

Graphical Representation of the Instantaneous Compensation Power Flow for Single-Phase Active Power Filters

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Abstract – The conventional graphical representation of the instantaneous compensation power flow for single-phase active power filters(APFs) simply represents the active power flow and the reactive power flow which flowing between the power source and the active filter / the load. But, this method does not provide the information about the rectification mode and the compensation mode of APFs, especially, the loss for each mode was not considered at all. This is very important to understand the compensation operation characteristics of APFs. Therefore, this paper proposes the graphical representation of the instantaneous compensation power flow for single-phase APFs considering the instantaneous rectification mode and the instantaneous inversion mode. Three cases are verified in this paper - without compensation, with compensation of the active power ‘p’ and the fundamental reactive power ‘q’, and with compensation of only the distorted power ‘h’. To ensure the validity of the proposed approach, PSIM simulation is achieved. As a result, we could confirm that the proposed approach was easy to explain the instantaneous compensation power flow considering the instantaneous rectification mode and the instantaneous inversion mode of APFs, also, Total Harmonic Distortion(THD)/Power Factor (P.F) and Fast Fourier Transform(FFT) analysis were compared for each case.

Keywords: Instantaneous compensation power flow, Graphical representation, Single-phase active power filters(APFs), Rectification mode, Inversion mode, THD, P.F, FFT analysis.

1. Introduction

Power factor improvement and harmonics suppression are important issue to obtain the high power quality of the power system because the modern industrial devices contain the sensitive devices. Active power filters(APFs) [1-11] have been accepting as an efficient device for compensating the harmonics and reactive power of nonlinear loads such as thyristor controlled rectifiers or variable speed drives. In order to compensate the harmonics and reactive power using APFs, APFs should be operated to the instantaneous rectification mode and the instantaneous inversion mode during the compensation operation. Also, the compensation performance of APFs are directly decided by the generated instantaneous compensation power [12-17]. But the conventional of graphical representation of the compensation power flow [12-15] for APFs is only presents the active power and reactive power flows for APFs compensation operation.

This method can not present the rectification mode which is charging the compensation energy and the compensation mode which is discharging the compensation energy. Furthermore, the loss for each mode was not considered at all, also the distortion power flow can not describe. Therefore, if the instantaneous compensation

power which flowing between APFs and AC power source can be illustrate in graph, then, it can be easily understood the compensation operation of APFs.

This paper briefly discusses the graphical representation of the instantaneous compensation power flow which could be practicable to understand the harmonics and reactive power compensation for single-phase APFs in both case of behaving in the instantaneous rectification mode and the instantaneous rectification inversion mode. The instantaneous compensation power can be decomposed into the active component, the fundamental reactive component and the distorted component. Compensation operation modes of single-phase APFs are represented by each decomposed power components. Distorted and reactive powers of nonlinear loads can be independently controlled by single-phase active power filters, and its instantaneous power flows of before and after compensation can be illustrated in graph.

To ensure the validity of the proposed approach, computer simulation was performed. Three case verifications - without compensation, with compensation (active power ‘p’ and fundamental reactive power ‘q’), and with compensation (only distorted power ‘h’) were achieved in this paper. As a result, we could confirm that the proposed approach can illustrate more exquisitely and more significantly the instantaneous compensation power flow of single-phase APFs considering the instantaneous rectification mode and the instantaneous inversion mode.

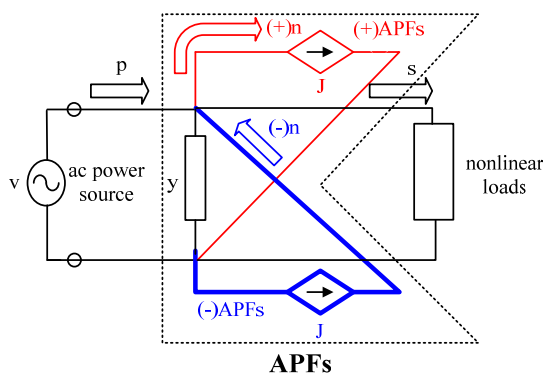
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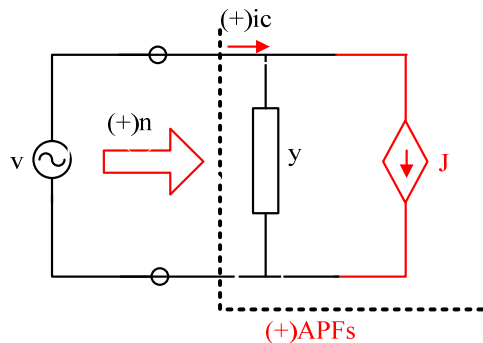
Finally, THD / P.F and FFT results for each case is compared and discussed.

