Universal power quality conditioner

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Abstract: - This manuscript proposes a novel control technique for three-phase shunt active power line conditioner to determine the compensation current associated with three-phase parallel converters. The proposed control scheme is effective in achieving purely sinusoidal balanced source currents in phase with respective source voltages. The method assumes that the active power line conditioning system (APLC) supplies all the real power and imaginary power of the load that differ from positive sequence fundamental average power consumed by the load. Asymmetry, unbalance and distortion in the terminal voltages and load currents have been considered in this manuscript. Since the proposed control technique considered asymmetry, unbalance and distortion in both terminal voltages and load currents, the developed APLC system can be treated as a universal power quality conditioner for the power quality problems. The supremacy of the proposed approach has been discussed and compared with synchronous detection equal current approach (SDECA).

Key-Words: - APLC, parallel converters, PSFAP, SDECA, asymmetry, unbalance, distortion, THD

1 Introduction

Three-phase parallel converters are used to feed controlled electrical power to electrical loads. The application of three-phase parallel converters is increasing due to high power demand, high reliability and distributed power. However the unbalance, asymmetry and distortion in terminal voltages and source currents introduced by these parallel converters eventually lead to poor power quality. Control of harmonics, asymmetry, negative and zero sequence components associated with three-phase parallel converters is very important from the power quality point of view.

Active power filter (APF) systems have been practically installed as a viable solution for harmonic elimination and reactive power compensation [1]. Several control strategies based on instantaneous $p-q$ method have been proposed and reported for the APF systems [1-5]. In [6-8] authors have reported the application of APF to control negative and/ zero sequence components associated with unbalanced systems. APF systems have been successfully applied to control zero-sequence currents associated with three-phase parallel converters [9]. In [10] authors have proposed a new control scheme based on instantaneous $d-q$ current method to nullify harmonics, negative, and zero sequence components. However, in [9-10], the unbalance and distortion in the terminal voltages have been neglected. One may note that application of three-phase parallel converters introduces unbalance and distortion in the source currents as well as in terminal voltages. The synchronous detection algorithm proposed in [11-12] is ineffective in determining the compensation current associated with three-phase parallel converters due to the presence of average power contribution from negative and zero sequence components as well as harmonic components. Although instantaneous $p-q$ method [2] is historically popular, since $abc-\alpha\beta$ transformation is based on balanced sinusoidal conditions, the method performs very poorly under unbalanced and distorted conditions. Sine the calculations proposed in instantaneous $d-q$ current method [13] are based on balanced condition and fundamental frequency, this method also is ineffective in determining the compensation current associated with three-phase parallel converters.

This manuscript proposes a novel control technique to determine the compensation current associated with three-phase parallel converters. The method assumes that the APLC system supplies all the real power and imaginary power of the load that differ from the positive sequence fundamental average power. Detailed analysis of the power quality problems associated with three-phase parallel converters has been included in the second section of this manuscript. The control scheme based on extraction of positive sequence (fundamental) average power (PSFAP) proposed in this manuscript is detailed in the third part of this research article. Simulation results shown in the third part of this paper illustrate the effectiveness of the proposed control technique for the determination of compensation current associated with three-phase parallel controllers.

2 Power quality problems associated with three-phase parallel converters

Application of three-phase parallel converters introduces unbalance and distortion in terminal voltages and load currents. Under such situation instantaneous value of terminal voltage for phase A $v_{ta}(t)$ could be expressed as [14]:

$$\sum_{m=1}^{\infty}\begin{pmatrix}\sqrt{2}V_{zm}\sin(\omega_m t+\phi_{zm})+\sqrt{2}V_{pm}\sin(\omega_m t+\phi_{pm})\\ +\sqrt{2}V_{nm}\sin(\omega_m t+\phi_{nm})\end{pmatrix} \quad (1)$$

Similarly, the instantaneous value of load current for phase A $i_{la}(t)$ could be expressed as [14]:

$$\sum_{m=1}^{\infty}\begin{pmatrix}\sqrt{2}I_{lzm}\sin(\omega_m t+\delta_{zm})+\sqrt{2}I_{lpm}\sin(\omega_m t+\delta_{pm})+\\ \sqrt{2}I_{lnm}\sin(\omega_m t+\delta_{nm})\end{pmatrix} \quad (2)$$

One may note that similar equations are valid for phase B and phase C.

The resulting power expressions are as follows [14]:

The real power

$$p=\sum_{m=1}^{\infty}\begin{pmatrix}3V_{pm}I_{lpm}\cos(\phi_{pm}-\delta_{pm})+\\ 3V_{nm}I_{lnm}\cos(\phi_{nm}-\delta_{nm})+\end{pmatrix}$$

$$\sum_{\substack{x=1\\x\neq m}}^{\infty}\left[\sum_{m=1}^{\infty}3V_{px}I_{lpm}\cos((\omega_x-\omega_m)t+\phi_{px}-\delta_{pm})\right]+$$
$$\sum_{\substack{x=1\\x\neq m}}^{\infty}\left[\sum_{m=1}^{\infty}3V_{nx}I_{lnm}\cos((\omega_x-\omega_m)t+\phi_{nx}-\delta_{nm})\right]+$$
$$\sum_{x=1}^{\infty}\left[\sum_{m=1}^{\infty}-3V_{px}I_{lnm}\cos((\omega_x+\omega_m)t+\phi_{px}+\delta_{nm})\right]+$$
$$\sum_{x=1}^{\infty}\left[\sum_{m=1}^{\infty}-3V_{nx}I_{lpm}\cos((\omega_x+\omega_m)t+\phi_{nx}+\delta_{pm})\right] \quad (3)$$

