A REFERENCE DETECTION ALGORITHM FOR SERIES ACTIVE POWER FILTERS, AIMED AT CURRENT HARMONICS AND REACTIVE POWER COMPENSATION

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Abstract. This paper proposes a control algorithm to compensate current harmonics and reactive power simultaneously in series active power filters combined with passive shunt filters. Imposing load current to have the same level of distortion as the source voltage for harmonics compensation and to its phase for reactive power compensation is performed. Approximately unity power factor can be attained without using PLL block. Reference voltage for PWM converter is calculated by estimated load current in three-phase system on the contrary to other control methods of series APFs in which two-axes estimation have been performed. This method is less time consuming and can donate reactive power compensation. Simulation results are presented in two different algorithms: harmonics compensation only and simultaneous harmonics and reactive power compensation.

I. Introduction

In recent years, along with growing and developing powerelectronics devices utilization in distribution systems, such as rectifiers, thyristor converters and arc furnaces, harmonics generation is an inevitable effect[1], [2].

Passive filters can improve performance of distribution systems. But problems like possibility of occurring series resonance with source impedance or parallel resonance between source impedance and passive filter, which is named as harmonics amplifying phenomenon, led researchers to active filters [3]. In the inception of utilizing APF (active power filters), shunt APF was the only type. Shunt active filter is a controlled active current source that injects a compensation current to the load to retain source current sinusoidal. Along with the improvement of the powerelectronics devices, PWM inverters have been found as the best choice instead of using amplifier to inject compensation current [4]. Because of high cost of shunt APFs and less merit in large scale cases, series APFs have been considered. To make series filters serviceable in large scale systems using a passive shunt filter as an accessory is fulfilled. In fact active filters participate in the compensation action to recover defects of passive shunt filter. Series active filters are harmonics isolators. They retain harmonics current in the load side and avoid contaminated current appearing in the source side [1], [2], [5]. In addition, voltage of point of common coupling is more regulated in series filters.

In most performed control algorithms for series APFs the reference voltage, which has to be injected, is calculated by transformed load current into two-axes representation. Reference current is calculated by real and imaginary powers in two-axes system and then retransformed into three phase system [6]. To achieve orthogonal two-axes currents, mean values of the source current have to be calculated and applied to orthogonal synchronous frame transformation matrix. Attained currents have to be retransformed into three phase system. The reference current is converted to reference voltage by an impedance gain. Another reference voltage is calculated due to vanishing source currents harmonics. These two references have to be superposed. Because of numerous multiplication and division operations that have to be performed for control strategy, this method semblances as a time consuming one.

For reactive power compensation and achieving unit power factor a PLL blocked is utilized in most schemes. Source current phase can be regulated by injecting voltage to remain in the phase of PCC voltage without using PLL block.

Kumar Jain presents a new control algorithm for shunt APF to compensate current harmonics and reactive power in nonlinear loads, without using two-axes system [7]. In this method, injected current is calculated based on constraining load current to include the same order of distortion as PCC voltage for harmonics compensation and have the same phase as PCC voltage for reactive power compensation. This theory can be utilized to estimate the reference injected voltage.

This paper proposes a method to calculate reference voltage of series active filter. The reference voltage is estimated by the principle of constraining load current to include distortion ratio of PCC voltage. The injected voltage is set in a scheme that drives passive filter to interpolate the difference between reference current and load current. Therefore, all calculations will be performed in three phase system. The verity of this scheme is tested in a simulated system.

