Control System for Three-Phase Active Power Filter Which Simultaneously Compensates Power Factor and Unbalanced Loads

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Abstract— **The effectiveness of an active power filter depends basically on three characteristics: a) the modulation method used; b) the design characteristics of the PWM modulator; and c) the method implemented to generate the reference template. For the last characteristic there are many methods, most of them complicated and hence difficult to implement and adjust. In this paper, a new method, which has simplicity at its main characteristic, is presented. The method is based on "Sample and Hold" circuits, synchronized with the peak value of the phase-to-neutral mains voltage. This method is useful for shunt active power filters and is capable to eliminate harmonics, compensate power factor, and correct unbalance problems simultaneously. It also has the ability to slow-down sudden transient changes in the load. Experimental results, with the reference template obtained with the method, are presented in the paper.**

I. INTRODUCTION

ACTIVE power filters play an important role in reducing harmonic contamination in power lines. In the past twenty years, the proliferation of nonlinear loads such as static power converters, arc furnaces, and others have resulted in a variety of undesirable phenomena in the operation of power systems, which in many cases cannot be solved with passive *LC* filters. The basic difference between *LC* filters and active filters is that the active filters have the capability to compensate randomly varying currents.

One of the most popular active power filters is the "Shunt Active Power Filter," shown in Fig. 1. A current source, connected in parallel with the nonlinear load, is controlled to generate the required harmonic currents. In this form, the mains only needs to supply the fundamental current, avoiding contamination problems along the power line. In most cases, the load also needs reactive power, which can also be generated by the same current source. Then, this kind of filter can simultaneously compensate harmonics and power factor problems [1]–[3]. In three-phase unbalanced loads it is also possible to redistribute and equalize the mains phase-currents, providing that the total amount of active power remains the same. In this form, the filter can solve three problems at once: a) elimination of unwanted harmonics; b) power factor compensation; and c) redistribution of power to keep the system balanced.

In the practical implementation of this kind of filter, force commutated, current-controlled voltage-source inverters (CC-VSI) are widely used. The quality and performance of the active power filter depends mainly on three considerations [4], [5]: a) the design of the power inverter (semiconductors, inductances, capacitors, dc voltage); b) the modulation method used to follow the current template (hysteresis, triangular carrier, periodical sampling); and c) the method implemented to generate the reference template, which is the topic of this work. In Fig. 1, a block diagram called "**Reference Current Calculator**" has been implemented to generate the reference template. The principle of operation is based on "Sample and Hold" circuits, used as storage elements for calculating the active component of the load current. The circuit generates templates able to compensate harmonics, power factor and unbalanced loads.

Most of the methods proposed to generate the reference template for active power filters are based on the theory of instantaneous reactive power [6–8]. This theory gives a very precise solution to get the reference template, and permits to obtain a clear differentiation between instantaneous active and reactive power. However, there are some particularities in this method. First, in many cases, and from the mains point of view, the separation of the average active power in a defined period is more convenient than the instantaneous active power, because the first solution avoids flickers and reduces transient problems in the mains. Another problem is the sophisticated electronic circuit necessary to obtain the reference, which includes *d-q* transformations, divisions and many multiplications, making it difficult to implement and adjust. In this work, a much simpler solution has been developed. This solution, based on Sample and Hold circuits (S&H), eliminates complicated transformations and mathematical operations such as multiplications and divisions.

II. THE PROPOSED METHOD

The Fig. 2 shows the control block of the proposed method. In this circuit, the overall process for phase A is explained. The load current is filtered through a Band-Pass filter to obtain the fundamental phase-current. This current is rectified and used as an input signal for a "Sample and Hold" circuit. The "Sample and Hold" circuit, synchronized with the peak value of the phase-to-neutral voltage, generates a dc signal, proportional to

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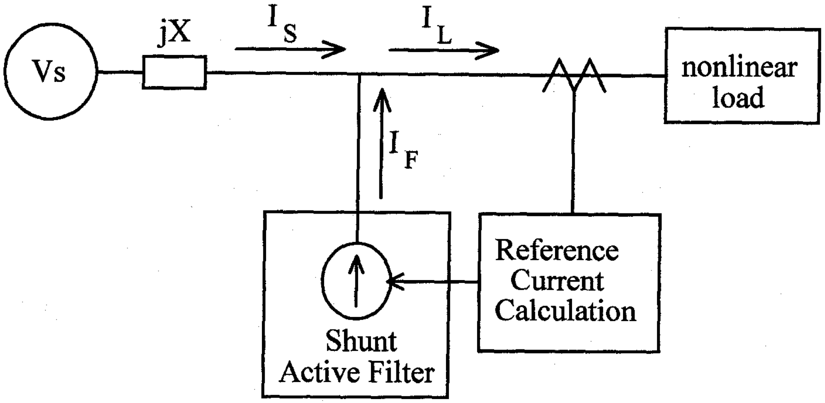


Fig. 1. Operation principle of shunt active power filter.

