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Comparision of Algorithms for Mitigation of Power Quality Problems

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***Abstract:** This paper demonstrates the comparative studies of algorithms to mitigate the power quality problems. The instantaneous reactive power (IRP) theory can be used to build an algorithm and hence mitigate the power quality problems like harmonics. But the algorithm based on IRP theory has severe draw backs like hidden harmonics. Also dqo transformation method used for sag detection and mitigation has several drawbacks. So a novel reference signal generation method which is based on Enhanced Phase Locked Loop and non linear adaptive filter is used to extract reference signals for Open Unified Power quality conditioner (UPQC). The reference signals for both shunt converter control and series converter control can be extracted from the same algorithm. The efficacy of the Novel Algorithm is compared with the algorithm based on P Q theory for shunt converter control and dqo transformation for series converter control. A system comprising diode bridge rectifier load is considered and power quality problems in it are mitigated using Open UPQC .The studies are done in Matlab/Simulink.*
***Keywords:** Instantaneous reactive power, Non-Linear Load, Reference signal generation, Unified Power Quality Conditioner (UPQC), MATLAB, Enhanced Phase Locked Loop.*

I. INTRODUCTION

Power quality problems have become more prevalent now a day as the integration of power electronic applications has increased tremendously. Power quality problems like harmonics can cause thermal stress on electrical transformers and capacitors used for power factor correction. Further they cause losses in the system. Voltage sags can cause poor performance of induction motor whereas swells can cause insulation failure. So there is a need for limiting the power quality problems in order for satisfactory operation. To mitigate these power quality problems, Open UPQC is used. Various algorithms are available for extracting the reference signals necessary for control of UPQC. The reference signals for series converter are obtained generally by dq0 transformation whereas the reference signals for shunt converter are obtained by instantaneous reactive power theory. Generally, the gate pulses are obtained for series converter by SVPWM whereas for shunt converter sinusoidal pulse width modulation technique is being used. In this paper, Hysteresis current control and voltage control methods [4] are used for generating the gate pulses for shunt and series converters respectively.

II. CONFIGURATION OF UPQC

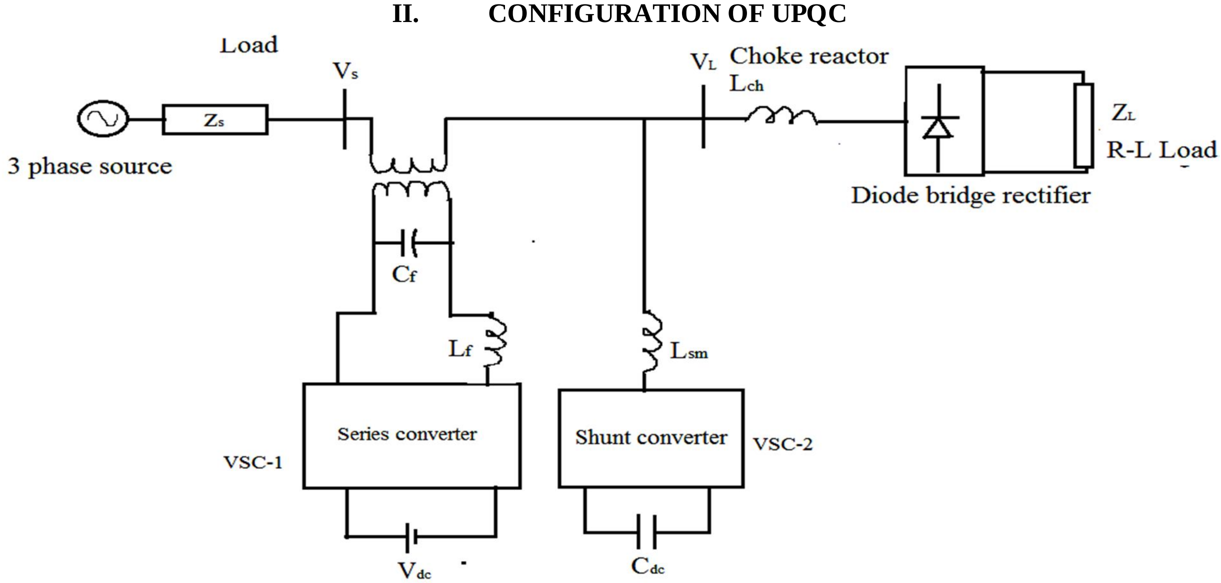

Fig.1 Block diagram of Open UPQC connected to diode bridge rectifier.

