Power Quality Improvement using Repetitive Controlled Dynamic Voltage Restorer for various faults

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Abstract— In this work a repetitive controller has been used in the control system of the DVR [1] to compensate for key power quality problems namely voltage sags, harmonic voltages and voltage imbalances. This control system contains a feed forward term to improve the transient response and a feedback term to enable zero error in steady state.

This paper proposes to verify results given for a line to line fault in the reference [1] and extends to conduct three phase fault and single line to ground fault. All results are presented and analyzed. MATLAB/SIMULINK software is used for simulation. The Simulation results shows that the repetitive control approach performs very effectively and yields excellent improvement in voltage quality problems.

***Index terms* – Dynamic voltage restorer (DVR), Harmonic Distortion, Power Quality (PQ),Repetitive Control, Voltage Sag.**

I. INTRODUCTION

THE importance of power quality (PQ) has risen very considerably over the last two decades due to a marked increase in the number of equipment which is sensitive to adverse PQ environments, the disturbances introduced by nonlinear loads, and the proliferation of renewable energy sources, among others. At least 50% of all PQ disturbances are of the 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 sags and swells, harmonic and inter harmonic voltages, and, for three-phase systems, voltage imbalances.

A voltage sag is normally caused by short-circuit faults in the power network [2], [3] or by the starting up of induction motors of large rating [4]. The ensuing adverse consequences are a reduction in the energy transfers of electric motors and the disconnection of sensitive equipment and industrial processes brought to a standstill. A comprehensive description of voltage sag can be found in [5].

Harmonics are produced by nonlinear equipment, such as electric arc furnaces, variable speed drives, large concentrations of arc discharge lamps, and loads which use power electronics. Harmonic currents generated by a nonlinear device or created as a result of existing harmonic voltages will exacerbate copper and iron losses in electrical equipment. In rotating machinery, they will produce pulsating torques and overheating [6].

Voltage imbalances are normally brought about by unbalanced loads or unbalanced short circuit faults, thus producing overheating in synchronous machines and, in some extreme cases, leading to shut downs and equipment failure.

The DVR is essentially a voltage source converter connected in series with the AC network via an interfacing transformer, which was originally conceived to improve voltage sags [7]. The basic operating principle behind the DVR is the injection of an in phase series voltage with the incoming supply to the load, sufficient enough to reestablish the voltage to its presag state. Its rate of success in combating voltage sags in actual installations is well documented [8], this being one of the reasons why it continues to attract a great deal of interest in industry and in academic circles. Research work has been reported on DVR two-level [9] and multilevel topologies [10] as well as on control and operation. The latter may be divided into several topics.

1) The configuration, whether two-level or multilevel, relates to the availability, or otherwise, of energy storage [2] , the output filter [11], and the capacity to cancel out unbalanced voltages in three-phase four-wire systems [12].

2) The voltage-sag detection. Several techniques have been used to detect the instant of sag appearance, such as measurement of the peak value of the grid voltage. A comprehensive analysis of these can be found in [13].

3) The control strategy. The DVR may be operated to inject the series voltage according to several criteria, such as minimum energy exchange with the grid. The three most popular strategies to compensate voltage sags are [14]:

a) Presag compensation. The injected DVR voltage is calculated to simply compensate the load voltage to its presag condition;

b) In phase compensation. The DVR voltage is always in phase with the grid voltage;

c) Optimal energy compensation. This strategy minimizes the energy transfer between the energy storage and the grid during steady-state operation.

Although these are the best well-known control strategies, many efforts are being made to develop new ones to enable better DVR utilization as discussed in [15]-[18] .

4) The design of the control law. 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 (PI) control law implemented in a frame of reference which rotates with the frequency of the grid voltage. This basic approach is sufficient to enable voltage sag compensation, to warrant zero tracking

error for the fundamental component, and to compensate certain kinds of unbalanced conditions. However, this simple control law is insufficient when dealing with high-performance applications and more complex controllers are required [19], [20]. The former reference adds resonant control filters to the existing PI control scheme in order to eliminate the harmonic voltages [21]. The main draw back of this scheme is that one filter is required for each harmonic to be eliminated if the system is unbalanced, and only half that number if the system is balanced. The latter reference takes the approach of adding a feedforward loop to the feedback PI controller in order to improve the control overall performance, taking into account the time delay of the sampled system and the DVR output filter constraints.

