ANALYSING TWO CONTROL METHODS OF SHUNT ACTIVE FILTERS FOR UNBALANCED LOAD

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Abstract

A three-phase shunt active filter is used for current and/or voltage unbalance compensation. Two control schemes with two different theory, instantaneous power theory and Generalized Fryze are considered to compensate the unbalance of current, voltage, or both that are due to the unbalanced load. The compensation results of the different control schemes in unbalance case are simulated and results are shown here. Different compensation objectives can be achieved, i.e., balanced and unity power factor source current, balanced and regulated voltage, or both, by choosing appropriate control schemes by using Instantaneous Power theory. In the case of Generalized Fryze it is seen that the current compensated by means of the generalized Fryze currents method makes the compensated line current proportional to the corresponding phase voltage, that is, they have the same waveform and behave like a "pure resistive" load.

Key Words - Shunt activefilter, Instantaneous power theory, Generalized Fryze Theory, Unbalanced load.

1. Introduction

Unbalanced three-phase systems are quite common in power systems. It is well known, in agreement with the symmetrical component theory that positive and negative sequences result from unbalanced steady-state operation of a three-phase system. To compensate for unbalancing, some authors have proposed specific compensation techniques [1-5]. Among various power conditioner topologies, the shunt Active Power Filter (APF) is considered as an effective solution for low to medium power applications to reduce the current harmonics to acceptable limits, featuring capabilities of compensating load unbalance and reactive currents as well (Fig. 1).

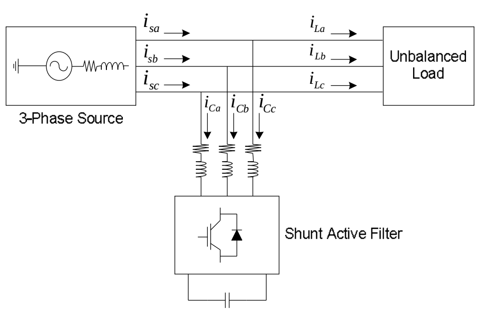


Fig. 1 General configuration of shunt active power filter

2. Unbalancing

For a three-phase, balanced, positive-sequence voltage, the presence of the negative-sequence components may be a serious problem. This section will analyse the case in which the voltages are sinusoidal waveforms with a frequency of ω, consisting of positive- and negative-sequence components as given below:

$$\begin{aligned} v_a &= \sqrt{2}V_+\cos(\omega t+\varphi_{v+}) + \sqrt{2}V_-\cos(\omega t + \varphi_{v-}) \\ v_b &= \sqrt{2}V_+\cos(\omega t-2\pi/3+\varphi_{v+}) + \sqrt{2}V_-\cos(\omega t+2\pi/3+\varphi_{v-}) \\ v_c &= \sqrt{2}V_+\cos(\omega t+2\pi/3+\varphi_{v+}) + \sqrt{2}V_-\cos(\omega t-2\pi/3+\varphi_{v-}) \end{aligned} \quad (1)$$

and the current consist of

$$\begin{aligned} i_a &= \sqrt{2}I_+\cos(\omega t+\varphi_{i+}) + \sqrt{2}I_-\cos(\omega t+\varphi_{i-}) \\ i_b &= \sqrt{2}I_+\cos(\omega t-2\pi/3+\varphi_{i+}) + \sqrt{2}I_-\cos(\omega t + 2\pi/3+\varphi_{i-}) \\ i_c &= \sqrt{2}I_+\cos(\omega t+2\pi/3+\varphi_{i+}) + \sqrt{2}I_-\cos(\omega t - 2\pi/3+\varphi_{i-}) \end{aligned} \quad (2)$$

Applying the Clarke transformation yields the following voltages and currents:

$$\begin{aligned} v_\alpha &= \sqrt{3}V_+\cos(\omega t+\varphi_{v+}) + \sqrt{3}V_-\cos(\omega t+\varphi_{v-}) \\ v_\beta &= \sqrt{3}V_+\sin(\omega t+\varphi_{v+}) - \sqrt{3}V_-\sin(\omega t+\varphi_{v-}) \end{aligned} \quad (3)$$

And

$$\begin{aligned} i_\alpha &= \sqrt{3}I_+\cos(\omega t+\varphi_{i+}) + \sqrt{3}I_-\cos(\omega t+\varphi_{i-}) \\ i_\beta &= \sqrt{3}I_+\sin(\omega t+\varphi_{i+}) - \sqrt{3}I_-\sin(\omega t+\varphi_{i-}) \end{aligned} \quad (4)$$