Various topologies are available for UPQC [3]. Here, Open UPQC topology has been chosen and studied on a test system. The test system comprises of a simple distribution line feeding a diode bridge rectifier load. The power circuit of Open UPQC consists of series converter (VSC-1) and shunt converter (VSC-2).The VSC-1 consists of 3 single phase H-bridge inverters whereas VSC-2 consists of a single 3 phase inverter. It operates under two modes. During normal conditions VSC-1 operates mitigating the harmonics, while during fault conditions which results in sag/swell on the distribution line both VSC-1 and VSC-2 operates simultaneously. Choke reactor L_{ch} is used to maintain the load current constant. L_f and C_f are filtering elements for series converter whereas Lsm is the filtering element for shunt converter. The values of various parameters are given in [1]

III. ALGORITHM BASED ON IRP THEORY FOR SHUNT CONVERTER CONTROL.

Instantaneous power theory [2] is widely used for developing algorithms for harmonic compensation. The main set back of it is hidden harmonic components. Furthermore, it fails to interpret the properties of power. The algorithm for harmonic compensation is based on Clarke's transformation which is given in the fig 2. The three phase currents and voltages are transformed from $abc-\alpha\beta o$ axis which is a stationary reference frame.

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \sqrt{2/3} \times \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} ..(1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{2/3} \times \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} ...(2)$$

The instantaneous active power and reactive power are given by equation.3 and 4.

$$P = u_\alpha . i_\alpha + u_\beta i_\beta \qquad (3)$$

$$Q = u_\beta i_\alpha - u_\alpha i_\beta \qquad (4)$$

These powers consists of both average and oscillating components

$$P = P_{osc} + P_{avg} ....(5)$$

$$Q = Q_{osc} + Q_{avg} ......(6)$$

The oscillating components are responsible for harmonics. The corresponding currents can be extracted through equation.8. In equation.7 consider $p_c^* = 0,\ q_c^* = Q_{osc}$

$$\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} P_{osc} \\ Q_{osc} \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} 0 \\ -q_c^* \end{bmatrix} \quad (8)$$

The compensating currents which are extracted on $\alpha\beta$ axis are transformed back to *abc* axis using the equation

$$\begin{bmatrix} i_{Ca}^* \\ i_{Cb}^* \\ i_{Cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ 1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix}$$

The algorithm for reference signal extraction for shunt converter using IRP theory is shown in fig.2. Only oscillating component of reactive power, Q_{osc} is considered. The harmonic components which are extracted are power amplified using Shunt active filter. The Gate pulses for the converter are generated using hysteresis current control [5].

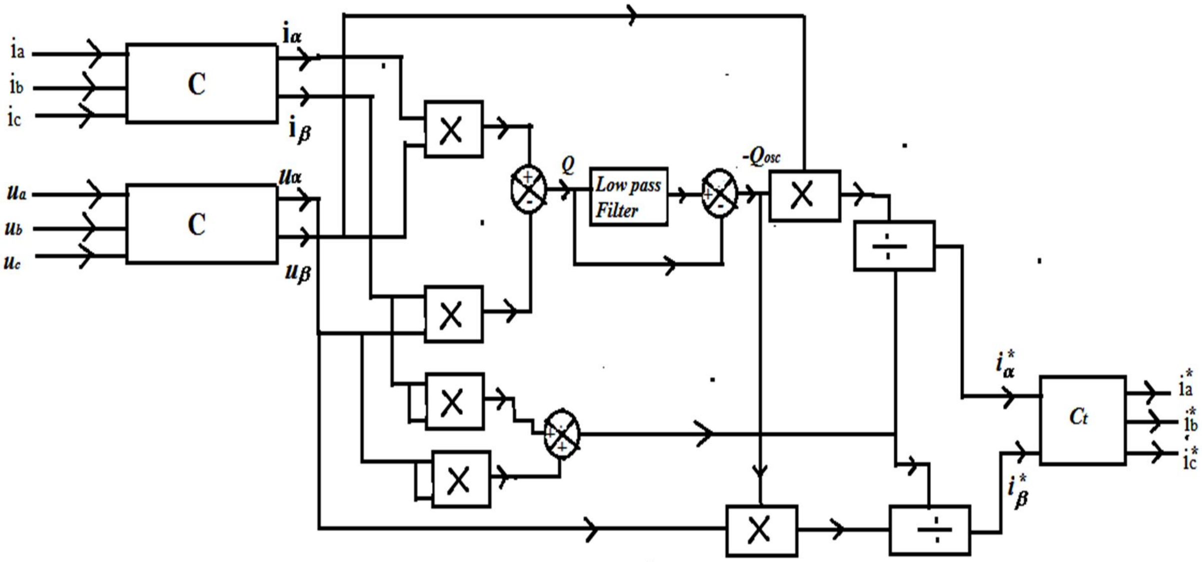

Fig.2 Block diagram of algorithm for shunt converter control using IRP theory.

