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A New Method of Harmonic Current Extraction for Shunt Active Power Filters

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Abstract:- **Application of active power filters (APFs) towards the ever increasing problem of harmonic distortion in industrial power system, due to nonlinear loads, has become a reliable and flexible alternative. In this paper, a new method of harmonic current extraction based on charge balance principle, for shunt active power filter towards mitigation of harmonics and maintaining unity power factor both under steady state and transient operating conditions, is presented. This method involves simple mathematical calculations devoid of any iterative estimation process, so as to facilitate easy hardware implementation for industrial use. Finally simulation results for a comparative study between the proposed method and the popularly used Instantaneous PQ theory (IPQT) method is presented which reveals improved performance of the former with respect to performance, theoretical simplicity and required computation for improvement in power quality.**

Index Terms— Active Power Filter, Charge Balance, Harmonic Current, Power Quality.

I. INTRODUCTION

In modern age, the use of power electronics devices have improved the performance of many electrical and electronic systems. But these power electronic devices operates on switching function, and draws required amount of current at certain instants. The switching instants and the amplitude of the current remain same over successive cycles of power supply, when the other conditions remain same. These devices behave as non-linear loads, and as a consequence pollute the power supply by injecting higher order harmonics.

Increasing applications of these power electronic devices have thus brought up challenges for maintaining power quality as per standard [1]. Over the years, passive filters are used for maintaining power quality, though it is simple and economical, but it has been failed to satisfy modern age requirements, such as variation in source and load condition, suppressing resonance, compact in size, light weight etc..

Therefore, to achieve above mentioned requirements active power filters (APF) are extensively used in the field of industrial electrical systems. There are several review reports [2]-[6], detailing the working of active power filters (APFs), which consists of an inverter, necessary voltage and current sensors, and reference current generator. After connecting APF in an electrical system, it either source or sink energy from the supply, in such a fashion that the resultant supply current becomes pure sinusoidal of supply frequency with unity power factor. Depending upon the configurations, APF can be broadly categorized into shunt active power filters and series active power filters, out of which the former type is mostly used since it can be easily maintained without interrupting the main power circuitry, hence it is more reliable [7].

Accurate harmonic current extraction from the load current plays a vital role in efficient functioning of APF. Therefore a lot of work in this regard have been published in the literature [7]-[26]. Among these frequency domain based, Discrete Fourier Transform (DFT) [8] is a popular method, but it suffers from spectral leakage problem and poor frequency resolution [9]. Among the time domain based methods instantaneous PQ theory (IPQT) [10]-[12] is the most widely used one owing to the easy mathematics and better performance in a balanced three phase system. But the results of the algorithm deteriorates in an unbalanced three phase system and frame transformation calculations in the algorithm increase the computation burden of the processor wherein it is implemented. Also, the use of low pass filters in the algorithm decreases the rate of execution of the algorithm [13]. Therefore to overcome these problems Synchronous Reference frame (SRF) [14]-[16] theory and other Phase Locked Loop (PLL) [17]-[18] based method have also been proposed. But, the speed of PLL is quite slow in frequency estimation [9]. As a result of this, methods based on Artificial Neural Network (ANN) [7], [19], adaptive learning [20]-[22], nonlinear least square based method [13], genetic algorithm [23], Kalman Filters [24] were subsequently proposed in the literature for the harmonic current extraction of APF's. However out of the above mentioned methods, ANN requires a lot of training data for reliable operation [13], the Kalman filtering method produces around 3 cycle delay for sudden load changes [13], the nonlinear least square approach involves heavy iterative computations [7]. The speed and accuracy of the adaptive learning based methods depends upon the learning rate of the weight update rule used [9] and all the other methods involves high amount of computations for the processor. In more recent times some control techniques have been proposed, which eliminates the need of harmonic detection for APF itself [25]. But under conditions of sudden load variations these methods efficiency becomes dependent upon how fast it reaches to its equilibrium state [26]. As mentioned above even after the introduction of so many other methods, the IPQT theory is the most commonly used method. Therefore authors in this paper has focused on developing a new harmonic current extraction algorithm which retains the above mentioned advantages of IPQT method and at the same time is able to eliminate the disadvantages of this most commonly used method which includes high amount of computation, dependence on the use of filters and poor efficiency under unbalanced supply conditions, and free parameters to be adjusted for tuning.

