

## Phantom Load: A Simulator of Non-Periodic Currents

Leszek S. Czarnecki, (Fellow IEEE) Guangda Chen,  
Herbert Ginn (Student Member IEEE) and Jun Hu

Electrical and Computer Engineering, Louisiana State University, Baton Rouge, LA 70803

**Abstract:** A great variety of features of non-periodic currents make experimental study on their properties, identification and compensation confined to only particular cases dependent on the loads used. To overcome this obstacle, a device can be developed that, supplied from a three-phase power grid, would have the line currents controlled, at the operator's discretion, by a computer. This device is referred to as a *phantom load* in the paper.

The phantom load described is built of two three-phase current inverters, a measurement and digital signal processing unit for the vector control of the inverters, a PC computer for generating the required wave-form of the phantom load line currents and for its control, as well as a synchronization unit. The synchronization unit provides the synchronization of the current waveform generated in the computer with the supply voltage of the supply power grid of 60 Hz frequency. The paper discusses the operational principle of such a device.

**Keywords:** Non-periodic currents, power quality, compensators, active filters, switching compensators.

### I. INTRODUCTION

Non-periodic components occur in distribution system currents due to various reasons. Such currents are caused by switching operations and faults. They also occur during the normal operation of some power equipment. For example, arc furnaces and cycloconverters, usually have non-periodic supply currents. They can occur as well in the supply current of adjustable speed drives. Also, the fast control of energy flow and control of industrial processes, facilitated by the development in the power electronics may contribute to an increase of non-periodic currents in distribution systems.

Like harmonics, non-periodic currents can increase power loss and disturb some power equipment. In general, like harmonics, non-periodic currents contribute to the supply quality deterioration in distribution systems. Unfortunately, these effects are even less known than the harmful effects of harmonics and consequently, some research is needed.

The experimental research on properties of non-periodic currents, identification of such currents, their harmful effects and compensation are made difficult because such currents exhibit a great variety of different features, while loads that generate such currents provide only very specific currents,

characteristic for particular loads. Also some loads that generate non-periodic currents, such as arc furnaces, are usually not available in labs for experimental studies.

Availability of a universal load that would be able to provide three-phase, non-periodic currents with a variety of specific time and frequency properties, would contribute to various research on power phenomena in systems both with periodic and with non-periodic currents. Such a device could facilitate the studies on identification of non-periodic currents and their compensation by providing a technical tool for verification of the mathematical and computer models developed for such studies. Moreover, such a device may be needed for laboratory tests of periodic and non-periodic current compensators. This could be particularly important when such a compensator is not dedicated to a particular load with a limited variety of the current features. If the compensator is to be a universal device then it is not easy to physically model various loads for the testing of such a compensator.

This paper describes and discusses the operational principle of a three-phase device that can simulate non-periodic currents that may occur in distribution system. The features of the simulated current waveform can be chosen at the discretion of the operator of the device. Such a simulator is referred to as a *phantom load* in this paper.

A vector controlled, pulse width modulating (PWM) three-phase inverter is a device that enables us to control the input current waveform. This waveform can be specified, at the operator of phantom load's discretion, by a computer program and conveyed next, as a reference, to the inverter switching control system.

The computer controlled load current simulated by the phantom load flows in a circuit supplied from the three-phase industrial grid of 60 (50) Hz frequency which changes at random in some range of deviation. Consequently, the voltage and the current do not have the same frequency. Therefore, a common frequency reference frame for the computer generated current waveform and the power grid voltage frequency is needed for the phantom load operation. This means that the waveform data transfer from the computer to the control system of the inverter has to be synchronized by the grid voltage frequency.

When a vector controlled PWM inverter is utilized as a switching compensator (commonly known as AC power filter [1] or active harmonic filter) of the load generated current harmonics and the load reactive current, then the only energy delivered to the device in a steady state is the energy

dissipated in the inverter and in the input inductor. This is because the mean value of the instantaneous power associated with harmonic and reactive currents is, at a sinusoidal supply voltage, equal to zero. Consequently, the voltage of the energy storage capacitor can be kept constant by providing an active current needed for the power loss compensation from the supply.