2. Compensation Operation of Single-Phase Active Power Filters

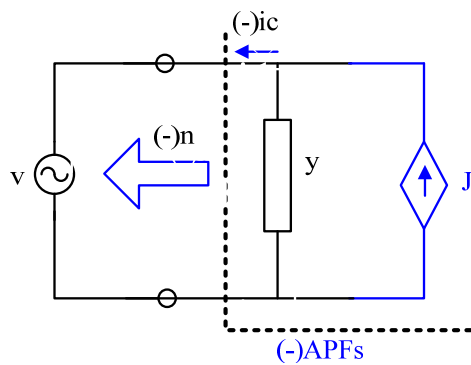
Fig. 1 (a) shows the equivalent circuit of single-phase active power filters during the compensation operation, where 's', 'p' and 'n' respectively denote the instantaneous apparent power, the instantaneous active power and the instantaneous non-active power.



(a) Basic equivalent circuit



(b) Rectification mode



(c) Inversion mode

Fig. 1. Equivalent circuit of single-phase active power filters (APFs) ('+') : rectification mode, '(-)' : inversion mode)

With two operation modes - the rectification and the inversion modes as shown in Figs. 1(b) and Fig. 1(c), single-phase active power filters generate the instantaneous compensation power 'n' (that is, the non-active power) to AC power source.

'(+)' denotes that single-phase active power filters operate as the rectification mode and '(-)' denotes the inversion mode. 'J' and 'y' refer the compensation current source of single-phase active power filters and equivalent admittance of single-phase active power filters. Also, i_c denotes the compensation current which generated from the current source 'J' of single-phase active power filters.

Fig. 2 shows the waveforms of compensation current i_c and power 'n' while i_L means the nonlinear loads current. The instantaneous compensation current i_c is generally composed of the fundamental reactive current i_r and the harmonic current i_h . First of all, for the rectification mode in interval (I, III) as shown in Figs. 2 and Fig. 3, the

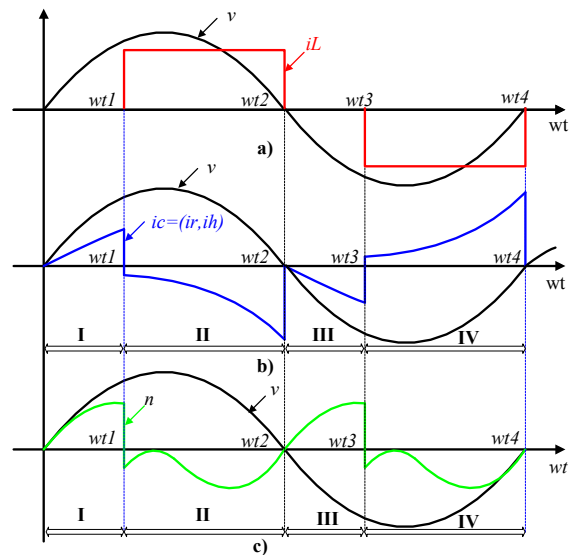


Fig. 2. Waveforms of the compensation current and power: (a) Load current i_L and source voltage 'v'; (b) compensation current i_c ; (c) Compensation power 'n'

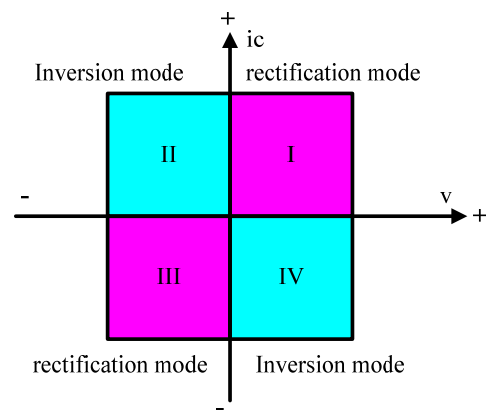


Fig. 3. Operation quadrants of single-phase APFs according to i_c

instantaneous non-active power (+)*n* is transferred from the AC power source to APFs. In the same time, (-)*n* is transferred from single-phase active power filters to the AC power source for the inversion mode in interval(II, IV).

3. Graphical Representation of the Instantaneous Compensation Power Flow

The instantaneous apparent power (supply power) ‘*s*’ is expressed in terms of two components – the instantaneous active power ‘*p*’, the instantaneous non-active power ‘*n*’, and their instantaneous values fulfill the following relation.

$$s = n + p \quad (1)$$

Also, the instantaneous compensation current *i_c* calculated by using the instantaneous load current *i_L* described as (2), and *i_c* is formulated by (3). As shown in Fig. 2(b), the instantaneous compensation current *i_c* is divided into (+) *i_c* for rectification and (-) *i_c* for inversion.