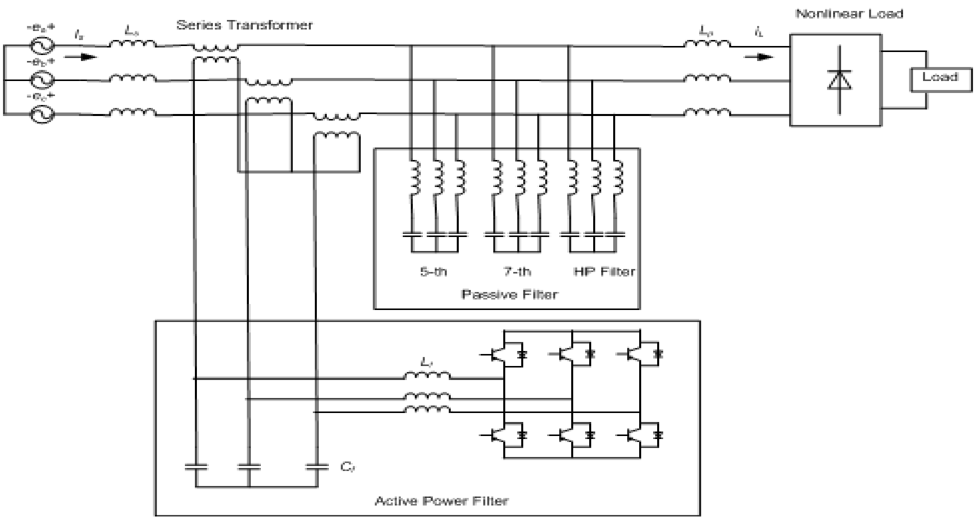
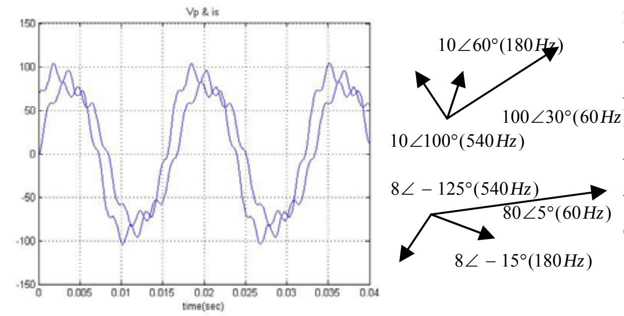
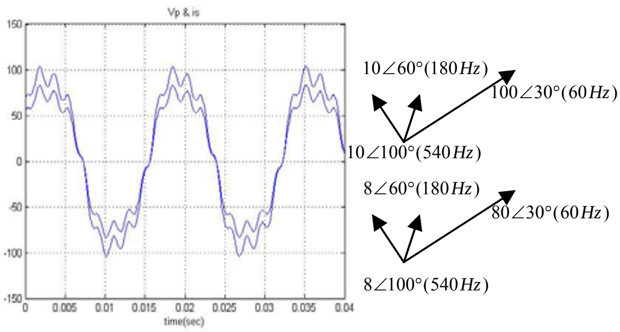


Fig. 1. Series active power filter with shunt passive filter



(a)



(b)

Fig. 2. Voltage and current distorted: (a) to the same extent; (b) to the same extent and same phase

II. System of the Series active Filter and Shunt Passive Filter

Series active power filter combined with passive shunt filter utilized in the system which includes nonlinear load, is shown in Fig. 1. Passive shunt filter comprises three paralleled filters: two of them are tuned for 5^{th} and 7^{th} harmonics, and one filter has to be tuned for high frequencies. Compensation voltage is generated by a PWM inverter and injected through series transformers. Nonlinear load is a three phase diode rectifier that is connected to an inductive load. Excess to series transformers main duty, that is induction of the compensation voltage, they are utilized to isolate the PWM inverter from the main system and to match voltage and current rating between the power system and the inverter.

The voltage of the passive filter can be controlled by controlling the injected compensation voltage of the series active filter. Therefore the passive filter current is also under control.

III. Principle Theory

A. Concept

As mentioned above, to isolate the load side and source side from the harmonics contamination point of view, it is possible to constrain load current to comprise the same harmonics distortion as PCC voltage. In fact the customer has to draw such current from the source. The prominent role of series active filter is supporting a voltage to drive passive filter to inject the difference between load current and desired reference current.