IV. HIDDEN HARMONICS

The reference signals extracted from the algorithm based on IRP theory contains hidden harmonics (unnecessary harmonic components) when unequal percentages of oscillating active P_{osc} and reactive powers Q_{osc} are selected for compensation [5].This can be depicted from the following equations. Suppose there is presence fifth harmonic in the load current. Let V_{fa} be the supply voltage of phase *a* and I_{5fa} be the fifth harmonic component of current of phase *a*. The oscillating powers can be calculated using equation 3,4.

$$V_{fa} = V_{1m} \sin wt......9$$

$$I_{5fa} = I_{5m} \sin(wt + \alpha_5)...10,$$

$$P_{osc} = -3V_{1m} I_{5m} \cos(6wt + \alpha_5)....11$$

$$Q_{osc} = -3V_{1m} I_{5m} \sin(6wt + \alpha_5)......12$$

The oscillating powers are due to harmonic currents which can be found out using equation 7 and seventh harmonics appears in the

$$i_{\alpha p5} = \sqrt{3/2} \bullet (I_{5m} \sin(5wt + \alpha_5) - I_{5m} \sin(7wt + \alpha_{-5}))...13$$

$$i_{\alpha q5} = \sqrt{3/2} \bullet (I_{5m} \sin(5wt + \alpha_5) + I_{5m} \sin(7wt + \alpha_{-5}))....14$$

$$i_{\beta p5} = \sqrt{3/2} \bullet (I_{5m} \cos(5wt + \alpha_5) + I_{5m} \cos(7wt + \alpha_{-5}))...15$$

$$i_{\beta q5} = \sqrt{3/2} \bullet (I_{5m} \cos(5wt + \alpha_5) - I_{5m} \cos(7wt + \alpha_{-5}))....16$$

The compensating currents are given by

$$i_\alpha^* = A_p.i_{\alpha p5} + A_q i_{\alpha q5}.....17$$

$$i_\beta^* = A_p.i_{\alpha\beta 5} + A_q i_{\beta q5}.....18$$

Because $P_c^*=0$,$Ap=0$ and Aq varies between 0 to 1.Hence compensating currents contain unwanted seventh harmonic current which is injected into the line using power amplifier ,i.e. ; shunt active filter. Another major setback of this algorithm is requirement of high no of mathematical operands The load and source current waveforms of the test system are given respectively in figure 3(a) and 3(b) respectively. The diode bridge rectifier draws a quasi square wave with 240^0 conduction. It can be seen from the figure that source current is smoothened by the shunt active filter. But due to hidden currents in the compensating currents as mentioned above the THD value is only limited to 7.22% which is revealed by FFT analysis as shown in figure 4.

