PI with Instantaneous Power Theory Based Shunt APLC for Power Quality

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***Abstract*— this article explores design and analysis of instantaneous power theory with proportional integral (PI) based Shunt Active Power Line Conditioners (APLC). This APLC compensates the reactive and harmonic currents drawn by the non-linear load besides power factor correction. 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. The shunt APLC is investigated under different steady state and transient conditions.**

***Keywords*—Shunt Active Power Line Conditioners (APLC), Instantaneous Power Theory, PI controller, Harmonics, 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 and harmonics generated by diode or thyristor rectifiers are matters of serious concern as they cause flicker or harmonic interference in industrial applications, transmission and distribution 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 been proposed for APLC and their implementation. APLCs are superior 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 a-b-c coordinates axes are fixed on the same plane, separated from each other by 120^o, as shown in Fig. 1.

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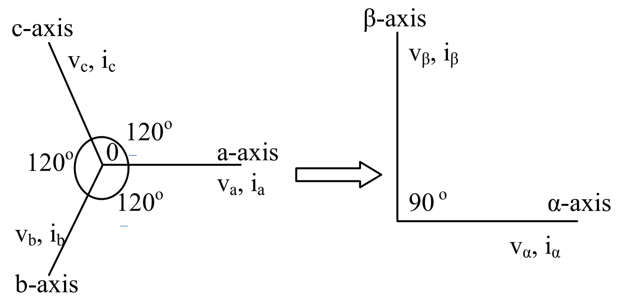

Fig 1 α-β coordinates transformation

The instantaneous space vectors, V_a and i_a are set on the a-axis, V_b and i_b are on the b axis, and V_c and i_c are on the c axis. These space vectors are easily transformed into α-β coordinates as follows [2]:

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

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

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

<u>P-calculation:</u>

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,

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

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

The instantaneous current on the α-β coordinates i_α and i_β are divided into two kinds of instantaneous current components, respectively:

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

α-axis instantaneous active current defined as

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

β-axis instantaneous active current:

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

Let the instantaneous powers in the α-axis and the β-axis is power p_α and p_β 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.

1) 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 waveshape is limited by switching frequency of the inverter and by the available driving voltage across the interfacing inductance.

2) 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.

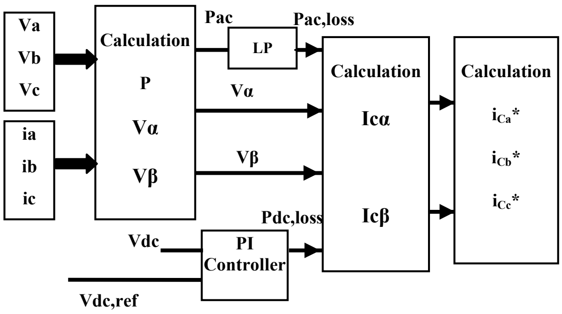

Fig 2 Current reference generator using p-q theory

The references of the compensating currents i_{Ca}*, i_{Cb}* and i_{Cc}* are calculated instantaneously without any time delay by using the instantaneous voltages and currents.

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

The 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.

3) Hysteresis Band Current Control:

Hysteresis current control is one of the simplest technique 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 e_{min} and e_{max} respectively. The range of the error signal, $e_{max} - e_{min}$, directly controls the amount of ripple in the output current from the inverter.

4) 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. It's defined as

$$H(s) = K_P + \frac{K_I}{s} \quad (12)$$

The proportional and integral gains [K_P =0.6, K_I =83,] are set such way that actual V_{dc} across capacitor is equal to the reference value of V_{dc} . The ripple voltage of the PWM-current controlled voltage source inverter is reduced by the Proportional Integrated controller.