For this purpose, the amplitude and phase of each harmonics component of the PCC voltage have to be calculated. To isolate harmonics components, the ratio between fundamental frequency amplitude of PCC voltage and the fundamental frequency amplitude of reference current has to be retained for the other harmonics components. If reactive power compensation is coveted, the phase of each reference current harmonics component has to be equal to the relative harmonics component phase of PCC voltage. But if the reactive power compensation is not required, the difference phase between each reference current harmonics component and PCC voltage harmonics component has to posses the current and voltage phase difference in fundamental frequency multiplied by the order of relative harmonics.

Fig. 1(a) shows the voltage (V_p) and the reference current (i_s) that is distorted to the similar level but not in the similar phase. Fig. 2 (b) shows the voltage (V_p) and the current (i_s) that is distorted to the similar level and in the same phase. In Fig. 1.(a) current harmonics compensation is taking into consideration only, but in the Fig. 1.(b), in addition to that concept, reactive power compensation is also contemplated.

As it is clear in Fig. 2 when harmonics compensation is the only purpose, the phase difference between voltage and current in each harmonics component is equal to the phase difference in fundamental frequency multiplied by the order of relative frequency.

B. Formulation

Harmonics components of the PCC voltage and load current can be attained by various methods. Fourier series, Fourier transform and Walsh function can be utilized. In this scheme Fourier transform is admitted. When amplitude and phase angle of each harmonics component is achieved, time domain signal can be represented by sum of sinusoidal expressions.

$$v_p(t) = \sum_{n=1}^{k} V_n \sin(n\omega t + \theta_n) \quad (1)$$

$$i_L(t) = \sum_{n=1}^{k} I_n \sin(n\omega t + \phi_n) \quad (2)$$

where $v_p(t)$ and $i_L(t)$ are PCC voltage and load current respectively, V_n and I_n are the amplitude of nth harmonics components of voltage and current, θ_n and ϕ_n are the phase angle of nth harmonics components of voltage and current.

Reference current can be calculated by the mentioned concept. Therefore reference current has to be calculated through load voltage. The reference current will have the same shape as PCC voltage but the magnitude will be the portion of the voltage. In practical cases, loss component is added to fundamental component of load current. It concludes that, for harmonics compensation, fundamental amplitude of reference current is the amplitude of fundamental component of load current plus loss current, and for both harmonics compensation and reactive power compensation, reference fundamental amplitude is equal to real part of fundamental component of load current plus loss current. Applying real part of load current will cause reactive power compensation. The mentioned subtleties about phase angles are authenticate. Therefore the reference current can be obtained by equations (3) and (4) in two cases.

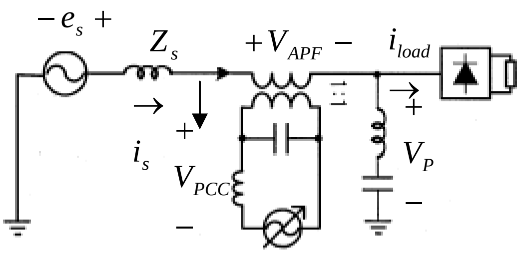


Fig. 3. Equivalent circuit of the power system, the hybrid series active filter and the nonlinear load

Harmonics compensation:

$$i_s^*(t) = \sum_{n=1}^{k} \left(\frac{I_1}{V_1}\right) V_n \sin\left(n\omega t + \theta_n + n(\phi_1 - \theta_1)\right), \quad (3)$$

$$I_1 = I_1 + I_{loss} \quad , for\ n = 1.$$

Simultaneous harmonics and reactive power compensation:

$$i_s^*(t) = \sum_{n=1}^{k} \left(\frac{I_1}{V_1}\right) V_n \sin\left(n\omega t + \theta_n\right) \quad , \quad (4)$$

$$I_1 = I_1 \cos\phi_1 + I_{loss} \quad , for\ n = 1.$$

where $i_s^*(t)$ is the estimated reference current. V_n, I_n, θ_n and ϕ_n are obtained from equations (3) and (4). The APF voltage has to be set in a way that causes passive shunt filter to inject the difference between load current and reference current.

