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A Comparative Study on Four Time-Domain Harmonic Detection Methods for Active Power Filters Serving in Distorted Supply

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***Abstract*—Active Power Filters (APFs) are the up-to-date solution to power quality problems. Shunt active filters (the most common type) allow the compensation of current harmonics, unbalance, together with power factor correction, and can be much better solution than the conventional approach. This paper discusses four different control strategies applied to shunt active power filter, the four control strategies are time-domain based strategies which are instantaneous reactive power theory (IRPT), synchronous reference frame (SRF), synchronous detection method (SDM), and a proposed method which presents a positive sequence detector that is used with an improved ABC reference frame formula based upon the p-q theory to solve the problem of non-ideal mains. The improved formula needs fewer calculations than the conventional p-q theory. Moreover, it is very easy to implement this algorithm on a digital signal processor (DSP).**

***Index Terms*—Distorted supply voltages, IRPT,SDM, Shunt APF, and SRF**

I. INTRODUCTION

With the rapid use of the power electronics converters which are considered non-linear loads, harmonic currents are drawn from the electrical network. Due to the network impedance the non-sinusoidal currents cause non-sinusoidal voltage drops resulting finally in distorted supply voltages. They also cause poor input power factors, low efficiency, and result in the destruction of other equipment. Conventionally, passive LC filters [1] are used to eliminate the line current harmonics and improve the P.F. Due to several demeritsof passive filters such as the fixed compensation, large size, and resonance, APFs are investigated and researched. Figure 1 illustrates the APF system components.

One of the most discussed software part (in the case of DSP implementations) of APF is the harmonic detection method [2-4]. In brief, it represents the part that has the capability of determining specificdetectionsignal attributes (for instance the frequency, the amplitude, the phase, the time of occurrence, the duration, energy, etc.) from input signals (that can be voltage, current or both) by using a special mathematical algorithm.

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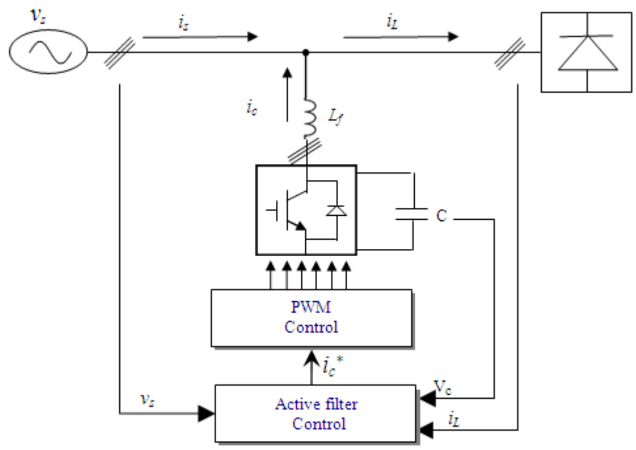

Fig.1 APF block diagram.

This work in this paper is applied for different detection and control strategies of APF serving in weak networks. The performance of the entire APF will be investigated and compared at the end.

II. IRPT THEORY

The p-q theory [5] is based upon algebraic transformation which transforms the measured voltages and currents from the conventional a-b-c frame to α-β frame as follows:

$$\begin{bmatrix} x_0 \\ x_\alpha \\ x_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} (1)$$

Where; x may be the voltage or current.In case of 3-wire system both v_0 and i_0 equal zero, as i_α and i_β are orthogonal, and the same for $v_\alpha$andv_β. Also;

$$\begin{bmatrix} p(t) \\ q(t) \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} (2)$$

Where; $p(t)$ is the instantaneous active power and $q(t)$ is the instantaneous reactive power.