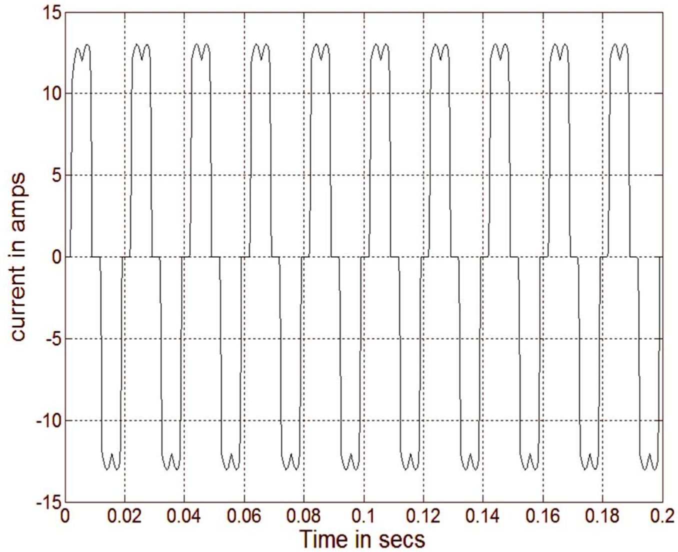

Fig. 3(b) Load current drawn by diode bridge rectifier

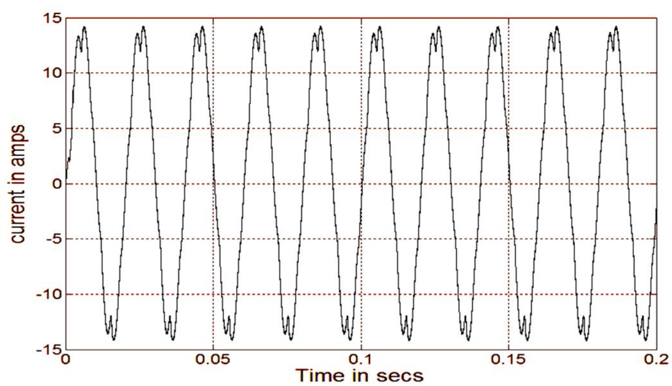

Fig. 3(a) Source current after harmonic compensation

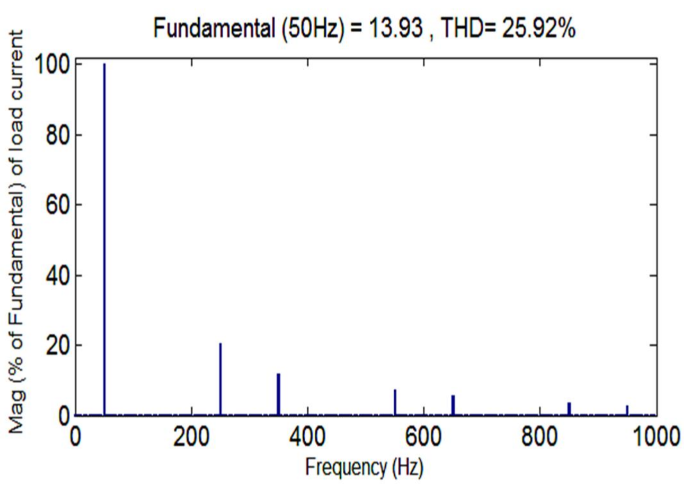

Fig 4(a).FFT analysis of Load current waveform

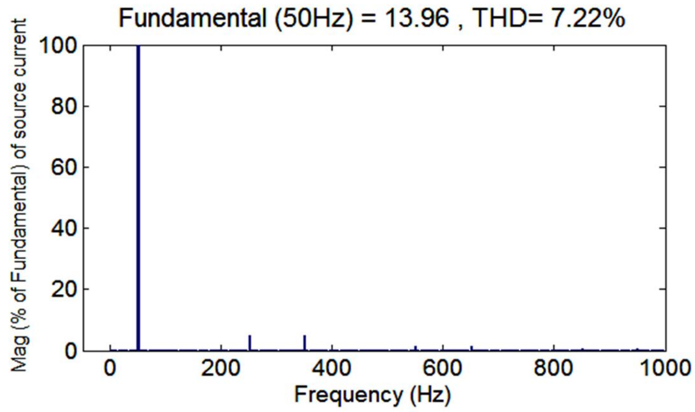

Fig.4 (b).FFT analysis of source current waveform

From this figures 3(a),3(b),4(a)and 4(b) it can be concluded that even though reactive power theory faces severe opposition in justifying the power properties as an algorithm it is successful in reducing the harmonic content in the supply waveform. But the THD of source current as shown in figure 4(b) is greater than IEEE limits i.e.; 5%. Hence there is a need for alternate algorithm for harmonic compensation.