Imaginary power

$$q=\sum_{m=1}^{\infty}\begin{pmatrix}3V_{pm}I_{lpm}\sin(\phi_{pm}-\delta_{pm})-\\ 3V_{nm}I_{lnm}\sin(\phi_{nm}-\delta_{nm})+\end{pmatrix}$$

$$\sum_{\substack{x=1\\x\neq m}}^{\infty}\left[\sum_{m=1}^{\infty}3V_{px}I_{lpm}\sin((\omega_x-\omega_m)t+\phi_{px}-\delta_{pm})\right]+$$
$$\sum_{\substack{x=1\\x\neq m}}^{\infty}\left[\sum_{m=1}^{\infty}-3V_{nx}I_{lnm}\sin((\omega_x-\omega_m)t+\phi_{nx}-\delta_{nm})\right]+$$
$$\sum_{x=1}^{\infty}\left[\sum_{m=1}^{\infty}-3V_{px}I_{lnm}\sin((\omega_x+\omega_m)t+\phi_{px}+\delta_{nm})\right]+$$
$$\sum_{x=1}^{\infty}\left[\sum_{m=1}^{\infty}3V_{nx}I_{lpm}\sin((\omega_x+\omega_m)t+\phi_{nx}+\delta_{pm})\right] \quad (4)$$

and the zero sequence power

$$p_z=\sum_{m=1}^{\infty}\left(3V_{zm}I_{lzm}\cos(\phi_{zm}-\delta_{zm})\right)+$$
$$\sum_{\substack{x=1\\x\neq m}}^{\infty}\left[\sum_{m=1}^{\infty}3V_{zx}I_{lzm}\cos((\omega_x-\omega_m)t+\phi_{zx}-\delta_{zx})\right]+$$
$$\sum_{x=1}^{\infty}\left[\sum_{m=1}^{\infty}-3V_{zx}I_{lzm}\cos((\omega_x+\omega_m)t+\phi_{zx}+\delta_{zx})\right] \quad (5)$$

In eq. (1)-eq.(5) m represents the harmonic order. V_{zm}, V_{pm}, V_{nm} are the rms values of zero-sequence, positive-sequence, negative-sequence components of terminal voltages respectively, I_{lzm}, I_{lpm}, I_{lnm} are the rms values of zero-sequence, positive-sequence, negative-sequence components of load currents respectively, ϕ_{zm}, ϕ_{pm}, ϕ_{nm} are the phase angles of zero-sequence, positive-sequence, negative-sequence components of voltages respectively, δ_{zm}, δ_{pm}, δ_{nm} are the phase angles of zero-sequence, positive-sequence and negative-sequence components of load currents respectively.

One may note that in three-phase system with parallel converters, there is real power and imaginary power contributions due to positive sequence, negative sequence and zero sequence components of fundamental as well as harmonic components. The real power and imaginary power consist of constant and time varying terms. In order to achieve purely sinusoidal balanced source currents in phase with respective source voltages, the compensator should supply all the components of load power other than the positive-sequence fundamental average power.

3 Active power line conditioner

Distribution system synchronous static compensators (DSTATCOM) are used for power quality improvement in distribution systems. The concept of flexible ac transmission systems (FACTS) is as equally valid in distribution systems and has extended to improve the power quality of distribution system customers [15]. APF and APLC systems are distribution system shunt compensators used power quality improvement. Active power filter is mainly used for harmonic elimination, by injecting a current equal in magnitude but in phase opposition to the harmonic current to achieve purely sinusoidal current waveform at the power system mains. Whereas active power line conditioners cover a wider range of application than that of the active power filters. The APLC systems are able to compensate reactive power, harmonics, zero sequence current, negative sequence current, voltage flicker, voltage sag/swell and voltage regulation etc.. One may note that even though the terminology of the compensation devices varies with application, topology of these devices remains the same.

The structure of a simple power system with APF OFF is shown in Fig.1 [16]. Analysis of Fig. 1 shows that with APF system OFF, both source and load currents are harmonic polluted and the source current is not in phase with the supply voltage. One may note that in Fig. 2, with APF system ON, even though load current is harmonic polluted, the source current is free of harmonics and in phase with supply voltage [16]. Simple application of Kirchoff's current law shows that APF system injects a current equal in magnitude but in phase opposition to harmonic current and reactive component of load current. A shunt active power filter is connected in parallel with the load at the point of common coupling.