The instantaneous load current *i_L* without DC offset component :

$$i_L = A1 \sin(\omega t) + B1 \cos(\omega t) + \sum [An \sin(n\omega t) + Bn \cos(n\omega t)] \quad (2)$$

The instantaneous compensation current *i_c* :

$$i_c = B1 \cos(\omega t) + \sum [An \sin(n\omega t) + Bn \cos(n\omega t)] = (+)i_c + (-)i_c \quad (3)$$

where (+) *i_c* ; interval I (0 < ω t < ω t₁) : rectification mode
interval III (ω t₂ < ω t < ω t₃) : rectification mode

(-) *i_c* ; interval II (ω t₁ < ω t < ω t₂) : inversion mode
interval IV (ω t₃ < ω t < ω t₄) : inversion mode

As mentioned above, (+)*i_c*, the first term of (4) refers the instantaneous compensation current of the rectification mode and it has the same polarity compared with ‘*v*’. And reversely, (-) *i_c*, the second term of (4) refers the instantaneous compensation current of the inversion mode and it has the reverse polarity compared with ‘*v*’. This means that the instantaneous compensation power ‘*n*’ which flowing between the AC power source and single-phase active power filters can be formulated by (5).

$$n = v i_c = v [(+)i_c + (-)i_c] = (+)n + (-)n \quad (5)$$

where (+) *n* ; interval I (0 < ω t < ω t₁) : rectification mode
interval III (ω t₂ < ω t < ω t₃) : rectification mode

(-) *n* ; interval II (ω t₁ < ω t < ω t₂) : inversion mode

interval IV (ω t₃ < ω t < ω t₄) : inversion mode

Now, let’s consider the loss *w_o* of single-phase active power filters such as DC energy charge-discharge loss, switching loss and input L-C filter loss of PWM converter. During single-phase active power filter works, single-phase active power filters produce the compensation loss *w_o* for each operation mode. Single-phase active power filters loss can be classified into two losses in (6) that is (+)*w_o* for rectification mode and (-)*w_o* for inversion mode respectively. But, generally, it is very difficult to know that the individual *w_o* for each operation mode as mentioned above.

$$w_o = (+)w_o + (-)w_o \quad (6)$$

where (+)*w_o* ; interval I (0 < ω t < ω t₁) : rectification mode
interval III (ω t₂ < ω t < ω t₃) : rectification mode

(-) *w_o* ; interval II (ω t₁ < ω t < ω t₂) : inversion mode
interval IV (ω t₃ < ω t < ω t₄) : inversion mode

But, we already know that the DC capacitor voltage of single-phase voltage source type active power filters should be controlled to constant voltage level, while the DC reactor current of the current source types should be controlled to constant current level, because of build up of the compensation energy.

Fig. 4 shows the compensation current and power waveforms considering the DC energy build up. The DC side energy control of single-phase active power filters aim at the DC energy build up for compensation. In order to build up of the DC capacitor voltage in case of the voltage source APFs, The current *i_o* in phase with source voltage ‘*v*’ is added to *i_c* as shown in Fig. 4(a). The current *i_o* is calculated by multiplying the unity ‘*v*’ by the DC voltage

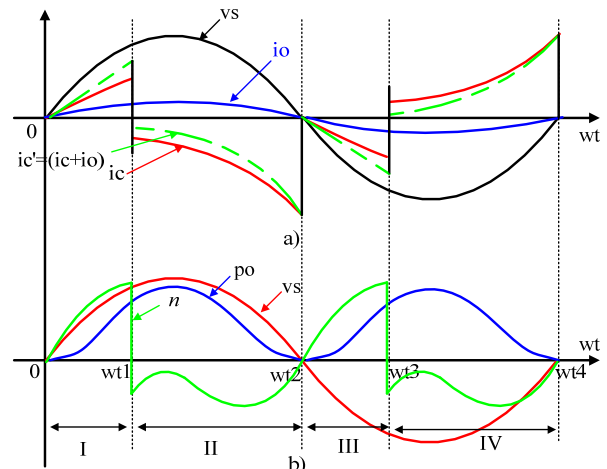


Fig. 4. Compensation waveforms considering the DC energy build up: (a) Compensation current *i_c*; (b) compensation power *p_o*

error (PI controller output) defined as the difference between the DC voltage reference and the DC capacitor voltage. Note that the DC energy build up compensation current i_0 and power ' p_0 ' are always the active components.

The loss w_0 in (6) can be represented by ' p_0 ' in Fig. 4(b). This means that w_0 is nearly equivalent to p_0 because the loss of the ideal APFs goes to zero, hence the DC energy build up of single-phase active power filters does not need. The power p_0 can be divided into two parts; $(+)p_0$ for the rectification mode and $(-)p_0$ for the inversion mode respectively. Unlike ' n ' in Fig. 4(b), note that $(-)p_0$ does not keep the reverse polarity compared with ' v ' over the inversion mode. That is, this means that p_0 still places in the inversion interval (II or IV) though it is positive.