Performing the inverse of the matrix in (2)

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\beta & v_\alpha \\ v_\alpha & -v_\beta \end{bmatrix} \begin{bmatrix} p^* \\ q^* \end{bmatrix} (3)$$

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$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} (4)$$

Where; i_a^* , i_b^* , and i_c^* are the reference compensator currents in the a-b-c frame and i_α^*, and i_β^* are the reference currents in the α-β frame. For the purpose of complete compensation (i.e. unity P.F.) and exploiting indirect current control $p^* = \bar{p}$, and $q^* = 0$.

III. SYNCHRONOUS REFERENCE FRAME (SRF)

SRF [6] is based onusing Clarke transformation at first to transform a-b-c currents to α-β currents as;

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} (5)$$

Then, transformed to d-q axis using Park transformation;

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\omega t & sin\omega t \\ -sin\omega t & cos\omega t \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} (6)$$

Inverse Clarke and inverse Park transformations are applied in 7 and 8;

$$\begin{bmatrix} i*_\alpha \\ i*_\beta \end{bmatrix} = \begin{bmatrix} cos\omega t & -sin\omega t \\ sin\omega t & cos\omega t \end{bmatrix} \begin{bmatrix} i*_d \\ i*_q \end{bmatrix} (7)$$

$$\begin{bmatrix} i*_a \\ i*_b \\ i*_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i*_\alpha \\ i*_\beta \end{bmatrix} (8)$$

As for the IRPT, the current in *d-q* frame can be composed by the instantaneous current $i_q = \bar{i_q} + \tilde{i_q}$ and the instantaneous current $i_d = \bar{i_d} + \tilde{i_d}$. The division of the dc and ac can be obtained using a low-pass filter.

IV. SYNCHRONOUS DETECTON METHOD (SDM)

SDM [7] method is basically used for the determination of amplitude of the source currents. The instantaneous real power $p(t)$consumed by the load could be calculated from the instantaneous voltages and load currents as;

$$p(t) = v_{sa}(t) * i_{la}(t) + v_{sb}(t) * i_{lb}(t) + v_{sc}(t) * i_{lc}(t) (9)$$

Where, $v_{sa}(t)$, $v_{sb}(t)$, and $v_{sc}(t)$ are the instantaneous values of supply voltages, and $i_{la}(t)$, $i_{lb}(t)$, and $i_{lc}(t)$ are the instantaneous values of load currents.

The average value P_{dc} is determined by applying $p(t)$ to a low pass filter. The real power is then split into the three phases as follows:

$$p_a = \frac{p_{dc}*V_{sma}}{V_{sma}+V_{smb}+V_{smc}} (10)$$

$$p_b = \frac{p_{dc}*V_{smb}}{V_{sma}+V_{smb}+V_{smc}} (11)$$

$$p_c = \frac{p_{dc}*V_{smc}}{V_{sma}+V_{smb}+V_{smc}} (12)$$

Thus, for three phase ideal supply voltages;

$$p_a = p_b = p_c = \frac{p_{dc}}{3} (13)$$

From (10), (11), and (12) the reference supply currents can be easily determined as follows:

$$i_{sa}^* = \frac{2\, v_{sa}(t)*p_a}{V_{sma}^2} (14)$$

$$i_{sb}^* = \frac{2\, v_{sb}(t)*p_b}{V_{smb}^2} (15)$$

$$i_{sc}^* = \frac{2\, v_{sc}(t)*p_c}{V_{smc}^2} (16)$$

V. THE PROPOSED METHOD

The proposed method consists of two parts. The first part is the positive sequence detector and the second one is the improved formula.

A. Positive Sequence Detector

After the three phase voltages are filtered using band pass filters tuned at the fundamental supply frequency (2nd order Butterworth band pass filters), the positive sequence detector is used. Fortescue defined a linear transformation from three phase components to a new set of components called symmetrical components. The advantage of this transformation is that for unbalanced three phase networks the equivalent circuits obtained for the symmetrical components (called sequence networks) are separated into three balanced uncoupled networks. As a result, sequence networks for many cases of unbalanced three phase systems are relatively easy to analyze. The symmetrical component method is basically a modeling technique that permits systematic analysis and design of three phase systems. Decoupling a detailed three phase network into three simpler sequence networks reveals complicated phenomena in more simplistic terms. The proposed positive sequence detector is ideal for use in any case of network conditions such as distorted or unbalanced supply.Figure 2 shows the block diagram of the positive sequence detector.