The powers given below are separated in their average and oscillating components:

$$
\begin{aligned}
\bar{p} &= 3V_+ I_+ \cos(\varphi_{v+} - \varphi_{i+}) + 3V_- I_- \cos(\varphi_{v-} - \varphi_{i-}) \\
\bar{q} &= 3V_+ I_+ \sin(\varphi_{v+} - \varphi_{i+}) - 3V_- I_- \sin(\varphi_{v-} - \varphi_{i-}) \\
\tilde{p} &= 3V_+ I_- \cos(2\omega t + \varphi_{v+} + \varphi_{i-}) + 3V_- I_+ \cos(2\omega t + \varphi_{v-} + \varphi_{i+}) \\
\tilde{q} &= 3V_+ I_- \sin(2\omega t + \varphi_{v+} + \varphi_{i-}) - 3V_- I_+ \sin(2\omega t + \varphi_{v-} + \varphi_{i+})
\end{aligned} \tag{5}
$$

The following conclusions can be written from the above equations for the real and imaginary powers [1]:

- The positive- and negative-sequence components in voltages and currents may contribute to the average real and imaginary powers.
- The instantaneous real and imaginary powers contain oscillating components due to the cross product of the positive-sequence voltage and the negative-sequence current, and the negative-sequence voltage and the positive-sequence current. Hence, even circuits without harmonic components may have oscillating real or imaginary powers.

The relation between the conventional concepts of powers and the new powers defined in the p-q Theory is better visualized if the powers p and q are separated in their average values $\bar{p}, \bar{q}$ and their oscillating parts $\tilde{p}, \tilde{q}$.

$$
\begin{aligned}
&\text{Real power:} && p = \bar{p} + \tilde{p} \\
&\text{Imaginary power:} && q = \bar{q} + \tilde{q}
\end{aligned} \tag{6}
$$

These generic power expressions elucidate the relations between the conventional and the instantaneous concepts of active and reactive power. For instance, it is possible to see that the well-known three-phase fundamental active power ($P = 3VI\cos\varphi$) is one term of the average real power $\bar{p}$, whereas the three-phase reactive power ($Q = 3VI\sin\varphi$) is included in the average imaginary power $\bar{q}$. All harmonics in voltage and current can contribute to the average powers $\bar{p}$ and $\bar{q}$ if they have the same frequency and have the same sequence component (positive or negative), as shown in (5). The presence of more than one harmonic frequency and/or sequence components also produce $\tilde{p}$and $\tilde{q}$, according to (5).

3. Compensation by Instantaneous Power Theory

The sinusoidal source current control strategy is a compensation method that makes the active filter compensate the current of a nonlinear load to force the compensated source current to become sinusoidal and balanced. In order to make the compensated current become sinusoidal and balanced, the shunt active filter should compensate all harmonic components as well as the fundamental components that differ from the fundamental positive-sequence current I_{+1}. Only this component is left to be supplied by the source. In order to determine the fundamental positive-sequence component of the load current, a positive-sequence detector is needed in the active filter controller. The control block diagram for the sinusoidal current control strategy is shown in Fig. 2. The positive-sequence detector block extract "instantaneously" the fundamental positive-sequence voltages v'_a, v'_b and v'_c that correspond to the phasor V_{+1} of the system voltage v_a, v_b and v_c. Therfore, the rest of active filter controller shown in Fig. 2 determines the compensating current references if the system voltage contains only a fundamental positive-sequence component.

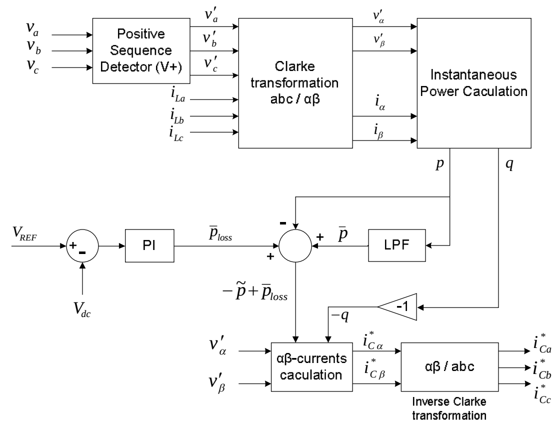


Fig. 2 Basic references generator scheme for Instantaneous Power method control of APF.

