HSCI' 2006 - 3rd International Conference on Hands-on Science -
Science Education and Sustainable Development,
4-9 Sept. 2006, University of Minho, Braga, Portugal ISBN: 989-9509-50-7

Development of a Low Cost Digital Energy Meter

José G. O. Pinto, João L. Afonso
University of Minho, Campus de Azurém 4800-058 Guimarães, Portugal
gpinto@dei.uminho.pt, jla@dei.uminho.pt

Abstract. *This paper presents a versatile low cost equipment that allows simultaneous display of usually required measurements in electric circuits, like true RMS (Root Mean Square) values of mains voltage and current, line frequency, power factor, active, reactive and apparent power, and energy.*

The equipment is based on a microcontroller that interfaces current and voltage transducers through 16 bits sigma-delta ADCs (Analog to Digital Converters). The microcontroller controls the periodic acquisition of the measured signal waveforms, makes the respective calculations and presents the results on an alphanumeric display. The equipment also provides a serial port that enables the communication with other devices allowing the interface through a SCADA (Supervisory Control and Data Acquisition) system.

Keywords. Power and Energy Measurement, RMS Voltage and Current Measurement, Digital Measurement.

1. Introduction

Traditionally, in AC systems, electric voltage signals have sinusoidal waveforms that can be mathematically expressed as (1), where *v(t)* is the instantaneous value at a time instant, *t*, *V* is the peak value of the voltage (voltage amplitude) and *w* is the angular frequency. The electric current represented by (2) is also a sinusoidal signal with an initial phase shift φ in respect to the voltage signal. The equation (3) expresses the relation between the angular frequency and the frequency, *f*, of the signal.

$$v(t) = V\sin(wt) \tag{1}$$

$$i(t) = I\sin(wt - \varphi) \tag{2}$$

$$w = 2\pi f \tag{3}$$

The line cycle period, *T,* is the inverse of the frequency (4).

$$T = \frac{1}{f} \tag{4}$$

Figure 1 shows a graphical representation of sinusoidal voltage and current signals with a $\pi/4$ phase shift between them. In this figure it is possible to see the amplitude and the period designated in boldface. In this figure Δt is the time shift between voltage and current signals and is directly proportional to the phase shift (φ). The relation between the time and phase shifts is given by the expression (5).

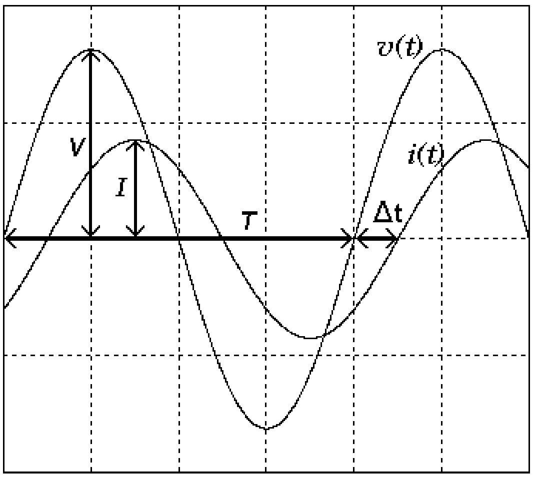

Figure 1. Voltage and current waveforms

$$\varphi = \frac{\Delta t}{T} \cdot 2\pi \tag{5}$$

Electric power (6) is defined as the rate of energy flow from the source to the load at every instant of time [1] and is calculated by the product of the instantaneous values of voltage and current.

$$p(t) = v(t) \cdot i(t) \tag{6}$$

Figure 2 shows the resulting power waveform for the voltage and current waveforms presented in the same figure, where $\varphi = \pi/4$.

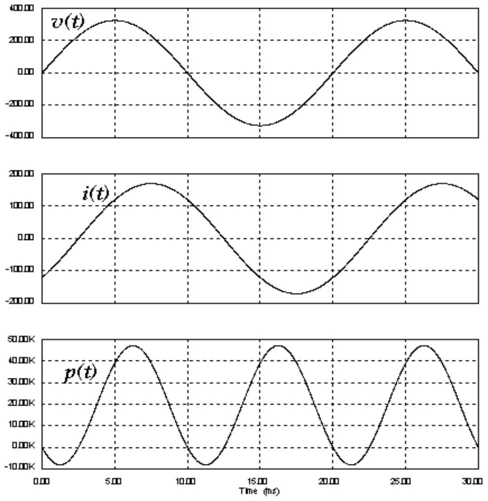

Figure 2. Instantaneous power

According to the definition of electric power, the energy (7) can be achieved by the integration of power with respect to time [1].

