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RATIONAL BUILDING ENERGY CONSUMPTION BY ADVANCED CONTROL TECHNOLOGIES BASED ON INSTANTANEOUS AVERAGE ACTIVE POWER MEASUREMENT

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Abstract: Fast and accurate measurement of the instantaneous average active power (IAAP) is useful for building Energy Management System (EMS) in order to assure quality of service such as continuity, optimize energy consumption and reduce carbon dioxide emission.

In this paper the problems connected to the measurement of the instantaneous average active power for energy usage improving are discussed, also as the operational processes which deal to solve such problems.

Keywords: instantaneous average active power (IAAP), building Energy Management System (EMS), energy consumption optimization.

1. INTRODUCTION

Building energy consumption tends to grow in proportion to increase of large-sized building appliances such as heating, ventilation, air-conditioning, lighting, fire safety and security. Energy usage must be improved to reduce carbon dioxide emissions and black-out risks. Energy Management System (EMS) is an effective means for saving energy without nevertheless reducing the quality of life [1-3]. Fast and accurate measurement of the instantaneous average active power (IAAP) is a useful tool for EMS [4]. In addition, both instantaneous true RMS voltage and current, instantaneous apparent power, instantaneous non active power, instantaneous power factor measurements can be obtained. The algorithm is suitable for EMS and consequently for saving energy. In fact the electric time constant is greatly smaller than building thermal time constant; therefore the electrical state can be split up into a series of periodic steady state, whose duration is a multiple of the input quantities period. Each periodic steady state is separated from the other by a relatively short transient, which has a poor interest compared with the thermal quantities condition. Thus the variations of the electrical quantities, defined through their average values, can be immediately detected and all connected loads (heating, ventilation, air conditioning, cooker, freezer and other building appliances) can be opportunely controlled and managed in order to avoid excessive peaks of electrical power demand and to overrun contractual clauses.

Measurement device is simple and low cost and operates both as a quick and accurate meter of the instantaneous average active power and as a quick and sensitive detector of its variations between two successive periodic steady state; moreover it is reliable because based on a valid parameter such as the instantaneous average active power.

2. INSTANTANEOUS AVERAGE ACTIVE POWER MEASUREMENT METHOD

For system voltages and currents with harmonic components, i.e.,

$$v(t) = \sum_{j=1}^{J} \sqrt{2}\, V_j \sin(j\omega t + \alpha_j) \tag{1}$$

$$i(t) = \sum_{m=1}^{M} \sqrt{2}\, I_m \sin(m\omega t + \beta_m) \tag{2}$$

The instantaneous power is defined as follows

$$p(t) = v(t)i(t) = P_0 + \sum_{n=1}^{N} P_n \sin(n\omega t + \varphi_n) \tag{3}$$

where N=J+M; J is the highest order of harmonic voltages and M is the highest order of harmonic currents.

The average active power or power is defined as

$$P = \frac{1}{T}\int_0^T p(t)\,dt = \frac{1}{T}\int_0^T \left[P_0 + \sum_{n=1}^{N} P_n \sin(n\omega t + \varphi_n) \right] dt = P_0 \tag{4}$$

where $T=2\pi/\omega$ is the period of the fundamental frequency 50 Hz.

As well known, in the presence of load fluctuations, the average active power is usually obtained by dividing the energy flow $W_{\Delta t}$ during a specified time interval Δt, by the time Δt

$$P_m = \frac{W_{\Delta t}}{\Delta t} \quad (5)$$

However, the indirect measurement of P_m based on this definition is useful to analyze a posteriori the average value of the power in the specified time interval Δt, but is not suitable for detecting active power variations, which is necessary to know for building energy usage improving. A more general definition, useful in automation and control problems, because it uses acquired samples of voltage and current, is the instantaneous average active power $P_0(t)$ at time t

$$P(t) = \frac{1}{T}\int_{t-T}^{t} v(t)i(t)\,dt = \frac{1}{T}\int_{t-T}^{t}\left[P_0(t) + \sum_{n=1}^{N} P_n \sin(n\omega t + \varphi_n)\right]dt = P_0(t) \quad (6)$$

In this way, the instantaneous average active power $P_0(t)$ becomes a time dependent quantity, which is obviously constant in steady state condition, while it has not a physical meaning during a transient but it is able to detect instantaneously any variation of the average active power as a consequence of a transient.