B. The Improved Formula

As the positive sequence detector results finally in balanced non-distorted three phase supply voltages expressed in ABC reference frame, the p-q theory will have a good performance. In attempt to reduce the calculations in the p-q theory, the improved formula is used. The improved formula omits any additional transformations and applies the whole control loop in the ABC reference frame.

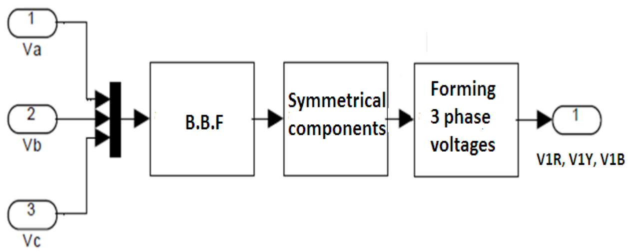

Fig.2 Block diagram of the positive sequence detector.

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From the law of energy conservation Eqn. (17) can be formed easily. The instantaneous active power $p(t)=V.I^T$,

$$V = [v_a \quad v_b \quad v_c], I = [i_a \quad i_b \quad i_c] \quad (17)$$

From (1) and (2) Eqn. (18) can be formed as;

$$q(t) = \frac{1}{\sqrt{3}}(i_a * v_{bc} + i_b * v_{ca} + i_c * v_{ab}) \quad (18)$$

For three phase, 3-wire system;

$$v_a + v_b + v_c = 0 \quad (19)$$

$$i_a + i_b + i_c = 0 \quad (20)$$

From (17), (19), and (20);

$$p(t) = i_a * v_{ac} + i_b * v_{bc} \quad (21)$$

And from (18), (19), and (20);

$$q(t) = \sqrt{3}\, i_a * v_b - \sqrt{3}\, i_b * v_a \quad (22)$$

$$\begin{bmatrix} p(t) \\ q(t) \end{bmatrix} = \begin{bmatrix} v_{ac} & v_{bc} \\ \sqrt{3}v_b & -\sqrt{3}v_a \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} \quad (23)$$

Performing the inverse of the matrix in (23):

$$\begin{bmatrix} i_a \\ i_b \end{bmatrix} = \frac{1}{\gamma} \begin{bmatrix} v_a & \frac{v_{bc}}{\sqrt{3}} \\ v_b & -\frac{v_{ac}}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} p(t) \\ q(t) \end{bmatrix} \quad (24)$$

Where; $\gamma = v_a v_{ac} + v_b v_{bc}$

p(t)andq(t) are the same for the conventional p-q theory. So, they can be treated as mentioned before, the reference compensation currents can be calculated as follows:

$$\begin{bmatrix} i_a^* \\ i_b^* \end{bmatrix} = \frac{1}{\gamma} \begin{bmatrix} v_a & \frac{v_{bc}}{\sqrt{3}} \\ v_b & -\frac{v_{ac}}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} p^* \\ q^* \end{bmatrix} \quad (25)$$

$$i_c^* = -i_a^* - i_b^* \quad (26)$$

The improved formula reduces the number of multiplication signs from 39 to only 15 signs and the addition or subtraction signs from 24 to only 8 signs. This means about 33% reduction in detection time. Moreover the implementation of the whole control scheme will be in the ABC frame without any additional transformation.

VI. SIMULATION RESULTS

The presented simulation results were obtained by using Matlab/SIMULINK Power System Toolbox software. The load is taken as a three phase uncontrolled bridge rectifier feeding resistive load of 50Ω with line inductance of 0.7mH to reduce current spikes. The D.C. bus voltage is controlled at 930V. A distribution transformer is used with a leakage inductance of 1mH to simulate the weak network.