In the proposed scheme the measured load current over the past half cycle is integrated for calculating total charges through the load, and thereafter the charges under the fundamental component is calculated, which is then used for generating reference sinusoidal function, finally the required harmonic current is extracted by subtracting reference sinusoidal function from present load current. The above estimation repeats for every positive and negative half cycles, and for every phases of three phase system. This proposed scheme is simple and involves less computation as it does not requires any computationally intensive transformation, Phase Lock Loop (PLL), filters etc. In spite of being less computation intensive and simple, the performance of the proposed scheme found to be equal or better than the popular IPQT method especially under transient operating conditions.

The complete study is presented in this paper in four sections: Methods, Results, and Discussion & Conclusion. The proposed scheme for generation of reference current is presented in Section II. The obtained simulation results are presented in Section III, followed by discussion and conclusion in Section IV and V respectively.

II. METHOD

In this Section the proposed algorithm for extraction of harmonic current is presented. This section also includes the zero crossing detection technique and schematic representation as used for verification of the proposed scheme.

Charge Balance (CB) method of harmonic current extraction:
At first, the zero crossing point (ZCP) of the measured voltage signal is detected to calculate the supply frequency from eq.1, where *N* is the total number of data samples measured in each half cycle and t_S is the sampling period of the data acquisition device.

$$f = 1/(2 \times N \times t_S) \quad (1)$$

For a non linear load the load current can be written as,

$$I_{Load} = I_F + I_h \quad (2)$$

where, I_{Load}, I_F and I_h are the load current, fundamental component of the load current and harmonic component of the load current respectively. The charge carried by these currents in every half a cycle are given by Q_{Load}, Q_F and Q_h obtained as shown below.

$$\int_0^\pi I_{Load} = \int_0^\pi I_F + \int_0^\pi I_h$$

$$or, Q_{Load} = Q_F + Q_h \quad (3)$$

Without an APF both these I_F and I_h components of the supply current is supplied by the AC supply source current I_{Supply} thereby increasing its total harmonic distortion percentage (THD) beyond the standard permissible limits.

An APF comprising of a voltage source inverter (VSI) is connected in such non linear circuits in a way as shown in Fig.1. The function of this APF is to supply the I_h component of the load current such that I_{Supply} becomes equal to I_F only. Therefore the nonlinear load draws the same current as before but the supply current becomes free from harmonics and its THD value is brought down within the permissible limit.

Since APF supplies the I_h component of the load current, therefore this I_h is the required reference current taken by the VSI part of the APF. Appropriate gating signals are generated such that the VSI tracks this reference current and finally produce the required current given as I_{APF} in fig.1.

Now, under ideal lossless condition after every half cycle the net total charge consumed by the APF becomes equal to zero. Therefore after each half cycle $\int_0^\pi I_h$ becomes equal to zero i.e. $Q_h = 0$, such that

$$Q_F = Q_{Load} \quad (4)$$

Therefore at the completion of each half cycle marked by the detected ZCP, Q_F is used to calculate the amplitude A of current I_F by eq.5

$$A = Q_F \times \pi \times f \quad (5)$$

The formula given by eq.5 is derived as follows:-
The fundamental component of the load current can be represented as

$$I_F = A \sin \omega t \quad (6)$$

wherein A is the amplitude of the fundamental component of load current, $\omega = 2 \times \pi \times f$, f being the frequency of the fundamental component of the load current.

Integrating eq.6 on both the sides for half a cycle we get,

$$\int_0^\pi I_F \, dt = \int_0^\pi (A \sin \omega t) dt$$

$$or, \quad Q_F = -\frac{A}{\omega}[\cos \pi - \cos 0]$$

$$or, \quad A = \frac{Q_F \times \omega}{2}$$

$$or, \quad A = \frac{Q_F \times 2 \times \pi \times f}{2}$$

$$or, \quad A = Q_F \times \pi \times f$$

Therefore finally using the known quantities A and f the fundamental component of the load current is calculated at the end of each half cycle by eq.7.

$$I_F = (A + L.f.) \sin(2\pi f t_s) \quad (7)$$

Wherein, L.f. is the loss factor provided by the PI controller used to maintain stable DC voltage (V_{dc}) across the APF, as shown in fig.1.

