Cascaded Multilevel Inverter based Active Filter for Power Line Conditioners using Instantaneous Real-Power Theory

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***Abstract*--This paper presents a three-phase, five-level cascaded multilevel voltage source inverter based active filter for power line conditioning to improve power quality in the distribution network. The active filter compensates both reactive power and harmonic currents drawn by non-linear loads; additionally it facilitates power factor corrections. The compensation process is based on concept of p-q theory. However, in the proposed approach only calculation of real-power (p) losses are conducted. This method is simple and different from conventional methods; it provides effective compensation for harmonics. The cascaded multilevel inverter switching signals are derived from the proposed triangular-sampling current controller that results in a good dynamic performance under both steady state and transient operations. The dc-bus capacitor voltage of the cascaded inverter is controlled and reduced ripple voltage using PI-controller. This proposed cascaded active power filter system is validated through extensive simulation under transient and steady state conditions with different non-linear loads.**

***Index Terms*-- Shunt Active Filter, Instantaneous power theory, Power quality, Triangular-sampling current modulator.**

I. Introduction

Non-linear electronic components such as diode/thyristor rectifiers, switched mode power supplies, arc furnaces, incandescent lighting and motor drives are widely used in industrial and commercial applications. These non-linear loads create harmonic or distortion current problems in the transmission and distribution network [1]. The harmonics induce malfunctions in sensitive equipment, overvoltage by resonance and harmonic voltage drop across the network impedance that affect power quality [2]. Traditionally passive LC filters have been used to compensate the harmonic distortion and the reactive power; but passive filters are large in size, have ageing and tuning problems and resonate with the supply impedance [3]. Recently Active Power Line Conditioners (APLC) or Active Power Filters (APF) overcome these problems and are designed for compensating the harmonics and suppressing the reactive power simultaneously [4]. Since basic principles of active filter compensation were proposed by Gyugyi and Strycula in 1976[5]. In 1984, Hirofumi Akagi introduced a new concept of instantaneous reactive power (p-q theory) compensators [6]. It dealt with three-phase system, being later worked by Watanabe and Aredes for three-phase four wires power systems [7]. The generalized instantaneous reactive power theory which is valid for sinusoidal or non-sinusoidal and balanced or unbalanced three-phase power systems with or without zero-sequence currents was later proposed by Peng and Lai [8]. The active filter can be connected in series or in parallel with the supply network. The series active power filter is suitable for voltage harmonic compensation. Most of the industrial applications need current harmonic compensation, so the shunt active filter is popular than series active filter [9]. Currently, remarkable progress in the capacity and switching speed of power semiconductor devices such as insulated-gate bipolar transistors (IGBTs) has spurred interest in APF [10].

The shunt active power filter compensation process is based on the instantaneous real-power theory; it provides good compensation characteristics in steady state as well as transient states [11]. The instantaneous real-power theory generates the reference currents required to compensate the distorted line current harmonics and reactive power. It also tries to maintain the dc-bus voltage across the capacitor constant. Another important characteristic of this real-power theory is the simplicity of the calculations, which involves only algebraic calculation [12].

This paper present an instantaneous real-power compensator based cascaded shunt active power filter for the harmonics and reactive power elimination. The cascaded H-bridge multilevel VSI has been applied for active filter applications due to increased number of voltage levels, low switching losses and higher order of harmonic compensation. The cascade M-level inverter consists of (M-1)/2 H-bridges and each bridge has its own separate dc source [13-17]. The cascaded multilevel voltage source inverter switching signals are generated using proposed triangular-sampling current controller; it provides a dynamic performance under transient

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and steady state operating conditions. The compensation process involves calculation of real-power (p) losses only that is derived from sensing phase voltages and distorted source currents. The PI-controller is used to maintain the capacitance voltage of the cascaded inverter constant. The shunt APF system is validated through extensive simulation and investigated under steady state and transient conditions with different non-linear loads.

