ACTIVE FILTER ENERGY STORAGE REQUIREMENTS FOR NON-PERIODIC CURRENT COMPENSATION

Leon M. Tolbert[1] tolbert@utk.edu
Yan Xu[1] yxu3@utk.edu
Jianqing Chen[1] jchen5@utk.edu
Fang Z. Peng[2] fzpeng@msu.edu
John N. Chiasson[1] chiasson@utk.edu

[1]Department of Electrical and Computer Engineering
The University of Tennessee
Knoxville, TN 37996-2100

[2]Department of Electrical and Computer Engineering
Michigan State University
East Lansing, MI 48824-1226

Abstract

This paper presents a discussion of the compensation of non-periodic currents such as those associated with arc furnaces. Based on the compensation objectives for different types of load waveforms, the energy storage requirements of the compensator are also presented. Further, basic concepts required in the definition of non-active current are presented and illustrated by simulations for a variety of different compensation characteristics of non-periodic currents.

Key Words

non-active power, reactive power, compensator, non-periodic current, arc furnace

1. Introduction

The widespread use of non-linear loads and power electronics converters has increased the generation of non-sinusoidal and non-periodic currents and voltages in power systems. Generally, power electronics converters generate harmonic components which have frequencies that are integer multiples of the line frequency. However, in some cases, such as cycloconverters and line-commutated three-phase thyristor-based rectifiers, the line currents may contain both sub-harmonics (frequency lower than the line frequency) and super-harmonics (frequency higher than the line frequency but not the integer multiple of line frequency). These waveforms are considered as non-periodic, although mathematically the currents may still have a periodic waveform, but in any event, the period of the currents is not equal to the period of the line voltage [1],[2].

Arc furnaces are another example of a non-linear load that may draw non-periodic currents because they draw rapidly changing power from the source and the waveshape and amplitude are constantly changing. Voltage flicker and harmonic penetration problems associated with arc furnaces have been reported in several papers [3].

A transient disturbance may also be considered as one kind of non-periodic current from the compensation point of view. The disturbance may be caused by the sudden addition of a large load to the system such as starting a motor, a fault, or other reasons.

Definition and compensation of non-sinusoidal and non-periodic currents and power has been a concern for some time [4]-[8]. However, most of the previous efforts have focused on the compensation of periodic non-sinusoidal currents instead of non-periodic currents. The diversity of the features of non-periodic currents makes their compensation quite difficult, and theoretically, their compensation is very different than that for periodic distorted currents. However, from a practical point of view, these two cases may be very close to each other [9]. Anyway, in both cases a sine wave with a constant rms magnitude is preferred for the source current after compensation.

If the conventional shunt active filter is used as the compensator, the compensator (in both cases) must inject all current components that are the difference between the desired source currents and the required load currents. Starting from this viewpoint, the work here characterizes the required compensation current, and in particular, determines the energy storage requirements for various non-periodic currents based on a new definition of non-active current [8].

2. Definition of Non-Active Current

For a single or polyphase power system, a shunt compensator to minimize the nonactive power/current required of the source can be configured as in Figure 1. It is assumed here that the shunt compensator consists only of passive components (inductor and/or capacitor) and/or switching devices and no external power source. As a consequence, (neglecting the compensator’s power loss),

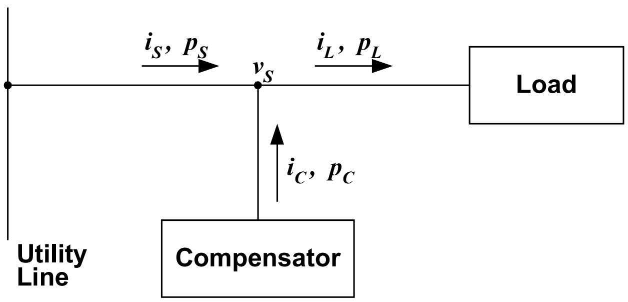


Figure 1. A shunt compensator configuration.