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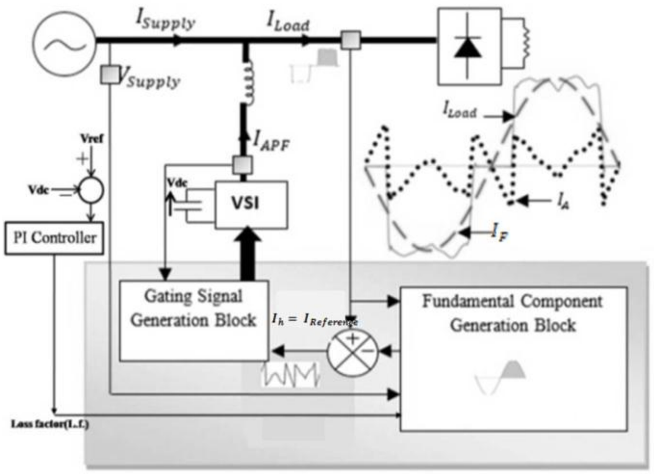

Fig.1 Schematic diagram of APF functioning by the proposed method

Finally the required harmonic current(also known as compensating current) waveform of the APF, can be obtained by subtracting I_F from the measured load current I_{Load} of the present half cycle by eq.8

$$I_{APF}(n) = I_{Load}(n) - I_F(n) \quad (8)$$

for discrete time system, with sample number n.

Zero Crossing Detection Scheme: In this scheme,to detect the zero-crossing point for every measured voltage sample $V_A(n)$ and its previous value $V_A(n-1)$ are checked for the following conditions; $V_A(n) > 0$, $V_A(n) < 0$, $V_A(n-1) > 0$, and $V_A(n-1) < 0$. Then, the binary results with comparisons i.e. true or false in the form of '1' or '0' respectively are stored into a four bit register and the register content is continuously checked for every new sample, whether it matches with any one of the four binary patterns as shown in Table I below. By matching the output of the ZCD, it becomes true, indicating occurrence of zero crossing.

Table I: Conditions for Zero Crossing Detection

$V_A(n) < 0$	$V_A(n) > 0$	$V_A(n-1) < 0$	$V_A(n-1) > 0$
1	0	0	1
0	1	1	0
0	0	0	1
0	0	1	0

Fig.2 below shows the flow chart representation of the CB method wherein $I_{Lx}(n)$, $I_{Fx}(n)$, and $I_{Ax}(n)$ represent x phase n[th] sample of the load current, fundamental component current, and compensating current respectively. Here, $V_{sx}(n)$ represents the x phase supply voltage, $N^{\sim}$is the total number of samples as acquired in previous half cycle, and t_s is the sampling time interval for measurement of voltages and currents.

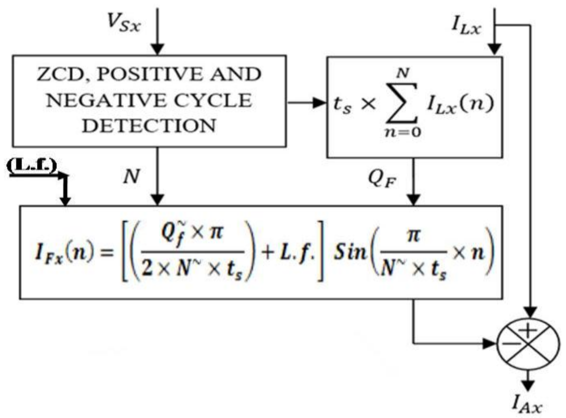

Fig.2 Flow diagram of the proposed CB based algorithm for generation of compensating current

III. SIMULATION RESULTS

To validate the theory above simulation experiments are carried out in Simulink environment with both the CB and IPQT methods wherein the non-linear load is a three phase bridge rectifier with a resistor and capacitor (RC type of load) connected in parallel across it. Hysteresis Control method is used for gating pulse generation [27]. The other system parameters used are given in Table II below. The performance of both the methods are analysed on the basis of percentage total harmonic distortion (%THD) of the compensated supply current and supply voltage which should be below 5% and 3% respectively as per the IEEE standards[1].

