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Comparison of Control Methods for Power Quality Improvement Using Dynamic Voltage Restorer and Hybrid Active Power Filter

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ABSTRACT :*Power quality is the most common factor which is looked by both power consumers and power suppliers. The power industry has to supply power to the consumers at rated magnitude and frequency and also uninterrupted. But due to the use of various nonlinear loads by domestic as well as industrial consumers this has become a very difficult task. To reduce the power quality problems many Custom Power Device's (CPD) are used. The voltage quality can be improved using Dynamic Voltage Restorer (DVR) whereas current quality can be improved using Hybrid Active Power Filter(HAPF). In this paper two control methods are discussed and the results are compared for both the methods. DVR, HAPF and the control methods are simulated using MATLAB/SIMULINK environment.*

***Keywords** -Custom Power Devices (CPD), Dynamic Voltage Restorer (DVR), MATLAB, Hybrid Active Power Filter (HAPF), Power Quality, SIMULINK.*

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I. INTRODUCTION

The quality of power supplied to the consumers play a very important role in the working of various equipment which are connected on the consumer end. The power quality problems are classified as voltage imbalance, interruption, flicker, transient, distortion, harmonics, voltage sag and voltage swell. Usually around 10 to 90% of power quality problems are originated by voltage sags and swells. Inrush currents, faults, lightning strokes are the causes for voltage sags whereas voltage swells are caused due to single line to ground fault or sudden lowering of loads (8). Voltage sag is the reduction in voltage magnitude from 0.1 to 0.9 p.u. of its nominal value and it lasts for 0.5 cycles to one minute. Voltage swell is the increase in voltage magnitude from 1.1 to 1.8 p.u. of its nominal value. Voltage sags even for a short duration leads to the damage of computer equipment, variable speed drives etc. (1). CPD's are used to reduce power quality problems. CPD's can be either series or shunt compensators. Series compensators are connected in series with the load on the distribution side through a coupling transformer like Dynamic Voltage Restorer (DVR). Whereas shunt compensators are connected in parallel to the load like Active Filters (2). In this paper DVR and HAPF are simulated using MATLAB Simulink environment.

II. Dynamic Voltage Restorer(DVR)

Dynamic Voltage Restorer(DVR) is an important CPD used to reduce voltage sags and swells in the distribution network. DVR is a solid-state device that regulates the voltage on the load side by injecting the voltage into the system. DVR is usually installed between the source and the load at the Point of Common Coupling(PCC). DVR can reduce voltage sag and voltage swell. DVR can also limit fault current, reduce transients in the voltage and also compensate voltage harmonics (3). Fig 1. shows the basic block diagram of DVR.

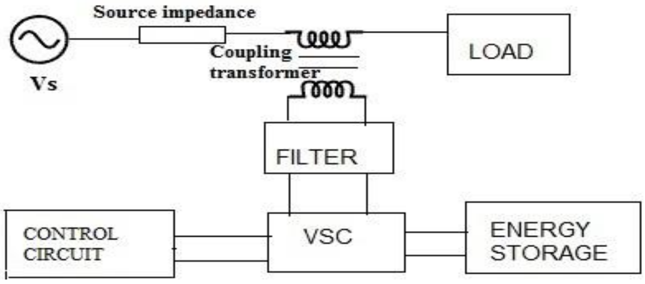

Figure 1 Block Diagram of DVR

DVR consists of a coupling transformer, harmonic filter, energy storage device, a Voltage Source Converter(VSC) and a control system for triggering the switches of VSC. The basic idea of a DVR is to inject voltage generated by the inverter to the bus through a coupling transformer. The injected voltage compensates for the reduction of voltage sags and swells. (4). The equivalent circuit diagram of DVR is given in Fig. 2.

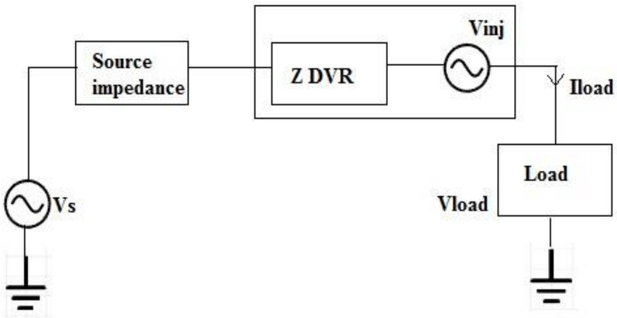

Figure 2 Equivalent circuit diagram of DVR

When the system voltage drops from a specific value due to any fault, series voltage V_{DVR} is injected by the DVR through an injection transformer or coupling transformer such that the load voltage, V_{load} is maintained at the desired value

$$V_{DVR} = V_{load} + Z_s * I_{load} - V_s \qquad (1)$$

Where V_{load} = Load voltage , Z_s = Source impedance, I_{load} = Load Current, V_s = Source voltage. Considering I_{load} as I_L, V_{load} as V_L, Zs as Z_{Th} and Vs as V_{Th}.