However, an electrical transient in the building energy management, has a short duration compared with the duration of a thermal transient between two successive steady state. Therefore the interest of our investigation is in analyzing a series of successive electrical steady state conditions, that the proposed algorithm is able to detect quickly and reliably because it operates with a whole period of sampled data.

Similarly the instantaneous true RMS voltage V(t) and current I(t), the instantaneous apparent power S(t), the instantaneous power factor PF(t) and the instantaneous non active power $P_{na}(t)$ are defined

$$V(t) = \sqrt{\frac{1}{T}\int_{t-T}^{t} v(t)^2\,dt} \quad (7)$$

$$I(t) = \sqrt{\frac{1}{T}\int_{t-T}^{t} i(t)^2\,dt} \quad (8)$$

$$S(t) = V(t)\,I(t) \quad (9)$$

$$PF(t) = \frac{P_0(t)}{S(t)} \quad (10)$$

$$P_{na}(t) = \sqrt{S^2(t) - P_0^2(t)} \quad (11)$$

Thus the active $i_a(t)$ and non active $i_{na}(t)$ components of the current and can be introduced

$$i_a(t) = \frac{P(t)}{V^2(t)} v(t) \quad (12)$$

$$i_{na}(t) = i(t) - i_a(t) \quad (13)$$

These definitions are valid in periodic steady state conditions. Therefore it is necessary to implement the proposed algorithm with a fast device able to provide with reliable and valid results, passing from an electric periodic steady state to the successive, except for a short transient.

3. RESULTS

The measurement algorithm has been verified to investigate the validity of this technique. Test results are illustrated in the following.

The voltage and the relative current waveforms, as an example of a domestic utilization, are assumed sinusoidal and the passage from a periodic steady state to the successive is instantaneous. The proposed technique is valid also in nonsinusoidal conditions and in the presence of a non-instantaneous transient.

The current waveform may change as a consequence of the connection or disconnection of loads. $P_0(t)$ is a constant quantity in steady state conditions, but it is able to detect instantaneously any variation of the active power as a consequence of a transient.

Thus the connected loads can be opportunely controlled and managed to avoid the overrun of the nominal power P_n=3 kW. However, to avoid inopportune disconnections of loads, only at the overcoming of a threshold value P_t=(P_n+1.5%), EMS may intervene by modulating or disconnecting a load on the basis of an assigned priority and according to the IAAP slew rate at P_t overcoming.

2.1. Example 1

Fig. 1 shows the waveforms of voltage and current and the instantaneous power

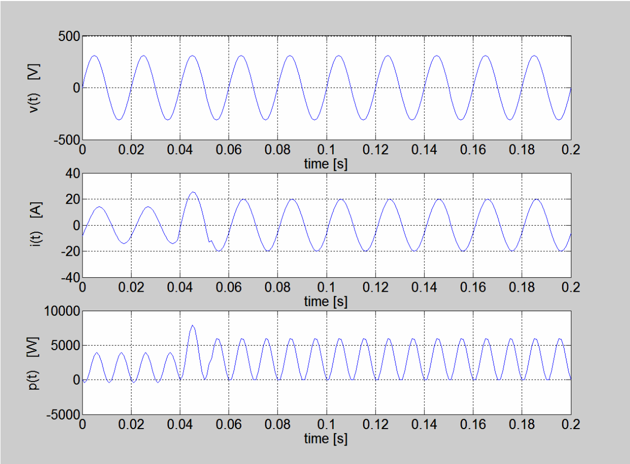

Fig. 1 Voltage and current waveforms, instantaneous power.

Fig. 2 illustrates the instantaneous average active power.

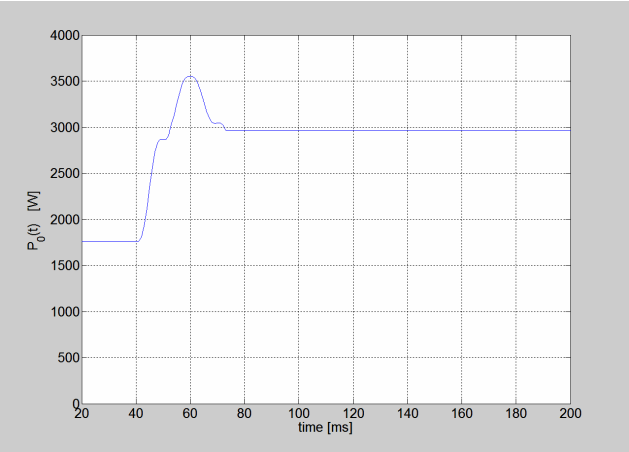

Fig. 2 Instantaneous average active power.