A phantom load should be able, however, to simulate real loads with a non zero active power,  $P$ . The energy storage device of the inverter accumulates in steady state a constant amount of energy. Therefore, if the active power,  $P$ , of the phantom load is not equal to zero, then the energy delivered to this device has to be transferred back to the power grid by a second inverter. Therefore, a phantom load that simulates loads with a non-zero active power has to be a two-inverter device. Though a phantom load is built for a different purpose, its has a structure which is identical to the structure of a unified active power line conditioner described in References [2,3].

The first inverter of the phantom load provides the required waveform of the load current, the second inverter keeps the energy stored in the energy storage capacitor at a constant level. A block diagram of the phantom load under consideration in this paper is shown in Fig. 1.

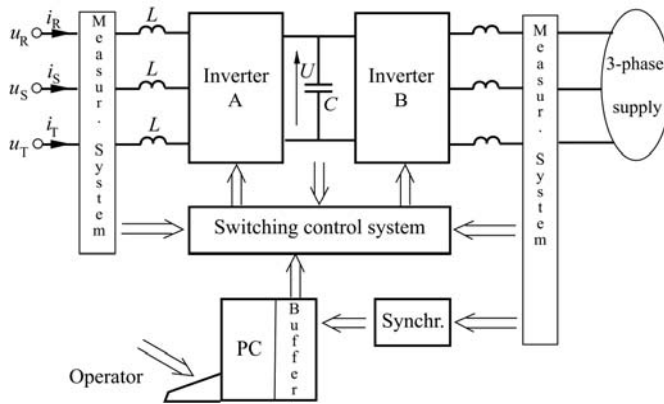


Fig. 1. Block diagram of phantom load

Inverter A in this diagram is controlled in such a way that its input currents and, at the same time, the phantom load currents, have the waveform generated by the computer. The instantaneous values, in digital form, of the waveform of the phantom load currents, generated in the computer are stored in the buffer and conveyed to the switching control system of inverter A. These values form an analog reference signal for the switching control system. They are conveyed to this system according to synchronizing signals that are in phase with the distribution voltage. Inverter B charges or discharges the capacitor  $C$  to the 3-phase distribution system in such a way that the capacitor voltage  $U$  is kept constant, independently of the active power,  $P$ , of the phantom load. The measurement systems provide the actual value of two line voltages and two line currents needed for the inverter switching control systems.

## II. PHANTOM LOAD CURRENT WAVEFORMS

The time and frequency features of a phantom load currents are only limited by the switching capability of the inverter switches, respective the switching frequency. The values of these currents depend, of course, on the inverter switches and the available power of the three-phase supply source. There is only one more constraint that results from the structure of the phantom load under consideration. Since this is a three-wire system, the sum of the line currents has to be equal to zero, namely

$$i_R(t) + i_S(t) + i_T(t) \equiv 0, \quad (1)$$

which means, that only two of three line currents can be shaped at the operator's discretion. Consequently, the phantom load cannot provide current harmonics of the zero sequence order. Within these limits the currents of the phantom load can have any waveform.

Depending on whether or not the value of the integral

$$\int_{-\infty}^{\infty} i^2(t) dt, \quad (2)$$

is limited, a load current can be classified as a current of

- (i) unlimited energy, or
- (ii) finite energy.

Periodic currents belong to the first class, while currents having the form of single pulses belong to the second class. The supply current of a spot welder [5] is an example of such a current.

With respect to the current waveform predictability, the phantom load current can be classified as

- (i) Defined.
- (ii) Semi-defined.
- (iii) Random.

The semi-defined waveforms are those which have some components or features defined while some of them are random. For example, the fundamental component of a current can usually be defined while some additive components change at random. The randomness should be, of course, confined to specified statistical properties. In each case the waveforms can be described, respectively, in:

- (i) time-domain,
- (ii) frequency-domain,
- (iii) hybrid domain.