The resultant instantaneous compensation power n' considering the DC energy build up can be expressed by (7)-(11).

$$\text{Rectification mode : } (+)n' = (+)p_0 + (+)n \quad (7)$$

$$\begin{aligned} (+)n &= (+)i_c v \\ &= [(+)i_r + (+)i_h] v \\ &= (+)q + (+)h \end{aligned} \quad (8)$$

$$\text{Inversion mode : } (-)n' = (-)p_0 + (-)n \quad (9)$$

$$\begin{aligned} (-)n &= (-)i_c v \\ &= [(-)i_r + (-)i_h] v \\ &= (-)q + (-)h \end{aligned} \quad (10)$$

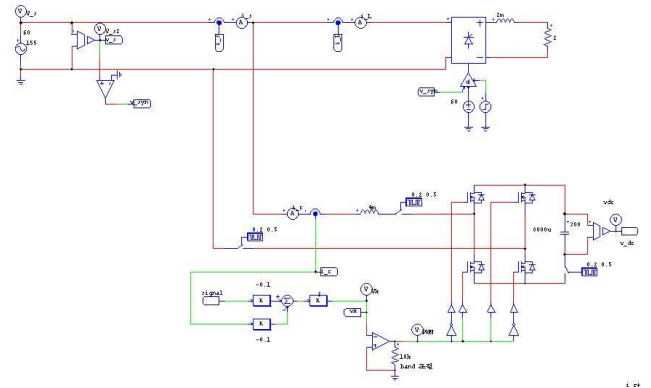
As mentioned above, $(-)p_0$ means that p_0 still places in the inversion interval(II or IV) though it is positive.

Hence;

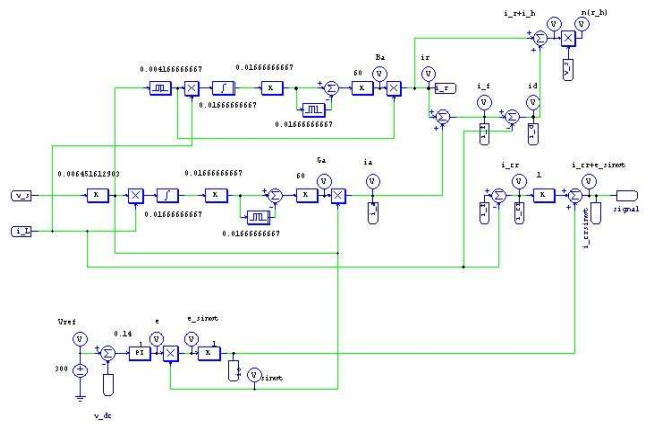
$$\begin{aligned} n' &= (+)n' + (-)n' \\ &= [(+)p_0 + (+)q + (+)h] + [(-)p_0 + (-)q + (-)h] \\ &= [(+)p_0 + (-)p_0] + [(+)q + (-)q] + [(+)h + (-)h] \\ &= p_0 + (q + h) \end{aligned} \quad (11)$$

4. Simulation and Verification

In order to obtain the proposed instantaneous compensation power flow diagram of single-phase APFs, computer simulation using a PSIM simulation software was done as shown in Fig. 5. The power theory for the compensation current calculation was based on the general Fourier Series Method. Table 1 shows the simulation parameters. As shown in Table 1, the AC source voltage (155V/60Hz) supplies to the non-linear thyristor loads. Voltage source type single-phase active power filter serve as the compensator of the reactive and distorted power generated from thyristor loads. To build up of DC capacitor voltage, PI controller is used, and Hysteresis Current Control(HCC) is applied to control of the compensation current i_c '. Three cases - without compensation, with compensation (active power ' p ' and fundamental reactive



(a) Power circuit



(b) Control block diagram

Fig. 5. PSIM simulation model

Table 1. Simulation parameters

v_s	155V(peak)/60Hz
i_L	68A(peak)
V_{dc}	300V
Compensation current control	Hysteresis Current Control(HCC)
Coupling inductor	$L_f = 3\text{mH}$
DC voltage PI controller	DC capacitor=3000uF P=1, I=0.14
Non linear Thyristor load	Current source type, $L_L = 2\text{mH}$, Firing angle=60°, R load=2Ω

power ' q ') and with compensation (only distorted power ' h ') are verified and the power quality of each case is compared in this paper.

4.1 Without compensation

Fig. 6 shows the instantaneous compensation power flow by the graphical representation for no compensation, and Fig. 7 shows the simulated results.