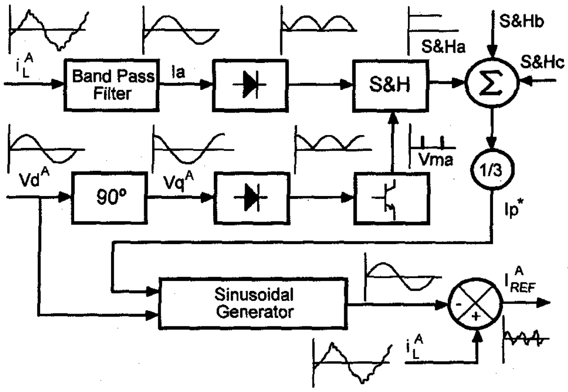


Fig. 2. Control block of the proposed method.

the amplitude of the active component of the current. A similar situation takes place in the other two phases and hence three dc signals are obtained, as shown in Fig. 2 (S&Ha, S&Hb and S&Hc). These three dc signals, with the information of the total active power in the load, are averaged to balance the system. Then, by multiplying the averaged dc signal for a set of balanced reference waveforms (in phase with the mains voltage), three in-phase balanced currents for each phase are obtained. Finally, these currents are subtracted from the real load currents to get the required compensation currents. These compensation currents are then able to correct the harmonic distortion, the power factor and the unbalances of the load. In this form, the mains see the load as a pure balanced resistance.

The proposed method avoids multiplications, divisions, and transformations, and is based on the recovering of the fundamental active currents (in-phase currents) in the load. Once this currents are obtained, they are subtracted from the total load currents to get the desired reference waveform.

Let to assume that I_L is the total load current in one phase. This current contains basically three components

$$I_L = I_P + I_Q + I_H \tag{1}$$

where I_P, I_Q and I_H are the fundamental active current (in-phase component), the in-quadrature fundamental (reactive component) and the harmonic component (also reactive), respectively. The active filter has to be capable to eliminate, from the source point of view, I_Q and I_H. This objective can be reached in two different ways: a) by evaluating I_Q and I_H, or b) by subtracting I_p from I_L. The last method has been developed in this work.

First, the load currents are sensed and filtered to eliminate the armonics (I_H), and then the total fundamental currents (one for each phase) are obtained. These currents have to be separated in their active and reactive components (in-phase and in-quadrature currents respectively)

$$I = I_P + I_Q \tag{2}$$

where

$$I_P = |I| \cos \phi \tag{3}$$

represents the required magnitude of the in-phase fundamental current. Equation (3) allows, through the knowledge of the phase angle "ϕ", the evaluation of I_P for each phase. However, the angle "ϕ" does not need to be known, because the term "$|I| \cos \phi$" can be obtained from the time function of the fundamental when the mains voltage reaches its maximum value. Let

$$v_S(wt) = V_M \sin(wt) \tag{4}$$

be the instantaneous phase-to-neutral source voltage, and

$$i_L{}^f(wt) = |I| \sin(wt + \phi) \tag{5}$$

the instantaneous fundamental load current. At the instant (angle) $wt = \pi/2$

$$v_S(wt) = V_M \tag{6}$$

and

$$i_L{}^f(wt) = |I| \sin(\pi/2 + \phi) = |I| \cos \phi = I_P. \tag{7}$$

Then, the instantaneous value of $i_L{}^f(wt)$, at $wt = \pi/2$ is exactly the magnitude of the in-phase fundamental current. This value is reached when $v_S(wt) = V_M$ and hence I_P can be obtained each time the mains voltage reaches its maximum value. Fig. 3 explains graphically the idea. Then, following the method explained graphically in Fig. 3, I_P