Table II: APF system parameters as used for simulation

Parameter	Value
Line-Line Voltage, Frequency	100V, 50Hz
Source Inductance	0.1mH
DC Link Capacitor DC Link Voltage	2200uF 300V
Filter Inductor	5mH
Non Linear Load	3-phase diode rectifier. Load across: R=50 Ω, C= 3000 µF.

Case-1: Steady state performance analysis.

In this group of test the steady state performance is checked with two different types of nonlinear load ,i.e. firstly with only resistor (50 Ω) across the 3 phase diode bridge rectifier and secondly with a resistor and capacitor (R=50 Ω, C= 3000 µF) in parallel with the bridge rectifier. It is found that in both the test cases both the CB and IPQT method are equally able to compensate the supply current as per the IEEE standards. Therefore the results of the CB method is presented in Fig.3 and Fig.4.

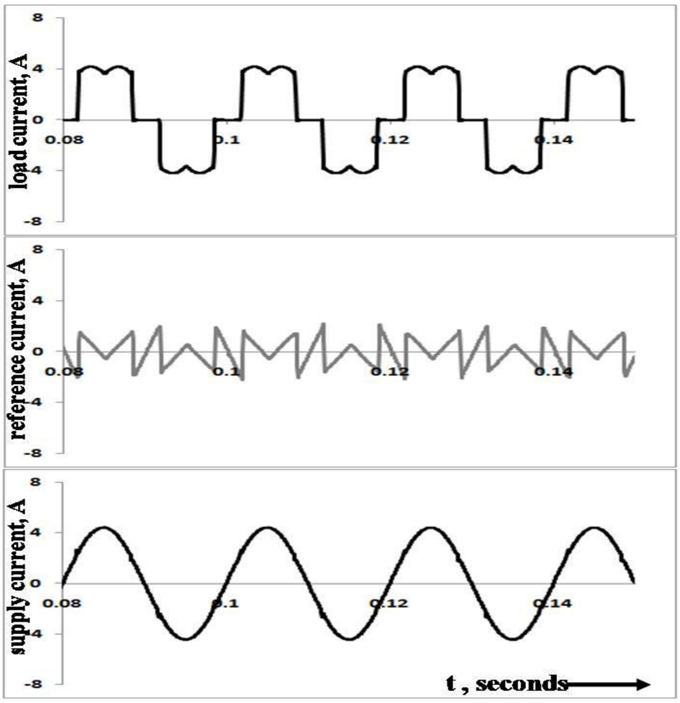

Fig.3 Load Current, Reference Current and Supply Current for resistive load, across 3 phase diode bridge rectifier ,with CB method

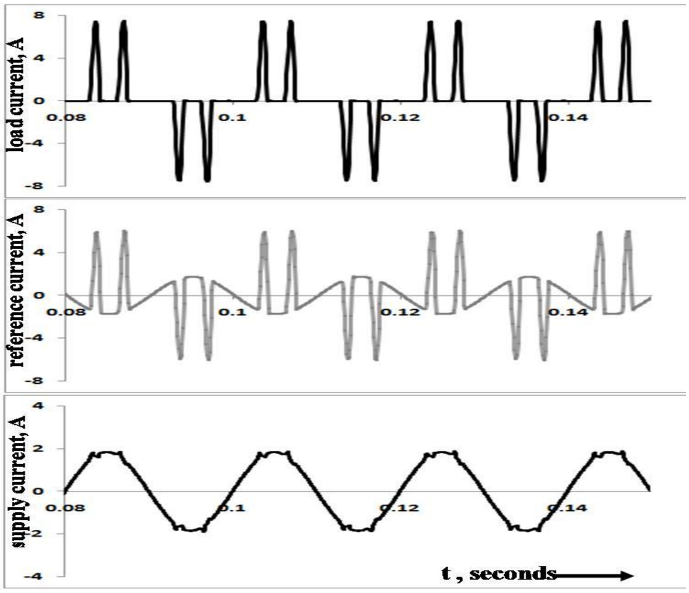

Fig.4 Load Current, Reference Current and Supply Current for resistive capacitive load, across 3 phase diode bridge rectifier ,with CB method

Case-2: Transient Performance Analysis.

