Control Of Shunt Active Filter Based On Instantaneous Power Theory

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***Abstract*: This paper presents a shunt active power filter based on instantaneous power theory. The active filter will be connected directly to utility in order to reduce THD of load current, in this case the utility is TNB. The objective is to study different control strategies for real time compensating current harmonics at different load conditions. The compensation process is based on the calculation of real power losses using p-q theory and the PI controller reduces the ripple voltage of the dc capacitor of the PWM-VSI. This approach is different from conventional methods and provides effective solution. The switching is done according to gating signals obtained from hysteresis band current controller.**

Keywords: *Shunt Active Power Line Conditioners (APLC), Instantaneous Power Theory, PI controller, Reactive power, Hysteresis Current Controller HCC).*

I. INTRODUCTION

Much research has been performed on active filters for power line conditioning and their practical applications. The basic principles of compensation were proposed around 1970; however actual designs of active filters were proposed by Gyugyi and Strycula in 1976[1]. In 1984, H. Akagi *et al.*[2] introduced a new concept of instantaneous reactive power theory. It dealt with 3-phase voltages and currents considering their distortion content, being later worked by Watanabe and Aredes [3] for three-phase four wires power systems. A generalized instantaneous reactive power theory which is valid for sinusoidal or non-sinusoidal, balanced or unbalanced three phase power systems with or without zero-sequence currents was later proposed by Peng and Lai [4]. The variation of reactive power generated by arc furnaces andharmonics generated by diode or thyristor rectifiers are matters of serious concern as they cause flicker or harmonic interference in industrial applications, transmission anddistribution systems [5]. APLCs are inverter circuits, comprising active devices such as semiconductor switches can be controlled as harmonic current or voltage generators. Different topologies and control techniques have beenproposed for APLC and their implementation. APLCs aresuperior to passive filters in terms of filtering characteristics and improve the system stability by removing resonance related problems. In particular, recent remarkable progress in the capacity and switching speed of power semiconductor devices such as insulated-gate bipolar transistors (IGBTs) has spurred interest in active filters for power conditioning [6-7].

Review papers describe APLCs controlled on the basis of instantaneous real and reactive power theory; provide good compensation characteristics in steady state as well as transient states. At the same time, the following problems of APLCs are pointed out: (1) it is difficult to realize high power PWM inverters with rapid current response (2) At specific frequency and resonance occurs between the source impedance and the shunt APLC (3) The initial cost is high when compared with passive filters [5-8]. Yet the APLC improves the utility supply system power factor as the ac Source provides only active fundamental frequency of current.

The APLC additionally provides the Reactive-power compensation, Harmonic mitigation and Negative-sequence current/voltage compensation. This paper describes the design and analysis of a novel controller that uses instantaneous power theory along with PI controller for APLC. This computed sensing source voltage(s) and current(s) are used for instantaneous power calculation to generate reference currents. The dc capacitor ripple voltage of PWM-VSI inverter is reduced using Proportional Integrated controller. A hysteresis-band current controller generates switching signals for the APLC to follow the reference currents within specified band-limits. The shunt APLC is investigated under different steady state and transient conditions and found to be effective for power factor correction, harmonics and reactive power compensation.

II. INSTANTANEOUS POWER THEORY

The p-q theory or instantaneous power theory is based on time-domain; it makes operation in steady-state or transient state, as well as for generic voltage and current waveforms, allowing to control the active power filters in real-time. Another important characteristic of this theory is the simplicity of the calculations, which involves only algebraic calculation. The p-q theory performs a Clarke transformation of a stationary reference system of coordinates *a – b - c* to a reference system of coordinates *α* - β - *0*, also stationary. In ab-c coordinates axes are fixed on the same plane, separated from each other by 120o, as shown in Fig. 1.

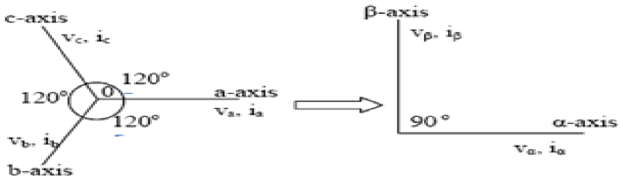


Fig.1 α-β Co-ordinates transformation

The instantaneous space vectors, Va and ia are set on the aaxis, Vb and ib are on the b axis, and Vc and ic are on the c axis. These space vectors are easily transformed into α-β coordinates as follows [2].