IV. Applying Series APF

Fig. 3 shows the equivalent circuit of the hybrid active power filter (series APF combined with shunt passive filter) and power system. Reference voltage of the series APF can be calculated by measuring PCC voltage and load current, based on the denoted theory. All harmonics components of voltage are heeded but fundamental component of load current is required only.

Reference voltage of APF has to be set to fluctuate source current. This fluctuation is done by means of passive shunt filter flowing current. The voltage of passive shunt filter can be expressed as follow.

$$V_P = e_s + Z_s i_s - V_{APF} \quad (5)$$

where V_p, e_s and V_{APF} are PCC voltage, source voltage and series APF voltage respectively; Z_s is the source impedance and i_s is source current.

Passive shunt filter has to flow a difference between reference and load current.

$$\frac{V_P}{Z_f} = i_f = i_s^* - i_{load} \quad (6)$$

where Z_f is the shunt passive filter impedance, and i_f, i_{load} are shunt filter and load currents, respectively.

Therefore the reference voltage of series APF can be calculated as follow.

$$V_{APF}{}^{*} = e_s + Z_s i_s - Z_f \left(i_s^* - i_{load}\right) \qquad (7)$$

Despite generation of even harmonics components by nonlinear load is possible, these components have no large enough amplitudes to effort drastic effect in current contamination level. Therefore even harmonics components are neglected in this work. If a delta-Y transformer is applied after source, three multiple harmonics components will be eliminated, but if there is no this kind of transformer, the above mentioned harmonics components have to be taken into account. In this paper, 13 is the last harmonics component that is utilized to estimate reference current.

A. Current Harmonics Compensation

If current harmonics compensation is the only purpose, equation (3) has to be applied in equation (7). By this scheme, source current (i_s) has the same distortion level as PCC voltage (V_P). Since every harmonics component phase angle of reference current is set to "n" times of fundamental phase difference between voltage and current ("n" is the harmonics order.), e.g. 5th harmonics component phase angle of reference current is equal to five times voltage-current phase angle, the source current keeps the PCC voltage shape but not in the similar phase. Therefore reactive power will not be compensated.

Every harmonics component of active filter voltage can be obtained by incorporating equations (3) and (7) in phasor domain as follow.

$$\overline{V}_{APF,n}{}^{*} = E_{s,n} + \overline{Z}_{s,n} I_{s,n}^* - \overline{Z}_f \left(I_{s,n}^* - I_n\right),$$
$$I_{s,n}^* = \left[\left(\frac{I_1}{V_1}\right) V_n\right] \angle\left(n\omega t + \theta_n + n(\phi_1 - \theta_1)\right) \qquad (8)$$

where subscript "n" is the harmonics order, and I_1 is the fundamental component amplitude plus loss current.

If the main voltage is presumed pure and not distorted, $E_{s,n}$ will be fundamental main voltage for first harmonics and vanished for others.

In practical cases, because of distorted supplies, such presumptions are not appropriate. Therefore to bolster the precision, main voltage at the point after source impedance is measured and harmonics components are extracted. Measurement of main voltage not only yields more accurate $E_{s,n}$, but also causes to rid of using source impedance that is alleged during various application points. Therefore if the supply voltage is measured, equation (8) will be represented as equation (9).

$$\overline{V}_{APF,n}{}^{*} = E_{s,n}{}^{m} - \overline{Z}_f \left(I_{s,n}^* - I_n\right),$$
$$I_{s,n}^* = \left[\left(\frac{I_1}{V_1}\right) V_n\right] \angle\left(n\omega t + \theta_n + n(\phi_1 - \theta_1)\right) \qquad (9)$$

where $E_{s,n}{}^{m}$ is the nth component of the measured supply voltage.