Performance of the APF due to sudden change in operating condition have been studied, for comparison in transient behaviors. The obtained results by providing step change in (1) load magnitude (increase and decrease), (2) load type, (3) supply frequency and (4) unbalance supply voltage are discussed in the following subsections.

1) *Step change in load magnitude.*

The transient waveforms of load and compensated supply currents as recorded for both of the APFs due step increase and decrease of load are presented in Fig. 5 and Fig. 6 respectively.

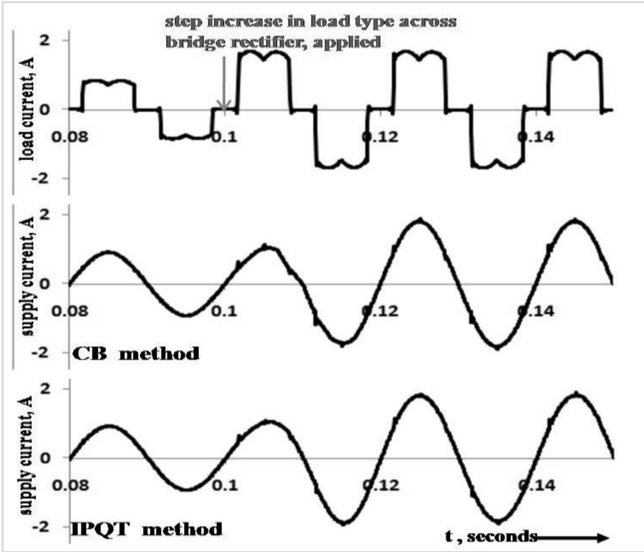

Fig 5 Load Current (top) and Supply Current (bottom) waveforms for sudden step increase in load at t = 0.1s (marked on Fig.), obtained from the APFs operated through CB method and (b) IPQT method

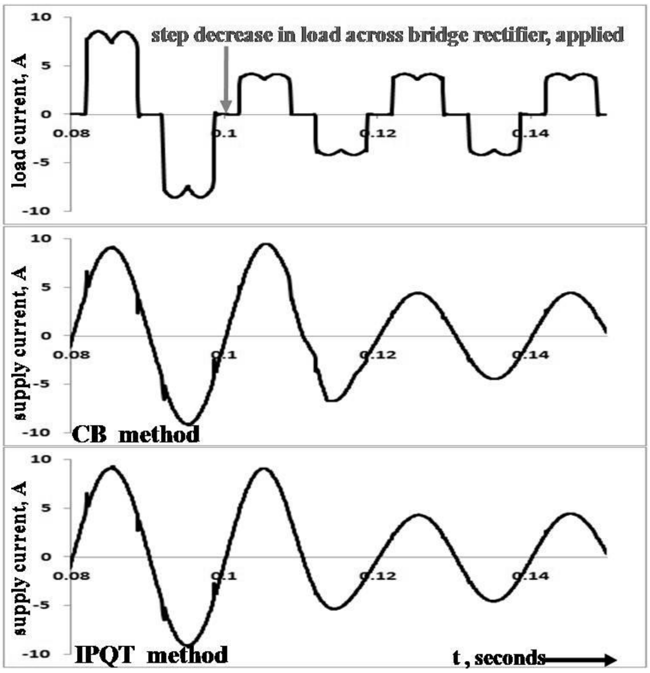

Fig.6 Load Current (top) and Supply Current (bottom) waveforms for sudden step decrease in load at t = 0.1s (marked on Fig.), obtained from the APFs operated through CB method and (b) IPQT method

Under these sudden load changing condition it is observed that time taken to restabilize by the APF with CB method was much lesser (i.e.12ms) than that with IPQT method which took 22 ms for the same condition. The reason behind this is the use of low pass filters in the IPQT algorithm which introduces a delay in processing of the measured signals[13].This was validated by observing the change obtained in the DC voltage waveform across the capacitor connected in parallel to the APF, as shown in Fig.7 and Fig.8 respectively.