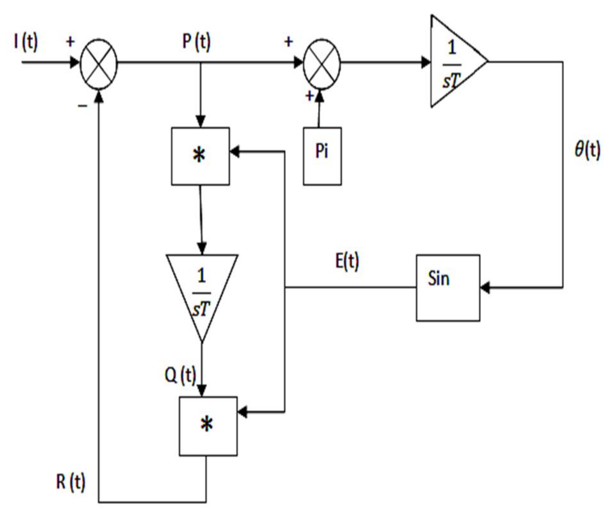

Fig.5. Block diagram of novel algorithm

I(t) = Input signal
P(t)= Difference between input and the synchronized fundamental component
Q(t)= Amplitude of I(t)
R(t)=The synchronized fundamental component
E(t)= EPLL signal
$\Phi(t)$ = Phase angle of R(t)

From the fig it can be seen that at the moment of exciting the algorithm,

$$I(t) = P(t) = \sin wt .....(19)$$

For the first half cycle

$$\Phi(t) = 100 * \int_0^{0.01} (\sin wt + \pi).dt....(20)$$

$$\Phi(t) = 100 * ((-\cos wt / w) + \pi t).....(21)$$

First term being small compared to second term

$$\Phi(t) = 100\pi t....(22)$$

Therefore, $E(t) = \sin(100\pi t)$ this is Enhanced Phase Locked loop signal

$$Q(t) = \int P(t).E(t)dt....(23)$$

For the first half cycle,

$$Q(t) = 1/0.01* \int_0^{0.01} (\sin wt.\sin wt) + C_i$$

$$Q(t) = 1/2, R(t) = 0.5\sin wt, P(t) = 0.5\sin wt$$

Substituting these values for the second half cycle integration, in equation we get

$$Q(t) = 1/4 + C_i$$

$C_i = 1/2$ from the first half cycle

Therefore, $Q(t) = 1/4 + 1/2$,

$Q(t) = 1/2 + 1/4 + 1/8 + 1/16 + ...\infty......(24)$, for the next consecutive half cycles, which is equal to 1

Hence it is proved that $Q(t)$ follows the magnitude of $I(t)$.Therefore this signal is used for checking the magnitude of voltage whether it is in IEEE prescribed limits or not.

In case $I(t)$ contains harmonics, Suppose that

$$I(t) = \sin wt + 0.3\sin 5wt....(25)$$

Here fifth harmonic has to be seperated and compensated at power levels.

During first half cycle, $I(t) = P(t) = \sin wt + 0.3\sin 5wt$ from the figure.5

$$Q(t) = 1/0.01* \int_0^{0.01} ((\sin wt + 0.3\sin 5wt).\sin wt) + C_i$$

$$Q(t) = 1/2,$$

Its value approaches 1 in the next few consecutive half cycles, similar to the case when $I(t)$ is harmonic free.

Now, $R(t) = Q(t)\sin wt$

Hence, $R(t) = \sin wt$

Now, $P(t) = I(t) - Q(t).....26$

Hence, $P(t) = 0.3\sin 5wt.....27$

It means the algorithm is able to separate the harmonic current component in per unit. i.e; $P(t)$

V. SHUNT CONVERTER CONTROL

When *I(t)* is load current in per unit. Various extracted components are given in the figure below. Among these reference signals *P(t)* is the signal which contains the harmonic components. This signal is given to the gate pulse generator which might employ various techniques like sinusoidal pulse width modulation technique or hysteresis current control method to generate gate pulses for shunt converter, each of them having their own advantages. Hysteresis current control technique is simple but one has to carefully choose the hysteresis band [4].The block diagram of shunt converter control is given in fig.

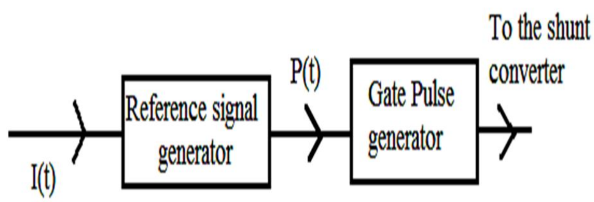

Fig.6 Block diagram of shunt converter control.

The source and load current waveforms of phase '*a*' and their FFT analysis after compensation using this novel algorithm is given in figure. It can be seen that the THD value of the source current is reduced to 4.42% which is well within IEEE limits (5%).