This work focuses on the design of a closed-loop control law for a two-level DVR, based on the so-called repetitive control, aiming at compensating key voltage-quality disturbances, namely, voltage sags, harmonic voltages, and voltage imbalances.

Repetitive control was first introduced in [22] to eliminate periodic disturbances and to track periodic reference signals with zero tracking error. The repetitive control was originally applied to eliminate speed fluctuations in electric motors but it has since been adopted in a wide range of power-electronics applications. A detailed analysis of various repetitive control configurations is reported in [23]. In [24], a repetitive controller is applied to obtain an output voltage with low distortion in a constant voltage, constant frequency three phase PWM inverter. In [25], a repetitive controller is used to achieve to zero tracking error in the output current of a three phase rectifier in order to improve its power factor.

The repetitive controller presented in this work has a wider range of applicability; it is used in a DVR system to ameliorate voltage sags, harmonic voltages, and voltage imbalances within a bandwidth. 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 a closed-loop control which comprises a feedback of the load voltage with the repetitive controller in order to warrant zero tracking error in steady state.

This paper is organized as follows. The DVR model is presented in section II. The fundamentals of the control system and the proposed control scheme are studied in section III. The modeling of the repetitive controller using the graphical facilities available in MATLAB/ SIMULINK and the simulation results are presented in section IV. The main conclusions are drawn in section V. The design of the closed loop control scheme is given in [1] along with the necessary equations. The same control system has been used here for the design of DVR.

II. MODEL OF THE DVR –CONNECTION SYSTEM

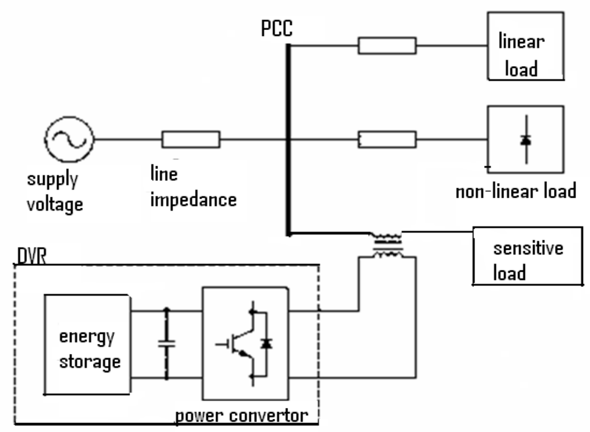


fig 1 system configuration across sensitive load

A typical test 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, 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

III. DESIGN OF THE CONTROL SYSTEM

The aim of the control system is to regulate the load voltage in the presence of various kinds of disturbances. The control structure proposed in this paper is based on the use of a feed forward term of the voltage at the PCC to obtain a fast transient response, and a feedback term of the load voltage to ensure zero error in steady state.

The load voltage is

$$V(S) = e^{\left(-\frac{2\pi}{\omega_1}\right)s} V^{*}(S) + \left[1 - e^{\left(-\frac{2\pi}{\omega_1}\right)s}\right] e^{-t_0 s} + \left[1 - e^{\left(-\frac{2\pi}{\omega_1}\right)s}\right] \left[(1 - e^{-t_0 s}) V_{PCC}(S) - P_2(s) I(S)\right] \quad (1)$$

But by using this controller the delay t_0 is not exactly known and the closed loop system will not be stable. To tackle this problem, a modified controller C(S) is proposed as

$$C(S) = \frac{Q(S) e^{-(T - \bar{t}_0)s}}{1 - Q(S) e^{-Ts}} \quad (2)$$

Where Q(S) is the transfer function of a low pass filter t_0 is the estimated value of the time delay for DVR with $T = \frac{2\pi}{\omega 1} - \beta$.

The transfer functions F(S), $F_W(S), F_i(S)$ with the new modified controller C(S) are :

$$F(S) = \frac{[e^{-t_0 s} + Q(s)e^{-Ts}\left(e^{-\delta s} - e^{-t_0 s}\right)}{1 + Q(s)e^{-Ts}\left(e^{-\delta s} - 1\right)} \quad (3)$$

$$F_W(S) = \frac{[1 - e^{-t_0 s}][1 - Q(s)e^{-Ts}]}{1 + Q(s)e^{-Ts}\left(e^{-\delta s} - 1\right)} \quad (4)$$

$$F_i(S) = -\frac{[1 - Q(s)e^{-Ts}]P_2(S)}{1 + Q(s)e^{-Ts}\left(e^{-\delta s} - 1\right)} \quad (5)$$

With $\delta = t_0 - \hat{t}_0$.