3.2 Structure of an APLC system

Figure 3 shows the basic structure of a three-phase active power conditioning system feeding a three-phase load. Three-phase parallel converters feeding

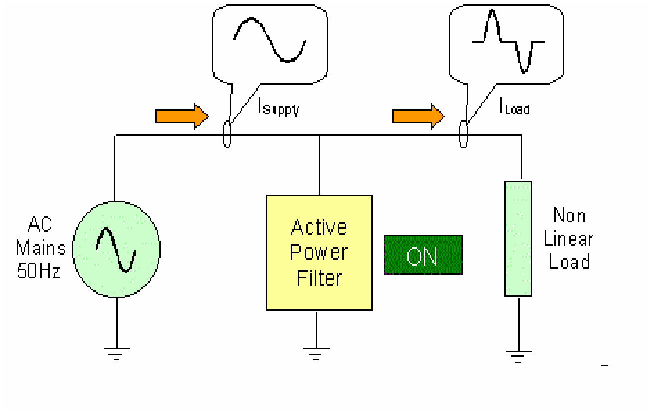

Fig. 1 Structure of a simple power system with APF OFF

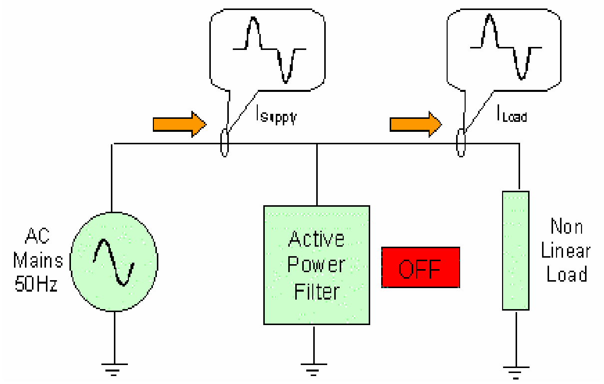

Fig. 2 Structure of a simple power system with APF ON

a common resistance-inductance (R-L) load with different firing angles have been taken as the three-phase load. Parallel converters have been set in the rectifier mode. APLC system is connected in parallel to the load at the point of common coupling. The APLC system consists of two distinct main blocks namely, PWM inverter and the active filter controller. The three-phase, six-pulse PWM voltage source inverter is made up of IGBT switches with anti-parallel diodes as shown in Fig. 4. A separate dc power supply has been used as the dc source of the IGBT inverter. It has been observed that for successful operation of the APLC system the voltage of the dc source should be 1.5 times the amplitude of line-line supply voltage. If the dc voltage is lower than the amplitude of the ac voltage, the inverter may lose its controllability. The PWM current control forces the voltage source inverter to behave as a controlled current source. In order to avoid high $\frac{di}{dt}$, the coupling of a voltage