II. PROPOSED INSTANTANEOUS POWER THEORY

The proposed instantaneous real-power (p) theory derives from the conventional p-q theory or instantaneous power theory concept and uses simple algebraic calculations. It operates in steady-state or transient as well as for generic voltage and current power systems that allowing to control the active power filters in real-time. The active filter should supply the oscillating portion of the instantaneous active current of the load and hence makes source current sinusoidal.

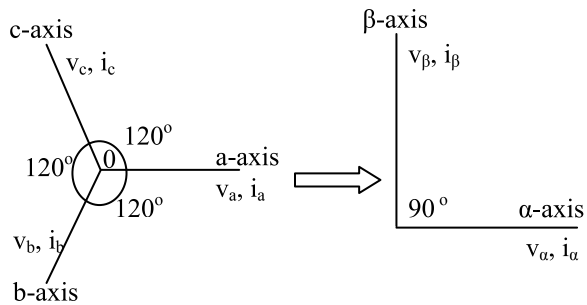

Fig 1 α-β coordinates transformation

The p-q theory performs a Clarke transformation of a stationary system of coordinates $a-b-c$ to an orthogonal reference system of coordinates $\alpha-\beta$. In $a-b-c$ coordinates axes are fixed on the same plane, apart from each other by 120° that as shown in Fig 1. The instantaneous space vectors voltage and current V_a, i_a are set on the a-axis, V_b, i_b are on the b axis, and V_c, i_c are on the c-axis. These space vectors are easily transformed into $\alpha-\beta$ coordinates. The instantaneous source voltages vsa, vsb, vsc are transformed into the $\alpha-\beta$ coordinate's voltage v_α, v_β by Clarke transformation as follows:

$$\begin{pmatrix} v_\alpha \\ v_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{pmatrix} \quad (1)$$

Similarly, the instantaneous source current isa, isb, isc also transformed into the $\alpha-\beta$ coordinate's current i_α, i_β by Clarke transformation that is given as;

$$\begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{pmatrix} \quad (2)$$

Where α and β axes are the orthogonal coordinates. They V_α, i_α are on the α-axis, and V_β, i_β are on the β-axis.

Real-Power (p) calculation:

The orthogonal coordinates of voltage and current v_α, i_α are on the α-axis and v_β, i_β are on the β-axis. Let the instantaneous real-power calculated from the α-axis and β-axis of the current and voltage respectively. These are given by the conventional definition of real-power as:

$$p_{ac} = v_\alpha \, i_\alpha + v_\beta \, i_\beta \quad (3)$$

This instantaneous real-power (p_{ac}) is passed to first order Butterworth design based 50 Hz low pass filter (LPF) for eliminating the higher order components; it allows the fundamental component only. These LPF indicates ac components of the real-power losses and it's denoted as $\overline{p_{ac}}$

The DC power loss is calculated from the comparison of the dc-bus capacitor voltage of the cascaded inverter and desired reference voltage. The proportional and integral gains (PI-Controller) are determining the dynamic response and settling time of the dc-bus capacitor voltage. The DC component power losses can be written as

$$p_{DC(loss)} = \left[v_{DC,ref} - v_{DC}\right]\left[k_P + \frac{k_I}{s}\right] \quad (4)$$

The instantaneous real-power (p) is calculated from the AC component of the real-power loss $\overline{p_{ac}}$ and the DC power loss $p_{DC(Loss)})$; it can be defined as follows;

$$p = \overline{p_{ac}} + p_{DC(Loss)} \quad (5)$$

The instantaneous current on the $\alpha-\beta$ coordinates of $i_{c\alpha}$ *and* $i_{c\beta}$ are divided into two kinds of instantaneous current components; first is real-power losses and second is reactive-power losses, but this proposed controller computes only the real-power losses. So the $\alpha-\beta$ coordinate currents $i_{c\alpha}, i_{c\beta}$ are calculated from the v_α, v_β voltages with instantaneous real-power p only and the reactive power q is assumed to be zero. This approach reduces the calculations and shows better performance than the conventional methods. The $\alpha-\beta$ coordinate currents can be calculated as

$$\begin{pmatrix} i_{c\alpha} \\ i_{c\beta} \end{pmatrix} = \frac{1}{v_\alpha^{\,2} + v_\beta^{\,2}} \left\{ \begin{pmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{pmatrix} \begin{pmatrix} p \\ 0 \end{pmatrix} \right\} \quad (6)$$