Figure 3 shows the point of common coupling voltage, V_{pcc}, due to the distribution transformer inductance. Figure 4 illustrates the three phase load currents. Figures 3-5 showthe reference currents produced by the IRPT, the proposed method, SRF and SDM respectively. They show both the proposed method and SRF has good performance in contrast to the SDM and IRPT.

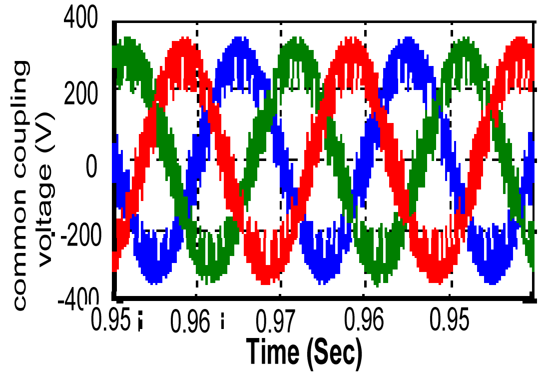

Fig.3 the point of common coupling voltages

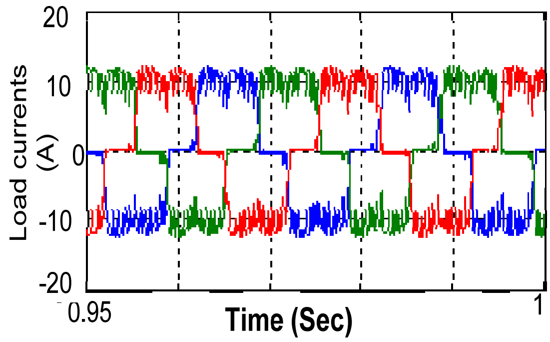

Fig.4 three phase load currents

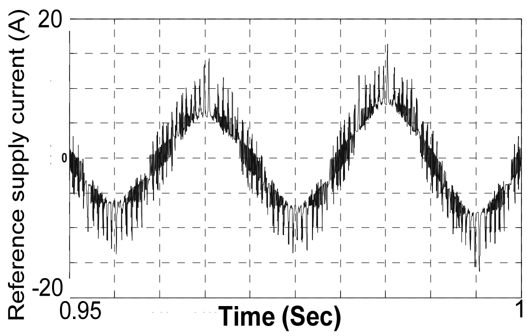

Fig.5 phase (a) reference current for the IRPT

Figures 6-9 show the phase (a) supply current for all methods. In case of SDM the resultant reference current has the same THD% of V_{pcc}, and SDM still has very bad performance under non-ideal supply voltages. However, in case of the small distortion in supply voltages and the hysteresis switching technique, the SDM has, somehow, acceptable performance (the simulation results may be deceitful).

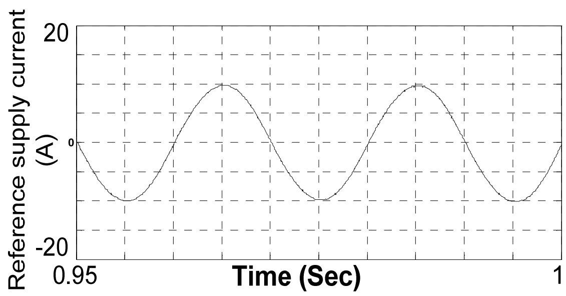

Fig.6 phase (a) reference current for the proposed method

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Figure 10 shows the load power. Figures 11-14 show the supply power for all detection techniques. The proposed method and SDM have the most flat profile.