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

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

P-calculation

The conventional instantaneous real power on the three phase circuit can be defined as follows,

$$P=P_{AC(loss)}+P_{DC(Loss)} \quad (3)$$

Where,

$$P_{DC(Loss)}=\left[v_{DC,ref}-v_{DC}\right]\left[k_p+\frac{k_i}{s}+k_D(s)\right] \quad (4)$$

$$p_{AC(loss)}=\left[v_\alpha i_\alpha+v_\beta i_\beta\right] \quad (5)$$

Instantaneous current on the α-β coordinates iα and iβ are divided into two kinds of instantaneous current components, respectively,

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}=\frac{1}{{v_\alpha}^2+{v_\beta}^2}\left\{\begin{bmatrix} v_\alpha \; v_\beta \\ v_\beta - v_\alpha \end{bmatrix}\begin{bmatrix} p \\ 0 \end{bmatrix} n\right\} \quad (6)$$

α-axis instantaneous active current defined as,

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

β-axis instantaneous active current,

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

Let the instantaneous powers in the α-axis and the β-axis is power pα and pβ respectively. They are given by the conventional definition of real power as follows,

$$P(t)=v_\alpha(t)i_\alpha(t)+v_\beta(t)i_\beta(t) \quad (9)$$

$$P(t)=v_\alpha(t)\left[\frac{v_\alpha P}{{v_\alpha}^2+{v_\beta}^2}\right]+v_\beta(t)\left[\frac{v_\beta P}{{v_\alpha}^2+{v_\beta}^2}\right] \quad (10)$$

The instantaneous real power coincides with three times the conventional reactive power per one phase. It is evident that instantaneous real power extracts the harmonics and make three-phase ac main sinusoidal.

III.DESIGN OF SHUNT ACTIVE POWER LINE CONDITIONERS

Voltage and current sources sensing signal used to generate reference current shown in fig 2. The proposed shunt APLC block diagram and the main section of the active power line conditioners shown in figure 3 is PWM voltage source inverter connected to a dc capacitor. Current harmonics reduction is achieved by injecting equal but opposite current harmonics components at the PCC (point of common coupling), there by canceling the original distortion and improving the power quality of the connected power system.

A.PWM inverter

The active filter is based on a PWM voltage source inverter is connected to the point of common coupling through interface filter; the active filter is connected in parallel with the load being compensated. This inverter uses dc capacitors as supply and can switch at high frequency to generate a signal that will cancel the harmonics from non-linear load. The current waveform for canceling harmonics is achieved by using VSI in the current controlled mode and the interface filter. The filter provides smoothing and isolation for high frequency components. The desired currents are obtained by accurately controlling the switching of the IGBT inverter. Control of the current wave shape is limited by switching frequency of the inverter and by the available driving voltage across the interfacing inductance.

B. Reference Current control strategy

The control scheme of a shunt APLC must calculate the current reference waveform for each phase of the inverter, maintain dc capacitor voltage almost constant and generate the inverter gating signals. The block diagram (see fig.2) of the control scheme generates the reference currents required to compensate the load current harmonics and reactive power and also try to maintain the dc capacitor voltage constant. Here p-q theory with PI controller is used to find out reference value of currents to be compensated.

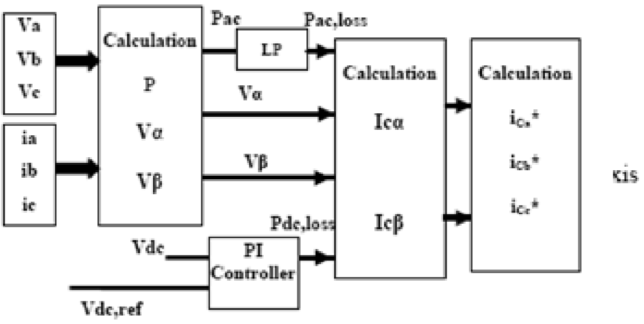


Fig.2. Current reference generator using P-Q theory

The references of the compensating currents iCa*, iCb* and iCc* are calculated instantaneously without any time delay by using the instantaneous voltages and currents,

$$\begin{bmatrix} {i_{ca}}^* \\ {i_{cb}}^* \\ {i_{cc}}^* \end{bmatrix}=\frac{\sqrt{2}}{3}\begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{ca} \\ i_{cb} \end{bmatrix} \quad (11)$$

The small amount of real power is adjusted by changing the amplitude of fundamental component of reference current and the objective of this algorithm is to compensate all undesirable power components. When the power system voltages are balanced and sinusoidal, it will lead to simultaneously, constant instantaneous power and balanced sinusoidal currents at ac power supply.