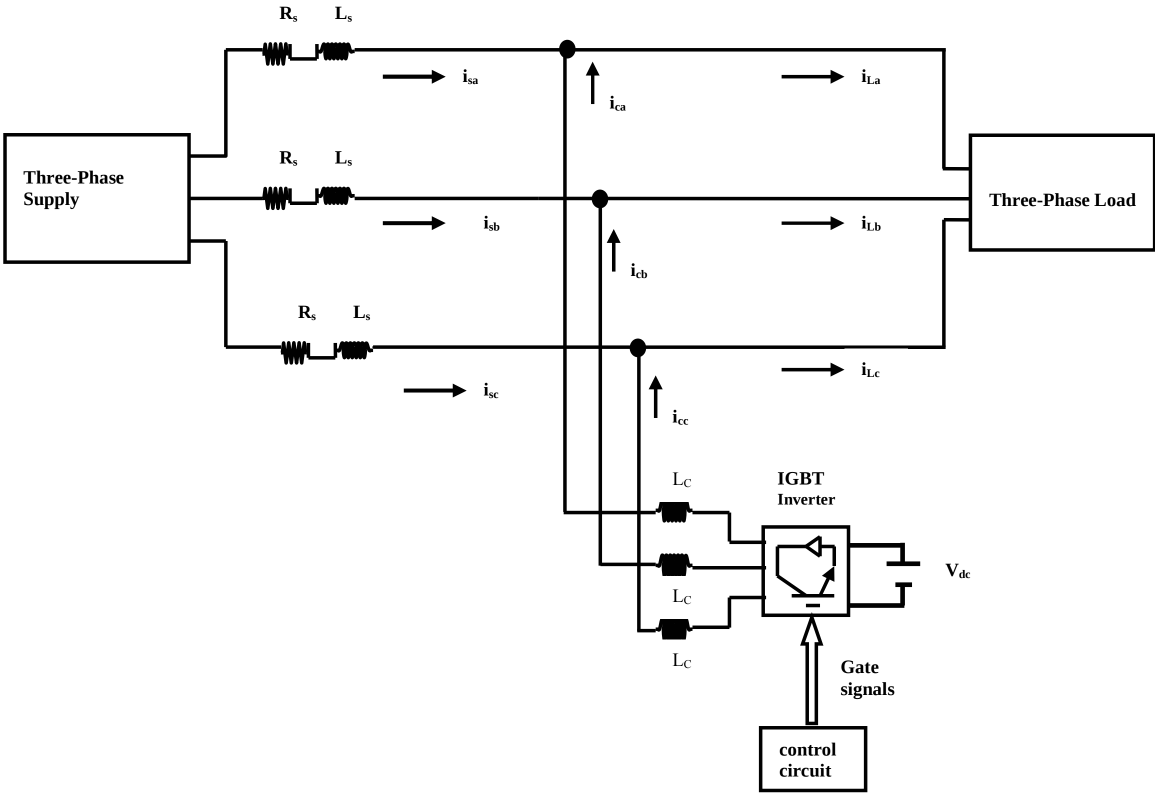

Fig. 3 Structure of a three-phase APLC system

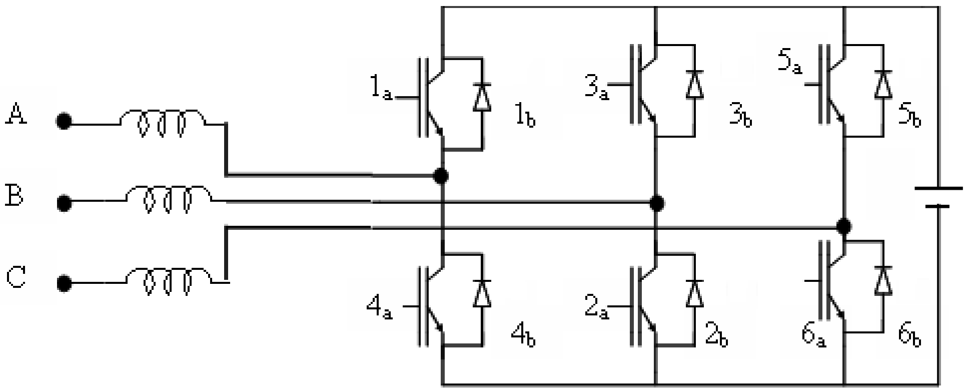

Fig. 4 Structure of a voltage source inverter

source inverter to the power system has been made through a series inductor, commonly known as booster inductor. The switching patterns of the VSI are determined by the control circuit. The design of the control circuit varies with the application of APLC system. One may note that APLC system could be used for harmonic elimination, power factor improvement, cancellation of zero-sequence and negative-sequence components, voltage sag/swell, etc. or combination of all these. Control circuit should be properly chosen based on the specific application. The performance of the APLC system is based on three basic design criteria namely the design of the inverter, PWM control method and methods used to generate reference current template. The active power line conditioner should supply all the harmonic power, negative sequence power and the zero sequence power to achieve purely balanced sinusoidal source currents in phase with respective source voltages and hence

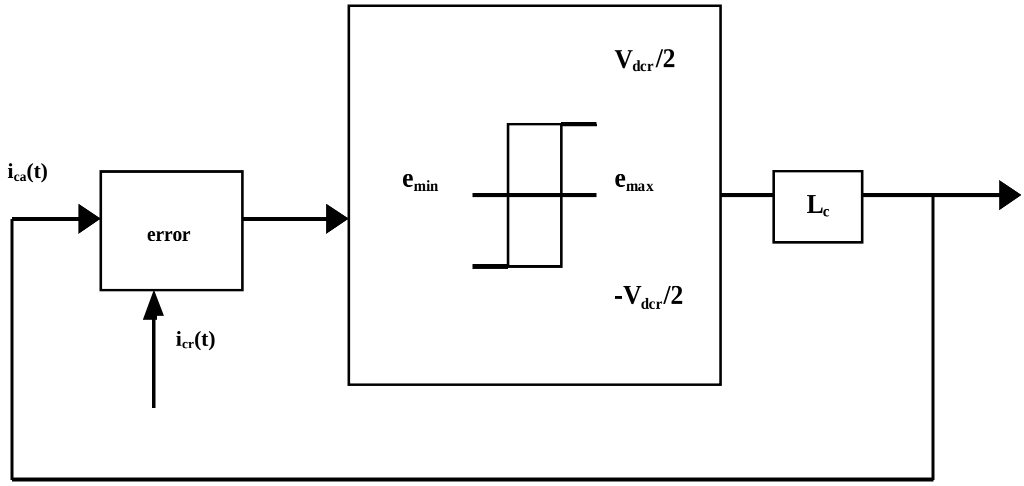

Fig. 5 Block diagram of a hysteresis current controller

a separate dc power supply has been used for the VSI rather than the dc capacitor.

Hysteresis current control (HCC) is a common PWM control used in voltage source inverters to force these inverters to behave as controlled ac current source to the power system. In a hysteresis current controller the switching patterns are generated by comparing the instantaneous APLC reference compensation currents ($i_{cr}(t)$) with the actual currents ($i_{ca}(t)$ that is being injected by the APLC system. A