A hybrid domain means both the time- and the frequency-domain, i.e., same components or the current waveform features are specified in a time-domain while others in a frequency domain. For example, a common current of a linear load supplied from a sinusoidal voltage source and the current of an AC/DC converter with an inductive filter could be specified in a hybrid domain. The first current can be specified by its complex RMS (CRMS) value, i.e., in the frequency-domain, while another by the waveform of its pulses, i.e., in the time-domain.

Moreover, a data record, obtained from a field measurement, can be used as an input data for the phantom load. This enables us to duplicate any field situation respective the current waveform in the lab environment.

As it was discussed in paper [5], in power systems, where generators produce a sinusoidal voltage of approximately fixed 60 or 50 Hz frequency, non-periodic currents occur mainly as an effect the load parameter variability. This variability can cause modulation or could generate additive components to the load current. This load parameter variability could be periodic, but with a period other than the period  $T$  of the distribution voltage or it could be non-periodic.

The non-periodic components of the current are usually transient, while the periodic ones are permanent. Such periodic components that have a period different than the period  $T$  of the voltage produced by the power system generators are referred to [5] as *non-coperiodic* components.

A non-periodic three phase supply current, expressed as a vector

$$i(t) = \begin{bmatrix} i_R(t) \\ i_S(t) \\ i_T(t) \end{bmatrix} = i, \quad (3)$$

usually contains a component,  $i_p$ , that is coperiodic with the distribution system voltage, transient  $i_t$  and non-coperiodic,  $i_b$ , components, namely

$$i = i_p + i_t + i_b = i_p + i_d, \quad (4)$$

where the current  $i_d = i - i_p$  is the component that disturbs the supply current periodicity.

Any periodic current at a sinusoidal supply voltage can be considered [4, 7] as a sum of four orthogonal components, namely, the active,  $i_a$ , reactive,  $i_r$  and unbalanced,  $i_u$ , components of the fundamental frequency and a harmonic current,  $i_h$ . Thus, the non-periodic currents can be decomposed as follows:

$$i = i_a + i_r + i_u + i_h + i_d, \quad (5)$$

Let us assume that the voltage at the input terminals of the phantom load be sinusoidal, symmetrical, positive sequence and arranged, as the line currents, into the vector:

$$u(t) = \begin{bmatrix} u_R(t) \\ u_S(t) \\ u_T(t) \end{bmatrix} = u, \quad (6)$$

The active power at the input terminals of the phantom load associated with the coperiodic component,  $i_p$ , is equal to

$$P_p = \frac{1}{T} \int_0^T u^T(t) i_p(t) dt = (u, i_p) = (u, i_a), \quad (7)$$

since the remaining components of the coperiodic current,  $i_p$ , are orthogonal to the voltage,  $u$ . This is because their scalar products with the supply voltage are equal to zero, namely

$$(u, i_r) = (u, i_u) = (u, i_h) = 0, \quad (8)$$

At the same time, the term

$$\frac{1}{T} \int_0^T u^T(t) i_d(t) dt = (u, i_d) = P_d(t) = \text{Variab.} \quad (9)$$

Formally, this formula does not provide the active power since the non-coperiodic component of the current does not

have the period  $T$ . We can consider the quantity  $P_d(t)$  only as a rate of mean value of energy flow, over period  $T$ , to the phantom load. Consequently, the rate of the mean value of energy delivered to the phantom load in one period of the supply voltage is equal to

$$\frac{\Delta W}{T} = P_p + P_d(t) = \text{Variab.} \quad (10)$$

Since the voltage  $U$  of the energy storage capacitor has to be kept constant, the energy delivered to the phantom load, reduced only by energy loss in the inverters and input inductors, has to be transferred back to the supply system by inverter B.

### III. CURRENT WAVEFORM SHAPING

The phantom load current waveform is shaped by the vector controlled PWM inverter A and associated switching control and measurement systems. Its structure is shown in Fig. 2.

The measurement and signal conditioning systems provide two line-to-ground voltages  $u_R(t)$  and  $u_S(t)$ , two line currents  $i_R(t)$  and  $i_S(t)$  and the capacitor voltage  $U$  to the Digital Signal Processing (DSP) System. These five quantities, along with the data on the reference waveform, transferred to the DSP system from the buffer, enable us to generate control pulses for the inverter switches. In the case of the phantom load under construction in this research, Insulated Gate Bipolar Transistors (IGBTs) were used as the switches.