The real and imaginary powers calculated in Fig. 2 do not match the actual powers of the load, because the unbalance at the fundamental frequency (fundamental negative-sequence) and harmonics, which eventually may be present in the system voltage, are not being considered. However, the calculated real and imaginary powers are still useful for determining all unbalances and harmonics present in the load current. The equations of powers in terms of symetrical components given with (5), are helpful for understanding this point. First, note that the instantaneous phase voltages v'_a, v'_b and v'_c that correspond to the phasor V_{+1} of the fundamental positive-sequence voltage are transfomred into the αβ coordinates by means of the Clark transformation block. Then, they are used in both the instantaneous powers calculation block and in the αβ currents calculation block. Together with the power being compensated, that is, $-\tilde{p}$and $-q$, the αβ currents calculation block determines exactly all current components in the load current that produce $-\tilde{p}$ and $q = \bar{q} + \tilde{q}$ with V_{+1}. In terms of symmetrical components, since only V_{+1} is being considered, onlyI_{+1} produces $\bar{p}$ and $\bar{q}$ (equations 5). Therefore, if the shunt active filter compensates the power portions $\tilde{p}$ and $\tilde{q}$of the calculated powers $p$and q, certainly it is compensating all components in the load current that are different from I_{+1} of the load. Note that this includes also the fundamental negative-sequence component I_{-1}.

The positive-sequence detector that will be describe, can determine instantaneously and accurately the amplitude, the frequency, as well as the phase angle of voltage component V_{+1} . The amplitude and phase angle of V_{+1} may be necessary in other controllers, although they are not important in the control algorithm implemented in Fig. 2. In order to extract the fundamental negative-sequence current and all current harmonics from the load current, it is necessary only that v'_a, v'_b and v'_c have the same frequency as the actual system voltage. The amplitude could be arbitrarily chosen but must be equal in all three phases. The phase angle could also be arbitrarily chosen, but the displacement angles between phases must be mainted equal to $2\pi/3$. However, in order to properly compensate the portion of the fundamental positive-sequence current that is orthogonal to the fundamental positive-sequence voltage, the phase angle and the frequency of the fundamental positive-sequence voltage V_{+1} must be accurately determined. Otherwise, the active filter controller cannot exactly determine the fundamental reactive power of the load ($\bar{q}$) that, in turn, cannot produce ac currents (I_{+1}) orthogonal to the ac voltages (V_{+1}) to produce only $\bar{q}$. Fortunately, the positive-sequence voltage detector used in Fig. 3, can determine accurately the voltage component V_{+1}.

The compensating powers $\tilde{p}$ and $\tilde{q}$ in the active filter controller includes all fundamental negative-sequence power, the fundamental reactive power, as well as the harmonic power. In other words, the active filter controller handles the load as "connected to a sinusoidal balanced voltage source". Thus, if $\tilde{p}$, $\bar{q}$, and $\tilde{q}$ are compensated by the shunt active filter, the source currents must be sinusoidal and contain only the active portion of the fundamental positive-sequence current that is in phase with V_{+1}. An important part of the positive-sequence detector is the phase-locked-loop (PLL) ciruit. Fig. 3 shows the complete functional block diagram of the fundamental positive-sequence voltage detector.

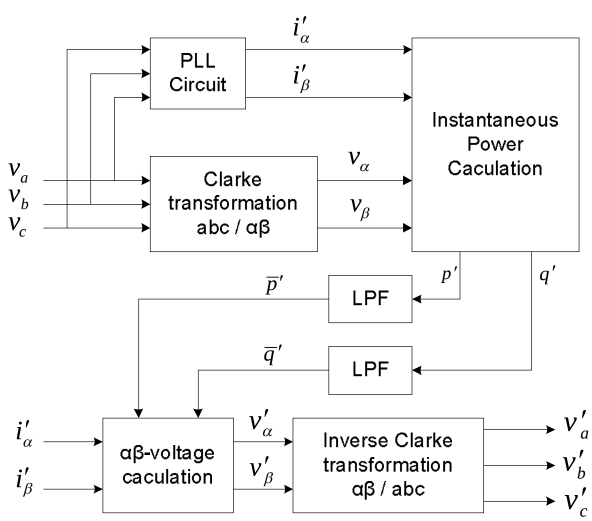


Fig3.Fundamental positive sequence voltage detector.