The load current I_L is given as

$$I_L = \frac{[P_L + j\,Q_L]}{V} \qquad (2)$$

The equation (2) can be rewritten by considering V_L as reference

$$V_{DVR}\angle \propto = V_L\angle 0 + Z_{Th}\angle(\beta - \theta) - V_{Th}\angle\delta \quad (3)$$

Where ∝, β and δ are the angles of V_{DVR}, Z_{Th} and V_{Th} respectively. Θ is the power angle.

$$\theta = \tan^{-1}\frac{Q_L}{P_L} \qquad (4)$$

The complex power injection of DVR is given as

$$S_{DVR} = V_{DVR}\, I_L^{*} \qquad (5)$$

III. Hybrid Active Power Filter (HAPF)

Harmonic Filters are CPD's used to reduce harmonics. These filters are passive, active and Hybrid filters. Passive filters are basically LC filters which can be tuned to reduce a particular harmonic. Passive filters cannot reduce the random changes in load current and voltage. (5) These are simple in operation but are bulky and as the rating increases and the elements have resonance problem (6). Active filter consists of an inverter circuit to reduce the harmonics. These filters do not have resonance problem and have good response compared to passive filters. HAPF are a combination of active and passive filters (7). Fig 3 shows the basic block diagram of a three-phase active filter.

In this paper, combination of 3-phase active filter and LC Passive filter, which is a HAPF is connected between source and load at the Point of Common Coupling(PCC) as shown in Fig 4.

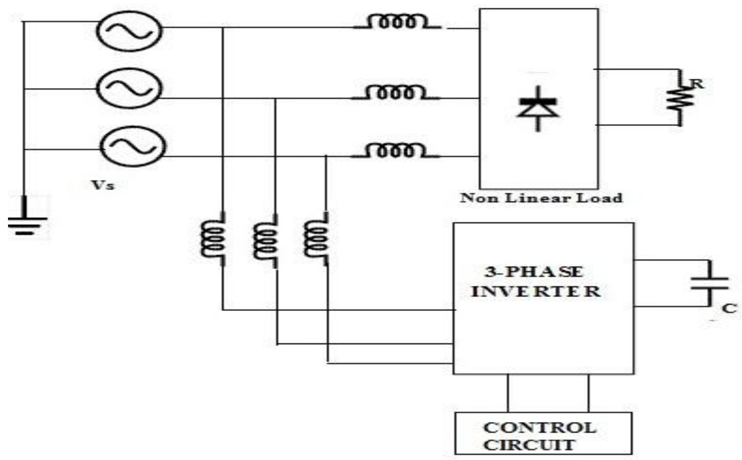

Figure 3 Three-phase Active Power Filter

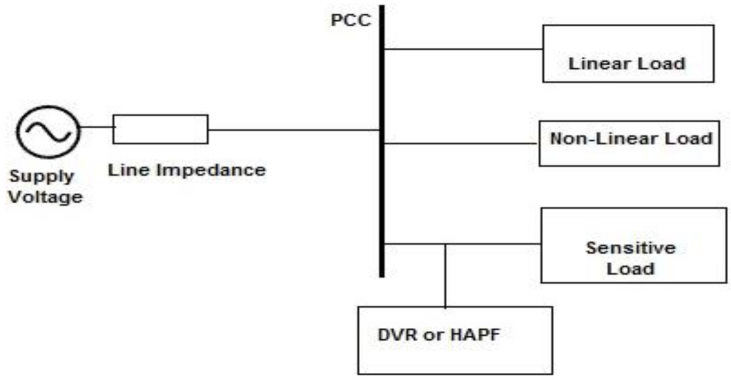

Figure 4 System across Sensitive Load

IV. Proposed Control Technique

4.1.Phase modulation control method:

The proposed method uses error signal which is the difference between the actual value and the measured value to trigger the switches of inverter. It is based on feed forward technique which uses the above error signal to produce the gate pulses. The load values are sensed by the sequence analyser and is then compared with the reference value. Pulse Width Modulation (PWM) technique is applied to the inverter to give the required voltages or currents to be added at the PCC. The control circuit in fig. 5. Fig.6 shows the circuit of phase modulation.