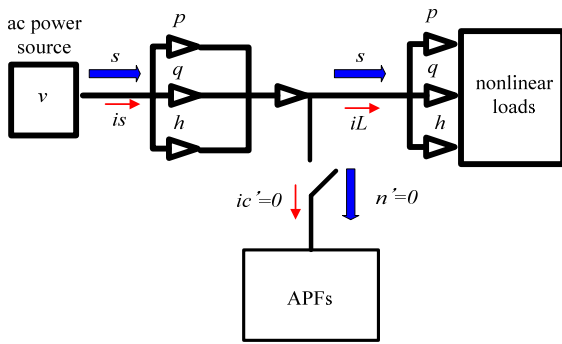
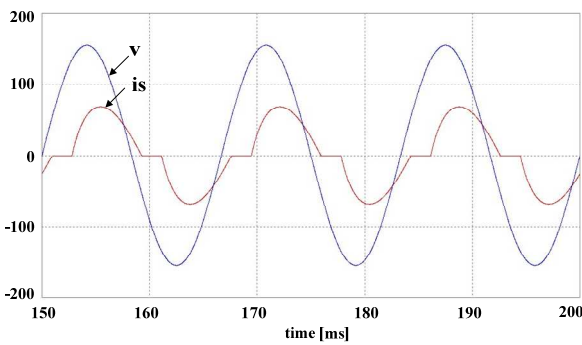
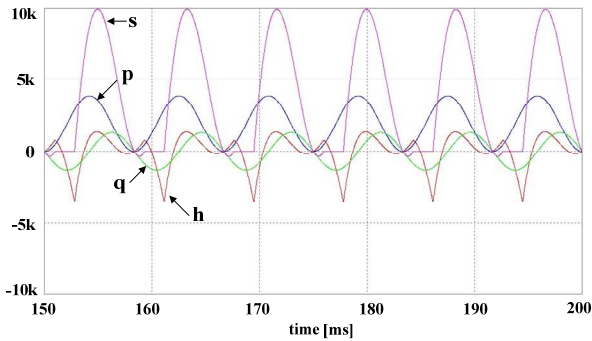


Fig. 6. The instantaneous compensation power flow diagram for no compensation



(a) Waveforms of v and i_s



(b) Waveforms of the decomposed source power components

Fig. 7. Simulated results for no compensation

As shown in Fig. 7(a), waveform of i_s is distorted and lagged in comparison with the phase of AC source voltage v . Fig. 7(b) shows that the instantaneous apparent power 's' can be decomposed into the active power 'p', the fundamental reactive power 'q' and the distorted power 'h'. The active power 'p' flows toward the one side direction while the 'q' and 'h' flow to the bi-direction.

As shown Fig. 6, during no operation of single-phase APFs, the power 'n' flowing between AC power source and single-phase active power filters are zero, and 's' is directly transferred to the nonlinear loads. But, if single-phase APFs operate, the compensation power appears between single-phase APFs and AC power source. Graphical representation in Fig. 6 is useful for describing the

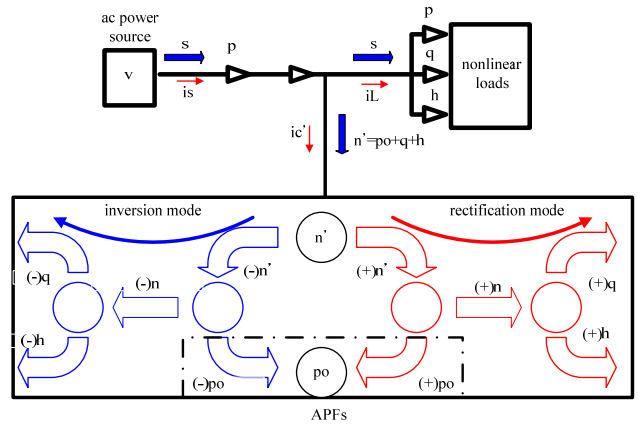
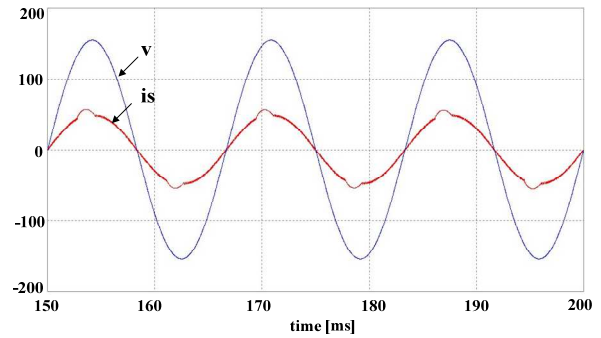
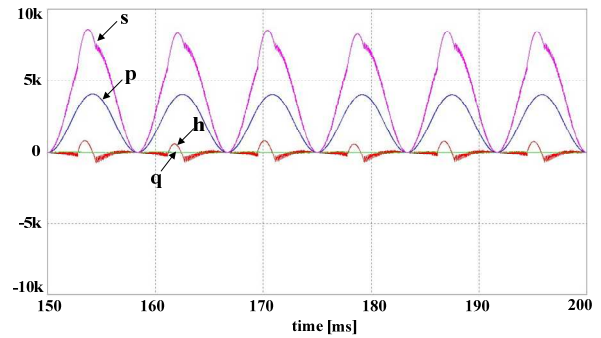


Fig. 8. The instantaneous compensation power flow diagram for 'q' and 'h' compensation



(a) Waveforms of v and i_s



(b) Waveforms of the decomposed source power components

Fig. 9. Simulated results for fundamental reactive power 'q' and distorted power 'h' compensation.

compensation power flow and the operation of single-phase active power filters.