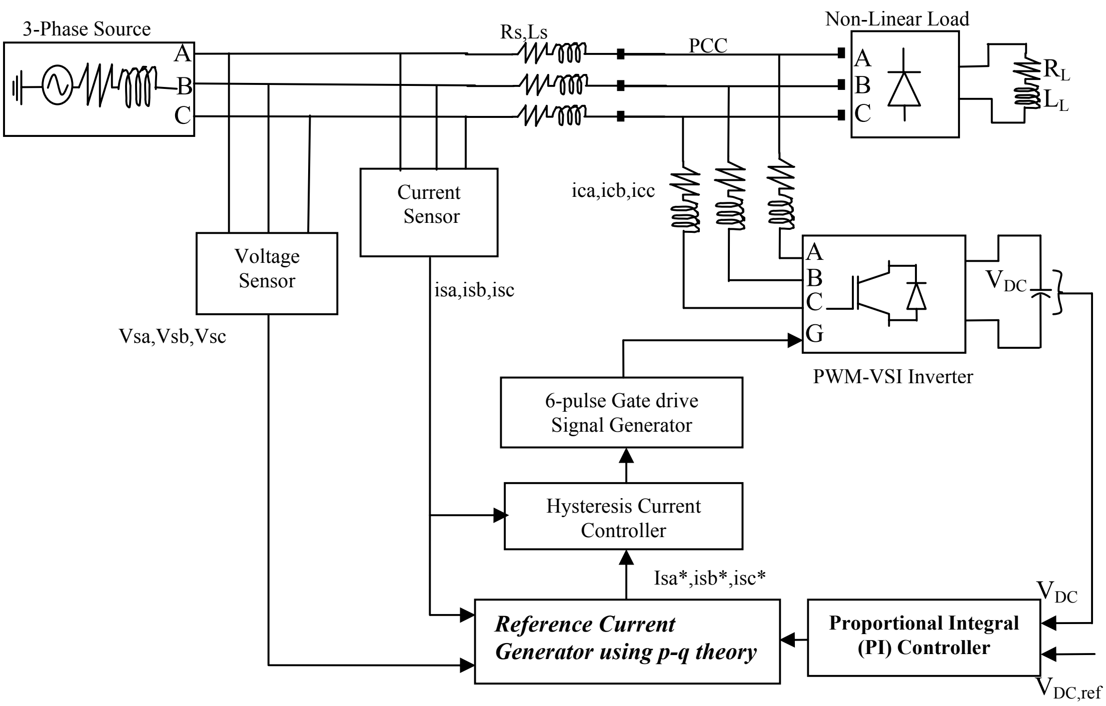

Fig 3 PI with p-q theory based Shunt APLC implemented with PWM-VSI Configuration

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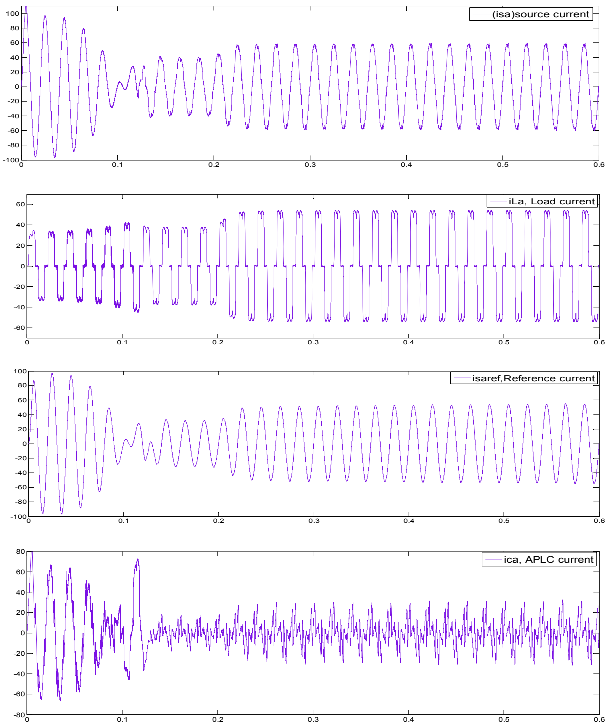
IV. SIMULATION RESULT AND ANALYSIS

The system parameters values are; source voltage (Vs) is 230 Vrms, System frequency (f) is 50 Hz, Source impedance R_S, L_S is 0.5 Ω; 1mH respectively, Filter impedance of R_c, L_c is 1 Ω; 1.77 mH, Load impedance R_L, L_L of diode rectifier RL load in Steady state: 20 Ω; 200 mH and Transient: 10 Ω; 100 mH respectively, DC link capacitance (C_{DC}) is 1700μF, Reference Voltage (V_{DC}) is 400 V and Power devices are IGBT with an anti parallel diode.

Case 1: Steady state condition

Instantaneous power theory with PI-controlled APLC system comprises a three-phase source, a nonlinear load (six pulse diode Rectifier RL load) and a PWM voltage source inverter with a dc capacitor input. The simulation time T=0 to T=0.6s with load of diode rectifier with R L load parameter values of 20 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 120^0 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.



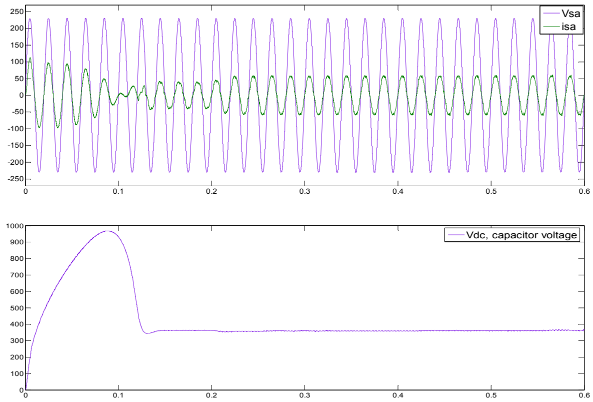


Fig.4 Simulation results for three-phase APLC under the steady state condition (a) Source current after APLC, (b) Load currents, (c)Reference currents by the controller algorithm, (d) Compensation current by APLC, (e) source voltage per current for unity power factor and (f) DC capacitor voltage

Fast fourier transform (FFT) is measured of the order of harmonics with respect to magnitude of the APLC using instantaneous power theory with PI controller, shown in fig 5.