C. Hysteresis Band Current Control

Hysteresis current control is one of the simplest techniques to implement; it's developed by Brod and Novotny in 1985. One disadvantage is that there is no limit to the switching frequency. But additional circuitry can be used to limit the maximum switching frequency. An error signal e (t) is used to control the switches in an inverter. When the error reaches an upper limit, the transistors are switched to force the current down. When the error reaches a lower limit the current is forced to increase. The minimum and maximum values of the error signal are emin and emax respectively. The range of the error signal, emax – emin, directly controls the amount of ripple in the output current from the inverter.

D. Control loop design

Voltage control of the dc bus is performed by adjusting the small power flowing in to dc capacitor, thus compensating conduction and switching losses. Proportional Integral controller is used In order to eliminate the steady state error and reduce the ripple voltage.

$$H(S)=K_P+\frac{K_I}{S}$$

The proportional and integral gains [KP =0.6, KI =83,] are set such way that actual Vdc across capacitor is equal to the reference value of Vdc . The ripple voltage of the PWMcurrent controlled voltage source inverter is reduced by the proportional integrated controller.

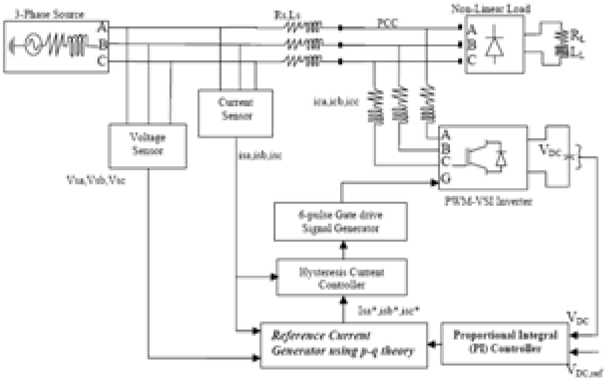


Fig.3 PI with P-Q theory based shunt APLC implemented with PWM-VSI Configuration

IV.SIMULATION RESULT AND ANALYSIS

The system parameters values are; source voltage (Vs) is 230 Vrms, System frequency (f) is 50 Hz, Source impedance RS, LS is 0.5 Ω; 1mH respectively, Filter impedance of Rc, Lc is 1 Ω; 1.77 mH, Load impedance RL, LL of diode rectifier RL load in Steady state: 20 Ω; 200 mH and Transient: 10 Ω; 100mH respectively, DC link capacitance (CDC) is 1700μF, Reference Voltage (VDC) is 400 V and Power devices are IGBT with an anti parallel diode.

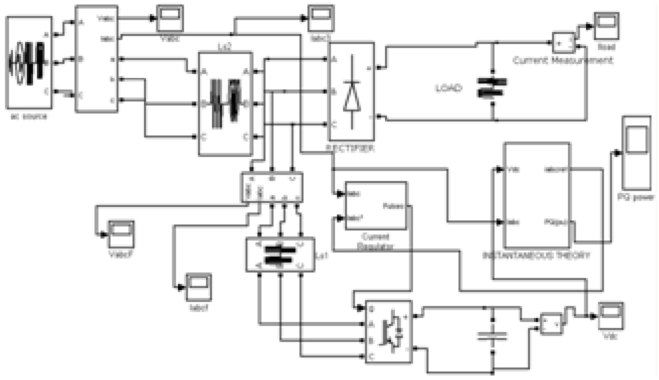


Fig.4 Simulink model for instantaneous power theory

A. Steady state condition

Instantaneous power theory with PI-controlled APLC system comprises a three-phase source, a nonlinear load (six pulsediode Rectifier RL load) and a PWM voltage source inverterwith a dc capacitor input. The simulation time T=0 to T=0.6swith load of diode rectifier with R L load parameter values of20 ohms and 200 mH respectively. The source current after compensation is presented in fig. 4 (a) that indicates the current becomes sinusoidal. The load current is shown in (b). These current waveforms are for a particular phase (phase a). Other phases are not shown as they are only phase shifted by 1200 and we have considered only a balanced load. The actual reference currents for phase (a) are shown in fig. 4(c). This wave is obtained from our proposed controller. The APPC supplies the compensating current that is shown in Fig. 6(d). The current after compensation is as shown in (a) which would have taken a shape as shown in (b) without APLC. It is clearly visible that this waveform is sinusoidal with some high frequency ripples. We have additionally achieved power factor correction as shown in Fig. 4(e), phase (a) voltage and current are in phase. The time domain response of the controller is shown in Fig. 4(f) that clearly indicates the controller output settles after a few cycles