The characteristic equation of the resulting closed loop system is

$$1 + Q(s)e^{-Ts}\left(e^{-\delta s} - 1\right)_{=0} \quad (6)$$

Where G(s) = $Q(s)e^{-Ts}\left(e^{-\delta s} - 1\right)$

In order to guarantee stability the term G(S) in (6) must comply with the nyquist criterion: if the number of unstable poles of the open loop system G(S) is equal to zero (p=0), then the number of counter clock wise encirclements of the point (-1,0) of the term G(jω) must be zero (N=0) with $-\infty < \omega < \infty$.

Since all the poles of Q(S) are stable, which implies that P=0, then N must be zero to guarantee stability, and a sufficient condition for Q(S) can be obtained by making

$$|G(s)| = \left| Q(s)e^{-Ts}\left(e^{-\delta s} - 1\right)\right| < 1 \ \forall\omega \quad (7)$$

Which is fulfilled if

$$2\left|\sin\left(\frac{\partial}{2}\omega\right)\right| |Q(j\omega)| < 1 \ \forall\omega \quad (8)$$

VI. CASE STUDY

A Simulink Model

The power system and the control system have been implemented in MATLAB .The test system is comprised of a 400 V 50 Hz source which feeds three different loads:

1) A squirrel –cage induction machine
2) A non-linear load which consists of an uncontrolled three phase rectifier with an inductive-resistive load and
3)A three phase sensitive load which consists of a star made up of a resistance connected in series with an inductance in each phase.

A two level DVR is connected between the PCC and the sensitive load by means of a 20-KVA coupling transformer with a unity turns ratio and a star connected secondary winding. The voltage of the DC storage device is 650 V.

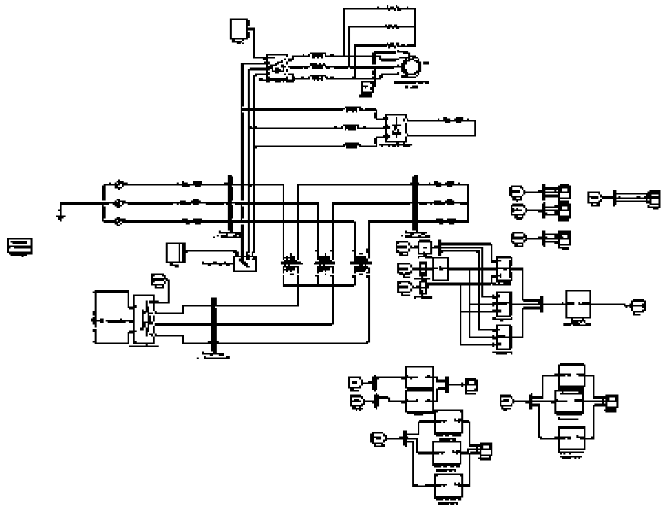


Fig 2 Simulink Model

Table 1: parameters of the system

PARAMETER	VALUE
RMS line-to-line voltage	400V
Resistance and inductance of line	RS=10mΩ, Ls=750µH
Motor connection inductance	L1=50µH
Nonlinear load connection inductance	L2=50µH
Mechanical power of the motor	Pm=46KW
DC load: resistance and inductance	R_{DC}=10Ω, L_{DC}=0.4H
Sensitive load: resistance and inductance	R_{SL}=3Ω, L_{SL}=50mH
Transformer: resistance and inductance	R=0.3Ω, L=6mH

A. Simulation Results

Case 1: Two Phase Short Circuit Fault:

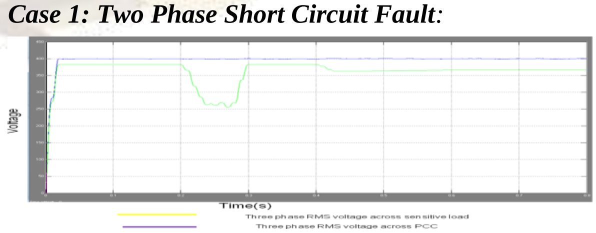


Fig 3 shows the RMS voltage for the sensitive load and at PCC for the interval of 0.8 seconds. A non-linear load and DVR are connected at t=0 secs. A two phase short circuit fault is applied at PCC from t=0.2 s to t=0.28 s. The induction machine is connected at t=0.4 s to t=0.65 s. The non-linear load is disconnected at t=0.65 s. The total simulation time is 0.8 s.