B. Simultaneous Current Harmonics and Reactive Power Compensation

If reactive power compensation is contemplated in addition to current harmonics components, equation (4) has to be applied in equation (7). Utilizing this method leads source current (i_s) to follow the distortion ratio of PCC voltage (V_P) and remain in the same phase as this voltage. This is because of setting each harmonics component phase angle of reference current equal to the PCC voltage phase angle in the same harmonics. e.g. 5th harmonics component phase angle of reference current is equal to θ_5. Therefore the source current keeps the PCC voltage shape and phase.

Incorporating equations (4) and (7) in phasor domain, yeilds every harmonics component of active filter voltage as follow.

$$\overline{V}_{APF,n}{}^{*} = E_{s,n} + \overline{Z}_{s,n} I_{s,n}^* - \overline{Z}_f \left(I_{s,n}^* - I_n\right),$$
$$I_{s,n}^* = \left[\left(\frac{I_1}{V_1}\right) V_n\right] \angle\left(n\omega t + \theta_n\right) \qquad (10)$$

A predominant point is that I_1 is the active part of load current fundamental component plus loss current.

Denoted subtleties about presuming main voltage, pure or not, are credible. It means measuring source voltage and extracting its harmonics components make the source impedance to vanish in (10).

V. Simulation Results

The system of Fig.1 is simulated. The system parameters is shown in table I. Six pulse diode rectifier connected to resistive-inductive load is utilized as nonlinear load. Load P.F. is 16% before any compensation. Total Harmonics Distortion (THD) of source current is 27%.

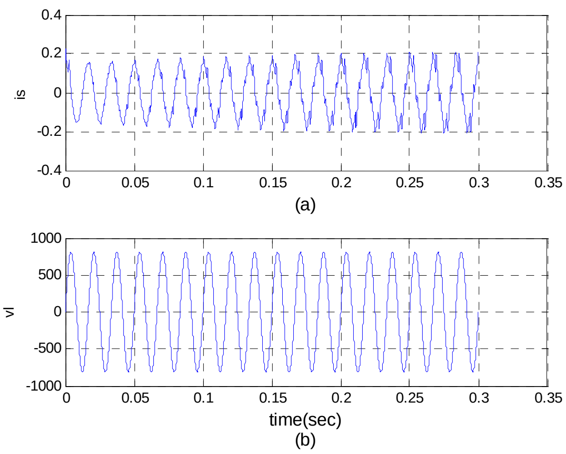


Fig. 4. Voltage and current before compensation: (a) Source current; (b) Source voltage.

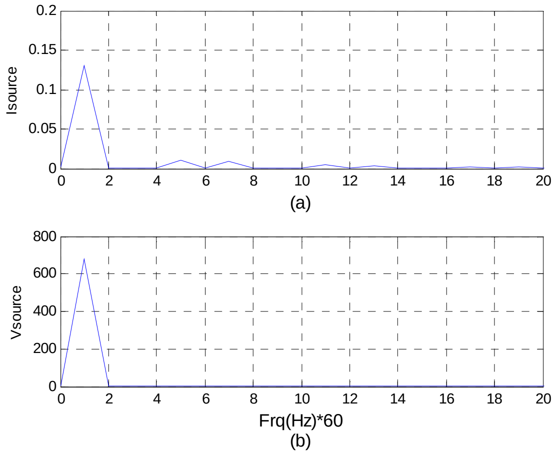


Fig. 5. Harmonic spectrum before compensation: (a) Source current; (b) Source voltage.