The switches of the inverters of the phantom load can be controlled with a vector control method, commonly used for the control of switching compensators (usually referred to as active harmonic filters). There is, however, one important difference.

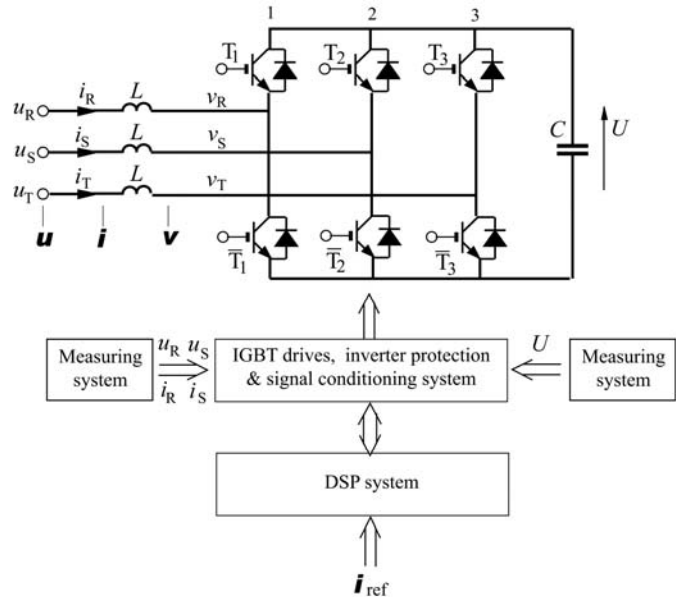


Fig. 2. Current shaping inverter and associated systems

Switching compensators, used for reducing current harmonics generated in a load along with the reactive current, are single inverter devices. Because of energy loss in the compensator, an active current has to be added to the input

current of the inverter. Otherwise, the energy would dissipate in the compensator at the cost of energy stored in the capacitor  $C$  and consequently, the capacitor voltage  $U$  would decline.

Such an active current cannot be added to the input current of the phantom load since this current has to have the waveform chosen by the phantom load operator. This would be possible only when this current is chosen in such a way that the associated active power  $P_p$  is higher than the power loss in the inverter A and the input inductors. Fortunately, since the phantom load has to have a second inverter for keeping the stored energy constant, such an additional active current is not needed.

The feedback control loop of the phantom load current waveform shaping circuit is shown in Fig. 3. The required current waveform of the phantom load is the input data, denoted as  $i_{ref}$ , while  $i$  is the actual current of the phantom load.

The phantom current  $i$  waveform is compared with the reference current  $i_{ref}$  waveform and their difference,  $\Delta i$ , is sampled and digitized by a A/D converter to obtain discrete values  $\Delta i_k$ . For sequential samples,  $\Delta i_k$ , the Clarke's complex current

$$\Delta \mathbf{J}_k = \Delta j_{\alpha k} + j \Delta j_{\beta k}, \quad (11)$$

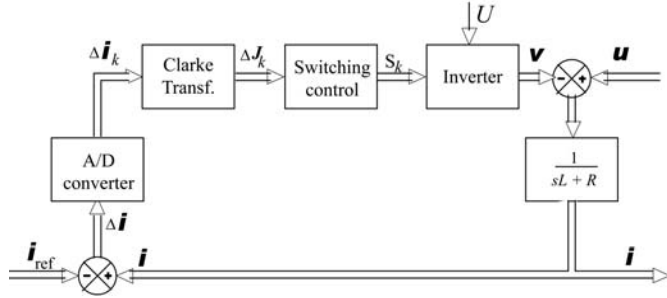


Fig. 3. Control diagram of the current waveform shaping

is calculated. The real and imaginary parts of this current are components of the Clarke's vector, calculated with the Clarke Transform which is defined as

$$\Delta \mathbf{J}_k = \begin{bmatrix} \Delta j_{\alpha k} \\ \Delta j_{\beta k} \end{bmatrix} = \begin{bmatrix} \sqrt{3/2} & 0 \\ 1/\sqrt{2} & \sqrt{2} \end{bmatrix} \begin{bmatrix} \Delta i_{Rk} \\ \Delta i_{Sk} \end{bmatrix} \quad (12)$$