4.2 With compensation ('q' and 'h')

Fig. 8 shows the instantaneous compensation power flow diagram, in case that the instantaneous compensation power component (fundamental reactive power 'q' and distorted power 'h') is simultaneously compensated by single-phase APF considering the DC voltage build up.

Fig. 9 shows the simulated results for 'q' and 'h'

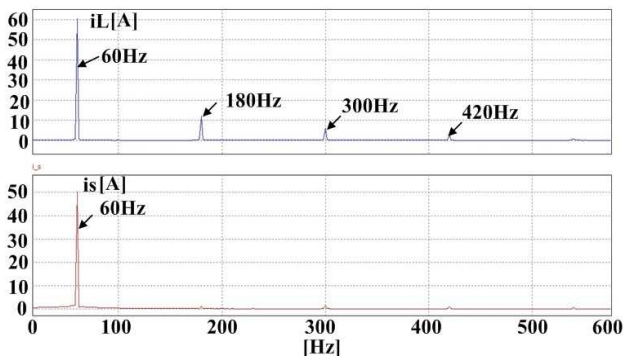


Fig. 10. FFT results of i_L and i_s for ‘q’ and ‘h’ compensation (x-axis: 100Hz, y-axis: 10A/div.)

Table 2. THD and each harmonics levels of current for ‘q’ and ‘h’ compensation

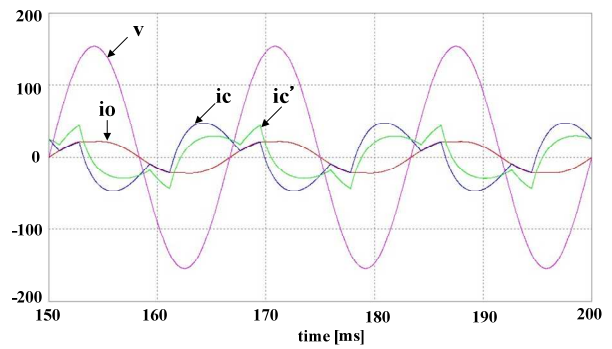
[A]	60Hz (1 st)	180Hz (3 rd)	300Hz (5 th)	420Hz (7 th)	THD [%]	P.F
i_L	60	12	6	2.5	22.7	0.80
i_s	50	1	1.4	1	4	0.99

compensation. Fig. 9(a) shows the AC source voltage ‘v’ and current i_s . As compared with Fig. 7(a), the waveform of i_s is nearly sinusoidal and in phase with ‘v’. Also, Fig. 9(b) shows the decomposed source powers. As expected, we can know that only ‘p’ remains in AC power source while the supply power ‘s’ is still supplied to the load side. This means that the P.F and THD of AC power source is improved.

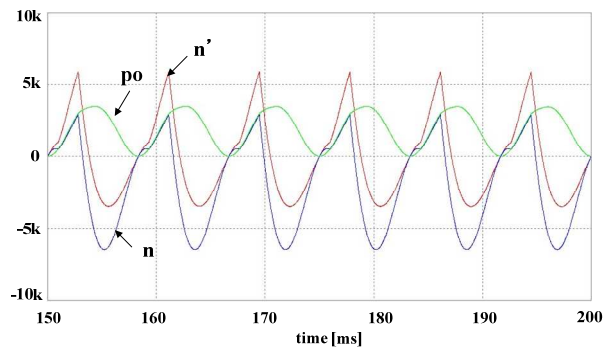
As the FFT results shown in Fig. 10, a non-linear thyristor load generates i_L with large 3rd harmonic content. As given in Table 2, the 3rd harmonic component of i_L reaches to 20% for the 60Hz fundamental component. After harmonics compensation is achieved, with respect to the source current i_s , the 3rd component of i_s is reduced to 2% for the 1st component as given in Table 2. These means that highly distorted i_s is changed into a sinusoidal waveform by compensation operation of the proposed system. As a result, the THD of i_s is improved, also the unity power factor (P.F) is obtained.

Fig. 11 shows the simulated results of the instantaneous compensation power and current for Fig. 9. Waveforms of Figs. 11(a)-(b) follow the compensation principle in Fig. 4. First of all, the compensation reference for the DC voltage build up should be re-calculated as ($i_c' = i_c + i_0$) in Fig. 11(a) because i_0 is added to i_c . As shown in Fig.11(b), the instantaneous compensation power $n' = p_o + (q+h) = p_o + n$ flows between single-phase APFs and AC power source.