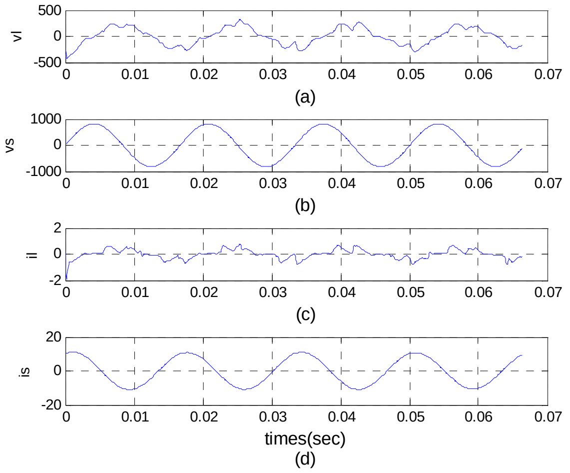


Fig. 6. Harmonics compensation scheme outputs: (a) Load voltage; (b) Source voltage; (c) Load current; (d) Source current.

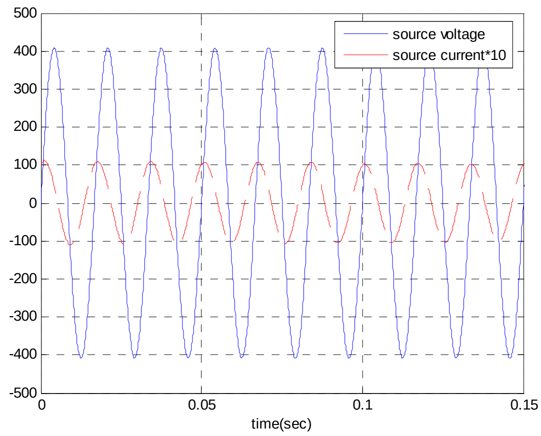


Fig. 7. Source voltage and current after harmonics compensation.

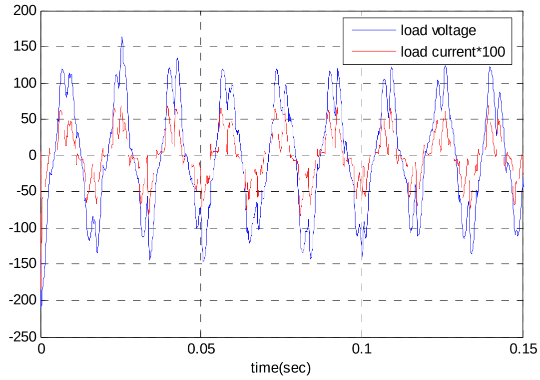


Fig. 8. Load voltage and current after compensation.

Table 1: System parameters

Main voltage	1000[V_ phase to phase]
Fundamental frequency	60[Hz]
5th passive filter	L=6.9640[H], C=1[uF]
7th passive filter	L=3.5531[H], C=1[uF]
Inverter output filter	L=1.4[mH], C=10[uF]
Load	R=1[kOhm], L=100[H]
Sampling frequency	10[kHz]
Series transformer	1[kVA], 240/240[V]

Fig. 4 displays the source voltage and source current before compensation.

Sampling frequency is prominent when high order harmonics extraction is desired. To avoid aliasing error, sampling frequency has to be more than twice that of the last harmonics component frequency. Since 13^{th} harmonics is the last considered harmonics in this paper, sampling frequency has to be more than 1560 Hz. To achieve more precision, sampling frequency is set to 10 kHz.

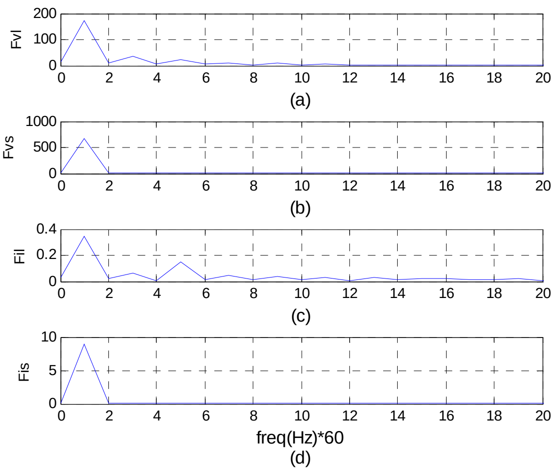


Fig. 9. Harmonic spectrum after current harmonics compensation: (a) Load voltage; (b) Source voltage; (c) Load current; (d) Source current.