A simplified inductor equation for the voltage and current vectors has the form

$$L \frac{di}{dt} = u - v. \quad (13)$$

Since  $\Delta i = i - i_{ref}$ , the inductor equation with respect to the current error  $\Delta i$  has the form

$$L \frac{d(\Delta i)}{dt} = u - v - L \frac{di_{ref}}{dt}. \quad (14)$$

The current shaping circuit is a discrete control circuit, with the sampling rate of the order of several kHz frequency. Therefore, it can be assumed the reference current  $i_{ref}$  does not change in a single sampling period  $T_s$ . The same is with the voltages  $u$  and  $v$ . Hence, the change of the current error over the sampling period from its value  $\Delta i_k$  to  $\Delta i_{k+1}$  satisfies the equation

$$L \frac{\Delta i_{k+1} - \Delta i_k}{T_s} = u_k - v(S_k), \quad (15)$$

where  $v(S_k)$  denotes voltage  $v$  at the inverter switches combination  $S_k$ . Hence, the current error changes over the sampling period to

$$\Delta i_{k+1} = \Delta i_k + \frac{T_s}{L} u_k - \frac{T_s}{L} v(S_k) \quad (16)$$

The only dependant variable in this equation is the inverter switches combination,  $S_k$ . It should be selected in such a way that the error  $\Delta i_{k+1}$  is as small as possible.

Equation (14) is not convenient for the inverter control since it has to be fulfilled, separately, for each phase, R and S. In the vector control method, commonly used for the switching compensator control, all vectors of phase quantities,  $\Delta i_k$ ,  $u_k$  and  $v(S_k)$  are transformed to Clarke's complex quantities  $\Delta \mathbf{J}_k$ ,  $\mathbf{W}_k$  and  $\mathbf{V}(S_k)$  in such a way that the structure of equation (14) is preserved, namely

$$\Delta \mathbf{J}_{k+1} = \Delta \mathbf{J}_k + \frac{T_s}{L} \mathbf{W}_k - \frac{T_s}{L} \mathbf{V}(S_k). \quad (17)$$

The Clarke's complex voltage  $\mathbf{V}(S_k)$  has, apart from zero, six different values, dependent on the inverter switches combination. These values form a regular hexagon on the complex plane. There are various strategies for reducing the value of  $\Delta \mathbf{J}_{k+1}$ . One of them is based on the selection of such a combination,  $S_k$ , of the inverter switches that the phase angle of  $\mathbf{V}(S_k)$  is the closest possible to the phase angle of the Clarke's complex current error,  $\Delta \mathbf{J}_k$ . This error declines also with the increase of the sampling frequency, i.e., with reduction of the sampling period  $T_s$ , and with the input inductance  $L$  increase.

#### IV. ENERGY FLOW HANDLING INVERTER

Inverter B of the phantom load controls the energy flow to and from the device and its storage in the energy storage capacitor. It has to remove energy from the capacitor  $C$  when the active power of the phantom load is positive or it has to provide it when this power is negative. Its structure with associated subsystems are shown in fig. 4

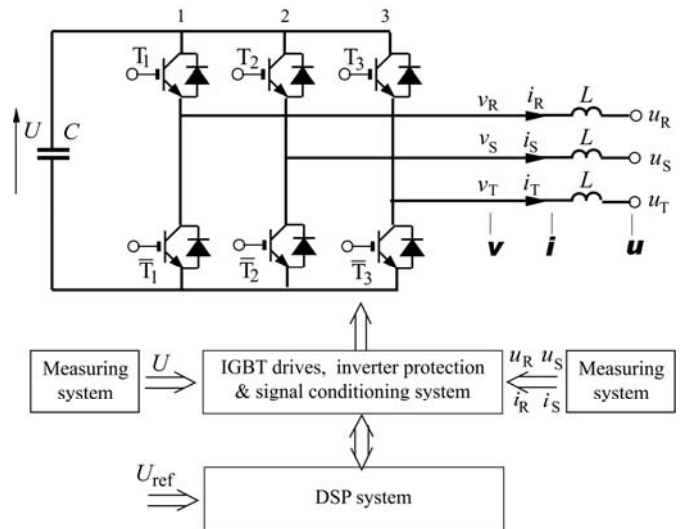


Fig. 4. Energy flow handling inverter B and associated circuits.