From this equation, we can calculate the orthogonal coordinate's active-power current. The α-axis of the instantaneous active current is written as:

$$i_{\alpha p} = \frac{v_\alpha p}{{v_\alpha}^2 + {v_\beta}^2} \qquad (7)$$

Similarly, the β-axis of the instantaneous active current is written as:

$$i_{\beta p} = \frac{v_\beta p}{{v_\alpha}^2 + {v_\beta}^2} \qquad (8)$$

Let the instantaneous powers $p(t)$ in the α-axis and the β-axis is represented as p_α and p_β respectively. They are given by the definition of real-power as follows:

$$p(t) = v_{\alpha p}(t)\ i_{\alpha p}(t) + v_{\beta p}(t)\ i_{\beta p}(t) \qquad (9)$$

From this equation (9), substitute the orthogonal coordinates α-axis active power (7) and β-axis active power (8); we can calculate the real-power $p(t)$ as follows

$$p(t) = v_\alpha(t)\left(\frac{v_\alpha p}{{v_\alpha}^2 + {v_\beta}^2}\right) + v_\beta(t)\left(\frac{v_\beta p}{{v_\alpha}^2 + {v_\beta}^2}\right) \qquad (10)$$

The AC and DC component of the instantaneous power $p(t)$ is related to the harmonics currents. The instantaneous real-power generates the reference currents required to compensate the distorted line current harmonics and reactive power.

III. Shunt Active Power Filter System

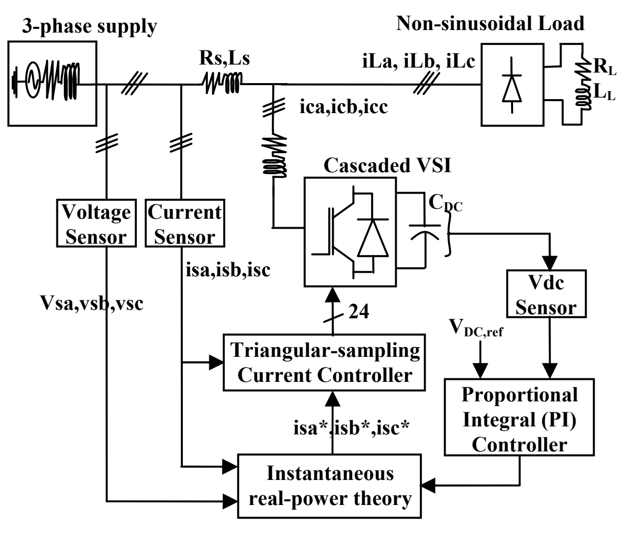

Fig 2 shunt active power line conditioners system

Instantaneous real-power theory based cascaded active filter for power line conditioning system is connected in the distribution network at the PCC through filter inductances and operates in a closed loop. The shunt active filter system contains a cascaded inverter, RL-filters, a compensation controller (instantaneous real-power theory) and switching signal generator (proposed triangular-sampling current modulator) as shown in the Fig 2.

The three-phase supply source connected with non-linear load and these nonlinear loads currents contains fundamental and harmonic components. If the active power filter provides the total reactive and harmonic power, $i_s(t)$ will be in phase with the utility voltage and would be sinusoidal. At this time, the active filter must provide the compensation current; $i_c(t) = i_L(t) - i_s(t)$ therefore, active power filter estimates the fundamental components and compensating the harmonic current and reactive power.