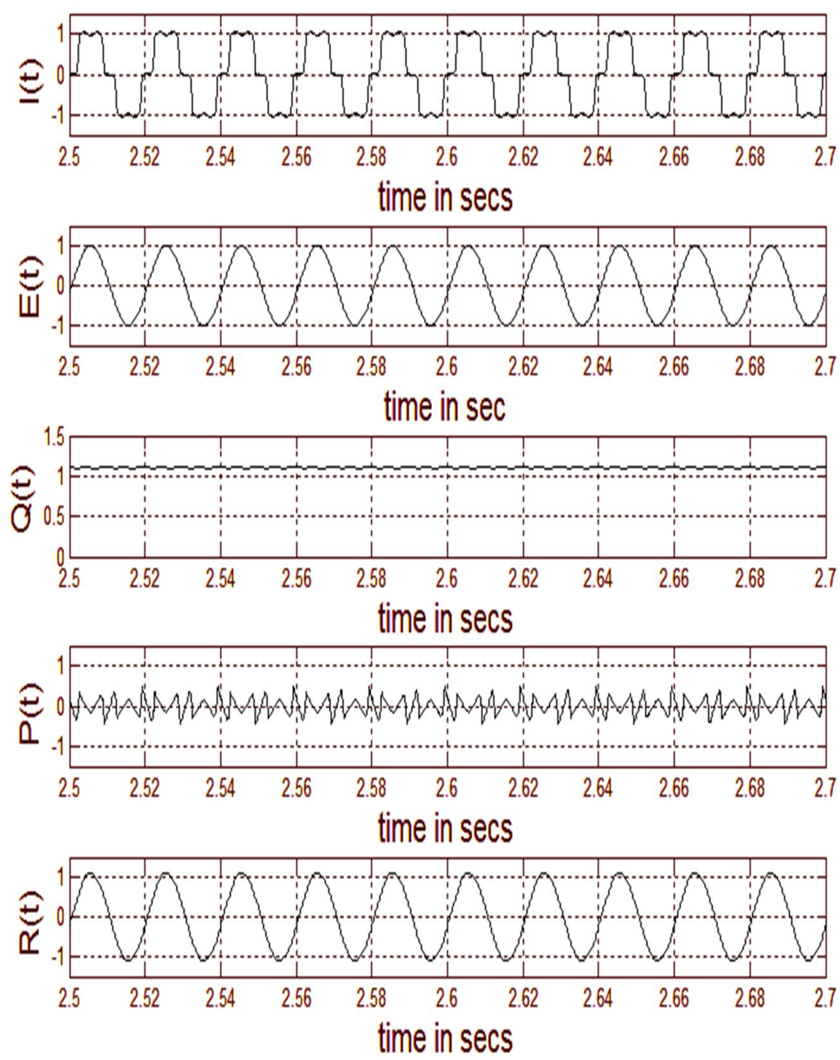

Fig.7 Reference signals extracted from the load current wave form.

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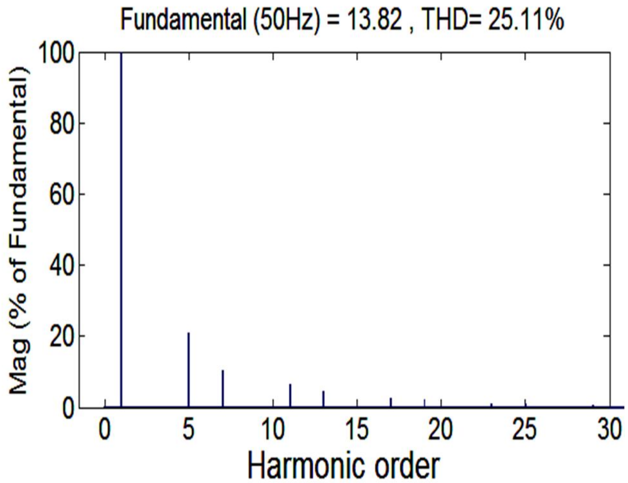

