter

In order to design the parameter of control system correctly, a nominal value for time delay $\hat{to}$ must be chosen. As the controller has been implemented by using continuous system provided by PSCAD/EMTDC, the time delay is only due to PWM switching. In this paper sinusoidal PWM scheme has been used to generate the switching signals for the power converter, which consist of three –branch three phase voltage source inverter.

A controller has been designed for each phase by using a three phase a,b,c co-ordinate system. The a,b,c reference frame is perhaps most popular alternative to control load voltage when operating under unbalanced condition.

Fig. 4 shows the Nyquist diagram of the term $Q(s)e^{-Ts}(e^{-\delta s}-1)$ where it can be seen that the number of Counterclockwise, encirclements of the point (-1,0) is zero(N=0) .Therefore recalling that the number of unstable poles of the open loop system G(s) is P = 0, the closed loop system is stable

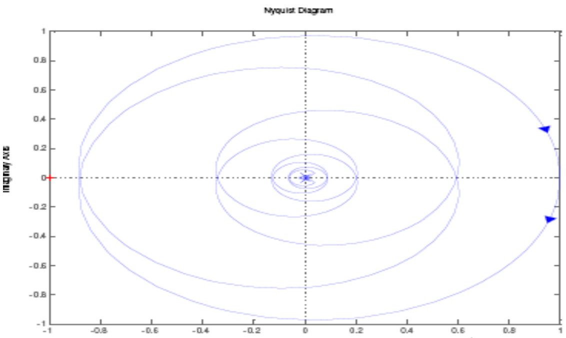

Fig 4 Nyquist diagram of the term Q(s) e^{-Ts} ($e^{-\delta s}$ - 1)

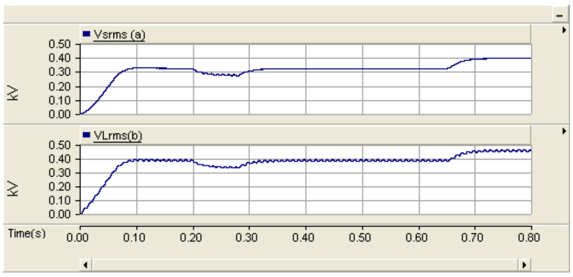

Fig 5.Threephase rms voltage(a) Vsrms Across the sensitive load (b) VLrms at the PCC

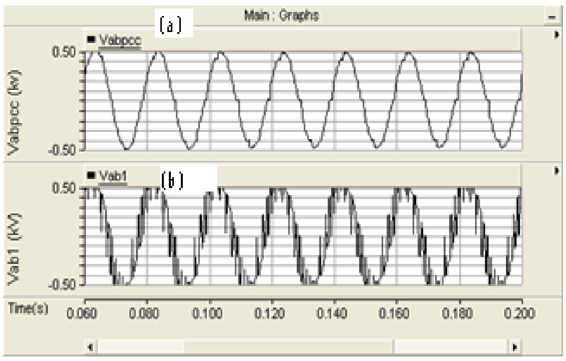

Fig.6 Line to Line voltage (a) at PCC (b) Across sensitive load for corresponding to the interval 0≤ t ≤ 0.2 sec

C .Simulation result

The simulation for case under study is carried out in PSCAD/EMTDC. The simulations are carried out as follows the non linear load and the DVR are connected at t=0s.A two phase short–circuit fault is applied at PCC from t=0.2s to t=0.28 s via a fault resistance of 0.2 Ω. This short circuit causes 45% voltage sag in the two affected phase with respect to their nominal values. The induction machine is connected at 0with a constant rotor speed of 0.97 p.u.(the slip has a value of s=3%) while the nonlinear load is disconnected at t=0.65 and I.M. is also disconnected at 0.65s. The total simulation is carried out in 0.8 s.

The fig 5(a) shows the tree-phase rms voltage V_{Lrms} across the sensitive load and fig5(b)V_{Srms} at the PCC .Initially the rms value of the voltage at PCC 346 V and this fails to 237 when the two- phase short–circuit fault is applied. When Induction motor is connected at t=0.1s, the voltage at PCC decrease to 339 V causing voltage sag of 16% with respect to nominal value. Finally when the non linear load is disconnected at t=0.65 and induction motor load is, the voltage at PCC rise to 380V. A comparison of V_{Lrms} and V_{Srms} shown in fig 5 shows that despite of the many voltage variations at the PCC the DVR is able to provide the sensitive load with the necessary voltage, maintaining an almost constant voltage level of 400V.