positive pulse is generated if the actual current is less than the reference current, whereas a negative pulse is generated if the actual current is greater than the reference current. This method controls the switches in an inverter asynchronously to ramp the current in an inductor up and down so that it tracks a reference current signal. A hysteresis current controller is implemented with a closed loop control as shown in Fig. 5 [17]. The expression for the maximum switching frequency of hysteresis controller is given by [18]:

$$f_{sw(\max)} = \frac{V_{dcr}}{9hL_c} \text{ where}$$

$f_{sw(\max)}$ – maximum switching frequency (Hz)

V_{dcr} – reference dc voltage (V)

L_c – booster inductance (H)

h –hysteresis limit (V)

$e_{\min}$ – lower hysteresis limit (V)

$e_{\max}$ – upper hysteresis limit (V)

The following subsections describe synchronous detection equal current approach and the proposed control technique based on positive sequence fundamental average power to estimate the amplitude of the reference source current.

3.1 Synchronous detection equal current approach

The control circuit of APF systems using SDECA method is shown in Fig. 6. In SDECA method [11], the average power consumed by the three-phase nonlinear load is extracted to determine the amplitude of the reference source current. The accuracy of this approach is quite acceptable under balanced conditions. However, one may note that authors haven't given any importance for the determination of amplitude of voltages $V_{tam}, V_{tbm}, V_{tcm}$. With distorted voltages, one should specify whether the terms $V_{tam}, V_{tbm}, V_{tcm}$ represent the amplitude of fundamental components of voltages or the amplitude of complex source voltage waveforms.