conservation of energy requires the active power of the compensator average zero. In more detail, let $p_S(t)$, $p_L(t)$, and $p_C(t)$ denote the instantaneous power of the source, load and compensator, respectively and their average values over a time interval T_C be given by

$$P_X(t) = \frac{1}{T_C}\int_{t-T_C}^{t} p_X(\tau)d\tau \text{ where } X = S, L, \text{ or } C. \quad (1)$$

Then

$$P_S(t) + P_C(t) = P_L(t) \quad (2)$$

and

$$P_S(t) = P_L(t),\ P_C(t) = 0 \text{ as } t \to \infty. \quad (3)$$

In (1), T_C is the averaging interval which can be zero, one fundamental cycle, one-half cycle, or multiple cycles, depending on the compensation objectives and the passive components' energy storage capacity. The subscripts "*S*", "*L*", and "*C*" denote the source, load, and compensator quantities as shown in Figure 1, respectively. Equations (1), (2) and (3) must hold true regardless of single-phase or polyphase, passive compensation or active compensation. Based on these physical and practical limitations, non-active power/current can be defined and formulated.

Here, Fryze's idea of non-active current/power [4] is extended by defining

$$i_p(t) = \frac{P_L(t)}{V_P^2(t)} v_P(t), \qquad i_q(t) = i(t) - i_p(t), \quad (4)$$

where $i_p(t)$ is the active current, $i_q(t)$ is the non-active current and

$$V_P(t) = \sqrt{\frac{1}{T_C}\int_{t-T_C}^{t} v_P^2(\tau)d\tau}\ . \quad (5)$$

$P_L(t)$ is the average active power over the interval [t-T_C, t], which is calculated from (1). $V_P(t)$ is the rms value of the voltage calculated using $v_P(t)$ over the interval [t-T_C, t] as in (5). Here $v_P(t)$ is the reference voltage whose specification depends on the compensation objectives. For example, this specification can be the terminal voltage $v_s(t)$ itself or it may be the fundamental component of $v_s(t)$ (i.e., $v_P(t) = v_f(t)$ where $v_s(t) = v_f(t) + v_h(t)$ and $v_f(t)$ is the fundamental and $v_h(t)$ is the harmonic component). The definitions (4) and (5) are valid for single- and polyphase circuits. However, in the case of polyphase circuits, the voltages and currents are expressed in vector form which, for a three-phase system, is

$$v = [v_a, v_b, v_c]^T,$$

$$i = [i_a, i_b, i_c]^T, \text{ and}$$

$$v^2 = [v_a, v_b, v_c]\cdot[v_a, v_b, v_c]^T = (v_a^2 + v_b^2 + v_c^2).$$

It was shown in [8] that this new definition has the following features: 1) flexible to meet different compensation objectives; 2) valid for non-sinusoidal and non-periodic systems; 3) valid for single phase and polyphase systems. Table 1 illustrates that by choosing different voltage reference and time averaging intervals, different source currents will result. Because of its flexibility in regards to compensation objectives, this definition is quite suitable for analyzing the compensation of non-periodic currents. This will be shown in the next section.

Table 1. Parameters for Different Compensation Objectives

Compensation Objective	v_P	T_C	Resulting Source Current
Single phase reactive current	v	$T/2$ or T	Unity pf and sinusoidal for sinusoidal v_s
Single phase reactive power and harmonic current	v_f	$T/2$ or T	Unity pf and sinusoidal regardless of v_s distortion
Instantaneous reactive power for polyphase system	v	$T_C \to 0$	Instantaneously unity pf for polyphase system
Non-periodic and disturbance current	v_f	nT	Smoothed sine wave with unity pf

3. Compensation of Non-Periodic Currents

For compensation of periodic currents with fundamental period T, choosing different T_C alone does not change the source current characteristics. With reference to (5), the average rms value of a periodic quantity does *not* depend on the time averaging interval T_C if it is an integer multiple of $T/2$.