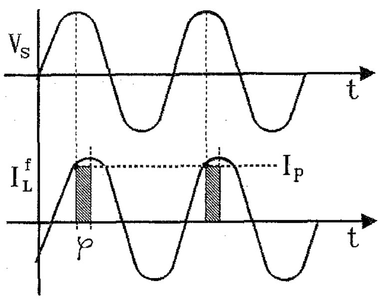


Fig. 3. Method used to capture I_p.

is captured and "stored" until the next sample of I_P is obtained to replace the old one. This action is executed with the help of "Sample and Hold" (S&H) circuits, which are synchronized with the mains peak voltage in each half a cycle. The synchronization pulses to trigger the S&H circuits are generated through the "zero-crossing" signals, obtained from a set of "in-quadrature voltages" $(Vq^{A,B,C})$. These "in-quadrature voltages" are generated in the control block using a three-phase, D_{z0} connection signal transformer, connected to the mains supply. This transformer also gives the "in-phase" components for each phase. The connection of this transformer and the generation of the "in-phase" (V_d) and the "in-quadrature" (V_q) voltages in phase "A" are shown in Fig. 8. It is convenient to say that it has been assumed that the mains is a perfectly balanced three-phase power supply.

With the method explained above, I_P is captured in a form of a "dc signal" per each phase. Now, if the load is balanced, the three values of I_P obtained, $I_P{}^A, I_P{}^B$ and $I_P{}^C$ are identical. However, they will not be the same in the general case and then, the unbalanced characteristics of the load will be transferred to the source. To avoid it, the three magnitudes of I_P can be averaged, because the total amount of power remains the same. Let P_A, P_B and P_C be the load active power in phases A, B, and C, respectively. Then, the total active power will be

$$P_L = P_A + P_B + P_C \tag{8}$$

or

$$P_L = \frac{|V_S{}^A|}{\sqrt{2}} \cdot \frac{I_P{}^A}{\sqrt{2}} + \frac{|V_S{}^B|}{\sqrt{2}} \cdot \frac{I_P{}^B}{\sqrt{2}} + \frac{|V_S{}^C|}{\sqrt{2}} \cdot \frac{I_P{}^C}{\sqrt{2}}. \tag{9}$$

To balance the power in each phase, the total active power can be averaged as follows:

$$P_A = P_B = P_C = P_L/3 \tag{10}$$

as the power source is balanced

$$|V_S{}^A| = |V_S{}^B| = |V_S{}^C| = V_S. \tag{11}$$

Replacing (11) into (9)

$$P_L = \frac{V_S}{2}(I_P{}^A + I_P{}^B + I_P{}^C) \tag{12}$$

averaging the power using (10) and (11), it yields

$$\frac{V_S I_P{}^A}{2} = \frac{V_S I_P{}^B}{2} = \frac{V_S I_P{}^C}{2} = \frac{P_L}{3}. \tag{13}$$

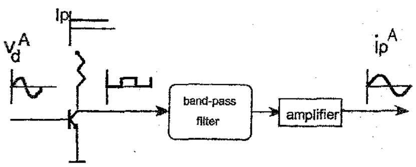


Fig. 4. The sinusoidal generator.

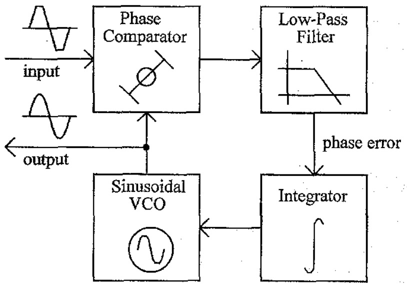


Fig. 5. Closed-loop filter to keep zero phase shift.

Equation (13) is satisfied only when

$$I_P{}^A = I_P{}^B = I_P{}^C = I_P{}^*. \tag{14}$$

From (13) and (14), P_L can be written as

$$P_L = \frac{3V_S}{2} I_P{}^*. \tag{15}$$

Now, from (12) and (15)

$$\frac{3V_S}{2} I_P{}^* = \frac{V_S}{2}(I_P{}^A + I_P{}^B + I_P{}^C). \tag{16}$$