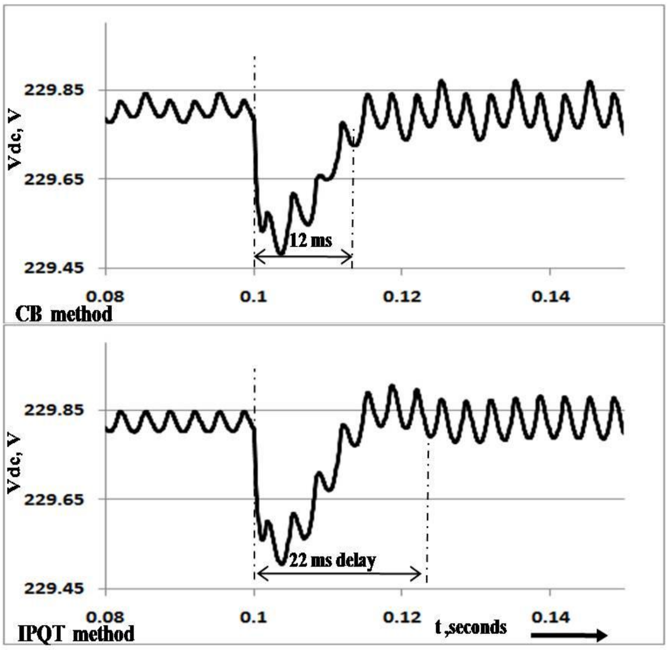

Fig 7 Voltage Vdc waveform across the APF capacitor, obtained under sudden step increase in load

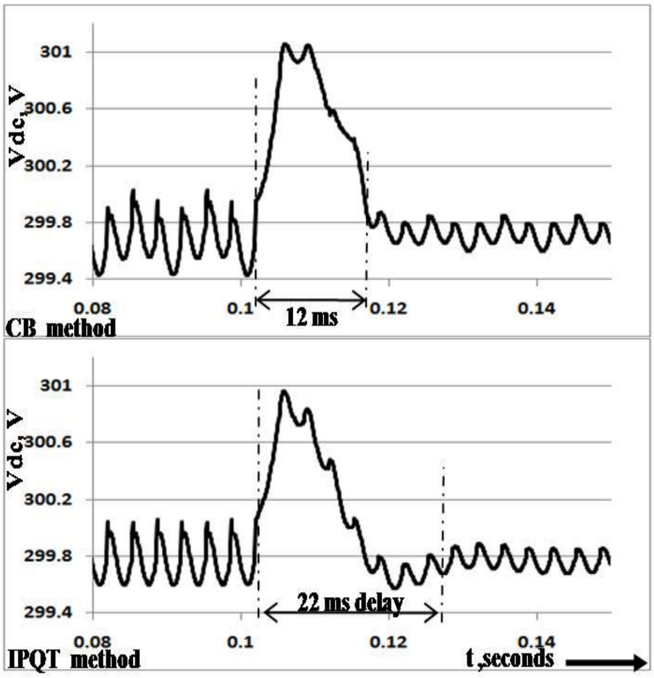

Fig 8 Voltage Vdc waveform across the APF capacitor, obtained under sudden step decrease in load

2) *Sudden change in Load type.*

In this testing condition the load type on the DC side of the 3 phase diode bridge rectifier is suddenly changed from resistive-capacitive type to resistive type. The transient waveforms as obtained for the APFs with CB and IPQT algorithms are presented in Fig. 9 and Fig. 10 respectively. From the figures similar kind of observations can be made as in previous case.