A) Power Converter:

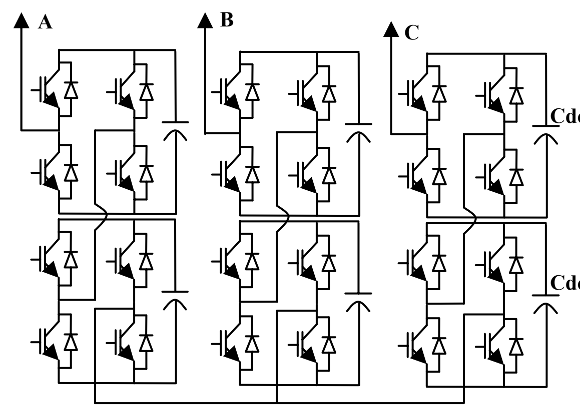

Fig 3 Design of cascaded multilevel active power filter

A cascaded multilevel active power inverter is constructed by the conventional of H-bridges. The three-phase active filter comprises of 24-power transistors with diodes and each phase consists of two-H-bridges in cascaded method for 5-level output voltage, shown in Fig 3. Each H-bridge is connected a separate dc-bus capacitor and it serves as an energy storage elements to supply a real-power difference between load and source during the transient period [16-17]. The capacitor voltage is maintained constant using PI-controller. The 24-power transistors switching operations are performed using triangular-sampling current controller and harmonics is achieved by injecting equal but opposite current harmonic components at Point of Common Coupling (PCC).

B) Reference Current control strategy:

The control scheme of the shunt active power filter must calculate the current reference signals from each phase of the inverter using instantaneous real-power compensator. The block diagram as shown in Fig.4, that control scheme generates the reference current required to compensate the load current harmonics and reactive power. The PI-controller is tried to maintain the dc-bus voltage across the capacitor constant of the cascaded inverter. This instantaneous real-power compensator with PI-controller is used to extracts reference value of current to be compensated.

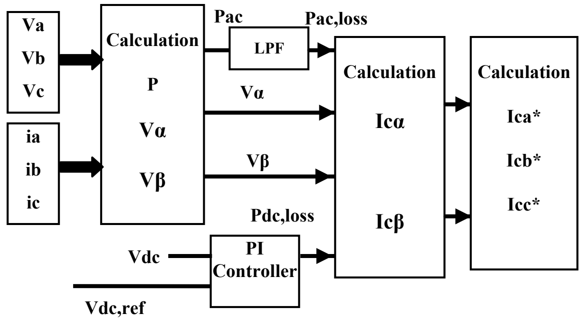

Fig 4 Reference current generator using instantaneous real-power theory

These reference currents $i_{sa}*, i_{sb}*\, and\, i_{sc}*$ are calculated instantaneously without any time delay by using the instantaneous $\alpha-\beta$ coordinate currents. The required references current derivate from the inverse Clarke transformation and it can be written as

$$\begin{pmatrix} i_{sa}* \\ i_{sb}* \\ i_{sc}* \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} i_{c\alpha} \\ i_{c\beta} \end{pmatrix} \quad (11)$$

The reference currents $(i_{sa}*, i_{sb}*\ and\ i_{sc}*)$ are compared with actual source current $(i_{sa}, i_{sb}\ and\ i_{sc})$ that facilitates generating cascaded multilevel inverter switching signals using the proposed triangular-sampling current modulator. The small amount of real-power is adjusted by changing the amplitude of fundamental component of reference currents and the objective of this algorithm is to compensate all undesirable components. When the power system voltages are balanced and sinusoidal, it leads to constant power at the dc-bus capacitor and balanced sinusoidal currents at AC mains simultaneously.

C) Control loop design using PI controller:

Voltage control of the dc-bus capacitor is performed by adjusting the small power flowing in to DC components, thus compensating conduction losses and switching losses. Proportional Integral controller is used in order to eliminate the steady state error and reduce the ripple voltage of the cascaded inverter. The transfer function is defined as

$$H(s) = \left[v_{DC,ref} - v_{DC}\right]\left[k_P + \frac{k_I}{s}\right] \quad (12)$$

The proportional and integral gains [K_P=0.7, K_I=1,] are set such way that actual V_{dc} across capacitor is equal to the reference value of V_{dc} voltage.