4. Generalized Fryze currents minimization method

Despite of the usefulness and flexibility of the p-q theory to design controller for active power line conditioners, other approaches may be found also suitable, depending on the objectives to be accomplished. For instance, the decomposition of the load current into active and non-active current portions through the current minimization methods can be used to design controllers for shunt active filters. The notions of the active and reactive currents have meanings that were established in electrical engineering long ago. The active current, defined by Fryze in 1932, is the smallest load current that is necessary [5] if the load at the supply voltage has the active power, P, and has the same waveform as the supply voltage. This current was defined as

$$i_w(t) = \frac{P}{V^2} v(t) = G_e v(t) \qquad (7)$$

Where V is the supply voltage RMS value. For three-phase, three-wire systems, shown in Fig. 1, Fryze's definition of the active current is generalized to the form [6]:

$$i_w(t) = \begin{bmatrix} i_{aw} \\ i_{bw} \\ i_{cw} \end{bmatrix} = \frac{P}{\|v\|^2} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = G_e v(t) \qquad (8)$$

where $\|v\|$ denotes the three-phase RMS value of the supply voltage, namely

$$\|v\| = \sqrt{V_a^2 + V_b^2 + V_c^2} \qquad (9)$$

The reactive current is the component of the supply current delayed by $\pi/2$ with respect to the supply voltage and is defined in single-phase systems with sinusoidal voltage and current as

$$i_q(t) = \frac{-Q}{V^2} \frac{d}{d(\omega t)} v(t) = B_e \frac{d}{d(\omega t)} v(t) \qquad (10)$$

For three-phase, three-wire systems this definition is generalized to [6]:

$$i_q(t) = \frac{-Q}{\|v\|^2} \frac{d}{d(\omega t)} v(t) = B_e \frac{d}{d(\omega t)} v(t) \qquad (11)$$

Both the active and reactive currents have an explicit physical meaning. They are associated with the presence of the active and reactive powers, P and Q , and are related to the load equivalent conductance, G_e, and susceptance, B_e. The concept of the active current is also important for the design of compensators [6].

In this case, if the supply voltage is sinusoidal and balanced, the compensated source current will be also sinusoidal and balanced. It was seen that the current compensated by means of the generalized Fryze currents method presents a minimum rms value to draw the same three-phase average active power from the source as the original load current. This reduces ohmic losses in the transmission system. In terms of p-q theory, it is the same as to saying that the shunt active filter is compensating the whole imaginary power ($q = \bar{q} + \tilde{q}$) of the load. However, the minimization methods and the methods based on the p-q theory differ a lot in the presence of zero-sequence components. It should be

remarked that the main purpose of the following control strategy, implemented under the concepts of generalized Fryze currents, is to guarantee linearity between the supply voltage and the compensated current. The background for designing this method for shunt current compensation is detailed in [1]. Here, only simulation results are presented.
An advantage of the generalized Fryze current control is the reduced calculation effort, since it works directly with the abc-phase voltages and line currents. The elemination of the clarck transformation makes this control strategy simple. Fig. 4 shows the complete control circuit for a real implementation of this method.The instantaneous equivalent conductance G_e is calculated from (8). The average conductance $\bar{G}_e$ is obtained, passing G_e through a low-pass filter. The instantaneous active portions $i_w(t)$ of the load current are directly obtained by multiplying $\bar{G}_e$ by the phase voltages $v(t)$ as given in (8). The shunt active filter should draw the inverse of the nonactive current of the load, that is, $i_C^* = -i_q = (i_w - i_L)$. An extra active portion of current is added, in order to draw a small amount of active power to compensate for switching and conducting losses in the shunt active filter, which tend to discharge the dc capacitor. This is realized by the addition of the signal $\bar{G}_{loss}$ to the average conductance $\bar{G}_e$.

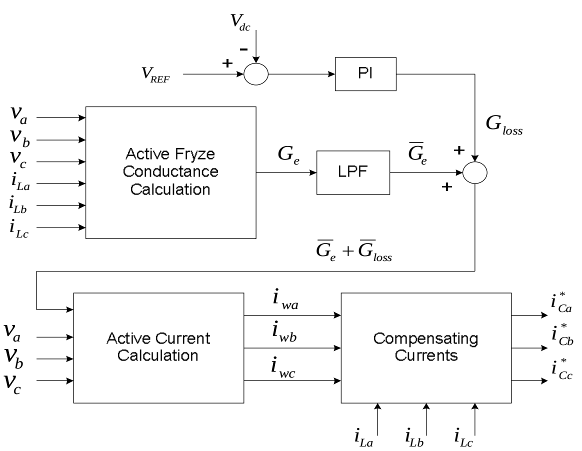


Fig.4 Generalized Fryze currents compensation control for APF.