Now this scenario becomes worsen with parallel converters with different firing angles. With distortion and unbalance in terminal voltages and load currents, there is power contribution due to fundamental positive-sequence component, fundamental negative-sequence component, fundamental zero-sequence component and positive, negative and zero sequence contributions from harmonics.

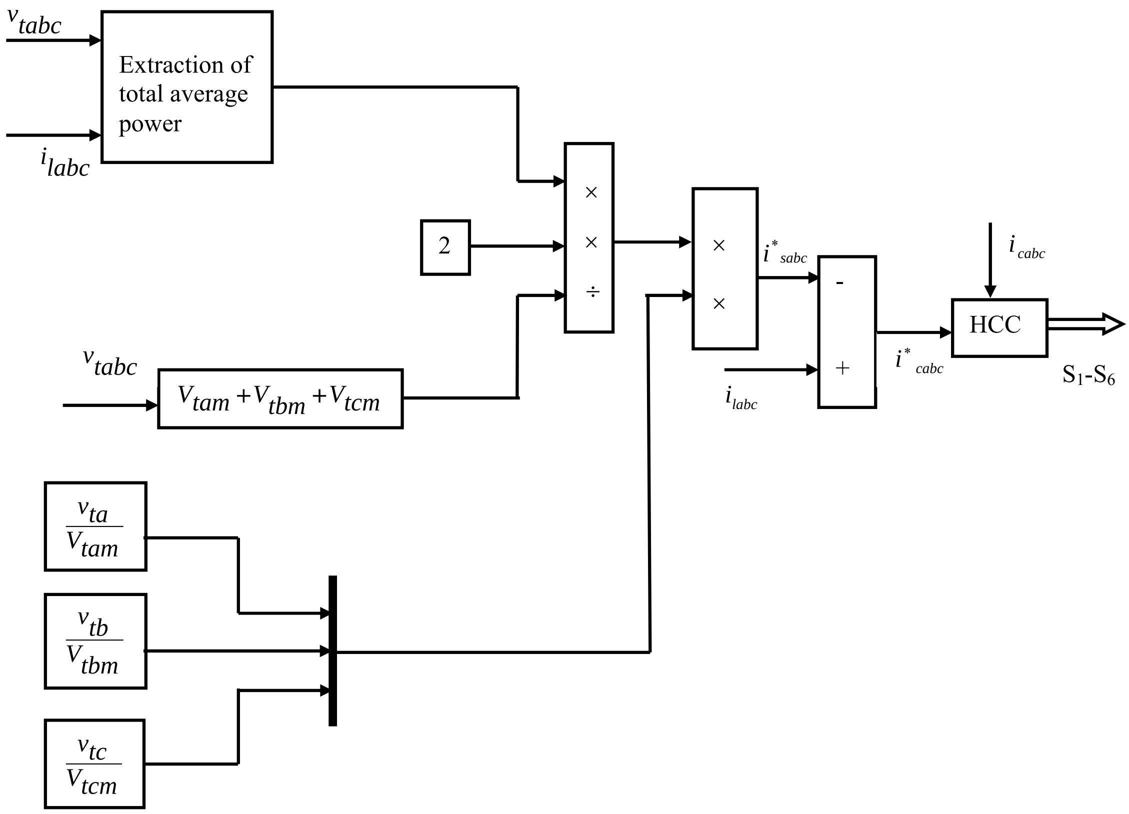

Fig. 6 SDECA control circuit of an APLC system

3.2 Positive sequence fundamental average power method

The proposed APLC control circuit is shown in Fig.7. The control circuit assumes that the APLC system supplies all the components of power other than the average power contribution due to positive sequence components (fundamental) and after compensation, the source currents are balanced sinusoids and in phase with the supply voltages. For the determination of reference source currents, three-phase positive sequence (fundamental) average power has been extracted and equally divided among the three phases and the amplitude of positive sequence (fundamental) components of terminal voltages has been extracted.

4 Results

MATLAB 6.1 toolbox is used to model the APLC system. The power supply voltages have been taken as balanced sinusoids (E_s/phase-220V; f_z-50Hz; R_s-0.1Ω; L_s-0.5mH) and current controlled VSI (L_c-4mH; V_{dc}-1000V) is used to implement the APLC system. To introduce significant unbalance, series resistances of different values (R_{sa}-20Ω; R_{sb}-5Ω; R_{sc}-1Ω) are connected at the ac side of the parallel converter load. Two thyristor parallel converters have been used to feed a common dc load (R_L-3Ω L_L-20 mH). A high-pass RC filter (R-4Ω; C-125 μF) has been incorporated at the filter terminals to reduce the high frequency components to be injected into the power system. The supremacy of the proposed method has been tested for different firing angles and results are tabulated in Table 1. The effectiveness of PSFAP method has been illustrated and compared with SDECA method in Figs. 8-11 with firing angle of converter 1 (α_1) and converter 2 (α_2) set as 0° and 90° respectively. One may note that APLC system is connected at 0.05s. Fig.8 illustrates that source currents obtained using PSFAP method are purely sinusoidal and balanced and in phase with respective supply voltages. Comparison of source current, load current and compensation current using PSFAP is shown in Fig. 9. Analysis of Fig. 10 illustrates that the proposed method is able to reduce the total harmonic distortion (THD) of all the phases below 5%. Plots of source current waveforms obtained using SDECA method are illustrated in Fig. 11.