Fig 6(a) and (b) shows results only for the case where non linear load and sensitive load and I.M. are connected. Notice that only 0.06 to 0.2 sec are plotted, although this case lasts for 0 to 0.2 sec. Fig 6(a) shows line- to-line voltages at the PCC V_{abpcc} , the waveform distortion is due to harmonic current drawn by the rectifier, while the total current provided to the sensitive load and the rectifier causes a voltage drop at PCC The Fourier analysis of line to line voltage shows that the rms value at the fundamental frequency is 338 V and the total harmonic distortion is THD_v=4.5% Fig 6(b) shows line to line voltage across sensitive load .The control system guarantees that the DVR not only counteracts the voltage drop but also cancel out harmonic caused by non linear load. In this case fundamental harmonic has rms voltage 403 V while the total harmonic distortion is THD_v =4.09%. Note that this harmonic distortion value is due to high frequency harmonics associated with PWM process

The results obtained when two phase short circuit occurs are plotted in figs 7-8. Since the fault causes unbalanced voltages at PCC, the three line-to-line voltages have been plotted in Figs 7 and 8. From t = 0.2 s to t=0.28 s, the fault is applied and causes an unbalanced voltage sag, is shown in
fig 7 and compensated voltages with repetitive controller are shown fig 8

At 0.4 to 0.65 sec induction motor effect, is observed this results in voltage sag of 83% of normal voltage at PCC this which shown in fig 9.By using repetitive controller the load voltage is increased to 99.5%. At t=0.65 s, the nonlinear load is disconnected from the system and only sensitive load remain connected.

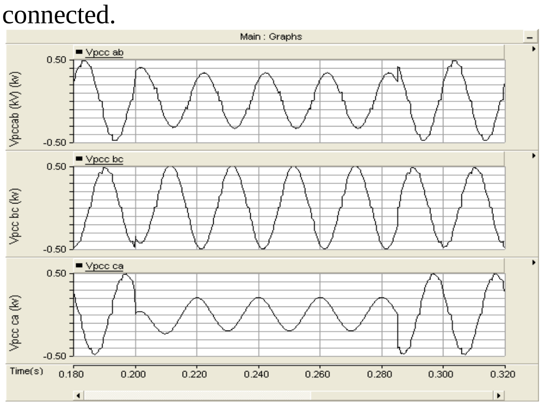

Fig.7 Line to Line voltage (a) at Vpcc $_{ab}$ (b) Vpcc $_{bc}$ (c) Vpcc $_{ca}$ Corresponding to the interval (s) 0.2≤ t ≤ 0.28 sec

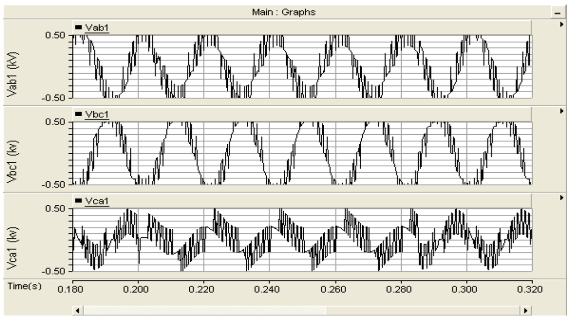

Fig.8 Sensitive-Load Line to Line voltage (a) at V_{ab1} (b) V_{bc1} (c) V_{ca1} Corresponding to the interval (s) 0.2 ≤ t ≤ 0.28 sec

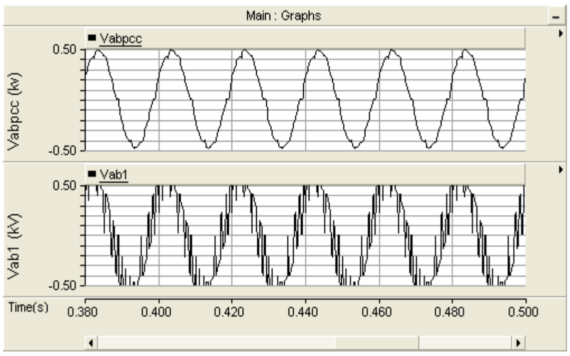

Fig.9 Line to Line voltage (a) At the PCC (b) Across the sensitive load Corresponding to interval 0.4 ≤ t ≤ 0.65

TABLE III
FUNDAMENTAL HARMONIC RMS VALUE OF VOLTAGE AND CURRENT TOTAL HARMONIC DISTORTION OF THE LINE-TO-LINE VOLTAGE AT THE PCC AND ACROSS THE SENSITIVE LOAD FOR DIFFERENT INSTANTS