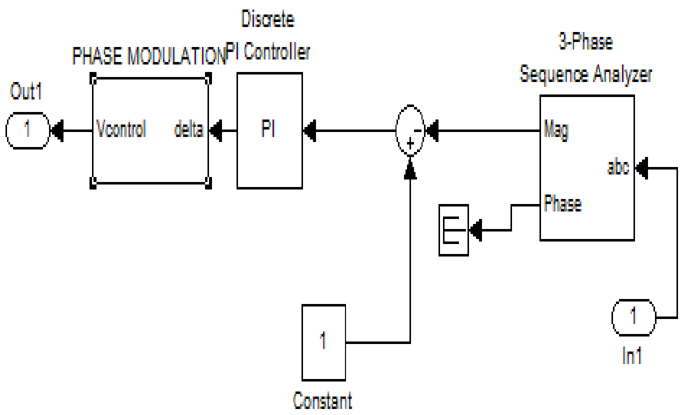

Figure 5 Control circuit

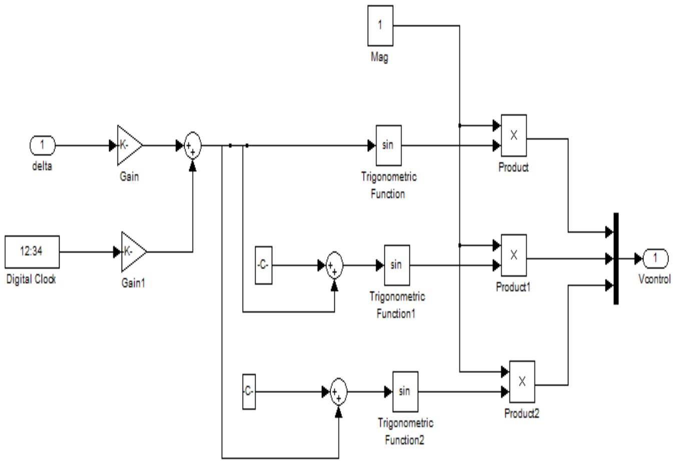

Figure 6 Phase modulation control circuit

4.2. Repetitive controller:

The main use of this controller is that it reduces the voltage disturbances in case of occurrence of any faults. In this control method the it uses the feed forward term of the voltage at the PCC to obtain fast transient response and feedback term to load voltage to ensure zero steady state error (9).
The load voltage equation is given as

$$V(S) = e^{\frac{(-2\pi)s}{(w1)}} V^*(S) + \left[1 - e^{\frac{(-2\pi)s}{(w1)}}\right] e^{-t_0 s} + \left[1 - e^{\frac{(-2\pi)s}{(w1)}}\right][(1 - e^{-t0s})V_{pcc}(S) - P_2(S)\, I(S) \quad (6)$$

By using this controller, the delay t_0 is not exactly known and the closed loop system will not be stable.
To check this problem a modified controller, C(S) is given.

$$C(S) = \frac{Q(S)\, e^{-(\tau - t_0)s}}{1 - Q(S)e^{-Ts}} \quad (7)$$

Where Q(S) is the transfer function of a low pass filter to is the estimated value of the time delay for DVR with $T = \frac{(2\pi)}{(w1)} - \beta$

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

$$F(S) = \frac{[\, e^{-t_0 s} + Q(s)e^{-Ts}(\, e^{-\delta s} - e^{-t_0 s})}{1 + Q(s)e^{-Ts}(\, e^{-\delta s} - 1)} \quad (8)$$

$$Fw(S) = \frac{[1 - e^{-t_0 s}][1 - Q(s)\, e^{-Ts}]}{1 + Q(s)e^{-Ts}(\, e^{-\delta s} - 1)} \quad (9)$$

$$F_i\,(S) = \frac{[\,1 - Q(s)e^{-Ts}]P_2\,(s)}{1 + Q(s)e^{-Ts}(\, e^{-\delta s} - 1)} \quad (10)$$

With $\delta = t_0 - t_0$^

The characteristic equation of the resulting closed loop system is

$$1 + Q(S)e^{-Ts}(\, e^{-\delta s} - 1) = 0 \quad (11)$$

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

In order to guarantee stability the term G(s) in equation (11) 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

$$G(s) = \left| Q(S)e^{-Ts}\left(e^{-\delta s} - 1\right)\right| < 1\forall\omega \qquad (12)$$

Which is fulfilled if $2\left|\sin(\frac{\partial}{2}\omega)\right| \left|Q(j\omega)\right| < 1\forall\omega$

V.Simulation Results

The test system of the DVR consists of 3-phase, 415V, 50Hz supply system. The output from supply unit feeds the primary of a 3-winding transformer. Two parallel feeders are drawn. DVR is connected in series to one of the feeder whereas the other feeder is kept as it is. The parameters are given in Table- I.