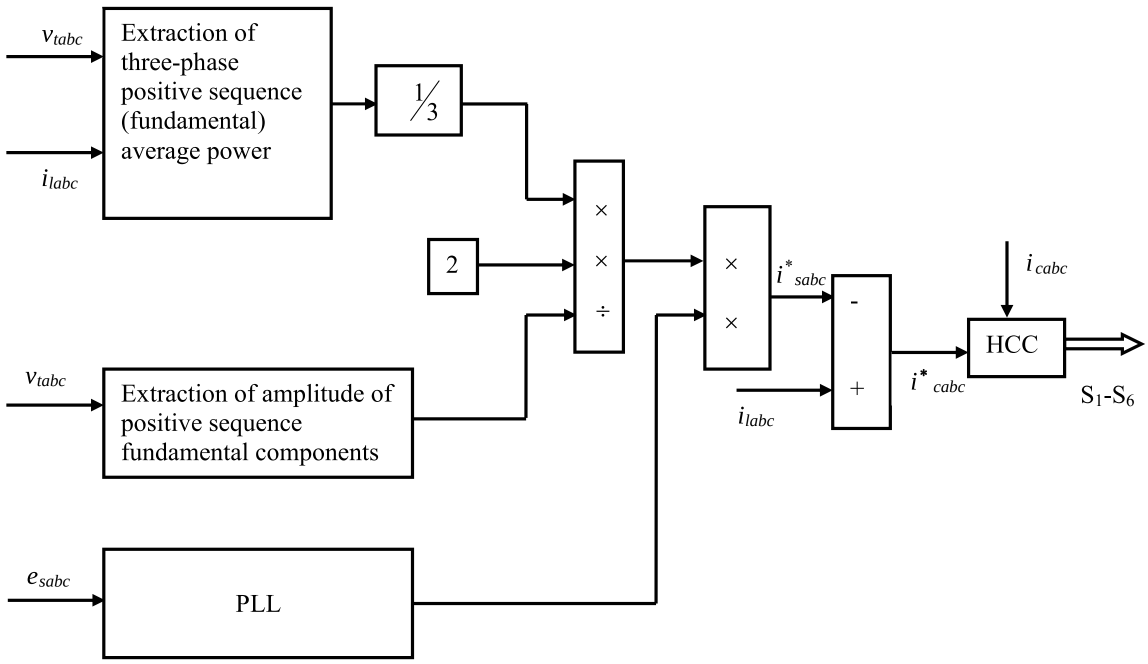

Fig. 7 PSFAP control circuit of an APLC system

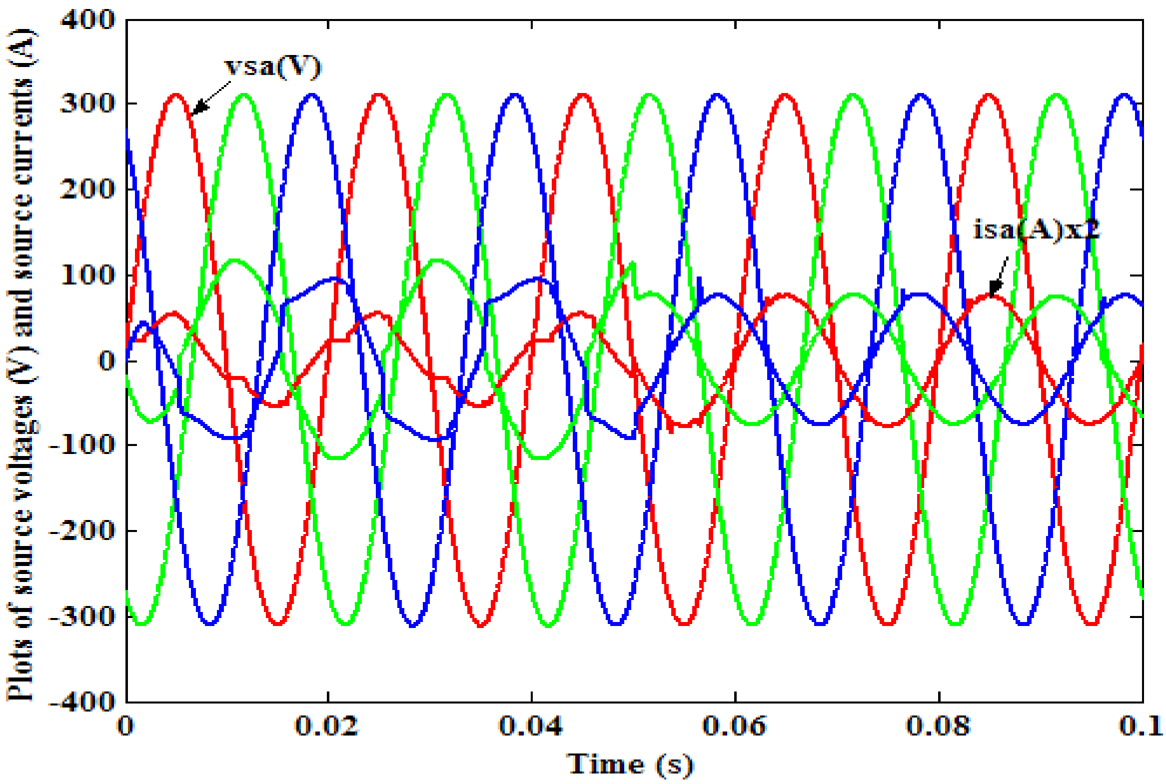

Fig. 8 Plots of source voltages (V) and source currents using PSFAP method

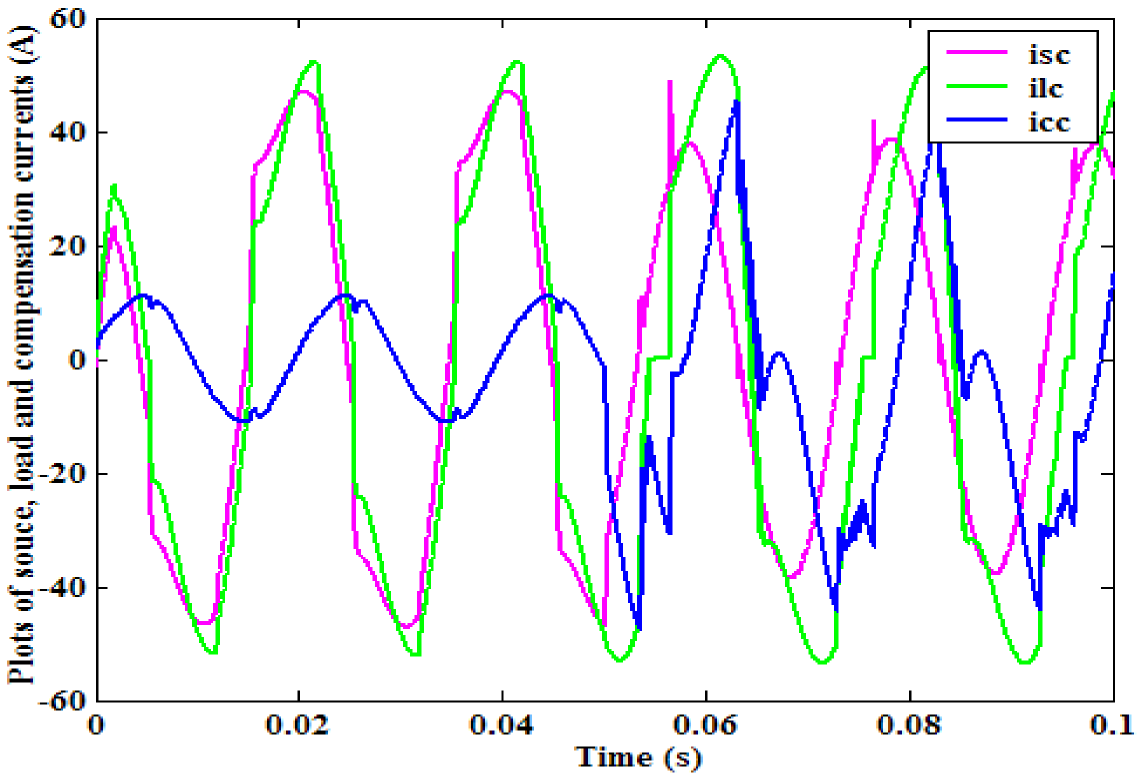

Fig. 9 Plots of source current, load current and compensation current in phase C using PSFAP method