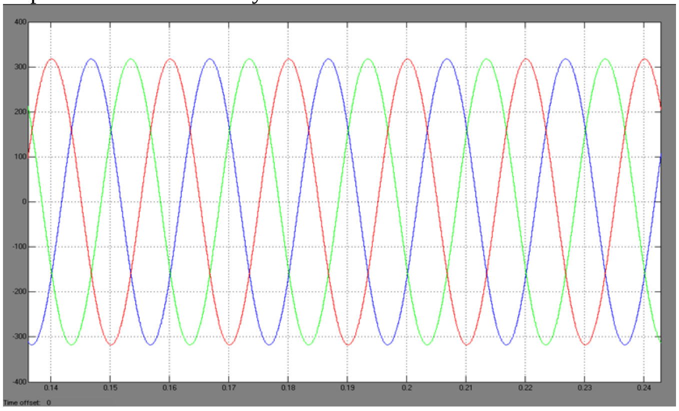


Fig.5 Input Current

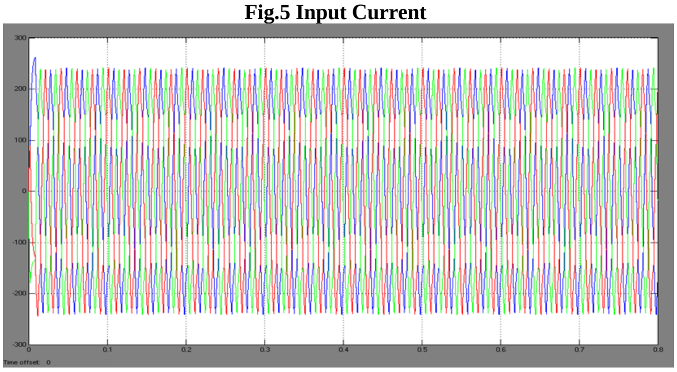


Fig.6 Current across the Filter

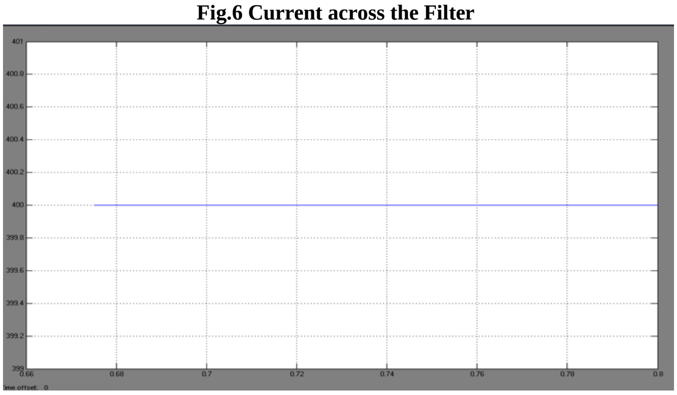


Fig.7 DC Input Voltage to Inverter

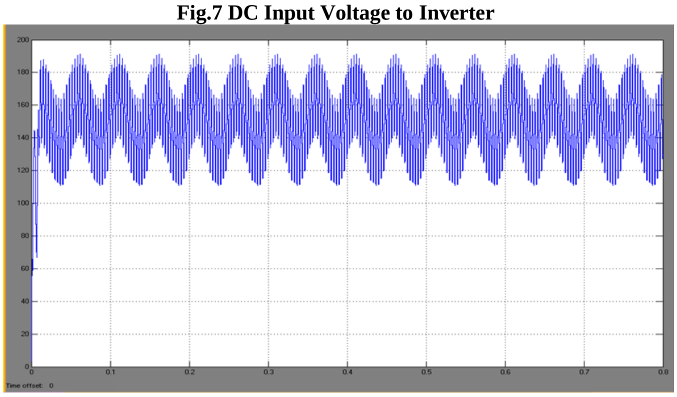


Fig.8 Current across the Load with Filter

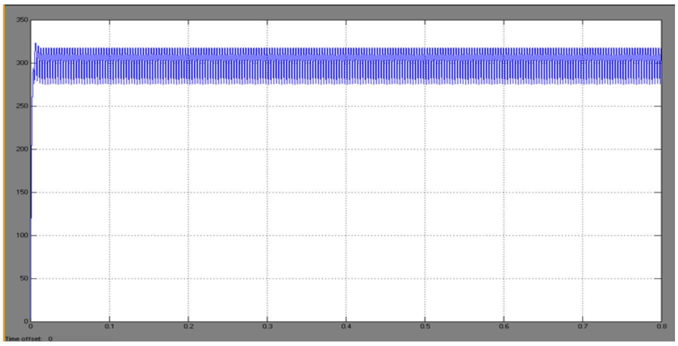
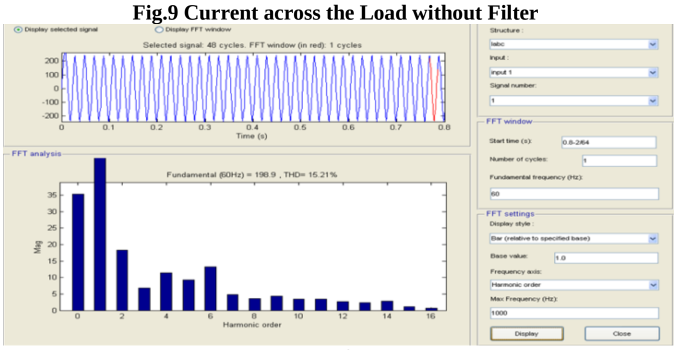


Fig.9 Current across the Load without Filter


● Display selected signal ○ Display FFT window

Selected signal: 48 cycles. FFT window (in red): 1 cycles

FFT analysis

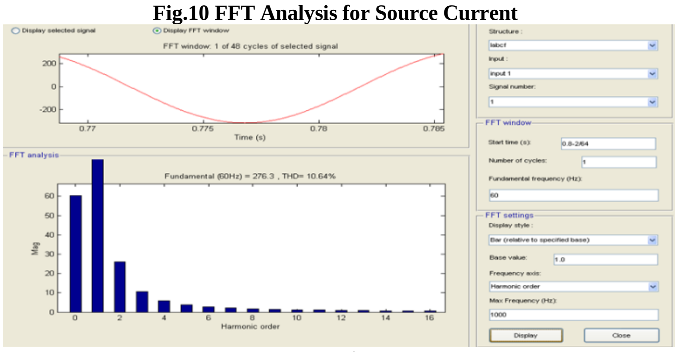
Fundamental (60Hz) = 198.9 , THD= 15.21%

Structure : Iabc
Input : input 1
Signal number: 1

FFT window