To keep the capacitor voltage  $U$  at the level of  $U_{\text{ref}}$ , set at the phantom load designer discretion, the energy

$$\Delta W = [P + P_d(t) - \Delta P]T = P_c(t)T, \quad (18)$$

has to be transferred from the capacitor  $C$  to the distribution system in each period  $T$  of the supply voltage. Symbols  $P$  and  $P_d(t)$  have the meaning explained in Section II and  $\Delta P$  denotes the active power loss in the power circuits of the phantom load. It means that the line current  $i$  of inverter B has to contain the active current,  $i_a$ , of such RMS value  $\|i_a\|$ , that

$$\|i_a\| \|u\| = P_c(t) \quad (19)$$

where  $\|u\|$  denotes the supply voltage RMS value. This active current, it means, a current in phase with the supply voltage  $u$ , namely

$$i_a = \frac{P_a}{\|u\|^2} u, \quad (20)$$

should occur in the supply current when the capacitor voltage  $U$  differs from the reference voltage  $U_{\text{ref}}$ . Therefore, this current serves as a reference current  $i_{\text{ref}}$  for the current control system of the inverter B. At such a current the energy stored in the capacitor remains constant.

The block diagram of the feedback control loop of the phantom load energy flow control is shown in Fig. 5.

The multiplier provides a signal proportional to the active current, which serves as the reference current for the energy flow control system to provide energy needed to keep the capacitor voltage constant.

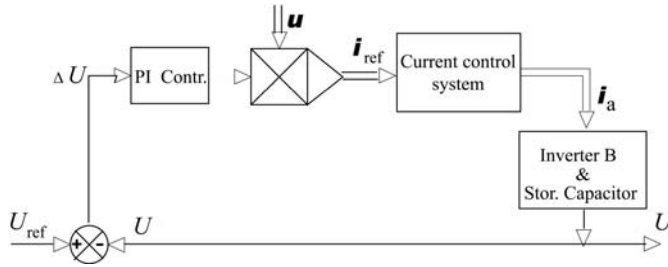


Fig. 5. Block diagram of the phantom load energy flow control system

The current control system of inverter B does not differ from the control system of the current waveform shaping inverter A. Only the reference current for this system is provided differently. This current is symmetrical and in-phase with the supply voltage and consequently, apart from switching noise, the input current of inverter B is symmetrical. However, it could be quasi-sinusoidal. This is because the mean value over period  $T$  of the energy flow between phantom load and distribution system, in the case of simulation of a non-periodic current, is not constant.

## V. VOLTAGE AND CURRENT SYNCHRONIZATION

The waveform of the phantom load line currents is generated by a computer. The frequency of this current has no relation to the frequency in the power grid where the phantom load simulates a load current. Therefore, synchronization of

the phantom load current with the distribution voltage is necessary for the normal operation of the phantom load. Even if the phantom load simulates a non-periodic current, there is always a relation between supply voltage frequency and the load current timing or its frequency. The same is when the phantom load current changes at random. The properties of this random current should be referenced to the voltage variability. The frequency and time relation between the phantom load current and the supply voltage has to be controlled by the phantom load operator. A synchronization system is needed for this.

The synchronization system used in the phantom load under development is composed of a zero detection circuit which provides information, in the form of pulses synchronous, with the distribution voltage,  $u_R(t)$  period  $T$ . These pulses are used for synchronization of a phase-locked loop (PLL) circuit that in the period  $T$  generates  $N$  equidistant pulses  $\Delta_k$ , used next as timing signals for the reference current  $i_{\text{ref}}$  generated by the computer. The number  $N$  is a parameter for the current waveform generating program which stores digital values of the generated reference current  $i(n)_{\text{ref}}$  in a buffer. These digital values are fetched by a D/A converter at instances specified by the  $\Delta_k$  pulses to convert them to continuous reference current  $i_{\text{ref}}$ . The block diagram of the synchronization system is shown in Fig. 6.