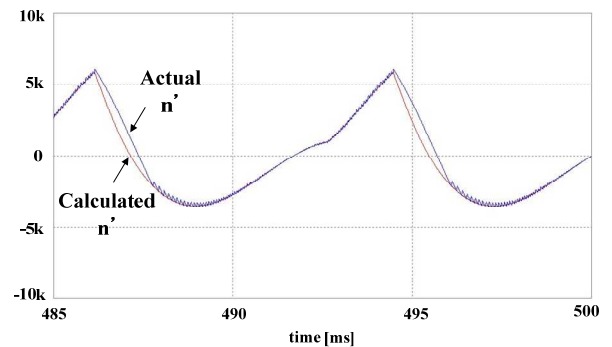
The compensation power ‘n’ is calculated by using ‘q’ and ‘h’ while p_o serves as the DC energy build up compensation power. Actually, ‘n’ reciprocates between single-phase APFs and AC power source. The proposed approach represents very well ‘q’ and ‘h’ for the rectification and inversion modes.



(a) Waveforms of the compensation current i_c



(b) Waveforms of the compensation power n'



(c) Comparison of the actual n' and the calculated n'

Fig. 11. Simulated results of the compensation current and power

Fig. 11(c) shows the comparison result of the calculated n' and the actual ‘n’. Because the calculated compensation reference power ‘n’ is seriously distorted, the actual compensation power ‘n’ can not follow in the suddenly changed point. As a result, the spikes periodically remain in the compensated source current i_s as shown in Fig. 9(a).

4.3 With compensation(‘h’)

Fig. 12 shows the instantaneous compensation power flow diagram in case that single-phase APFs control only ‘h’ component. Because only ‘h’ is controlled by single-phase APFs, ‘p’ and ‘q’ remain in AC power source as

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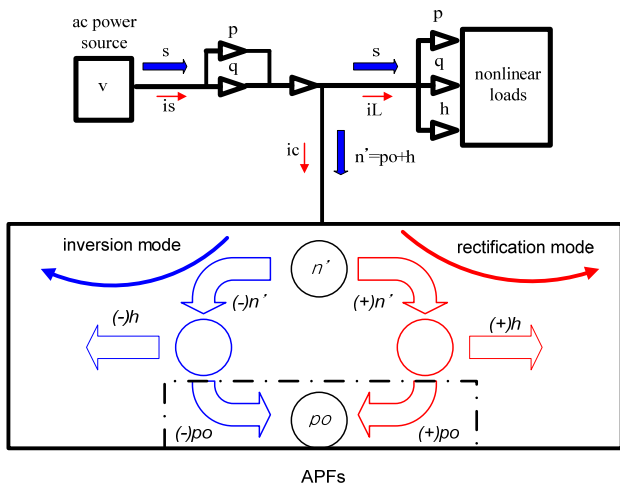


Fig. 12. The instantaneous compensation power flow diagram for only distorted power 'h' compensation

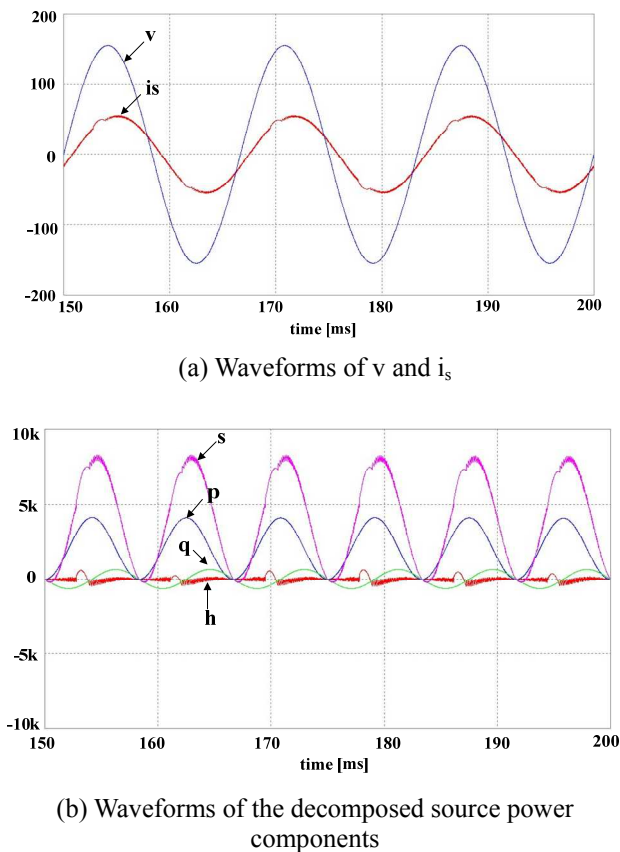


Fig. 13. Simulated results for only distorted power 'h' compensation

Table 3. THD and each harmonics levels of current for only 'h' compensation

[A]	60Hz(1 st)	180Hz(3 rd)	300Hz(5 th)	420Hz(7 th)	THD[%]	p.f
i_L	60	12	6	2.5	22.7	0.80
i_s	53.8	0.64	0.7	0.57	2	0.95