D) Proposed triangular-sampling current modulator:

The proposed triangular-sampling current modulator for active power filter line currents can be executed to generate the switching pattern of the cascaded multilevel voltage source inverter. There are various current control methods proposed; but the triangular-sampling current control method has the highest rate for cascaded active power filter applications. These current controller based inverter features are quick current controllability, switching operation induced the suppression of the harmonics, average switching frequency of each inverter is equality and unconditioned stability. The reference currents $i_{sa}*, i_{sb}*\, and\, i_{sc}*$ (extracted by instantaneous real-power compensator) compared with actual source current $i_{sa}, i_{sb}\, and\, i_{sc}$ to generate cascaded inverter switching signals using the triangular-sampling current modulator. The five-level voltage source inverter systems of the current controller are utilized independently for each phase. Each current controller directly generates the switching signal of the three A, B and C phases. The A-phase actual source current represented as isa and reference current represent as $i_{sa}*$ as shown in Fig 5, similarly represented the B and C phase currents.

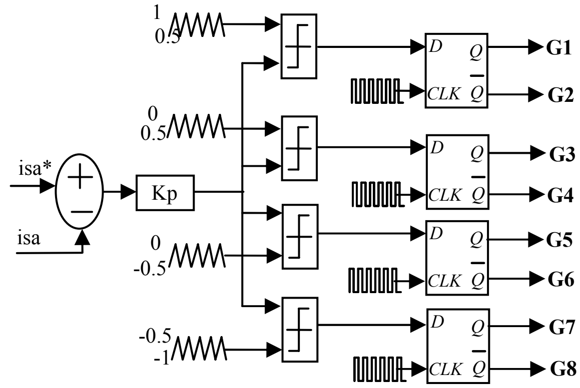

Fig 5 Proposed triangular-sampling current controller

To determine the switching frequency by means the error current [desired reference current compare with the actual source current] multiplied with proportional gain (Kp) and compared with triangular-carrier signals. The four triangular signals are generated; that is same frequency with different amplitude for cascaded multilevel inverter. Thus the switching frequency of the power transistor is equal to the frequency of the triangular-carrier signals. Then, the output signal of the comparator is sampled and held D-Latch at a regular interval Ts synchronized with the clock of frequency equal to $1/Ts$. Note that 4-external clock applied to each converter and Ts is set as 30 ns, because each phase in one converter does not overlap other phase. Therefore the harmonic currents are reduced as if the switching frequency were increased. The interface inductor between cascaded voltage source inverter and PCC suppresses the harmonics caused by the switching operation of the inverter.

IV. RESULT AND ANALYSIS

The performance of the proposed instantaneous real-power compensator cascaded multilevel inverter based active power filter is evaluated through Matlab/Simulink tools. The system parameters values are; Line to line source voltage is 440 V; System frequency (f) is 50 Hz; Source impedance of L_S is 1 mH; Filter impedance of R_c, L_c is 0.1 Ω; 1 mH; diode rectifier R_L, L_L load: 20 Ω; 100 mH; DC side capacitance (C_{DC}) is 2100 µF; Reference voltage ($V_{DC,ref}$) is 150 V; Power devices are IGBTs with diodes.

The non-linear diode rectifier R-L load is connected with ac mains and cascaded active filter is connected in parallel at the PCC for injecting the anti-harmonics and eliminating the reactive power. Simulation of the six-pulse rectifier load current or source current before compensation is presented in Fig 6 (a). This indicates the load current contains the fundamental and harmonic components.

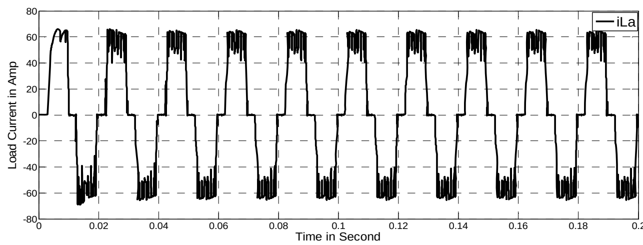

Fig 6 (a) source currents before compensation or load current

The reference fundamental current is extracted from the distorted current using the instantaneous real-power compensator that is shown in Fig. 6(b).