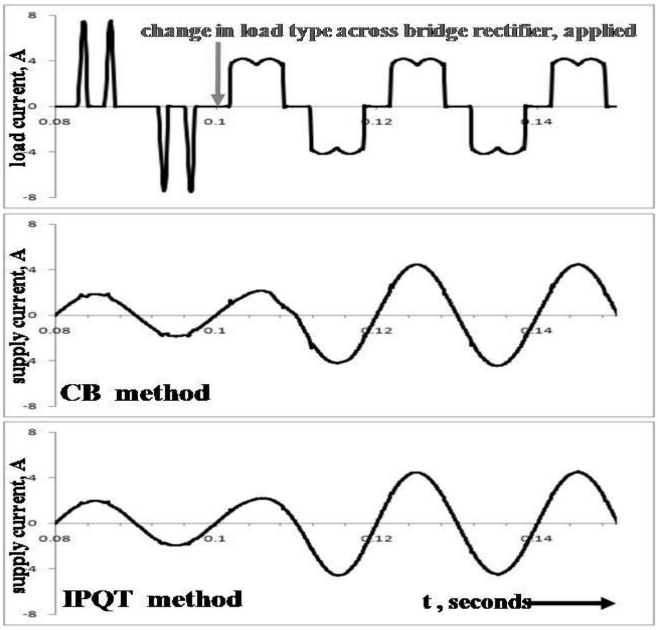

Fig 9 Load Current (top) and Supply Current (bottom) waveforms for sudden change in load type at t = 0.1s (marked on Fig.), obtained from the APFs operated through CB method and (b) IPQT method

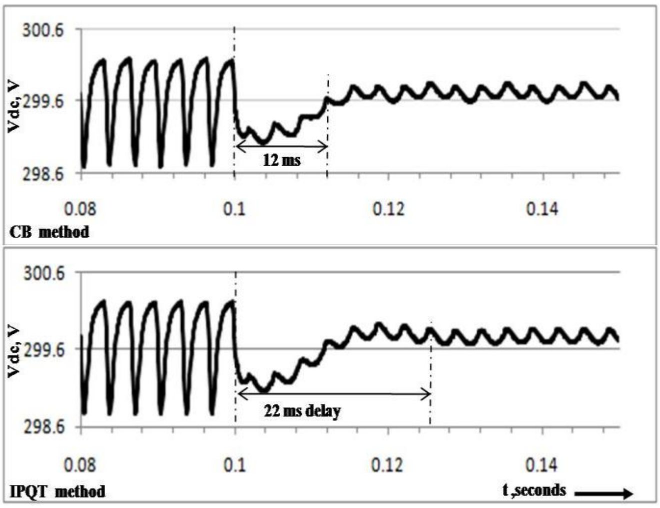

Fig 10 Voltage Vdc waveform across the APF capacitor, obtained under sudden change in type of load

3) *Step change in supply frequency*

In this test conditions the supply frequency of the three phase system was changed from 50Hz to 50.8Hz at time instant 0.1s and the transient performance of both the APFs were observed. Since for both the cases the supply current or the supply voltage where not affected therefore the results of CB method is presented in Fig. 11.

In Figure 11 it is also to be observed that the unity power factor of the system is maintained even when the supply frequency was changed.

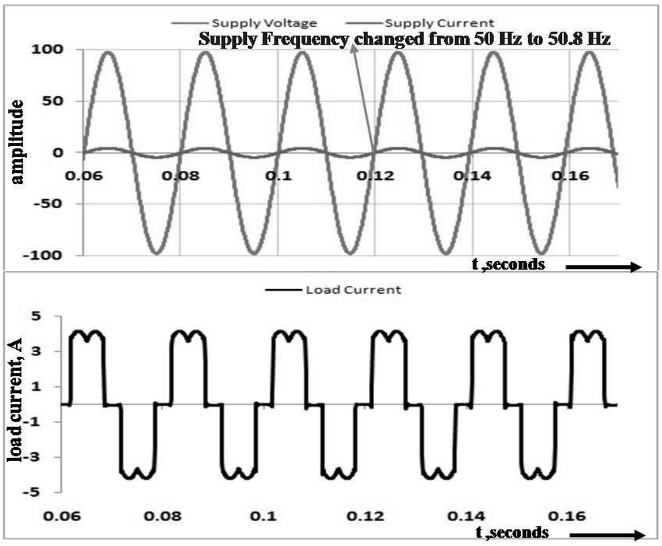

Fig. 11 Supply voltage, supply current and load Current for supply frequency variation from 50 Hz to 50.8 Hz, for the APFs operated through CB method and IPQT method