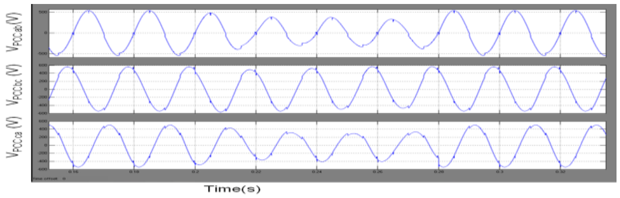


Fig 4 Line to Line Voltages at PCC in the Interval 0.2<t<0.28.When Two Phase Short Circuit Fault is Applied. The results are plotted when a two-phase short circuit fault is applied at the PCC.

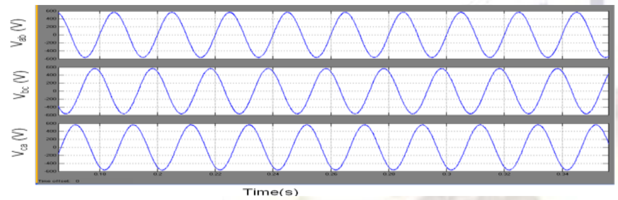


Fig 5 Sensitive Load Line to Line Voltages Corresponding to the interval 0.2<t <0.28. The results indicate that the line-to-line voltages across the sensitive load remain unaffected when a two phase short circuit fault is applied.

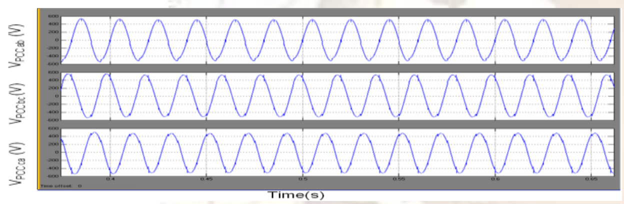


Fig 6 Line to Line Voltages When the Induction Motor is Connected at PCC in the Interval 0.4<=t<0.65. In this case induction motor connection causes balanced voltage sag at PCC, while the non-linear load continues to generate harmonic voltages.

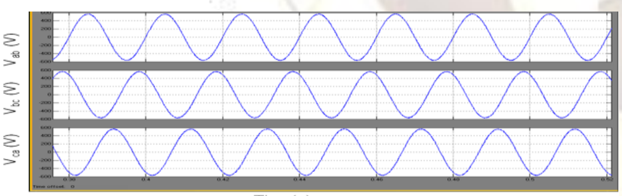


Fig 7 Line to Line Voltages When the Induction Motor is Connected at Sensitive Load in Interval 0.4<=t<0.65. The DVR once again counteracts the voltage sag and the low frequency voltage harmonics, thus protecting the sensitive load from these disturbances.

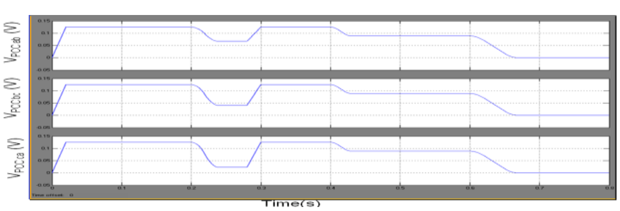


Fig 8 THD Values of Source Voltage at PCC for 0.8s During the interval of 0-0.2 seconds the wave form distortion is due to harmonic currents drawn by the rectifier, while the total current provided to the sensitive load and the rectifier causes a voltage drop at PCC. During the interval 0.4 to 0.65 seconds the harmonic distortion in the waveform is due to the balanced voltage sag caused by the starting of the induction motor. At t=0.65 s, when the non-linear load is disconnected we can see that the THD value obtained is 0%.