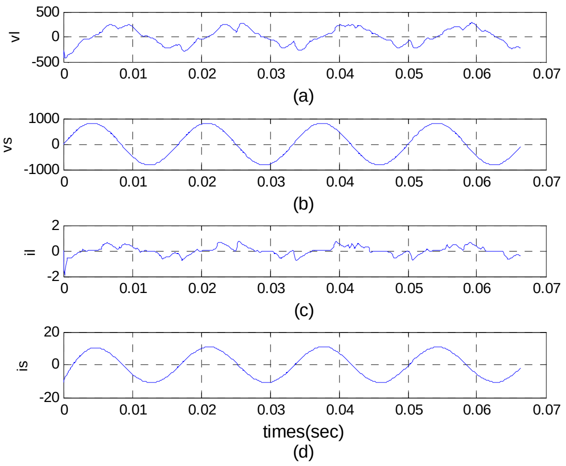


Fig. 10. Simultaneous harmonics and reactive power compensation scheme outputs: (a) Load voltage; (b) Source voltage; (c) Load current; (d) Source current.

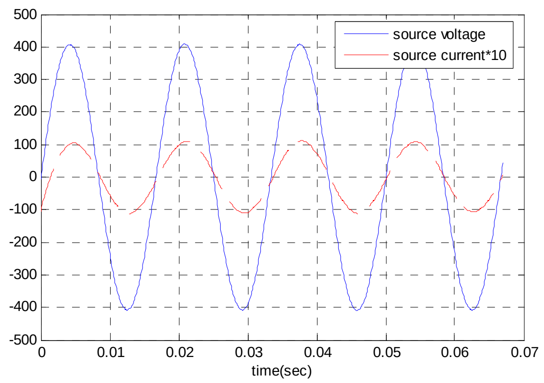


Fig. 11. Source voltage and current after simultaneous current harmonics and reactive power compensation.

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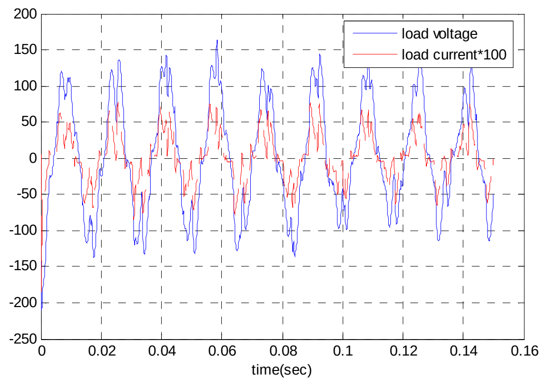

Fig. 12. Load voltage and current after simultaneous current harmonics and reactive power compensation.

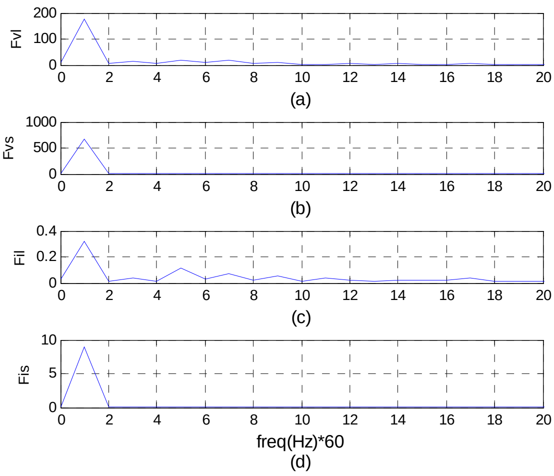

Fig. 13. Harmonic spectrum after simultaneous current harmonics and reactive power compensation: (a) Load voltage; (b) Source voltage; (c) Load current; (d) Source current.