Theoretically, the time averaging interval can be chosen as any arbitrary value in the case of non-periodic currents. However, it is desirable for the interval to be an integer multiple of the line frequency period because of the desire that the source current be sinusoidal and have the same frequency as the source voltage frequency. In general, the period of the line voltage is not the same as the period of the quasi-periodic current $i_p(t)$, or there is no period in the

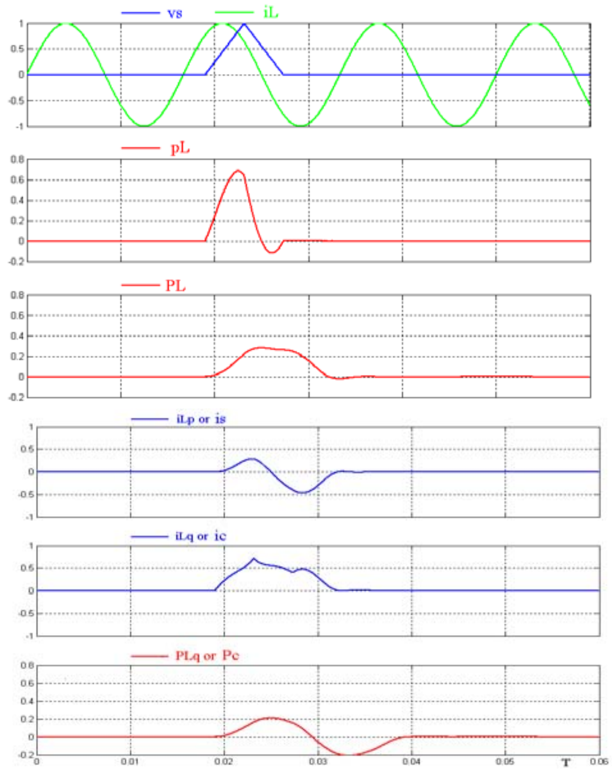


Figure 2 Simulation results for disturbance type non-periodic current compensation ($Tc = T/2$).

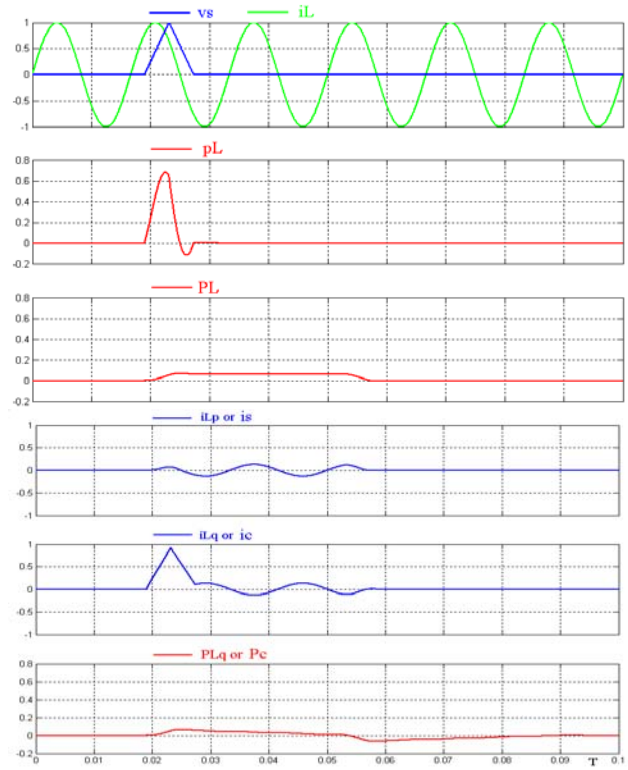


Figure 3 Simulation results for disturbance type non-periodic current compensation ($Tc = 2T$).

case of non-periodic load current. Thus, choosing different T_C will result in quite different compensator currents and source currents. Simulation results of the compensation of three different kinds of non-periodic currents are given in the following subsections.