4) Unbalanced Supply voltage condition

In this testing condition, simulation of unbalanced supply voltage condition is done by decreasing the supply voltage amplitude of phase 'a' at time t=0.1s from 100 volts to 85 volts, as shown in Fig.12. As a result, it is observed that for CB method the %THD value of the compensated supply current increases by 1% for phase 'a' and by 0.5% for the other two phases. But for IPQT method the %THD increase is by 3% in all 3 phases which in turn makes the total harmonic distortion percentage of the compensated supply current exceed the maximum permissible limit of 5% as prescribed in the IEEE standards. Thus the CB algorithm is able to maintain the %THD of the supply current within 5% even under conditions of unbalance in supply voltage which is not the case for IPQT algorithm as observed by other researchers [13].

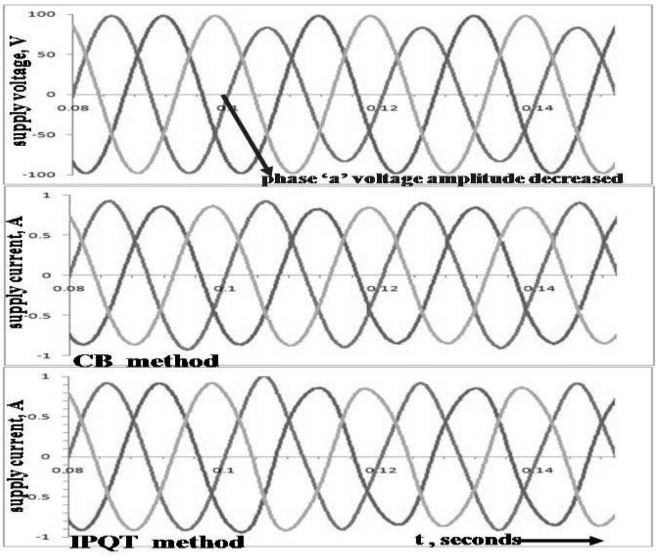

Fig.12 Supply Voltage (top) and Supply Current (bottom) for unbalanced supply voltage condition at phase 'a', for the APFs operated through CB method and IPQT method

IV. DISCUSSION

The above set of results clearly indicate that the proposed CB based method performs equally good as IPQT method under steady state conditions , but provides better results under transient conditions. It eliminates the use of low pass filters which therefore limits the response time for CB method to 12 ms in contrast to IPQT method which delays for 22ms. Of course in [13] authors have shown even a lesser delay time of 7ms, but the algorithm used involves heavy computations which requires a high speed processor for practical implementation [7].

Next for conditions of change in supply frequency the CB method is able to maintain unity power factor because after each half cycle, I_F is generated in phase to the supply voltage with the new updated frequency value obtained from the new zero crossing calculations.

Finally, since the calculation of harmonic current for the three phases are almost independent to each other in the proposed method, therefore it performs more efficiently in case of unbalanced supply voltage conditions

V. CONCLUSION

Rapid advancements in the field of power electronics has made the use of active power filter almost absolutely necessary especially in many industrial applications. Among the various active power filters algorithms proposed over last decades, IPQT algorithm for harmonic current extraction is common and popular, as it provides satisfactory results under balanced and sinusoidal conditions. However its response time increases due to the use of low pass filters and the results deteriorates under conditions of unbalanced supply voltage conditions. Authors in this paper has proposed a theoretically simple harmonic current extraction scheme based on charge balance principle for active power filters, which is able to retain the advantages of the IPQT algorithm and at the same time has eliminated the use of low pass filters, heavy computations so as to provide necessary compensation results under unbalanced supply voltage conditions. The ability to maintain unity power factor and elimination of heavy computations have also made the CB algorithm easy to be implemented in microcontroller or FPGA based system, making it a more practical tool in industrial applications of APFs.

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