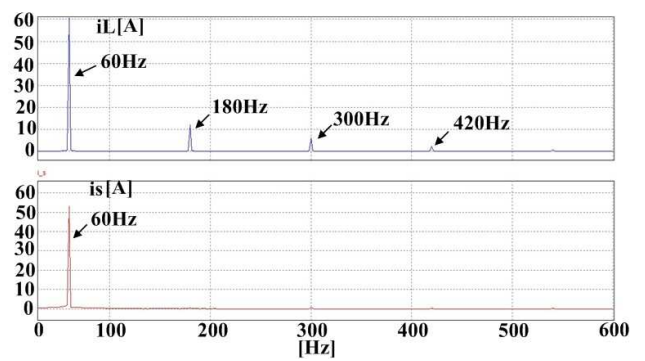
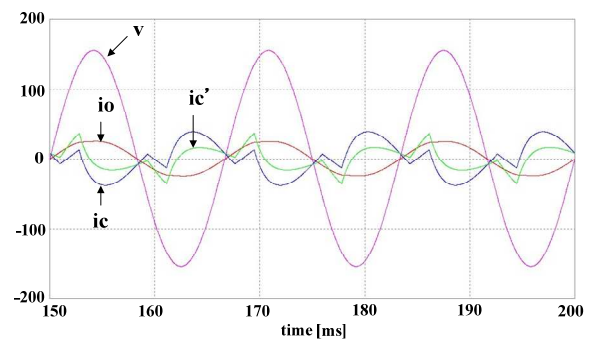
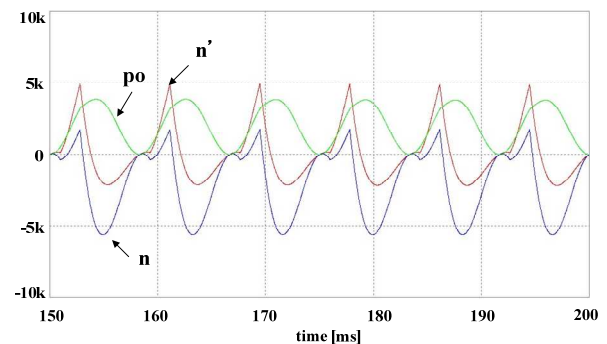


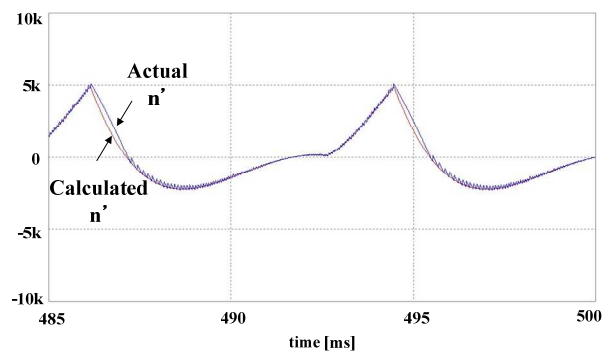
Fig. 14. FFT results of i_L and i_s for only 'h' compensation (x-axis: 100Hz, y-axis: 10A/div.)



(a) Waveforms of the compensation current i_c



(b) Waveforms of the compensation power n'



(c) Comparison of actual n' and calculated n'

Fig. 15. Simulated results of the compensation current and power

shown in Fig. 13(b), while the supply power 's' is still supplied to the load side. In this case, the AC source voltage 'v' and current i_s presented in Fig. 13(a).

Fig. 14 shows the FFT results for only distorted power 'h' compensation. As compared with Fig.10, it can be seen that there is a difference in the 60Hz fundamental component of the compensated i_s . Firstly, in case that only the distorted power is compensated, the 60Hz fundamental component in the compensated i_s is larger than in case of the two components compensation, because the 60Hz fundamental reactive component remains in the compensated supply current i_s . With respect to the THD and P.F of the compensated i_s , we can know that THD is 2% and P.F is 0.95.

Fig. 15 shows the simulated results of the compensation power 'n' and current i_c '. The operation principle is nearly similar as compared with 'q' and 'h' compensation in Fig.11.

5. Conclusion

This paper deals with the graphical method to present the instantaneous compensation power flow of single-phase active power filters (APFs) considering the rectification and inversion modes. The following conclusions can be derived from the results of this study. Compared with the conventional method, the proposed method is useful to illustrate the compensation principle of single-phase APFs by the graphical method. The equivalent circuit of single-phase APFs is obtained into the rectification and inversion modes in order to suit proposed approach. In case that the reactive and harmonic powers of nonlinear loads are simultaneously or independently controlled by single-phase APFs, and we could verified that the proposed approach was easy to explain the instantaneous compensation power flow. With respect to power quality such as the THD and P.F, in case that the distorted and fundamental reactive power are compensated, unity power factor was achieved, and in case that only the distorted power is compensated, THD was reduced to 2%.

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