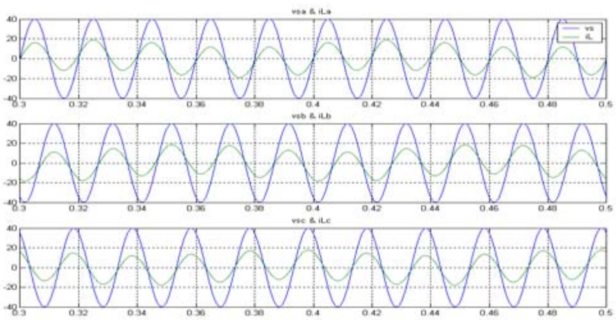
3.1 Non-periodic Disturbance Currents

The duration of a non-periodic current may be a fraction of the line frequency cycle, or it may be several cycles. For the remaining time period, the current may be zero or of a pure sine wave. Figures 2 and 3 show the simulation result of a single-phase disturbance current for two different cases: $T_C = T/2$ (Figure 2) and $T_C = 2T$ (Figure 3), and $v_P = v_f$ for both cases. To simplify the simulation, the voltage waveform is assumed to be a sine wave. Note, however, that the result will also apply in the case of a source voltage that contains harmonics and is non-sinusoidal.

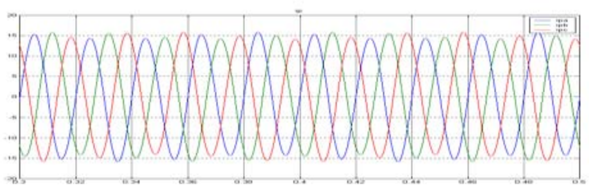
Because the disturbance energy is a fixed value, choosing a different time averaging interval T_C results in different average active power P_L; thus, a different magnitude of source current and compensator current will result. Larger values of T_C result in smaller peak values of $|i_s|$, i.e., the smaller disturbance seen from the source side. However, the compensator current rating will increase accordingly. Compensator design engineers must weigh the tradeoff between minimizing the source current against the cost of additional energy storage devices (capacitance) to accomplish this. The simulations show that by increasing T_C from $T/2$ to $2T$, the source current decreases by 200% (from 0.6 p.u. to 0.2 p.u. of the load current), but the compensator current increases by only 50% (from 0.6 p.u. to 0.9 p.u. of the load current). Thus, one can significantly decrease the source current with what may be a cost-effective increase in the compensator energy storage requirements. While these simulations are done for a single-phase case, the same result would be expected in three-phase cases.

3.2 Quasi-periodic or Subharmonic Currents

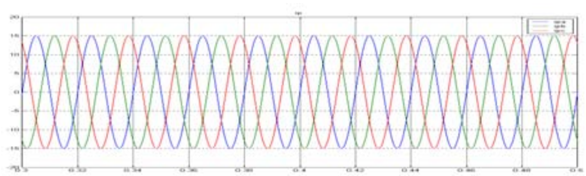
One important feature of this group of non-periodic currents is that the current waveform may have a repetitive period. The non-periodic currents generated by power electronics converters may fall into this group. In the simulation shown in Figure 4, the quasi-periodic current is composed by adding one subharmonic component (10 Hz) to the fundamental current (60 Hz). The simulation result shows that choosing T_C to be equal to at least ½ of the common period of both the sub-harmonic component and the fundamental will result in a sinusoidal source current. Choosing T_C smaller than ½ of the common period will result in a source current that still contains some subharmonic components. The larger the value of T_C, the closer the source current's waveform is to a sine wave.



(a) 3-phase load current and voltage waveforms.