Table- I.

DVR Parameters	
Supply voltage	3-phase, 415V
Supply frequency	50 Hz
Inverter parameters	IGBT based 3 arms, 6 pulses
Carrier frequency	1080Hz
Sample time	5µsec

5.1.DVR Results with phase modulation method

The system is analyzed for voltage sag, voltage swell and both sag and swell conditions. Fig. 7 shows the sag condition. Sag is created between 0.3 to 0.7 seconds and the magnitude reduces from 1 p.u. to 0.5 p.u. during this period. The Total Harmonic Distortion (THD) value is 49.79%.

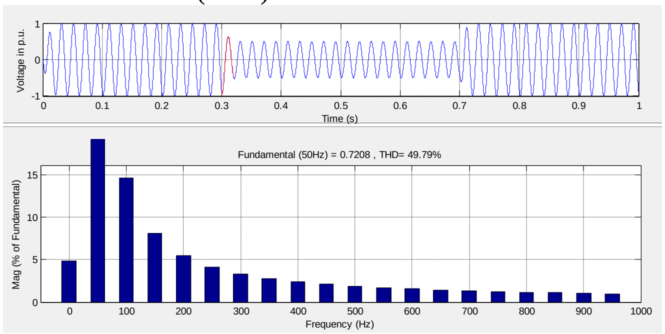

Figure 7 Source voltage and Harmonic spectrum with voltage sag

With DVR, the sag in the voltage is removed and the THD value reduces to 8.84% as shown in Fig. 8.

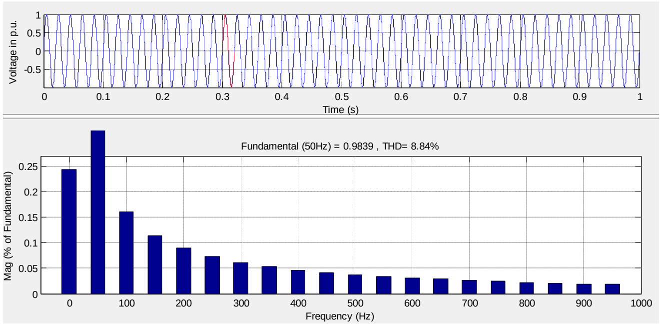

Figure 8 Load Voltage and Harmonic spectrum with DVR

Fig. 9 shows the source voltage with swell created during 0.3 to 0.7 sec. During the swell period voltage is increased from 1p.u. to 1.5p.u. Before compensation the THD value is 41.14%. With DVR voltage swell is compensated which is as shown in Fig. 10. The THD value is reduced to 8.56%.

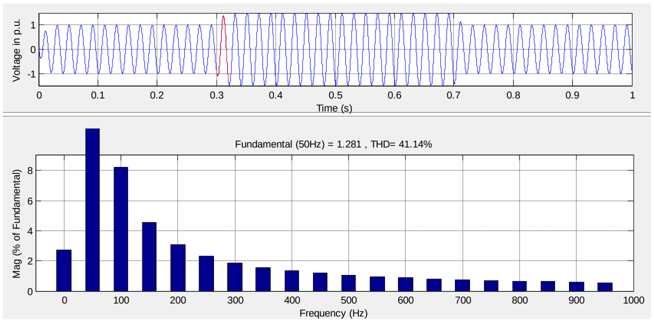

Figure 9 Source Voltage and Harmonic spectrum with Swell

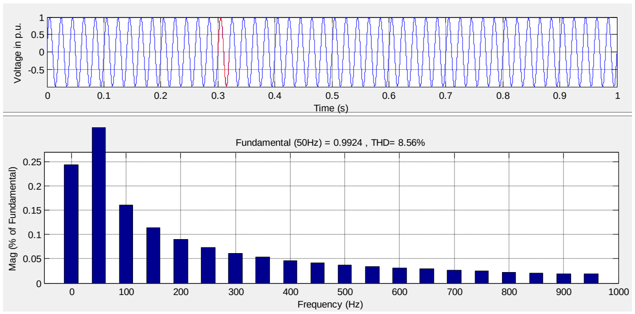

Figure 10 Load Voltage and Harmonic spectrum with DVR

Fig. 11 shows the voltage with both sag and swell. Sag is created between 0.1 to 0.3sec and swell is created between 0.5 to 0.7sec. Before compensation the THD value is 48.69%. But with DVR, voltage is improved and the THD value is reduced to 7.58% as shown in Fig. 12.