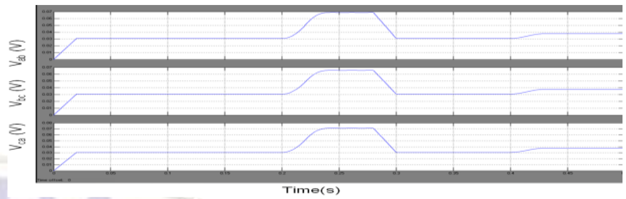


Fig 9 THD Values of Source Voltage at Sensitive Load.

The control system guarantees that the DVR not only counteracts the voltage drop but also cancels out the harmonic voltages caused by the non-linear load. Here the THD value is due to high frequency harmonics associated with the PWM process when the two phase short circuit fault is applied.

Case 2: Three Phase Short Circuit Fault

The same process is repeated by taking a three phase short circuit fault and results are obtained and the corresponding RMS voltages and THD values are given in table below

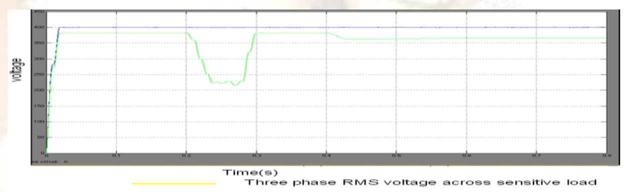


Fig 10 Three Phase RMS Voltage across Sensitive Load and at PCC for 3 Phase Fault

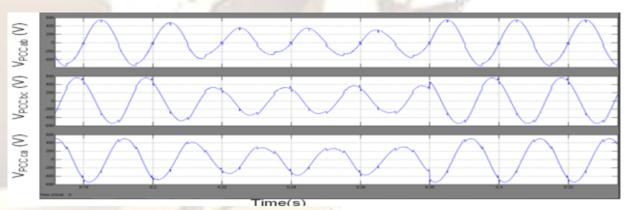


Fig 11 Line to Line Voltages at PCC Corresponding to the Interval 0.2<t <0.28 for 3 Phase Fault.

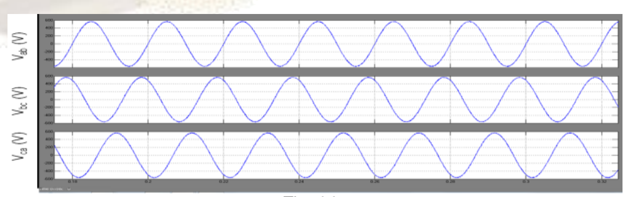


Fig 12 Line to Line Voltages at the Sensitive Load in the Interval 0.2<t<0.28 for Three Phase Fault.

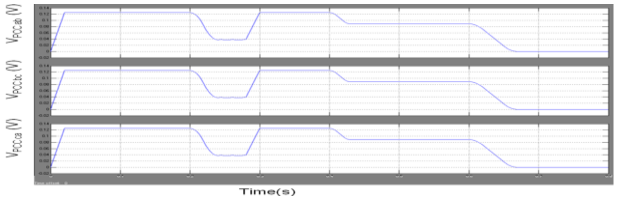


Fig 13 THD Values of Source Voltage at PCC

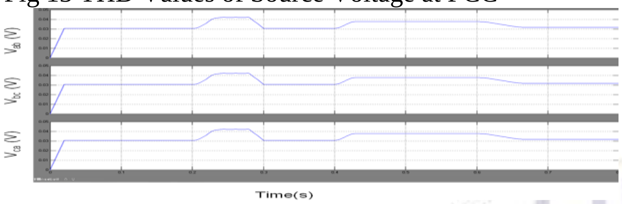


Fig 14 THD Values of Source Voltage at Sensitive Load.

Case 3: Single Line to Ground Fault

The same process is repeated by taking a single line to ground fault and results are obtained and the corresponding RMS voltages and THD values are given in table below.