Then, from (16) we finally get

$$I_P{}^* = (I_P{}^A + I_P{}^B + I_P{}^C)/3 \tag{17}$$

where $I_P{}^*$ is the current amplitude that represents the averaged value of I_P. Then, $I_P{}^*$ does not change the amount of active power. The same result is obtained if the instantaneous active power and the in-phase sinusoidal currents are used. This result is important because most of the active power filters cannot produce active power. Now the averaged current $I_P{}^*$, has to be multiplied by an unitary sinusoidal waveform in phase with the mains voltage. The multiplication can be avoided, using a simple transistor, fed with the dc signal $I_P{}^*$, which acts as a power supply. The base of the transistor is then activated with a fundamental waveform in phase with the mains (this waveform does not need to be perfectly sinusoidal). The output of the transistor will be a square wave with an amplitude proportional to $I_P{}^*$. This output is then filtered with a special band-pass filter, adjusted to get 180° phase-shift to compensate the inverting action of the transistor. With this operation, a sinusoidal in-phase waveform, whose amplitude is proportional to $I_P{}^*$ is obtained. The Fig. 4 shows the circuit used to implement this "multiplier." It is called **Sinusoidal Generator**.

The circuit of Fig. 4 is implemented for each one of the three phases to get three sinusoidal waveforms, which are proportional to the fundamental active power. The only

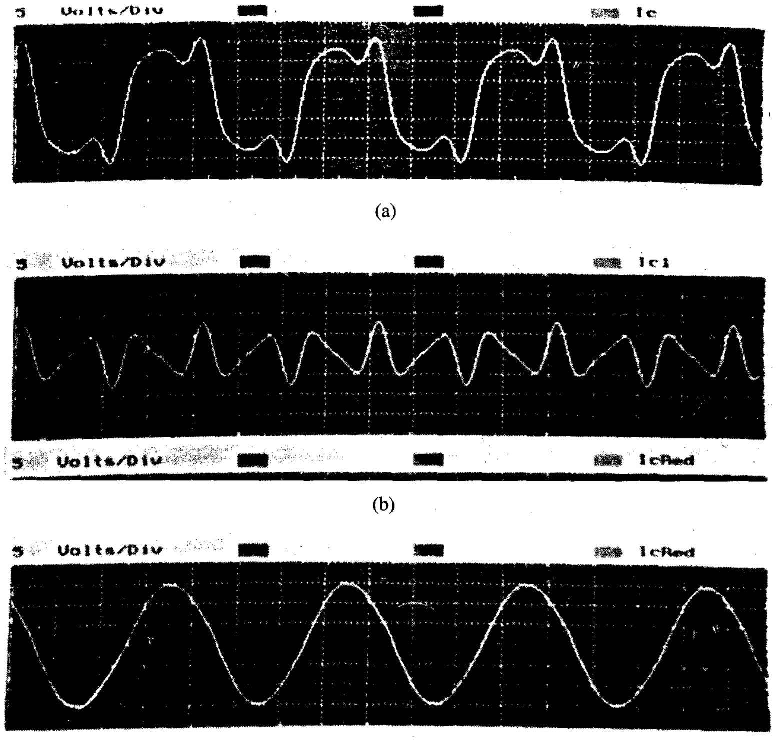


Fig. 6. Current waveforms for a steady-state operation: (a) total load current $i_L{}^A$; (b) reference template $i_{\mathrm{REF}}{}^A$; (c) resultant source current.

problem with this circuit is the phase-shift adjustment of the low-pass filters. This adjustment can be avoided by using the filter shown in Fig. 5, implemented with a phase-comparator, an integrator and a VCO, connected in a closed-loop. The integrator ensures that the VCO and the input signal are always at zero-degree phase-shift, even when the mains frequency changes. If this circuit is used, a real multiplier has to be used to get the sinusoidal active component.

Once the three sinusoidal, in-phase current waveforms are obtained, they are subtracted from the load currents $i_L{}^{A,B,C}$, and the desired current reference templates, $i_{\mathrm{REF}}{}^A, i_{\mathrm{REF}}{}^B$, and i_{REF}^C are generated

$$i_{\mathrm{REF}}^A = i_L{}^A - i_P{}^{A*} \tag{18}$$

$$i_{\mathrm{REF}}^B = i_L{}^B - i_P{}^{B*} \tag{19}$$

$$i_{\mathrm{REF}}^C = i_L{}^C - i_P{}^{C*} \tag{20}$$

were

$$i_P{}^{A*} = I_P{}^* \sin(wt) \tag{21}$$

$$i_P{}^{B*} = I_P{}^* \sin(wt - 120^\circ) \tag{22}$$

$$i_P{}^{C*} = I_P{}^* \sin(wt - 240^\circ). \tag{23}$$

The control circuit also has the capability to avoid flickers and transient phenomena in the source, which can be produced by sudden changes in the load current. To take care of this situation, the control system makes soft variations of $I_P{}^*$. However, this action requires energy storage components in the active power filter.