Fig.8 FFT analysis of Load current waveform

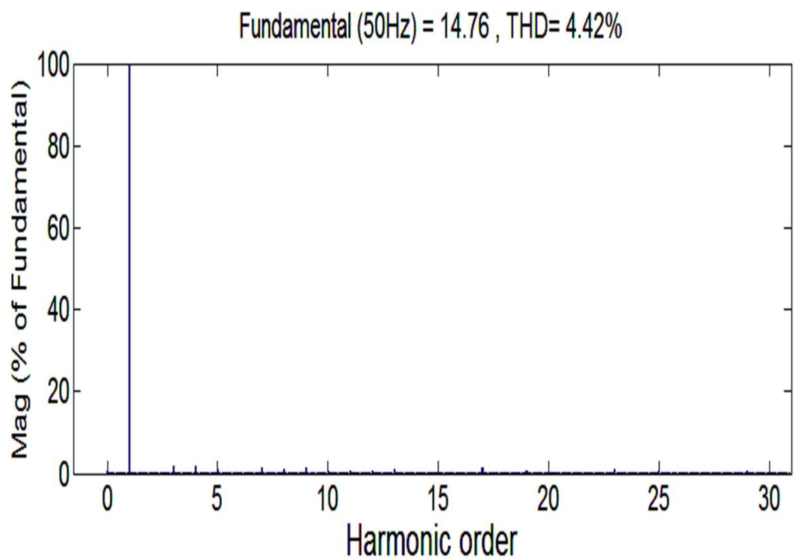

Fig.9 FFT analysis of source current waveform

VI. ALGORITHM BASED ON dq TRANSFORMATION FOR SAG COMPENSATION.

Generally, for sag detection and compensation the three phase voltages are transformed into two phase voltages using the formula given below.

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

Because the voltages are transformed to the rotating axes d and q, u_d and u_q are constant values. Hence the term $1 - \sqrt{u_d^2 + u_q^2}$ can be monitored for detection of sag, i.e.; whether it is within IEEE limits. But when low depth sag occurs on a single phase line due to LG fault, the algorithm fails to detect it. For example 0.18 p.u. single phase fault has occurred on phase a. Then it can be shown that from the above equation that the sag monitored in p.u. by $1-\sqrt{u_d^2+u_q^2}$ is 0.06 p.u. which is within the IEEE limits of sag i.e.; 0.1p.u. So, there is a need for alternate algorithm if unsymmetrical faults of less severity are to be detected and cleared.

VII. SERIES CONVERTER CONTROL USING NOVEL ALGORITHM.

When the input to the algorithm is voltage of phase *a* in p.u. The reference signals extracted when a 0.25 p.u. sag is created on the test system during 1.5 secs to 1.6 secs are given below.

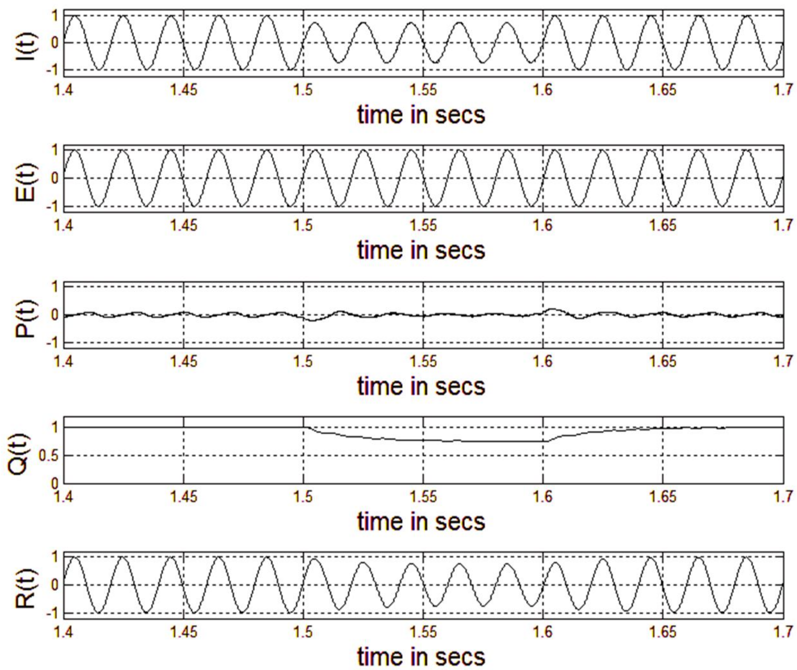

Fig.10 various reference signals extracted from source voltage

In these reference signals obtained *Q(t)* can be used for sag detection as it indicates amplitude of input signal. The difference between EPLL signal *E(t)* and *I(t)* is to be compensated at power level using series active filter .when Q(t) is in between 0.1 p.u to 0.9 p.u. The block diagram of series converter control is given in figure .11 For the gate pulses SVPWM or hysteresis voltage control methods can be used. The series converter mitigates sag by injecting the voltage that is reduced and hence load voltage is maintained constant which can be observed from the figure. It is proved that this algorithm detect low depth unsymmetrical faults unlike the algorithm based on *dq* transform