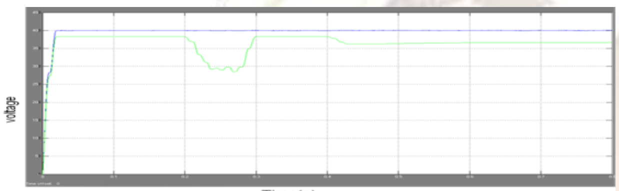
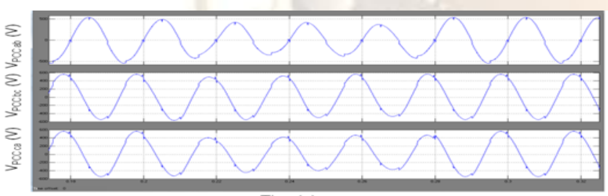


Fig 15 Three Phase RMS Voltage across Sensitive Load and at PCC for Line to Ground Fault



.Fig 16 Line to Line Voltages at PCC Corresponding to the Interval 0.2<t <0.28 for Line to Ground Fault

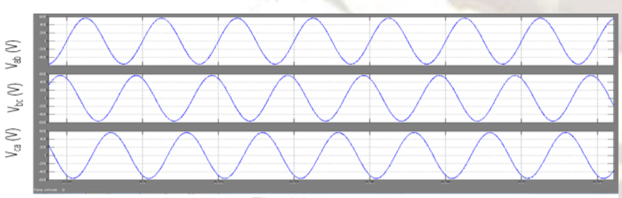


Fig 17 Line to Line Voltages across the Sensitive Load Corresponding to the Interval 0.2<t <0.28 for Line to Ground Fault

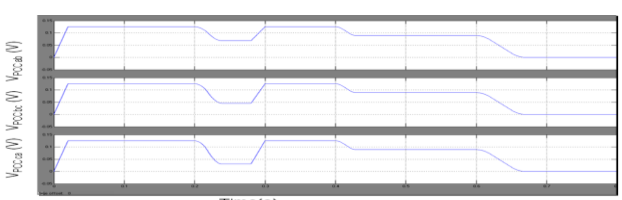


Fig 18 THD Values of Source Voltage at PCC for 0.8 S

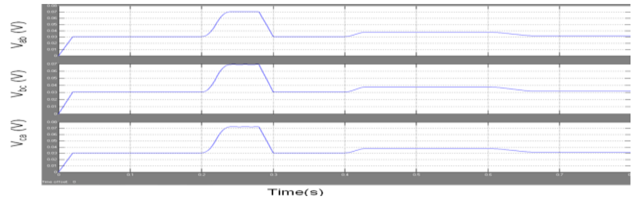


Fig 22 THD Values of Source Voltage at Sensitive Load for 0.8 sec

The table II summarizes the most significant results obtained during simulation for different types of faults (balanced and unbalanced). The table clearly indicates that the unbalanced faults cause deep sag for a short duration and balanced faults cause a balanced sag which is not that deep as compared to the unbalanced sags for a long duration

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	For two phase S.C fault		For 3 phase S.C fault		For L.G fault	
	$V^{(1)}_{rms}$ (V)	THD_V (%)	$V^{(1)}_{rms}$ (V)	THD_V (%)	$V^{(1)}_{rms}$ (V)	THD_V (%)
Time interval (s):			0<=t<0.2		(balanced conditions)	
PCC	385	12.52	385	12.52	385	12.52
Sens. load	399.63	3.07	399.63	3.07	399.63	3.07
Time interval (s):			0.2<=t<0.2 8		(unbalanced conditions)	
PCC(ab)	225.37	6.71	220	3.8	275	6.82
PCC(bc)	363.23	4.07	220	3.8	360	4.56
PCC(ca)	242.07	2.30	220	3.8	293	3.02
Sens. Load(ab)	399.33	6.88	399.63	4.2	399.23	7.05
Sens. Load(bc)	400.19	6.56	399.63	4.2	400.10	6.92
Sens. Load(ca)	399.77	3.77	399.63	4.2	400.15	7.25

TableII comparision of thr results of the three faults.

V. CONCLUSION

The DVR with the repetitive controller presented in this thesis is able to improve the Power Quality problems like the voltage sags, harmonic voltages and voltage imbalances for different types of faults .The results showed that irrespective of the magnitude and duration of the fault the DVR is able to improve the voltage sags, harmonic voltages and voltage imbalances across the sensitive load.

A special feature of this control scheme is its simplicity; only one controller does three jobs i.e., one controller eliminates the three power quality disturbances. This repetitive controller in this thesis has a fast transient response and ensures zero error in the steady state for any sinusoidal reference input and for any sinusoidal disturbance whose frequencies are an integer multiple of the fundamental frequency. To achieve this, the controller has been provided with a feed forward term and feedback term.

Simulation results using MATLAB show that the repetitive controller and the DVR have yielded good results in eliminating the PQ disturbances across the sensitive load.

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