	$V^{(1)}$rms (V)	THD v (%)
Time interval (s) 0 ≤ t ≤ 0.2 (balanced condition)		
PCC (ab)	338	4.45
Sensitive Load (ab)	403	4.09
Time interval (s) 0.2 ≤ t ≤ 0.28 (Unbalanced condition)		
PCC (ab)	235	4.39
Sensitive Load (ab)	395	5.18
PCC (bc)	353	1.07
Sensitive Load (bc)	528	2.35
PCC (ca)	142	0.09
Sensitive Load (ca)	203	7.2
Time interval (s) 0.4 ≤ t < 0.65 (balanced Condition)		
PCC (ab)	395	4.52
Sensitive Load (ab)	338	4.24
Time interval (s) 0.65 ≤ t < 0.8 (balanced Condition)		
PCC (ab)	393	0.05
Sensitive Load (ab)	412	2.29

V.CONCLUSION

The use of dynamic voltage restorer in power quality related application is increasing The most popular application is voltage sag amelioration but other voltage–quality phenomenon may also benefit from its use, provided that that the more robust control scheme than the basic PI controller is available. In this paper a repetitive controller is
design for dynamic voltage restorer which has fast transient response and ensures zero error in the steady state for sinusoidal reference input. To achieve this controller has been provided with feed forward term and feedback term. A key feature of this controller is only one controller is required to eliminate all four power quality disturbances namely voltage sag, voltage unbalance, voltage harmonics and current harmonics. This controller can be implemented stationary reference frame or rotating reference frame .In this paper highly developed graphical facilities available in PSCAD/EMTDC have been used very effectively to carry out all aspects of the system implementation. Simulation results shows that the repetitive controller of DVR yield excellent voltage regulation and also able to keep the current and voltage harmonics at load within limit, thus screening a sensitive load from upstream power quality disturbances

REFERENCES

[1] J.G. Nielsen, F. Blaabjerg, M.J. Newman, “Control and testing of a Dynamic voltage restorer at medium voltage level,” *IEEE Transactions On Power Electronics*, vol. 19, no.3, pp. 806-813, May 2004.

[2] J.G. Nielsen, F. Blaabjerg, and N. Mohan, “Control strategies for Dynamic voltage restorer compensating voltage sags with phase jump,” in *Proceedings IEEE 16th Annual Conference Applied Power Electronics*, vol. 2, pp. 1267-1273, March 2001.

[3] M.J.Newman, D.G.Holmes, J.G.Nielsen, and F, Baalbjerg,”A dynamic voltage restorer with selective Harmonic at medium voltage level”, IEEE Transaction on Industry application s,vol. 41, no. 6, pp1744-1753, November – December 2005

[4] H.Kim and S.K.Sul, “ Compensation voltage control in dynamic voltage restorers by use of feed forward and state feedback scheme “, IEEETransaction, On Power Electronics,vol.20,no.5,p.1169- 1177,September 2005

[5] S. Hara, Y. Yamamoto, T. Omata, and M. Nakano, “Repetitive control system: A new type servo system for periodic exogenous signals,”*IEEE Trans. Autom. Control*, vol. 33, no. 7, pp. 659–668, Jul. 1988.

[6] K. Zhou and D.Wang, “Digital repetitive learning controller for hreephase,CVCF PWM inverter,” *IEEE Trans. Ind. Electron.*, vol. 48, no.4, pp. 820–830, Aug. 2001

[7] K. Zhou and D. Wang, “Digital repetitive controlled three-phase pwm rectifier,” *IEEE Trans. Power Electron.*, vol. 18, no. 1, pp. 309–316, Jan. 2003.

[8] A. García-Cerrada, O. Pinzón-Ardila, V. Feliu-Battle, P. Roncero- Sánchez, and P. García-González, “Application of a repetitive controller for a three-phase active power filters,” *IEEE Trans. Power Electronics*, vol. 22, no. 1, pp. 237–246, Jan. 2007.

[9] P. R. Sanchez , E. Acha, J. E. O. Calderon, V. Feliu, A. G. Cerrada, “A Versatile Control Scheme for a Dynamic Voltage Restorer for Power-Quality Improvement”,

[10] K. J. Åström and B. Wittenmark, *Computer-Controlled Systems. Theory and Design*, ser. Prentice-Hall Information and System Science., 3rd ed. Upper Saddle River, NJ: Prentice-Hall, 1997.

[11] P. Horowitz and W. Hill, *The Art of Electronics*, 2nd ed. Cambridge, U.K.: Cambridge University Press, 1989.