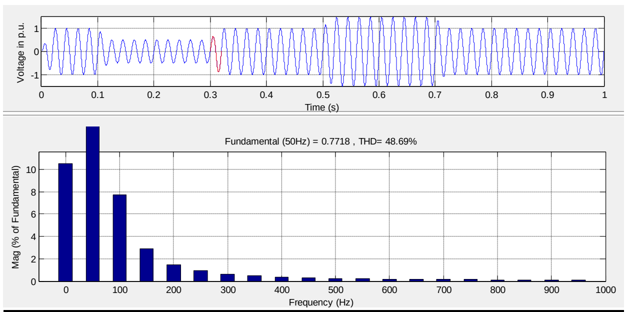

Figure 11 Source Voltage and Harmonic spectrum with sag and swell

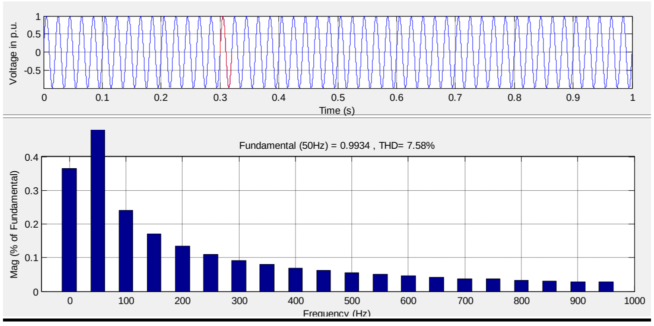

Figure 12 Load voltage and Harmonic spectrum with DVR

5.2 Simulation Results of Hybrid Active Power Filter with Phase Modulation method

The system parameters taken for HAPF are given in Table II. The passive and active filters are designed with the parameters given in Table II. With the proposed control method, simulation results are analyzed for various combination of filters.

TableII

HAPF Parameters	
Supply voltage	208 V
Supply frequency	50 Hz
Passive filter parameters	1.2 mH and 240 µF
Active filter parameters	3000 µF and 1 KΩ

Fig. 13 shows the source current with the Active Power Filter (APF). The THD value of the source current is 82.91%. With the combination of controller and APF, the THD value of the load current has reduced to 8.17% which is shown in Fig. 14.

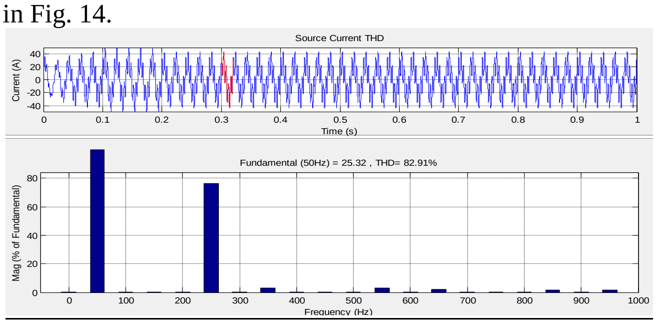

Figure 13 Source current and Harmonic spectrum with Active power filter

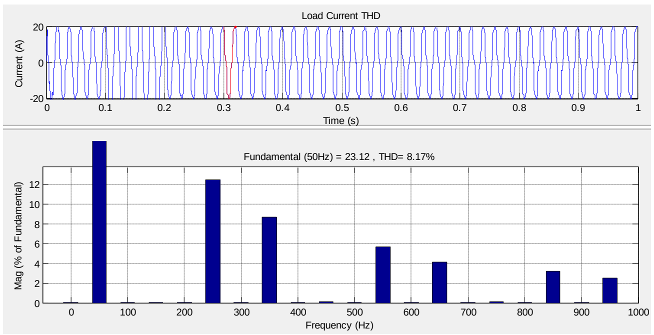

Figure 14 Load current and Harmonic spectrum with Active power filter

Fig. 15 shows the source current with HAPF and its THD value is 76.66%. The THD value of load current has reduced to 7.56% with HAPF and controller as shown in Fig. 16.