This control strategy makes the compensated line current proportional to the corresponding phase voltage, that is, theyhave the same waveform and behave like a "pure resistive" load. Therefore, since the source voltages are considered balance and only load is unbalanced here, the compensated voltage and current source are balanced.

5. Simulation Results

A power system corresponding to Fig. 1 was simulated in MATLAB®. A balanced three-phase voltage source is connected to an unbalanced load (Fig. 5). Fig. 6 and 7 show the results for the first method that is instantaneous power theory and Fig. 8 and 9 show the results for second method. The shunt active filter is started at t=0.2s as can be seen in the figures. Fig. 7(a) and Fig. 9(a) show the actual current i_c drawn by the shunt active filter before and after compensation. The level of imbalance was exaggerated to make easier and clear the simulation results. In this case Point of Common Coupling (PCC) voltages were unbalanced before compensation (t=0.2s) due to unbalanced load currents and their effects on impedance on the source side. By compensating unbalanced load currents using APF, one can see PCC voltages will be balanced.

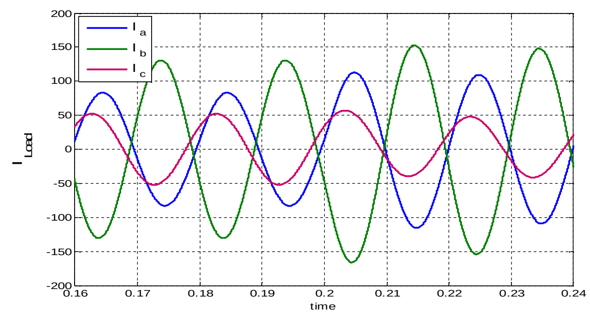
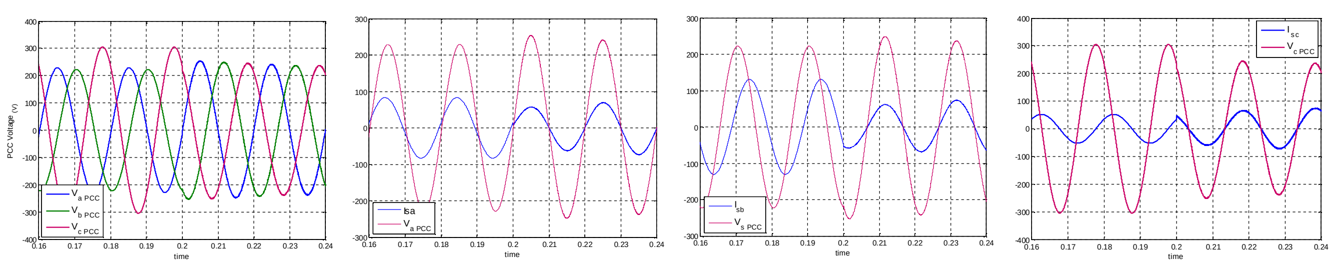
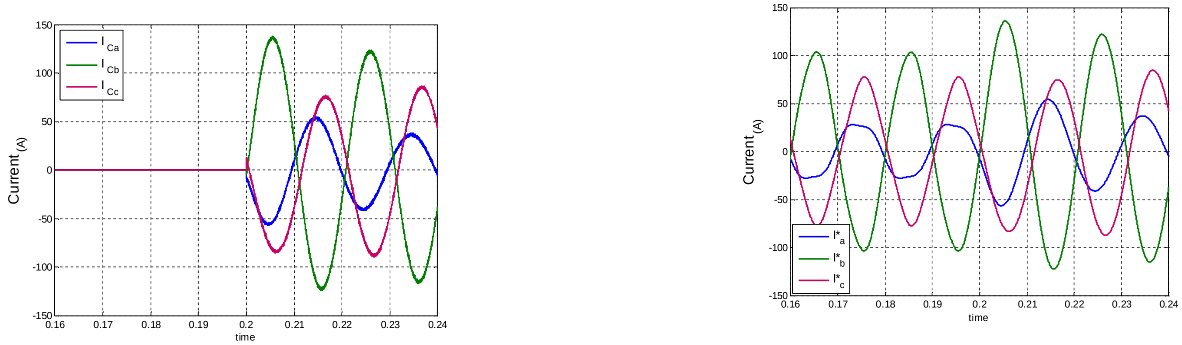


Fig .5 Unbalanced load currents.