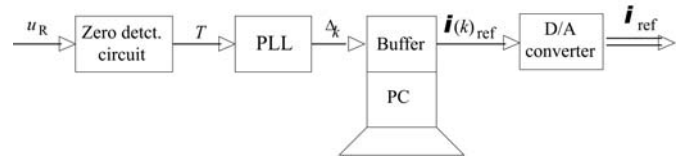


Fig. 6. Block diagram of the synchronization system

When the value  $N$  is selected by the phantom load operator as a period of the generated reference current, then the phantom load simulates currents that are coproperiodic with the supply voltage. In other cases the reference currents are non-coproperiodic. The timing pulses enable also the operator to control the timing of non-periodic events in the simulated current.

## VI. CONCLUSIONS

The paper presents the operation principle of a device that enables us to simulate non-periodic currents that may occur in distribution systems due to various time-variant loads. Such a simulator cannot be built, like switching compensators, as a single inverter device. It has to be built of two inverters, one for shaping the current waveform and a second one for handling energy flow. The current waveform features of the phantom load are bounded only by the switching capability of the power semiconductor switches of the inverter.

## ACKNOWLEDGEMENT

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## REFERENCES

- [1] L. Gyugyi and E.C. Strycula, "Active AC power filters," Conf. Rec., IEEE IAS, 1976, pp. 529-535.
- [2] H. Fujita and H. Akagi, "The unified power quality conditioner: the integration of series-and shunt active filters," IEEE Trans. on Power Electronics, Vol. 13, No.2, March 1998, pp. 315-322.
- [3] M. Aredes, K. Heumann and E.H. Watanabe, "An unified power line conditioner," IEEE Trans. on Power Delivery, Vol. 13, No. 2, April 1998, pp. 545-551.
- [4] L.S. Czarnecki, "Orthogonal decomposition of the current in a three-phase non-linear asymmetrical circuit with nonsinusoidal voltage," IEEE Trans. on Instrumentation and Measurement, Vol. IM-37, No. 1, March 1988, pp. 30-34.
- [5] L.S. Czarnecki and A. Lasicz, "Active, reactive, and scattered currents in circuits with non-periodic voltage of a finite energy," IEEE Trans. Instr. Meas., Vol. IM-37, No. 3, Sept. 1988, pp. 398-402.
- [6] L.S. Czarnecki, "Non-periodic currents: their properties, identification and compensation fundamentals," Proc. of the 2000 IEEE PES Summer Meeting.
- [7] L.S. Czarnecki, "Harmonics and power phenomena," Wiley Encyclopedia of Electrical and Electronics Engineering, John Wiley & Sons, Inc., Supplement 1, 2000, pp. 195-218.

## BIOGRAPHIES

**Leszek S. Czarnecki.** For biography and photo see the paper *An Overview of Methods of Harmonics Suppression in Distribution Systems* published in this Proceedings.

**Guangda Chen** (1953) received the B.S. and M.S. degrees from the Wuhan University of Hydraulic and Electrical Engineering, China, in 1977 and 1987, respectively. He is an Associate Professor at the Wuhan University of Hydraulic and Electrical Engineering. Presently he is a Visiting Research Associate at the Department of Electrical and Computer Engineering, Louisiana State University. His current research interests include control systems, DSP application, power quality improvement and power electronics.

**Herbert Ginn.** For biography and photo see the paper *Effectiveness of Resonant Harmonic Filters And Its Improvement*, published in this Proceedings.

**Jun Hu** (1972) received the B.S. and M.S. degrees from the Zhejiang University, China, in 1994 and 1997, respectively. Since 1999, he is with the Department of Electrical and computer Engineering, Louisiana State University as a research assistant. His research interests include power electronics and motor drives. (Electrical and Computer Eng., Louisiana State University, Baton Rouge/USA, LA 70803)