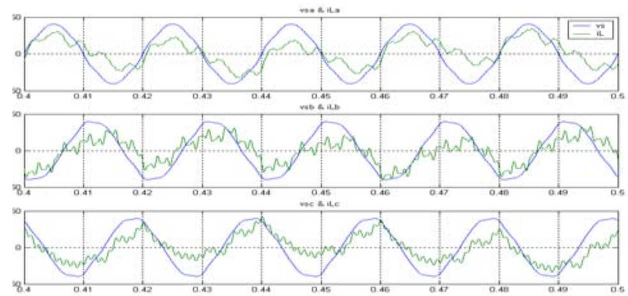


(b) Compensated load currents (*Tc*=*T*)

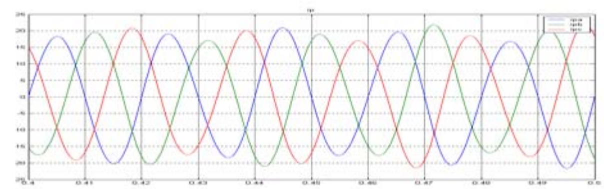


(c) Compensated load current (*Tc*=3*T*)

Figure 4. Simulation of subharmonic current compensation.



(a) 3-phase load current and voltage waveforms.



(b) Compensated load currents (*Tc*=*T*)

(c) Compensated load current (*Tc*=10*T*)

Figure 5. Simulation of stochastic current compensation.

3.3 Stochastic Non-Periodic Currents

The load currents of arc furnaces are typically quite irregular as shown in Figure 5. Thus, it is impossible to choose one specific T_C to get a sinusoidal source current. In the case of non-periodic waveforms, one can mathematically consider the period to be infinite. As can be seen from equations (4) and (5), as T_C goes to infinity, both P_L and V_p become constant and i_p tracks the voltage reference v_p. If v_p is chosen as v_f, then the source current will become sinusoidal. However, choosing the time interval to be infinite is not feasible in a practical application. But, it may still be possible to find some repetitive period in the current waveform that has most of the rms content of the waveform. Choosing that period as T_C may get an acceptable source current which is quite close to a sine wave as shown in Figure 5. In this way, the voltage flicker and harmonic penetration problem [10, 11] associated with this nonperiodic current waveform can be mitigated.

4. Compensator Energy Storage Requirement

The definition represented as (4) may be interpreted as the time average active power during T_C that is contributed by the active source current i_p where the average active power of the compensator $P_C(t)$ over T_C is assumed to be zero.

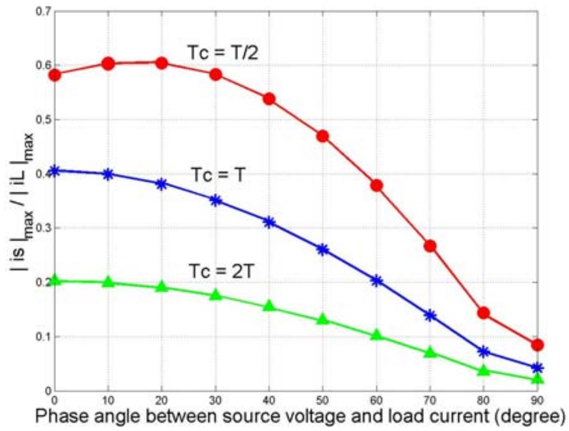
$$P_C(t) = \frac{1}{T_C} \int_{t-Tc}^{t} v^T(\tau) i_c \, d\tau = 0 , \qquad (6)$$

with $i_c = i_q$

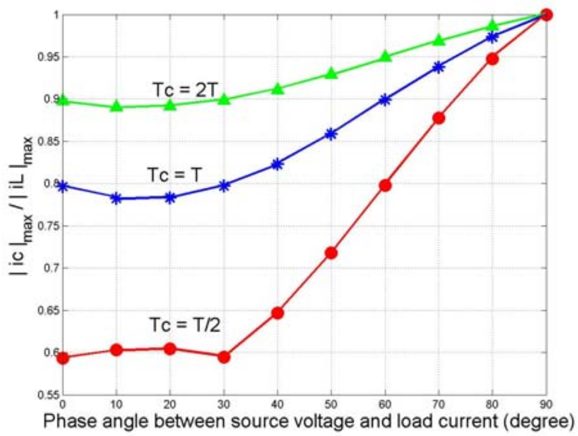
It has been shown in [5] that the compensator average active power defined by (6) is exactly zero in the periodic current case. However, during the interval T_C, the instantaneous active power is not necessarily zero so that the capacitor DC voltage will fluctuate as it supplies active power. Thus some limited energy storage requirement for the shunt active filter capacitor may be necessary to keep the DC voltage within an acceptable range. The energy storage requirement ΔE can be designed based on the following equation:

$$\Delta E = \int_{0}^{Tc} v^T i_q \, dt \qquad (7)$$

In the case of non-periodic currents, no fixed repetitive period exists so that for any fixed value T_C, the compensator active power defined by (6) will not be zero. This simply means that the compensator has to supply

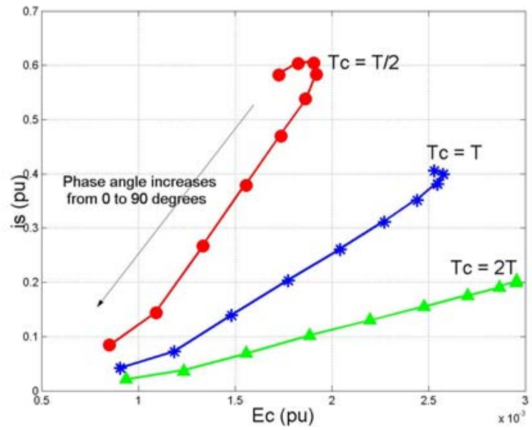


(a)

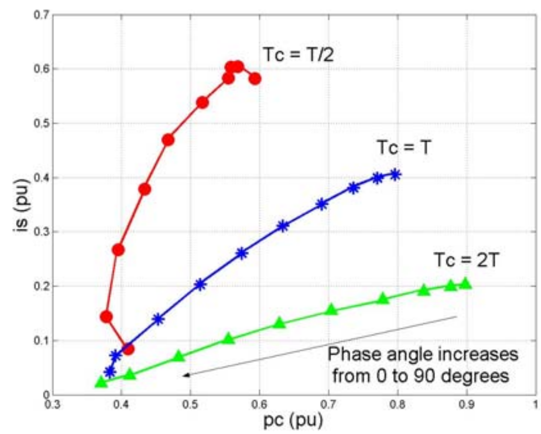


(b)

Figure 6. (a) Peak source current and (b) peak compensator current normalized with respect to load current for different compensation times and load current phase angles.



(a)



(b)

Figure 7. Peak source current plotted as a function of the compensator's (a) energy storage requirement and (b) instantaneous power requirement for different compensation times and load current phase angles.

active power continuously. Further, this load active power requirement fluctuates for non-periodic currents. If a sinusoidal waveform current is desired, the instantaneous active power difference between the load power and source power (constant or very close to constant) has to be supplied by the compensator. In this case, the energy storage requirement will be very high requiring rather large capacitor banks. In some cases, external energy sources may be necessary to meet such requirements.

The choice of the time averaging interval T_C is also significant in the energy storage design consideration. Choosing a longer T_C results in a smoother source current with smaller amplitude; however, this requires that the compensator current i_c increase as well as the energy storage requirement of the compensator.

Figure 6 shows the peak source current normalized with respect to load current for various compensation intervals and phase angles between the current pulse and source voltage for a pulse waveform such as that shown in Figures 2 and 3. With the averaging interval T_C changing from T/2 to 2T, i_s decreases from 0.6 p.u. to 0.2 p.u. of the load current while i_c increases only modestly from 0.6 to 0.9 p.u. of the load current.