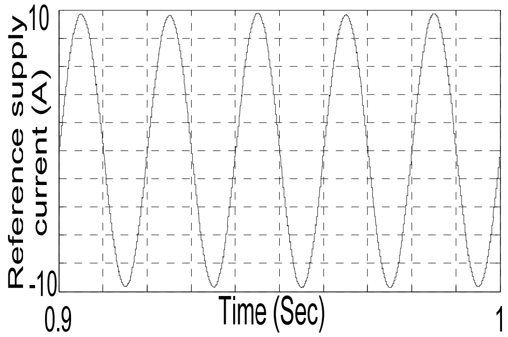

Fig.7 phase (a) reference current for SRF

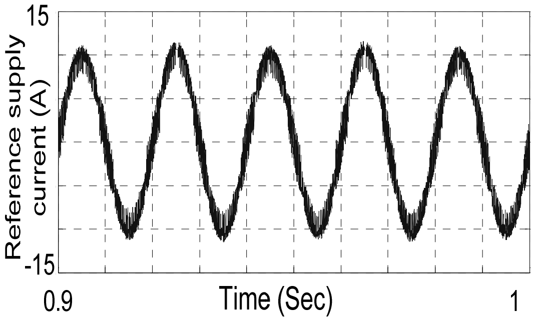

Fig.8 phase (a) reference current for SDM

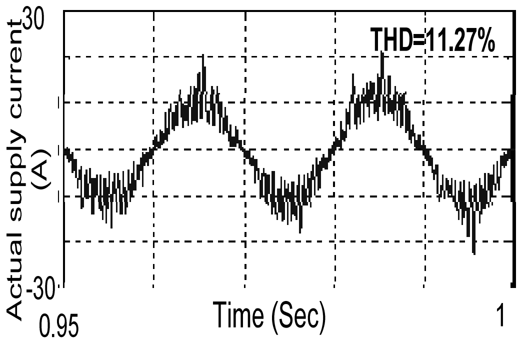

Fig.9 phase (a) supply current for IRPT

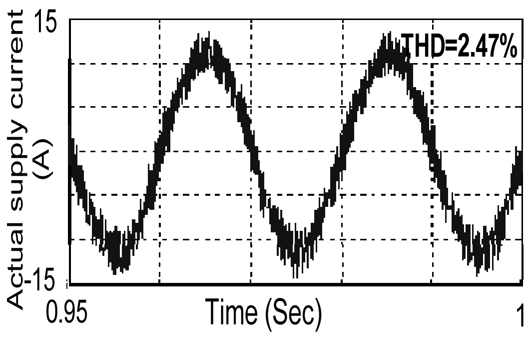

Fig.10 phase (a) supply current for the proposed method

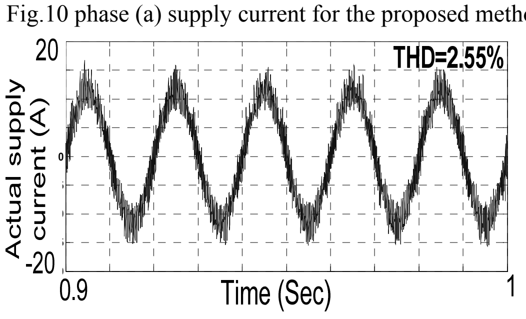

Fig.11 phase (a) supply current for SRF

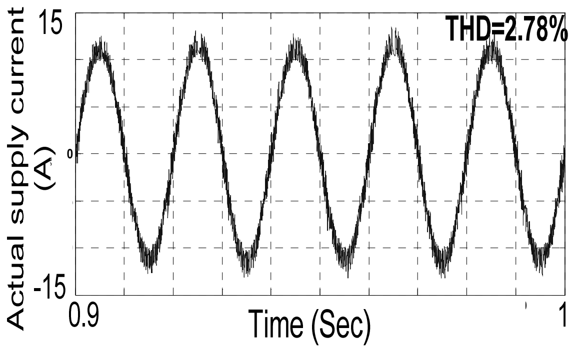

Fig.12 phase (a) supply current for SDM

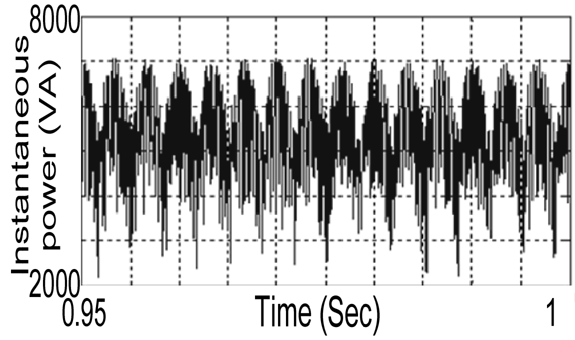

Fig.13 Load instantaneous power

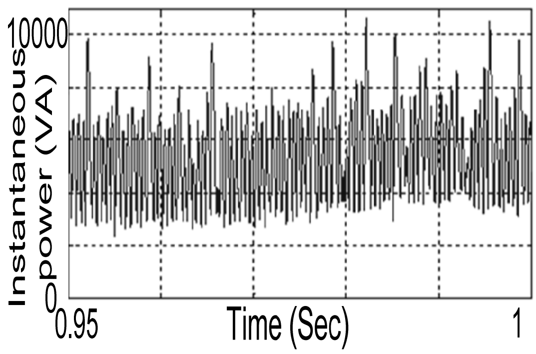

Fig.14 three phase supply instantaneous active power for the IRPT

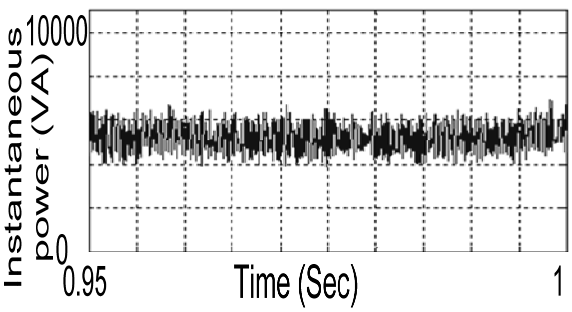