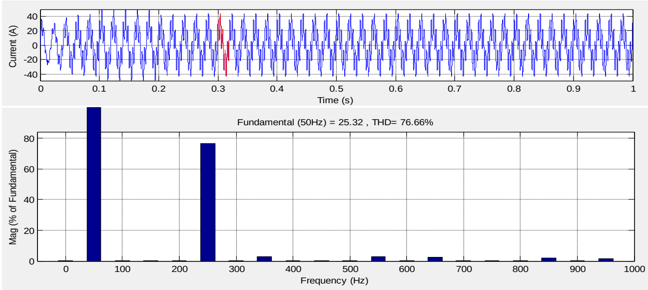

Figure 15 Source current and Harmonic spectrum with Hybrid Active Power filter

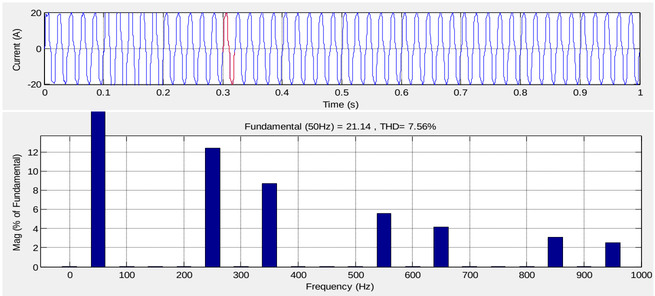

Figure 16 Load current and Harmonic spectrum with Hybrid Active Power Filter

5.3 Simulation Results of DVR with Repetitive Control method

The working of the DVR is analysed with Repetitive controller. A fault is created in the two phases, so sag is created between 0.2 to 0.3 sec. Fig 17 shows the source voltage with sag and the THD value is 15.42%. With DVR and the repetitive controller the load voltage has restored and the THD value has reduced to 3.5% as shown in Fig.18.

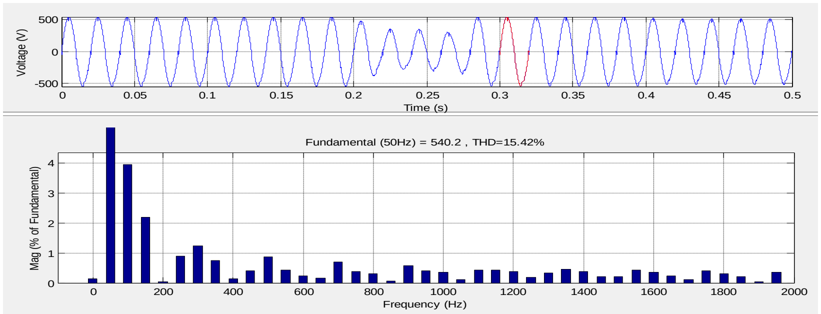

Figure 17 Source voltage and harmonic spectrum with sag

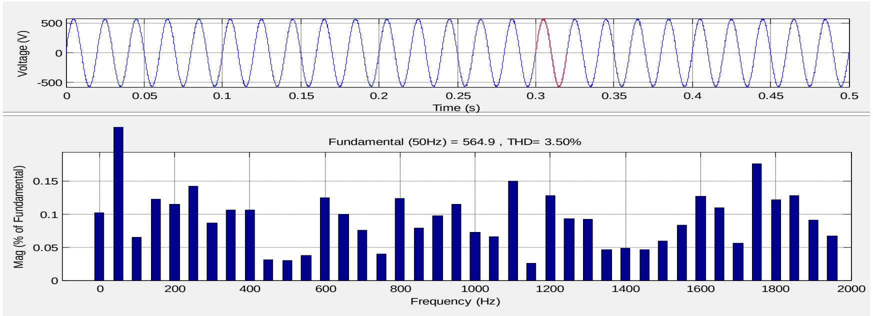

Figure 18 Load voltage and harmonic spectrum with sag

Fig.19 shows that the fault is created in the phase A and C. Hence sag can be seen from 0.2 to 0.3 sec. Fig.20 shows the compensating voltage. The restored load voltage can be seen in Fig.21.