The overcoming of P_t, in association with a IAAP slew rate less than 140 W/ms, leads to a disconnection of a 600 W load. After this transient $P_0(t)$ becomes constant, lightly below the nominal power P_n.

The minimum settling time of $P_0(t)$, when the transient from a periodic steady state to the successive is instantaneous, corresponds to one period of the network frequency. Instead, in the case of a non-instantaneous transient, the settling time of the measurement algorithm corresponds to one period of the network frequency plus the duration of the transient.

Fig. 3 shows the instantaneous true RMS voltage V(t) and current I(t)

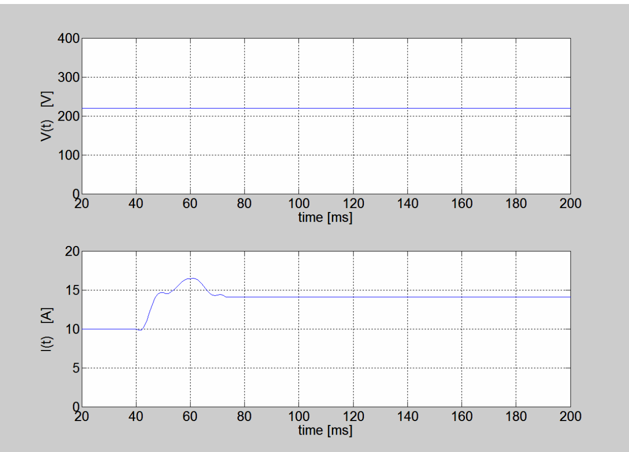

Fig. 3 Instantaneous true RMS voltage and current.

Fig. 4 illustrates the instantaneous apparent power S(t), the instantaneous power factor PF(t) and the instantaneous non active power $P_{na}(t)$

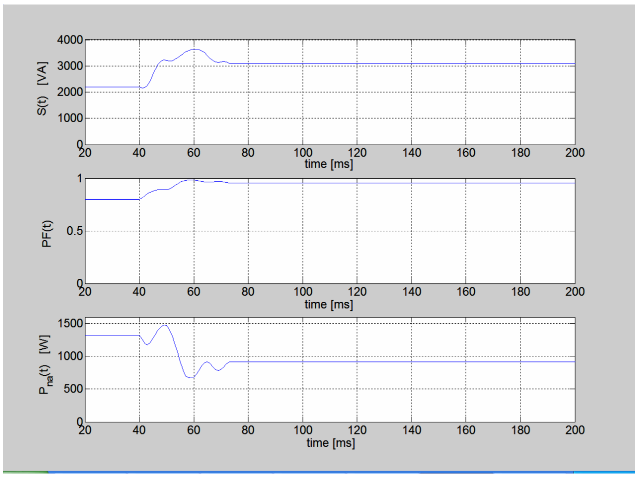

Fig. 4 Instantaneous apparent power, power factor and non active power.

Fig. 5 shows the instantaneous active $i_a(t)$ and non-active component $i_{na}(t)$ of the current.

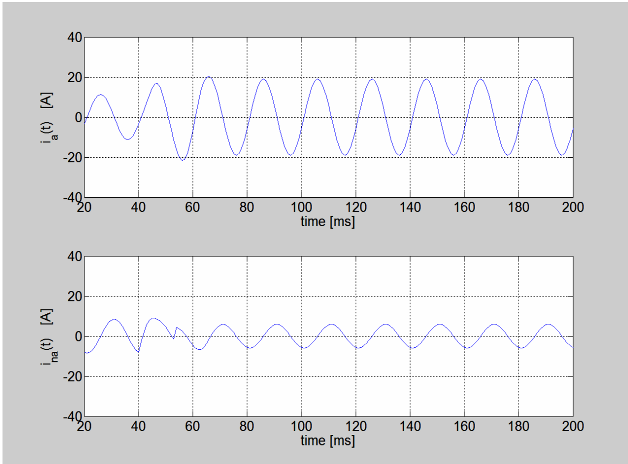

Fig. 5 Instantaneous active and non active component of the current.