Fig.15 three phase supply instantaneous active power for the proposed method

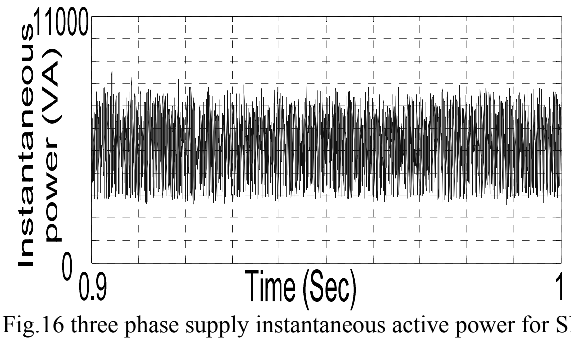

Fig.16 three phase supply instantaneous active power for SRF

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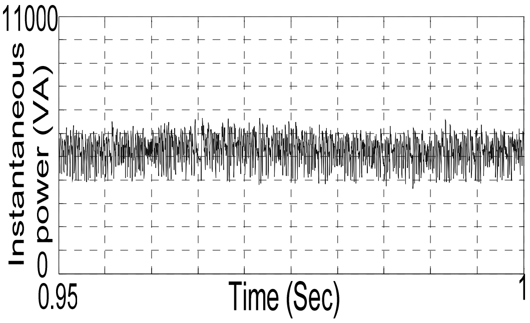

Fig.17 three phase supply instantaneous active power for SDM

VII. CONCLUSION

APF systems based on SDM, p-q theory, d-q, and proposed algorithm current detection methods have been successfully developed using MATLAB toolbox. The performance of each method was investigated under the reality of non-ideal conditions. It has been observed that the proposed method has feasible response as it has a sinusoidal reference current, low THD%, and almost a flat supply instantaneous power profile.

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