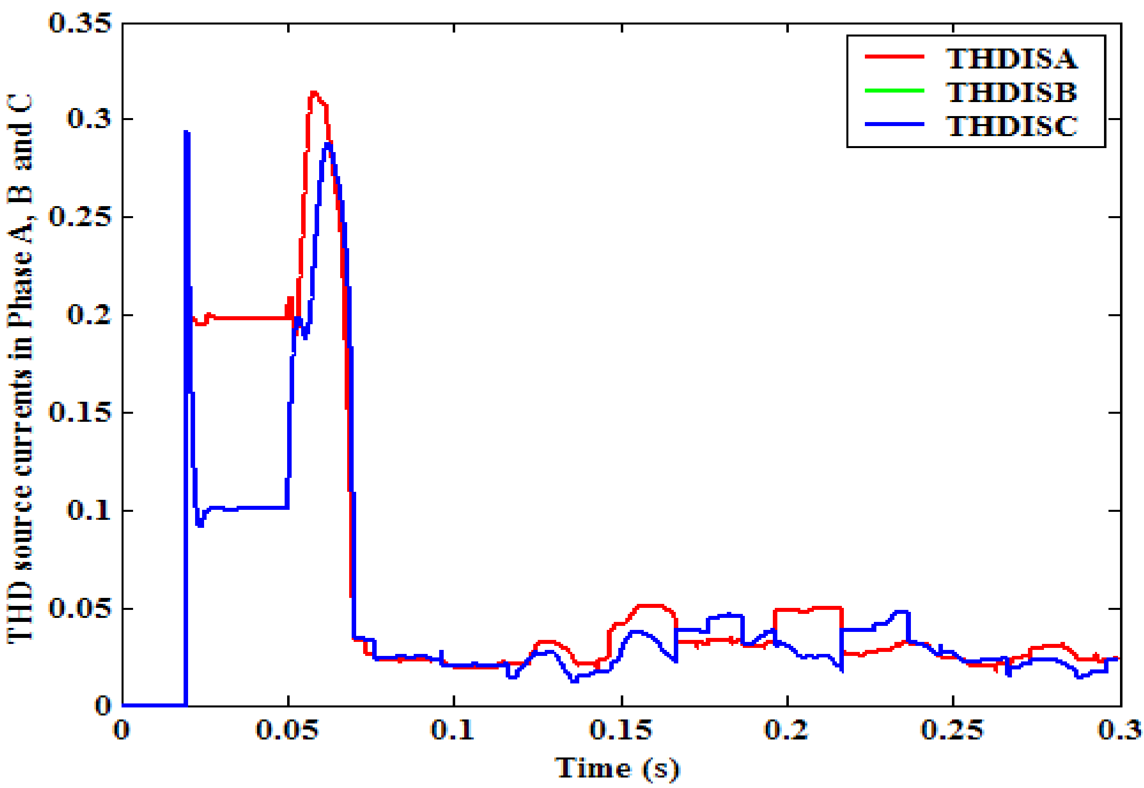

Fig. 10 THD of source currents in phase A, B and C using PSFAP method

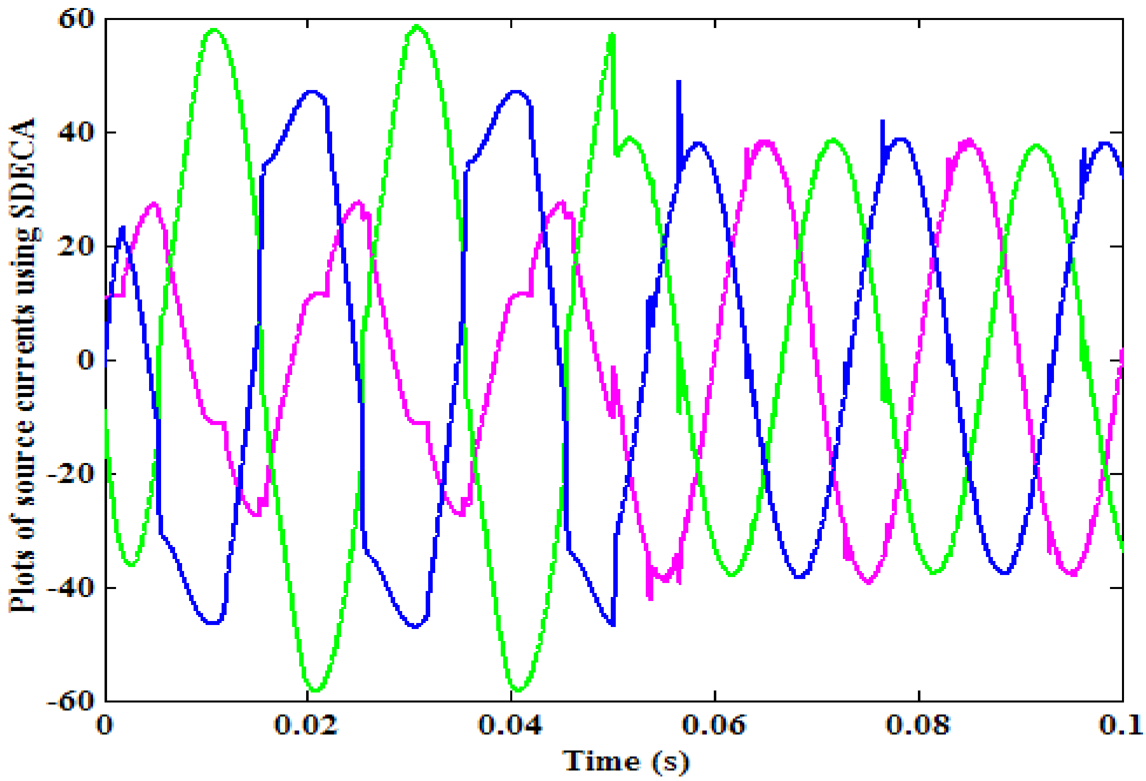

Fig. 11 Plots of source currents using SDECA method

Table 1 THD of source currents

		%THD PSFAP	%THD SDECA
$\alpha_1 = 0^{\circ}$ $\alpha_2 = 0^{\circ}$ (ilathd=23.3%; ilbthd=20.0%; ilcthd=28.2%)	isa	2.1	5.0
	isb	2.0	4.5
	isc	1.2	4.7
$\alpha_1 = 15^{\circ}$ $\alpha_2 = 60^{\circ}$ (ilathd=20.0%; ilbthd=8.5% ilcthd=15.0%)	isa	4.5	7.0
	isb	5.0	6.0
	isc	4	8.0

4 Conclusion

Power quality problems associated with three-phase parallel converters have been addressed in this manuscript. An APLC control technique based on positive sequence (fundamental) average power has been discussed. The performance and accuracy of SDECA is questionable when there is unbalance and distortion in both terminal voltages and load currents. The proposed PSFAP method shows supremacy over SDECA method independent of load conditions. PSFAP method is able to produce balanced sinusoidal source currents in synchronism with respective supply voltages. Since the proposed control technique considered unbalance, asymmetry, distortion in both terminal voltages and source currents the developed APLC system can be treated as a universal power quality conditioner.

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