III. SIMULATION RESULTS

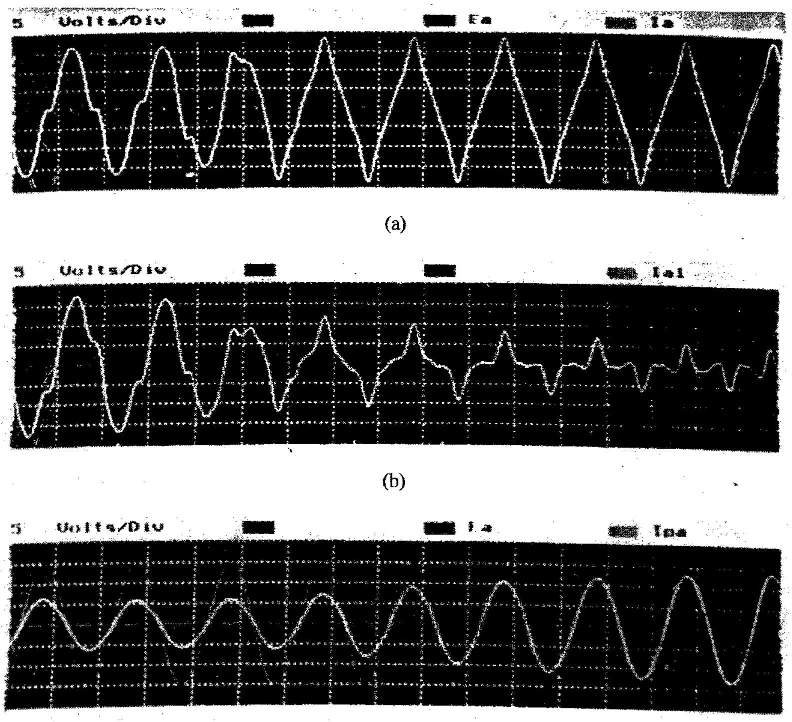
A number of simulations with different operating conditions were developed. Fig. 6 shows the resultant reference template obtained for the phase "A," when the load current has the waveform shown in this figure. The calculated source current results perfectly sinusoidal.

Fig. 7 shows a simulation of a step change in the phase angle of the fundamental in a distorted current. The angle "ϕ" changes from 65° to 0°. It can be observed that the amplitude of the source current increases to supply the higher amount of active power required. The angle of the source current remains at $\phi = 0^\circ$.

IV. EXPERIMENTAL RESULTS

To get experimental results, a three-phase control board was implemented and tested with the help of the circuit shown in Fig. 8. The loss of one phase, with balanced resistive load and source voltage with harmonic distortion, was implemented. The oscillograms of Fig. 9 show the lost phase ($i_L{}^A$), the three reference templates generated by the control block ($i_{\mathrm{REF}}{}^A, i_{\mathrm{REF}}{}^B$, and $i_{\mathrm{REF}}{}^C$), and the resultant source currents. It can be noted that these currents remain sinusoidal and perfectly balanced but their amplitudes decrease slowly. As it was mentioned before, this is convenient for the source because flickers and transient phenomena are avoided.

A second experiment, to simulate a sudden phase change was implemented with a synchronous machine, which also contributed with the generation of slot harmonics. To realize



(a)

(b)

(c)

Fig. 7. Current waveforms for a step change in phase angle: (a) total load current $i_L{}^A$; (b) reference template $i_{\text{Ref}}{}^A$; (c) resultant source current.