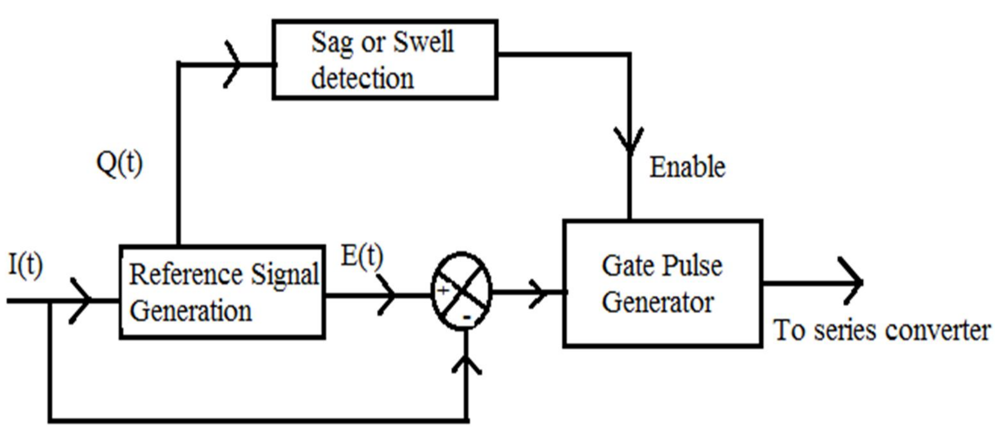

Fig.11 Block diagram of series converter control

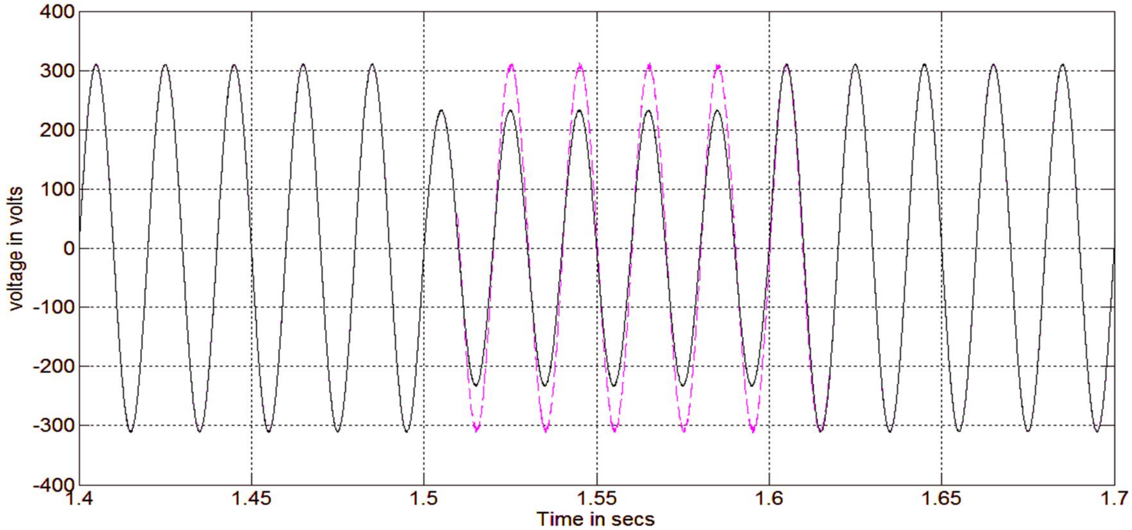

Fig.12 Source Voltage (solid) and Load Voltage (dotted)

VIII. CONCLUSION

The novel algorithm is been compared with Algorithm based on IRP theory for shunt converter control and algorithm based on *dq* transformation for sag detection and compensation for series converter control. In both the novel algorithm based on EPLL and non linear adaptive filter has been proved effective. It is proved that IRP theory algorithm for harmonic compensation suffers from hidden harmonics which is why the THD value of source current after compensation is 7.18% and source current compensated through novel algorithm has THD of 4.42%.Similarly the sag detection unit using *dq* transform method is ineffective for low depth sags on single phases whereas sag detection using the reference signal *Q(t)* from novel algorithm is able detect it as it deals all three phase voltage magnitudes unlike *dq* transform. The load voltage is maintained within the IEEE limits.

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