When the phase angle between the source voltage and pulse current is small, which is common for many systems, a small increase in energy storage capacity will result in a much better compensation (i.e., much smaller source current). In the case of a large phase angle difference with a compensation period of 2T, i_c increases 10% (from 0.9 to 1.0 p.u. of the load current); while in the case of a compensation period of T/2, i_c increases approximately 70% (from 0.6 to 1.0 p.u.). This is because if the compensator uses T_C = 2T, it must have a larger energy storage capacity (relative to using T_C = T/2) that is ready for not only a longer compensation interval, but also a larger instantaneous reactive component. Thus, a compensator with larger energy storage can obtain a better compensation and support a load that has a large reactive component.

Figure 7 shows the peak source current plotted as a function of the compensator's energy storage requirement and instantaneous power requirement for various compensation times and load current phase angles. At longer averaging intervals, the power drawn from the source is distributed during T_C so that it has a smaller peak value instead of a short duration, high power pulse. Of course, the compensator instantaneous power requirement is more concentrated so that a higher energy rating is needed when the compensation duration is short. Over the complete compensation period, the compensator provides only reactive power and does not consume or generate any active power because the load energy is always provided by the source. Thus, a trade-off between a smoother source current waveform with lower amplitude and the size of the compensator should be considered when choosing the appropriate T_C.

5. Conclusion

Compensation of non-periodic currents is feasible using conventional shunt active power filters that are controlled based on a definition of non-active currents as described in this paper. Simulation results for compensation of various kinds of non-periodic currents gives credibility to the applicability of the definition in both single-phase and three-phase cases. The choice of different averaging time intervals for the compensator determines the amount of energy storage required and the extent of distortion in the source current.

Acknowledgement

We would like to thank the National Science Foundation for partially supporting this work through contract NSF ECS-0093884.

References

[1] E.H. Watanabe, M. Aredes, Compensation of non-periodic currents using the instantaneous power theory, *IEEE Power Engineering Society Summer Meeting*, Seattle, USA, 2000, 994-999.

[2] L. S. Czarnecki, Non-periodic currents: their properties, identification and compensation fundamentals, *IEEE Power Engineering Society Summer Meeting*, Seattle, USA, 2000, 971–976.

[3] G. Carpinelli, M. DiManno, et. al., Ac and dc arc furnaces: a comparison on some power quality aspects, *IEEE Power Engineering Society Summer Meeting*, Edmonton, Canada, 1999, 499-506.

[4] H. Akagi, Y. Kanazawa, A. Nabae, Instantaneous reactive power compensators comprising switching devices without energy storage components, *IEEE Trans. Ind. Appl.*, vol. 20, May/June 1984, 625-630.

[5] L. Rossetto, P. Tenti, Evaluation of instantaneous power terms in multi-phase systems: techniques and application to power conditioning equipment, *ETEP,* vol. 4, no. 6, Nov./Dec. 1994.

[6] F. Z. Peng, J. S. Lai, Reactive power and harmonic compensation based on the generalized instantaneous reactive power theory for three-phase power systems, *Proceedings of the 7th International Conference on Harmonics and Quality of Power*, Las Vegas, USA, 1996, 83-89.

[7] L. M. Tolbert, T. G. Habetler, Survey of active and non-active power definitions, *IEEE International Power Electronics Congress*, Acapulco, Mexico, 2000, 73-79.

[8] F. Z. Peng, L. M. Tolbert, Z. Qian, Definitions and compensation of non-active current in power systems, *IEEE Power Electronics Specialists Conf.*, Cairns, Australia, 2002, 1779-1784.

[9] H. Akagi, Active filters and energy storage systems operated under non-periodic conditions, *IEEE Power Engineering Society Summer Meeting*, Seattle, USA, 2000, 965-970.

[10] S. R. Mendis, M. T. Bishop, J. F. Witte, Investigations of voltage flicker in electric arc furnace power systems, *IEEE Industry Applications Magazine,* 2(1), Jan./Feb. 1996, 28-34.

[11] M. M. Morcos, J. C. Gomez, Flicker sources and mitigation, *IEEE Power Engineering Review*, 22(11), Nov. 2002, 5-10.