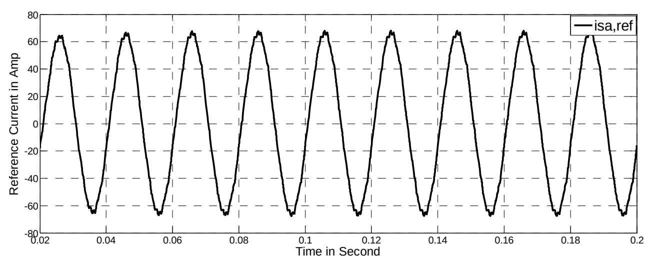

Fig 6(b) Extracted reference current.

The cascaded multilevel inverter based active power filter must provide the harmonic filter current or compensation current as $i_c(t) = i_L(t) - i_s(t)$, that is presented in Fig 6(c).

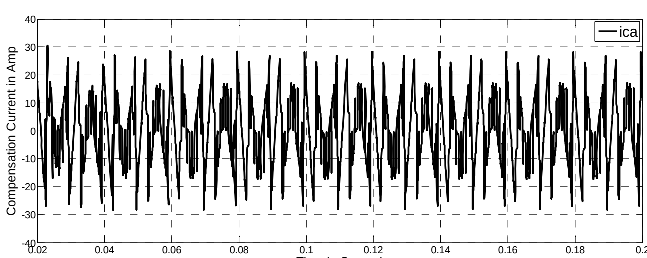

Fig 6(c) compensation current from cascaded APF

The simulation of source current after compensation is shown in Fig 6(d) that indicates the current is sinusoidal.

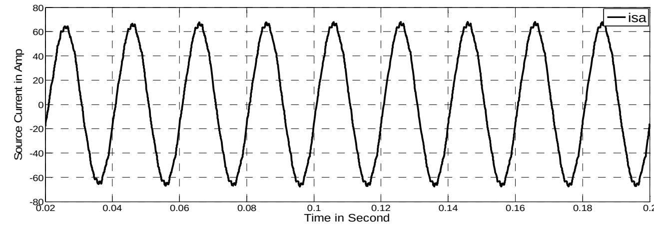

Fig 6(d) source current after compensation

We have additionally achieved power factor correction as shown in Fig. 6(e) that result indicate a-phase voltage is in-phase with a-phase current. These Figures are focused in A-phase only other phases is just phase shifted by 120^0

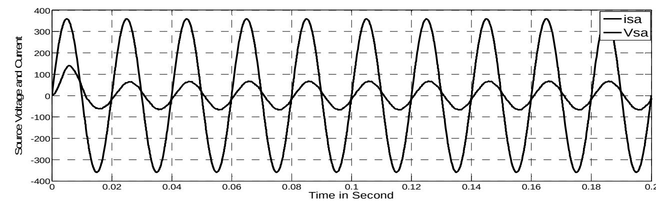

Fig 6(e) unit power

The DC-bus capacitors voltage of the cascaded multilevel inverter is controlled by PI-controller that is shown in Fig 6 (f). It serves as an energy storage element to supply real-power to operate three-phase cascaded multilevel inverter.

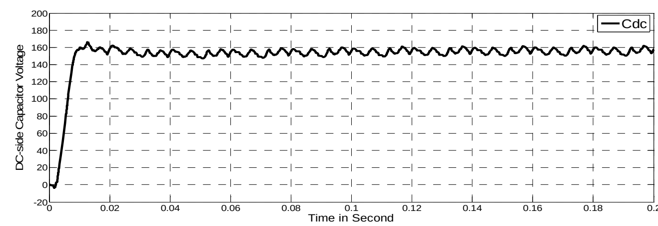

Fig 6 (f) DC-bus capacitor voltage of the cascaded inverter

The Fast Fourier Transform (FFT) is used for determining order of harmonics with the fundamental frequency at 50 Hz and is shown in Fig 7.