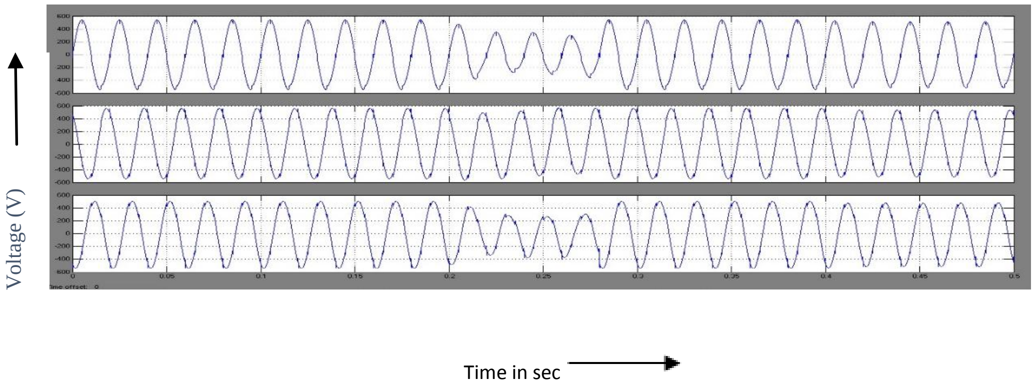

Figure 19 Source voltage with fault on two phases

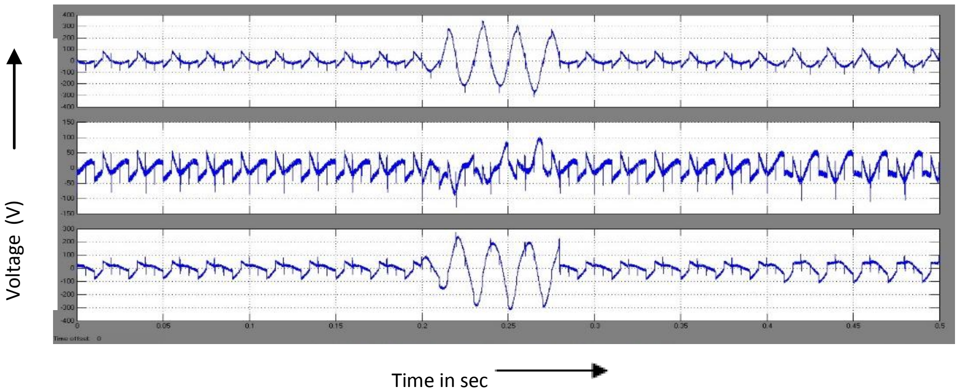

Figure 20 Compensating voltage

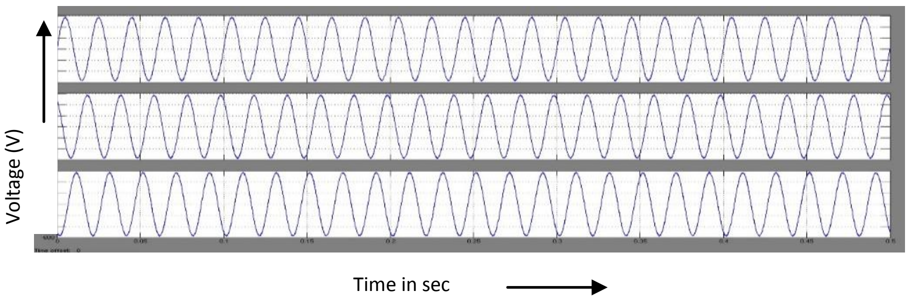

Figure 21 Load voltage with DVR

5.4 Simulation Results of Hybrid Active Power Filter with Repetitive Control method

The working of the filters with Repetitive controller is analysed in this section. The results of source and load currents are given for Active Power filter (APF) and HAPF. Fig.22 shows the source current with APF. The THD of source current is 21.88%. With the controller the THD has reduced to 4.03%.