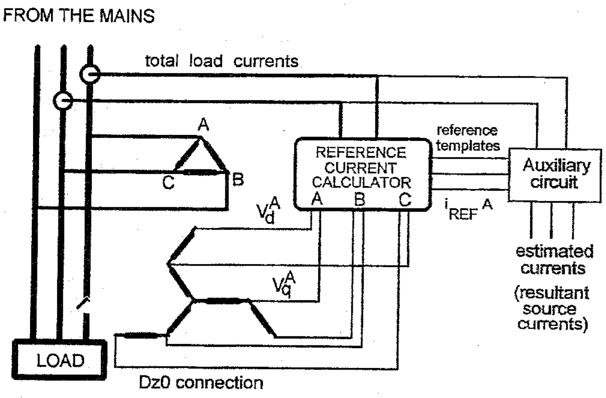


Fig. 8. Experimental implementation for loss of one phase.

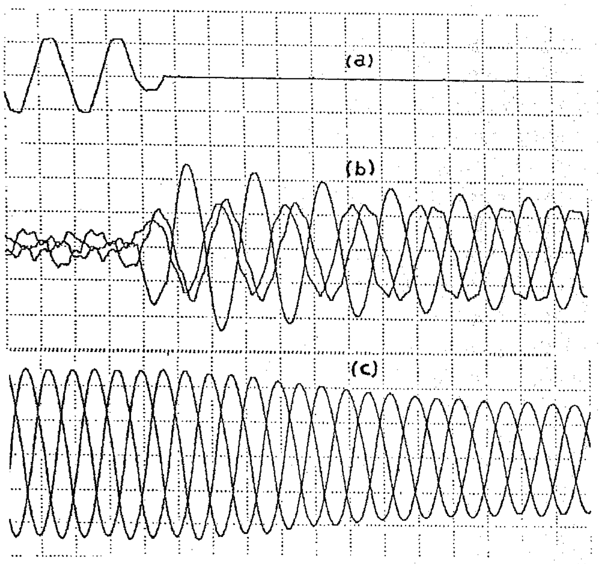


Fig. 9. Step response for loss of one phase: (a) total load current $i_L{}^A$; (b) reference templates $i_{\text{REF}}{}^A$; (c) resultant source currents.

this experiment, the resistive load shown in Fig. 8 was changed and replaced by the synchronous machine. The machine was operated at constant power and the excitation current was suddenly interrupted. The results of this experiment are shown in Fig. 10. It can be noted that source current remains in phase with the voltage and the magnitude does not change.

V. CONCLUSION

A simple and efficient control block, to generate current reference templates for active power filters has been implemented and tested. The control allows the elimination of unwanted harmonics, correction of power factor, and compensation of unbalanced load currents. The device also avoids that sudden changes of the active power load could be transmitted to the power source. Another interesting characteristics of the proposed method is that multiplications, divisions, and transformations can be avoided, making the control system cheaper, simpler, and more reliable. To be able to take full advantage of this control strategy, it would be required to have a very fast power converter and an appropriate modulation method to switch the semiconductors. Adjustments of the analog filter

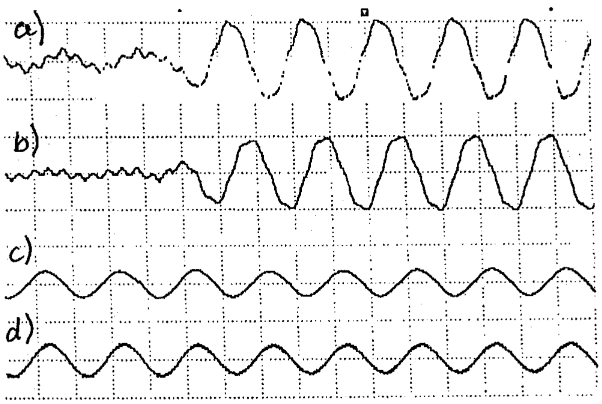


Fig. 10. Currents for a step change in phase angle: (a) machine current $i_L{}^A$; (b) reference template $I_{\mathrm{Ref}}{}^A$; (c) source voltage $v_S{}^A$; (d) resultant source current.

phase-shift is a drawback that can be avoided using special close-loop circuits like the one shown in Fig. 5. The proposed method can also be implemented digitally. For example, sinusoidal waveforms can be generated using EPROM look-up tables, synchronized with the zero crossings of the mains supply. The clock of the digital board is then used to control the S&H devices. The digital solution eliminates problems with analog filter phase-shifts. Switched capacitor filters are another option to get a good filtering of the load signals. Future work is also considering microprocessor control.

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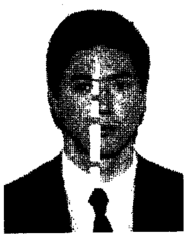

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