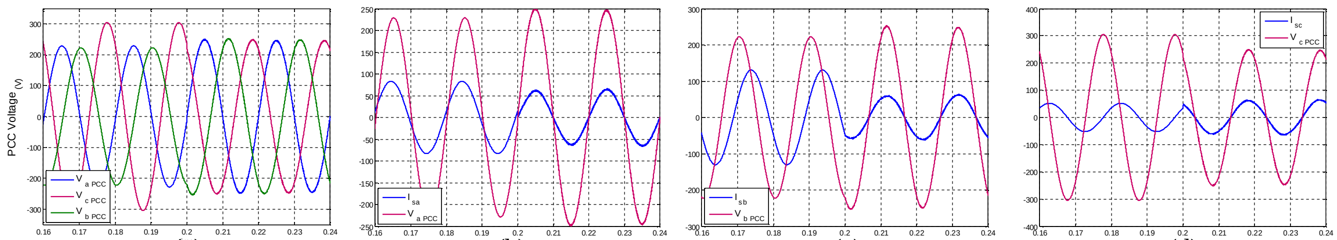
(a) (b) (c) (d)

Figure 6.Simulation results of voltageson PCC point and currents on source side. Compensation is started at t=0.2s by using Instantaneous Power theory. (a) Three-phase voltage on PCC point , (b) phase "*a*" Voltage and current, (c)phase "*b*" Voltage and current, and (d) phase "*c*" Voltage and current.



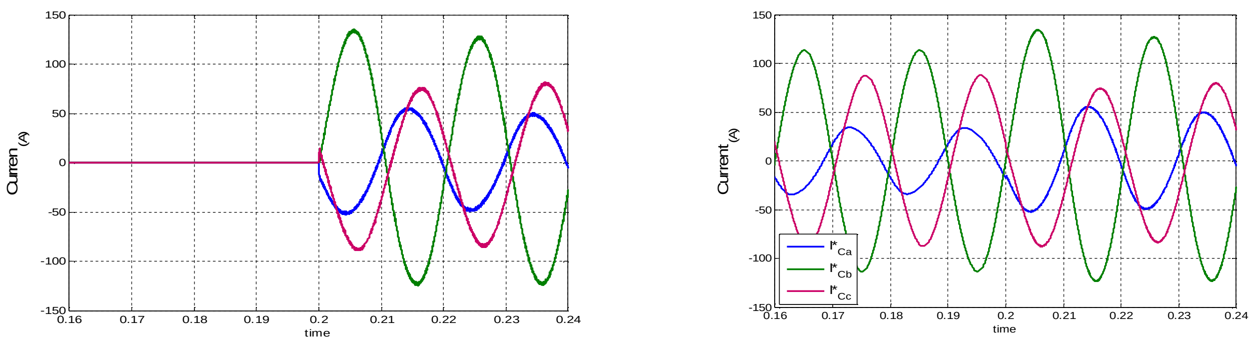
(a) (b)

Fig. 7Three-phase reference and real currents. (a) compensating currents that are the APF output currents and (b)references current by Instantaneous power theory.



(a) (b) (c) (d)

Fig. 8Simulation results of voltages on PCC point and Currents on source side. Compensation is started at t=0.2s by using Generalized Fryze theory. (a) Three-phase voltage on PCC point , (b) phase "a" Voltage and current, (c) phase "b" Voltage and current, and (d) phase "c" Voltage and current.



(a) (b)

Fig. 9Three-phase reference and real currents.(a) compensating currents that are the APF output currents and (b)references current by Generalized Fryze theory.

6. Conclusion

The first method, Instantaneous Power theory, is able to determine the fundamental positive sequence component of the load current under very high distortion conditions and does not care if the system voltage is balanced or not. The second method, Generalized Fryze theory, by using APF compensates the difference between the measured load current and the determined fundamental positive sequence current. Thus, it compensates also unbalances from negative sequence at the fundamental frequency. However this controller cannot compensate the unbalancing from source side. For solving this problem using PLL is necessary in this method but another problem will rise that is compensating reactive power compensation. Therefore this method presents a minimum rms value to draw the same three-phase average active power from the source as the original load current. This reduces ohmic losses in the transmission system. Both two theories are considered very powerful in different aspects of compensation that here is not possible to verify all these aspects.

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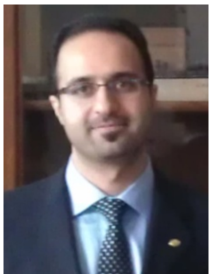
Biographies



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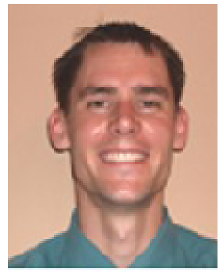

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