2.2. Example 2

Fig. 6 shows the waveforms of voltage and current and the instantaneous power

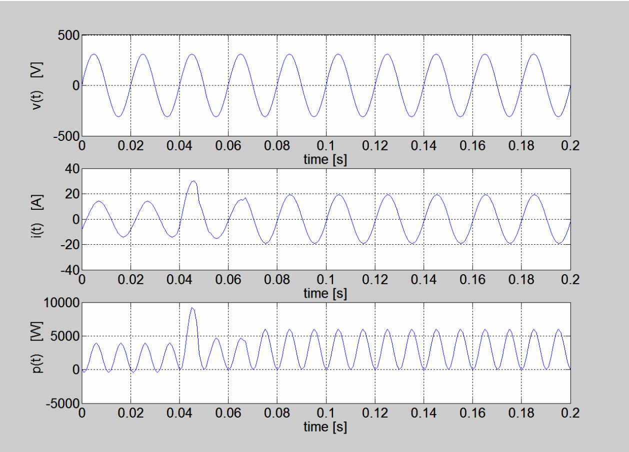

Fig. 6 Voltage and current waveforms, instantaneous power.

Fig. 7 illustrates the instantaneous average active power.

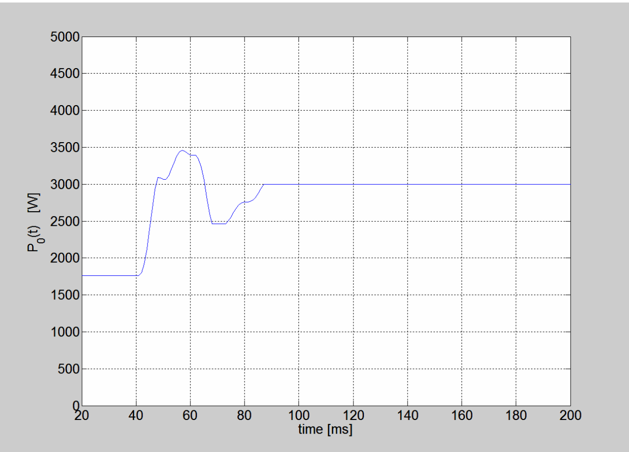

Fig. 7 Instantaneous average active power.

When the IAAP overcomes P_t, with a a slew rate in the range from 150 W/ms to 350 W/ms, EMS intervenes by disconnecting loads for an amount of 1000 W. After this transient $P_0(t)$ becomes constant, greatly below the nominal power P_n; thus EMS allows a new connection of a 500 W load.

Fig. 8 shows the instantaneous true RMS voltage V(t) and current I(t)

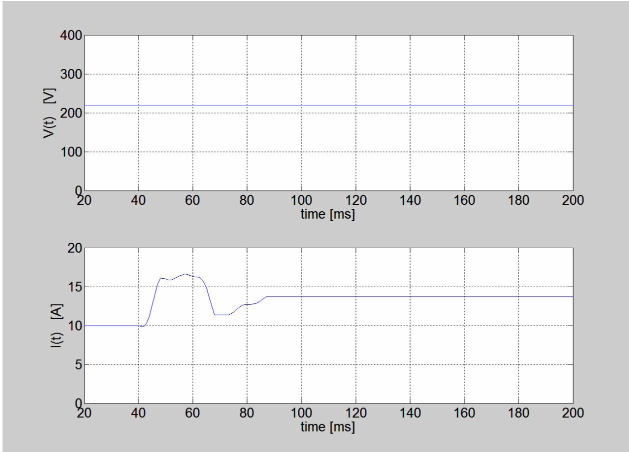

Fig. 8 Instantaneous true RMS voltage and current.

Fig. 9 illustrates the instantaneous apparent power S(t), the instantaneous power factor PF(t) and the instantaneous non active power $P_{na}(t)$

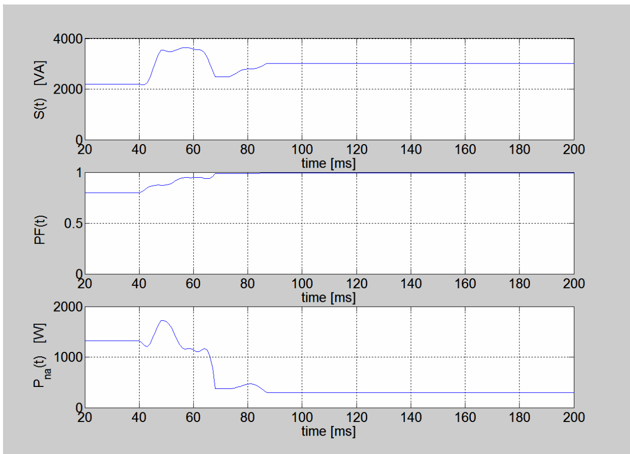

Fig. 9 Instantaneous apparent power, power factor and non active power.