Start time (s): 0.8-2/64
Number of cycles: 1
Fundamental frequency (Hz): 60

FFT settings
Display style : Bar (relative to specified base)
Base value: 1.0
Frequency axis: Harmonic order
Max Frequency (Hz): 1000

Fig.10 FFT Analysis for Source Current


○ Display selected signal ● Display FFT window

FFT window: 1 of 48 cycles of selected signal

FFT analysis

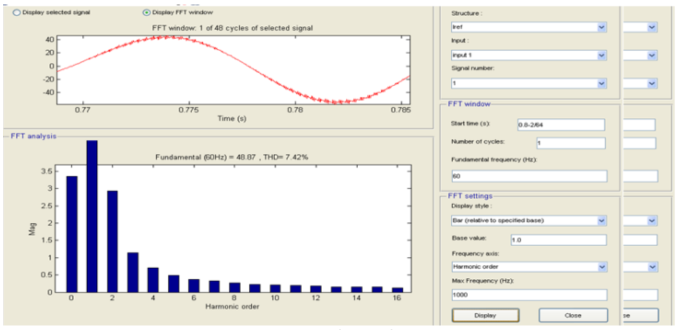
Fundamental (60Hz) = 276.3 , THD= 10.64%

Structure : Iabcf
Input : input 1
Signal number: 1

FFT window
Start time (s): 0.8-2/64
Number of cycles: 1
Fundamental frequency (Hz): 60

FFT settings
Display style : Bar (relative to specified base)
Base value: 1.0
Frequency axis: Harmonic order
Max Frequency (Hz): 1000