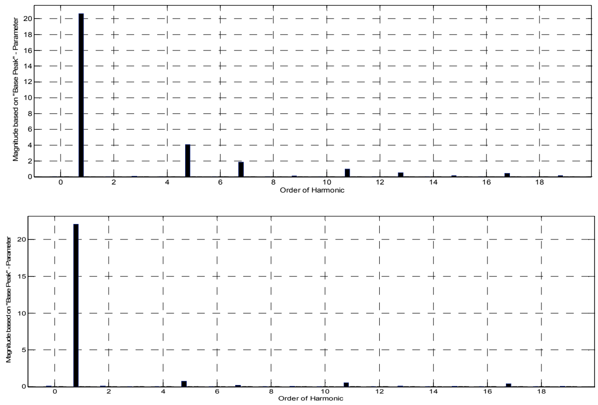


Fig5 Three-phase APLC under the steady state (a) FFT analys of Source current without APLC (THD=22.09%) (b) with APLC(THD=4.419%).

The active power (P) and reactive power (Q) are calculated by averaging the voltage-current product with a running average window over one cycle of the fundamental frequency, shown in fig 6

$$P = \frac{1}{T}\int_{t-T}^{t} V(\omega t)\times I(\omega t)dt \quad (13)$$

$$Q = \frac{1}{T}\int_{t-T}^{t} v(\omega t)\times i(\omega t - \pi/2)dt \quad (14)$$

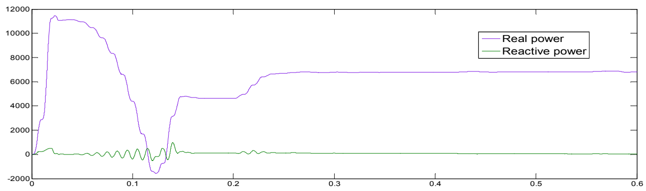


Fig 6 Active and Reactive power at diode rectifier RL load with APLC under the steady state condition (P=7.63 KW, Q=0.054 KW)

Case 2: Transient condition:

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First for simulation time T=0 to T=0.6s with load of rectifier with R L load of 20 ohms and 200 mH respectively and after the R L load of 10 ohms and 100 mH change for transient condition. The simulation waveforms are verified similar to steady state waveforms shown in fig 7.

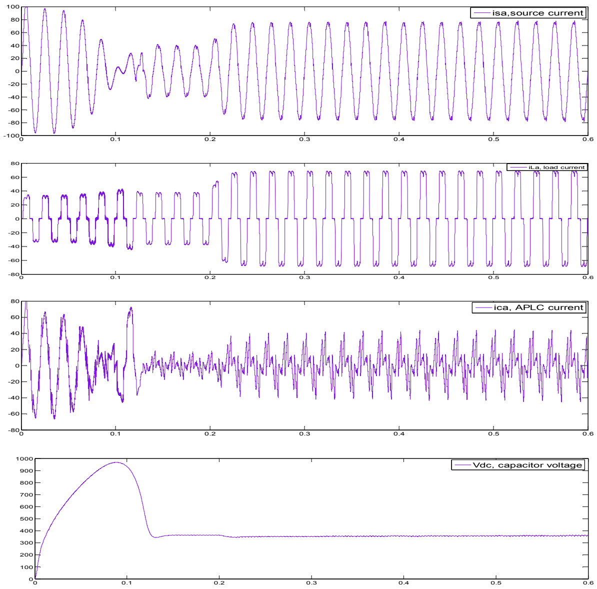

Fig.7 Simulation results for three-phase APLC under the transient condition (a) Source current after APLC, (b) Load currents, (c) Compensation current by APLC, and (d) DC capacitor voltage

The PWM- voltage source inverter of capacitance voltage (Vdc) controlled by PI controller. It's settling time in transient and steady state condition measured shown in table 1

Table 1 Vdc settling time measurement

Vdc settiling time in seconds	
Steady State	0.17s
Transient	0.23s

The instantaneous power theory with PI controller based APLC system suppress the reactive power and improve the power factor. The summarized Real (P) and Reactive (Q) power calculation under steady state and transient condition given below, shown in table 2.

Table 2 Real (P) and Reactive (Q) power measurement

Condition	Real (P) and Reactive (Q) power measurement	
	Without APLC	With APLC
Steady state	P=6.214 kW Q=1.417 kW	P=6.823 kW Q=0.026 kW
Transient	P=7.852 kW Q=1.983 kW	P=8.927 kW Q=0.0098 kW

The obtained result shows the source current and load current is small variation and compensator filter made balance responsibility in steady state and transient response. FFT analysis of the active filter brings the THD of the source current is less than 5% into compliance with IEEE-519 standards harmonic, shown in table 3

Table 3 FFT analysis of Total harmonic distortion

Condition(THD)	Source Current(I_S) without APLC	Source Current(I_S) with APLC
Steady State	22.09%	4.41%
Transient	20.43%	4.12%
Power factor	Lagging	Unity

V. CONCLUSIONS

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. The THD of the source current after compensation is 4.41% which is less than *5%,* the harmonic limit imposed by the IEEE-519 standard.

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