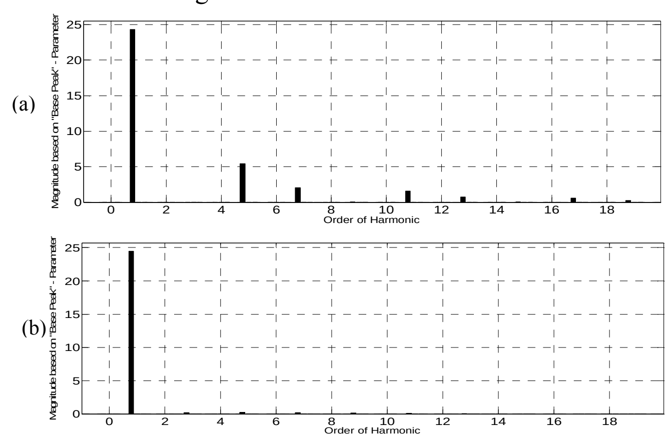

Fig 7 Instantaneous real-power compensator *based cascaded APF; Order of harmonics (a) the source current without active filter (THD=25.12%), (b) with active filter(THD=2.02%)*

The three-phase non-linear load currents or source currents before compensation are shown in Fig 8(a) that indicate that the source current is distorted or having harmonic currents. The three-phase source current after compensation is shown in Fig 8(b) that indicates that the current is sinusoidal.

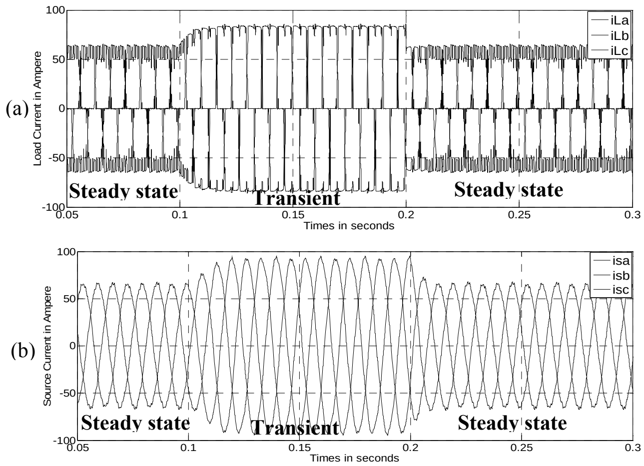

Fig 8 Instantaneous real-power compensator *based cascaded APF Simulation results (a) Load currents (b) Source current after active filter*

The total harmonic distortion (THD) is measured under both steady state and transient conditions. The THD parameters measured without APF and with APF are presented in Table 1.

Table 1 various parameters measured without APF and with APF

Conditions (THD)	Source Current(I_S) without APF	Source Current(I_S) with APF
Steady state	25.12%	2.02%
Transient	24.87%	1.97%
Power factor	0.8799	0.9808

The instantaneous real-power compensator based cascaded active filter simulation is done under various non-linear loads. FFT analysis indicates that APF brings down the THD of the source current to be less than 5% in compliance with IEEE 519 and IEC 61000-3 harmonic standards.

V. Conclusions

A five-level cascaded multilevel voltage source inverter based active filter using instantaneous real-power controller is found to be an effective solution for power line conditioning. Shunt active filter with the proposed controller reduces harmonics and provides reactive power compensation due to non-linear load currents; as a result source current(s) become sinusoidal and unity power factor is also achieved under both transient and steady state conditions. The proposed instantaneous real-power controller uses reduced computation for reference current calculations compared to conventional approach. The cascaded inverter switching signals are generated using triangular-sampling current controller; it provides a dynamic performance under transient and steady state conditions. As evident from the simulation studies, dc-bus capacitor voltage settles early and has minimal ripple because of the presence of PI-controller. The THD of the source current after compensation is 2.02% which is less than *5%,* the harmonic limit imposed by the IEEE-519 standard.

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