Fig.10 FFT Analysis for Filter Current


○ Display selected signal ● Display FFT window

FFT window: 1 of 48 cycles of selected signal

FFT analysis

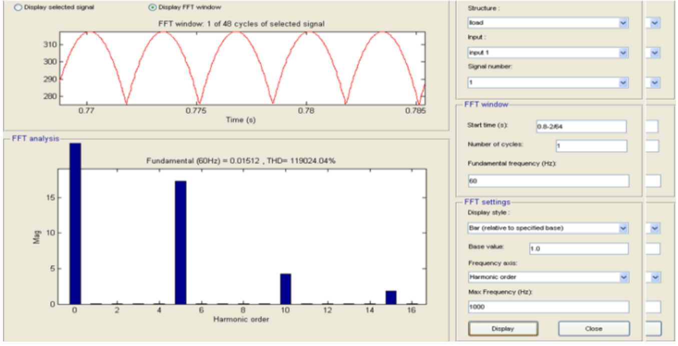
Fundamental (60Hz) = 48.87 , THD= 7.42%

Structure : Iref
Input : input 1
Signal number: 1

FFT window
Start time (s): 0.8-2/64
Number of cycles: 1
Fundamental frequency (Hz): 60

FFT settings
Display style : Bar (relative to specified base)
Base value: 1.0
Frequency axis: Harmonic order
Max Frequency (Hz): 1000

Fig.11 FFT Analysis for reference current


○ Display selected signal ● Display FFT window

FFT window: 1 of 48 cycles of selected signal

FFT analysis

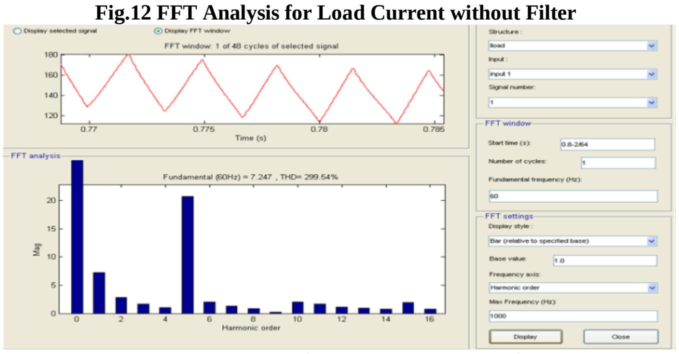
Fundamental (60Hz) = 0.01512 , THD= 119024.04%

Structure : Iload
Input : input 1
Signal number: 1

FFT window
Start time (s): 0.8-2/64
Number of cycles: 1
Fundamental frequency (Hz): 60

FFT settings
Display style : Bar (relative to specified base)
Base value: 1.0
Frequency axis: Harmonic order
Max Frequency (Hz): 1000

Fig.12 FFT Analysis for Load Current without Filter


○ Display selected signal ● Display FFT window

FFT window: 1 of 48 cycles of selected signal

FFT analysis

Fundamental (60Hz) = 7.247 , THD= 299.54%

Structure : Iload
Input : input 1
Signal number: 1

FFT window
Start time (s): 0.8-2/64
Number of cycles: 1
Fundamental frequency (Hz): 60

FFT settings
Display style : Bar (relative to specified base)
Base value: 1.0
Frequency axis: Harmonic order
Max Frequency (Hz): 1000

Fig.13 FFT Analysis for Load Current with filter

V_{dc} settling of time	
Steady State	**0.17s**
Transient	**0.23s**

Table1 V_{dc} settling time measurement

Condition	Real(p) and Reactive(Q) Power measurement	
Steady state	P=6.214 KW Q=1.417 KW	P=6.823 KW Q=0.026 KW
Transient	P=7.852 KW Q=1.417 KW	P=6.823 KW Q=0.026 KW

Table 2 Real(P) and Reactive (Q) Power Measurement

V.CONCLUSION

A novel controller that uses instantaneous p-q power theory along with PI controller is found to be an effective solution for power line conditioning. Shunt APLC with the proposed controller reduces harmonics and reactive power components of load currents; as a result sinusoidal source current(s) and unity power factor is achieved under both transient and steady state conditions. The proposed controller uses reduced number of sensors and less computation for reference current calculations compared to conventional approach. As evident from the simulation studies, dc-bus capacitor voltage settles early and has minimal ripple because of the presence of PI Controller.

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