Harmonic spectrum of source current and voltage is shown in Fig. 5. Source voltage is approximately pure but source current is very contaminated. The paramount point is remedy of source current without large declining in voltage quality.

Fig. 6 shows the outputs when harmonics compensation is the only purpose. Fig. 6 (a) shows the load voltage. If the impedance between passive shunt filter and the load is neglected, load voltage can be known as passive filter voltage. Fig. 6 (b) shows the PCC voltage. PCC voltage is the voltage that the supply considers it as source voltage. Fig. 6 (d) shows the source current that is compensated. As it is clear the harmonics are isolated in the load side and the source is low harmonics effect recipient. THD of the source current after compensation is improved to 1.58%.

Fig. 7 shows the source voltage and source current obtained by harmonics compensation only. Phase difference of voltage and current obey the mentioned rule (phase difference of nth harmonics component is “n” times phase difference of fundamental frequency.).

Fig. 8 shows the load voltage and current when harmonics compensation is performed. Total shapes of these curves are the similar. Since APF injects a voltage to compel passive filter to flow the difference between reference current and load current, the source current will have the shape of source voltage and the load current will have the shape of load voltage

Fig. 9 shows the harmonic spectrums after current harmonics compensation. The spectrum of the source voltage and source current are merit and they have low harmonics contamination. THD of the source voltage is 0.74% and source current THD decays to 1.58%. THD of load voltage and current is 32.22%.

Fig. 10 shows the outputs when simultaneous harmonics and reactive power compensation is performed. Fig. 10 (b) shows the PCC voltage that is considered as source voltage by the supply. Fig. 10 (d) is the compensated source current. Source current has to be sinusoidal and has to possess the phase angle of source voltage for reactive power compensation.

Fig. 11 shows the source voltage and current. Source current not only follows the source voltage in shape but also synchronizes its phase with source voltage.

Fig. 12 displays load voltage and current. They have similar shapes of distortion.

Harmonic spectrum after simultaneous current harmonics and reactive power compensation is depicted in Fig. 13. Source current includes 1.19% of THD and source voltage possesses 0.73%. Load voltage and current are contaminated 22.91%. It can be seen that contemplating reactive power compensation, excess to current harmonics compensation yields better harmonics compensation than that of using harmonics compensation only.

VI. Conclusion

A new reference voltage estimation method for hybrid series active power filters and shunt passive filters is proposed in this paper. Two-axis transformation is not used in the new scheme and reference voltage estimation is fulfilled in 3-phase system. This method is less time consuming because of avoiding 3-phase to two-axis and counter transformations. The passive shunt filter is driven by series active filter to absorb harmonics. The new scheme is able to compensate current harmonics and it has the knack of simultaneous current harmonics and reactive power compensation too. The obtained THD by this pattern is preferable than the last proposed methods. Approximately unity power factor can also be achieved by reactive power compensation.

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AKTİV GÜCÜN ARDICIL SÜZGƏCLƏRİNDƏ CƏRƏYAN HARMONİKALARININ VƏ REAKTİV GÜCÜN KOMPENSASİYASI ALQORİTMİ

KAZƏMİ A., DƏVƏRİ S.A.

Məqalədə passiv şunt süzgəclərnən birləşmiş aktiv güc ardıcıl süzgəclərində eyni zamanda cərəyan harmonikalarının və reaktiv gücün kompensasiyası alqoritmi verilmişdir.

АЛГОРИТМ КОМПЕНСАЦИИ ГАРМОНИК ТОКА И РЕАКТИВНОЙ МОЩНОСТИ В ПОСЛЕДОВАТЕЛЬНЫХ ФИЛЬТРАХ АКТИВНОЙ МОЩНОСТИ

КАЗЕМИ А., ДАВАРИ С.А.

В статье представлен управляющий алгоритм для компенсации одновременно гармоник тока и реактивной мощности в последовательных фильтрах активной мощности, объединенных с пассивными шунтирующими фильтрами.