Fig. 10 shows the instantaneous active $i_a(t)$ and non-active component $i_{na}(t)$ of the current.

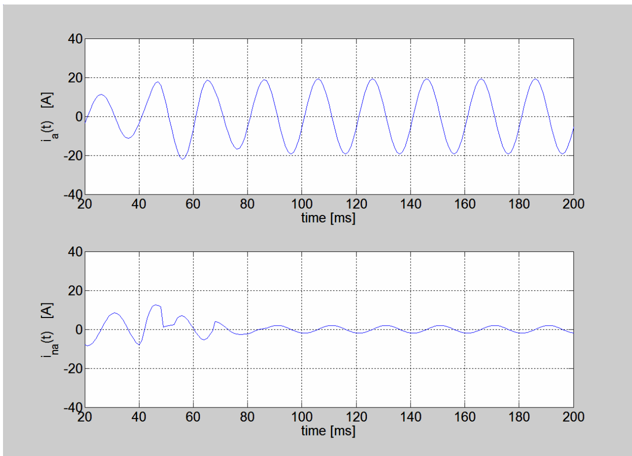

Fig. 10 Instantaneous active and non active component of the current.

2.3. Example 3

Fig. 11 shows the waveforms of voltage and current and the instantaneous power

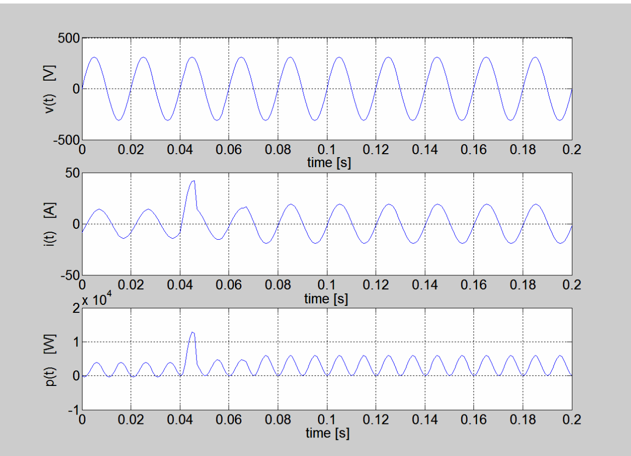

Fig. 11 Voltage and current waveforms, instantaneous power.

Fig. 12 shows the instantaneous average active power.

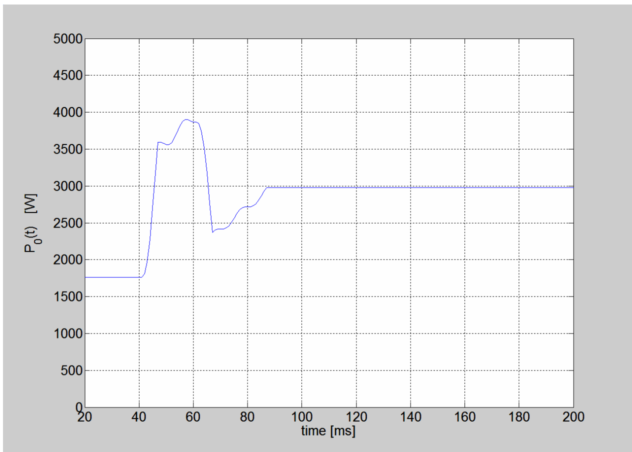

Fig. 12 Instantaneous average active power.

When the IAAP overcomes P_t, with a a slew rate in the range from 350 W/ms to 550 W/ms, EMS intervenes by disconnecting loads for an amount of 1500 W. After this transient $P_0(t)$ becomes constant, greatly below the nominal power P_n; thus EMS allows a new connection of a 600 W load.