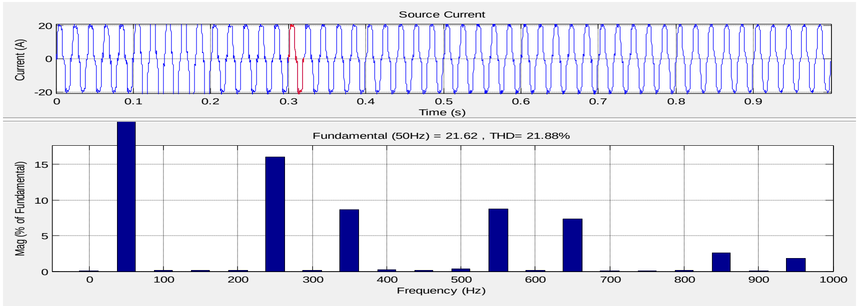

Figure 22 Source current and Harmonic spectrum with Active Power filter

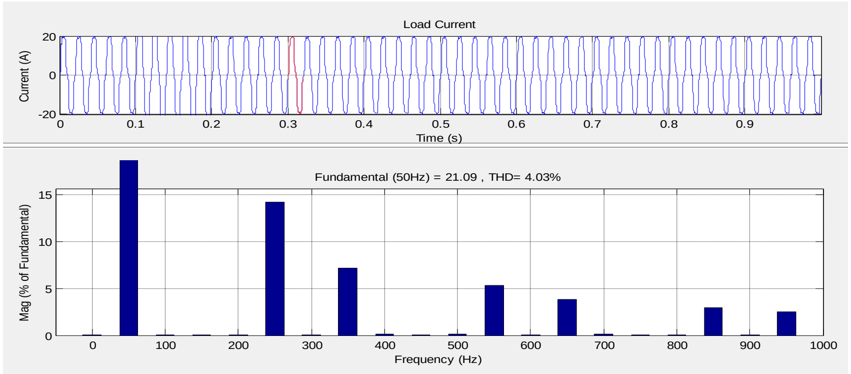

Figure 23 Load current and Harmonic spectrum with Active filter

HAPF is the combination of passive and active filter. With HAPF the source current waveform and the THD of 77.53% is shown in Fig.24. The THD has reduced to 3.52% with the controller as shown in Fig.25.

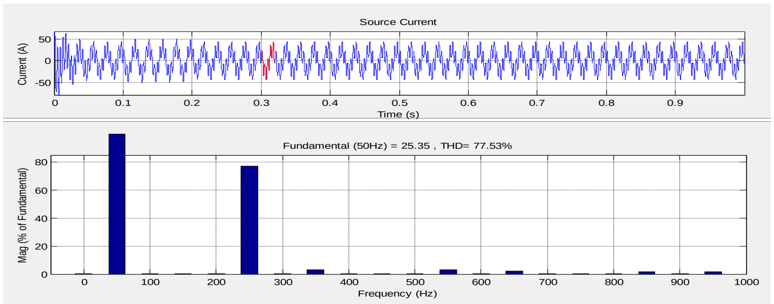

Figure 24 Source current and Harmonic spectrum with Hybrid Active Power filter

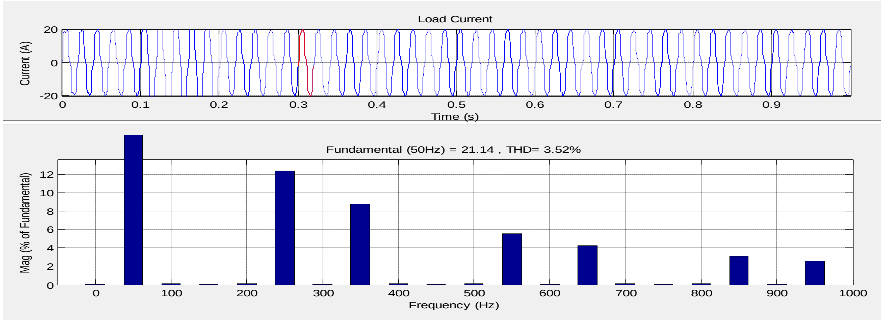

Figure 25 Load current and Harmonic spectrum with Hybrid Active Power filter

Table III

Total Harmonic Distortion with DVR		
% THD Value	**Phase modulation method**	**Repetitive control method**
Source Voltage	49.79%	15.42%
Load Voltage	8.84%	3.50%

Table IV

Total Harmonic Distortion with APF and HAPF		
% THD Value	**Phase modulation method**	**Repetitive control method**
Source current THD with APF	82.91%	21.88%
Load current THD with APF	8.17%	4.03%
Source Current THD with HAPF	76.66%	77.53%
Load Current THD with HAPF	7.56%	3.52%

V. Conclusion

Dynamic Voltage Restorer is used to reduce voltage sag, voltage swell and hence improve the voltage quality. Hybrid Active Power Filter is used to reduce the current harmonics injected due to nonlinear loads and hence make the current drawn to be sinusoidal. DVR and HAPF is build using MATLAB/SIMULINK environment. The Voltage THD of source and load are compared for phase modulation method and Repetitive control method and tabulated in Table-III. The source current and load current THD with APF and HAPF are compared for phase control method and Repetitive control method and tabulated in Table-IV. The THD value has dropped from 8.84% of phase control method to 3.50% with Repetitive control method. The load current THD with Phase modulation method with APF is 8.17% whereas with HAPF is 7.56%. The load current THD has reduced considerably with Repetitive control method to 4.03% with APF and 3.52% with HAPF.

When compared to phase modulation method, Repetitive control method is very efficient in reducing the voltage sags with DVR and also current harmonics with APF and HAPF. It is able to maintain the THD values within the range as per IEEE standards. With these two CPD's – DVR and HAPF the voltage and current profile can be improved.

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