Fig. 13 shows the instantaneous true RMS voltage V(t) and current I(t)

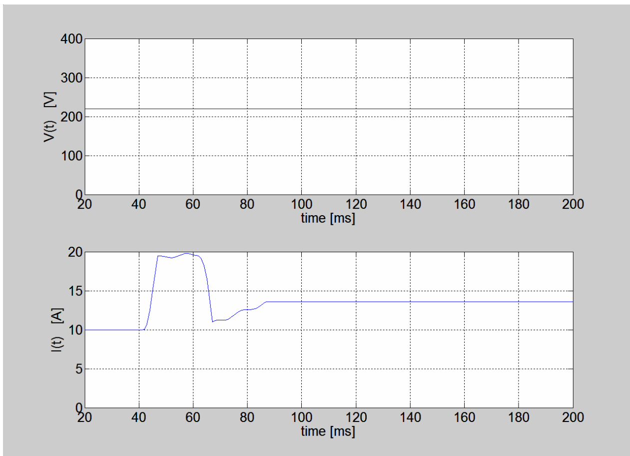

Fig. 13 Instantaneous true RMS voltage and current.

Fig. 14 illustrates the instantaneous apparent power S(t), the instantaneous power factor PF(t) and the instantaneous non active power $P_{na}(t)$

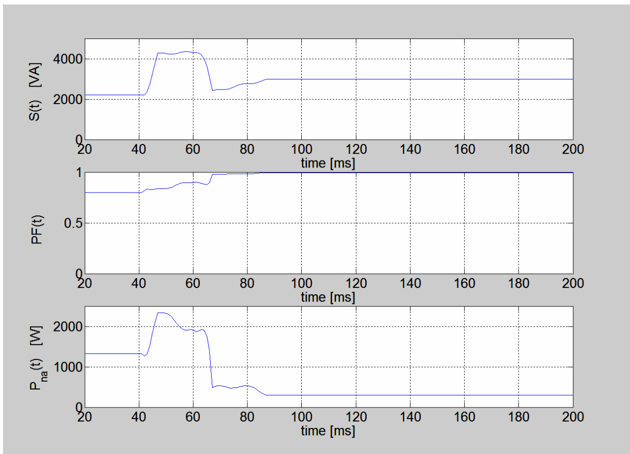

Fig. 14 Instantaneous apparent power, power factor and non active power.

Fig. 15 shows the instantaneous active $i_a(t)$ and non-active component $i_{na}(t)$ of the current.

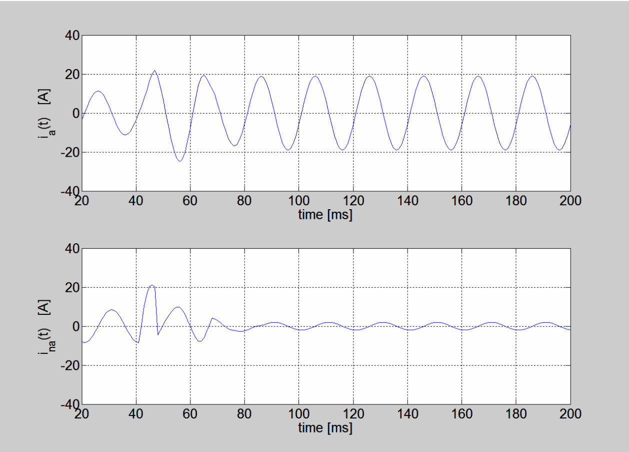

Fig. 15 Instantaneous active and non active component of the current.

In civil buildings the instantaneous active component of the current is the prevailing part, because it is due to loads in which the conversion from electric to thermal energy is carried out.

The non-active component of the current is essentially due to the harmonic and non-harmonic distortions of the current, while its reactive component is usually very little.

Knowledge of non-active components of power and current has had, in past times, not much importance in civil buildings with respect to industrial buildings.

Nowadays however, the growing utilization of inverters for air conditioning and for speed control of induction motors used by building appliances, increases the harmonic distortion and knowledge of non-active components of power and current becomes necessary for energy usage improving.

4. CONCLUSION

The proposed method for measurement of the instantaneous average active power is suitable for EMS and consequently for rational building energy consumption. In fact the electric time constant is greatly smaller than building thermal time constant; thus electrical quantities variations can be immediately detected and all connected loads can be opportunely controlled and managed in order to avoid excessive peaks of electrical power demand.

Measurement device is simple and low cost and operates both as a quick and accurate meter of the instantaneous average active power and as a quick and sensitive detector of its variations between two successive periodic steady state; moreover it is reliable because based on a valid parameter such as the instantaneous average active power.

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