$$E = \int p(t) \cdot dt \tag{7}$$

Usually when dealing with electric signals, RMS and average values are used in detriment of instantaneous values. By definition, the RMS value of an AC electric signal corresponds to the average value that causes the same heat dissipation in a fixed resistor. The RMS values of voltage and current are calculated by (8) and (9).

$$V_{RMS} = \sqrt{\frac{1}{T}\int_0^T v^2(t)dt} \tag{8}$$

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} \tag{9}$$

In Figure 3 it is represented the instantaneous value of a sinusoidal voltage and its correspondent RMS value, which is equal to the sinusoidal peak value (V) divided by $\sqrt{2}$.

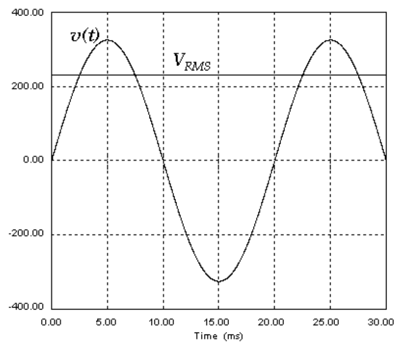

Figure 3. Instantaneous and RMS signals

The active power P corresponds to the average value of $p(t)$ and is achieved by the expression (10). This parameter can be rewritten in terms of RMS values as (11). The reactive power Q is calculated by (12) [1].

$$P = \frac{1}{T}\int_0^T p(t)dt \tag{10}$$

$$P = V_{RMS} . I_{RMS} \cos(\varphi) \tag{11}$$

$$Q = V_{RMS} . I_{RMS} \sin(\varphi) \tag{12}$$

The apparent power, S, is the product of the RMS voltage by the RMS current (13) and can be written in terms of the active and reactive power as (14). The quotient between active and apparent power gives the power factor (15).

$$S = V_{RMS} . I_{RMS} \tag{13}$$

$$S^2 = P^2 + Q^2 \tag{14}$$

$$PF = \frac{P}{S} = \cos(\varphi) \tag{15}$$

In order to simplify electric circuit analysis, a graphical approach based on vectorial representation of the electrical signals can be used. Figure 4 shows the representation of electric power signals in a phasor diagram.

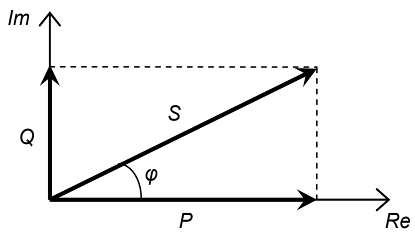

Figure 4. Electric power phasor diagram

2. Operation theory

In the previous heading, the relations between the presented electric parameters were introduced according to the IEEE standard definitions for the measurement of electric power quantities under sinusoidal conditions. In order to develop digital equipment, the analog electrical signals must be sensed, discretized and converted to digital values [2]. This operation is of most importance and requires some precautions. The equipment performance is very dependent on the accuracy of the voltage and current transducers.

In respect to voltage transducers there are two main solutions: resistive voltage dividers and voltage transformers. The first solution is usually the cheapest and with a correct selection of the employed resistors it presents better results. The second solution has the advantage of electrical isolation between the circuit under test and the equipment. The electrical isolation is an important factor for safe measurement of high voltages.

Concerning current transducers there are many options: current shunts are cheap and present good results; current transformers are a good solution that allow electrical isolation and enable the measurement of high current values with low power losses, but do not measure mean component values; Hall effect current transducers are very similar to current transformers with the advantage that they can be used in DC circuits; Rogowski coils also present electrical isolation and they are a good solution to a very large range of currents measurement, but are more expensive.

Normally the transducer prices increase directly with their accuracy. To make the choice of the correct transducer, parameters like the final equipment price, the equipment performance and the application range must be considered.

The equipment performance is also very dependent on the analog to digital conversion. The signal provided by the transducers is continuous in time and it is necessary to convert this to a flow of digital values. The resolution of the converter indicates the number of different discrete values that can be produced over the range of input values. A high resolution conversion means that the digital values are very similar to the analog values at the sample instant. The sampling rate defines the rate at which new digital values are sampled from the analog signal. In Figure 5a) it is possible to see the relation between the original analog signal *v(t)* and the acquired digital signal *v(n)*. In Figure 5b) the same analog signal is acquired with a sampling rate ten times higher. The result is that the digital signal acquired at a higher sampling rate is more similar to the analog signal.

To get a good performance, it is very important to use a high resolution ADC operating at high sampling rates.

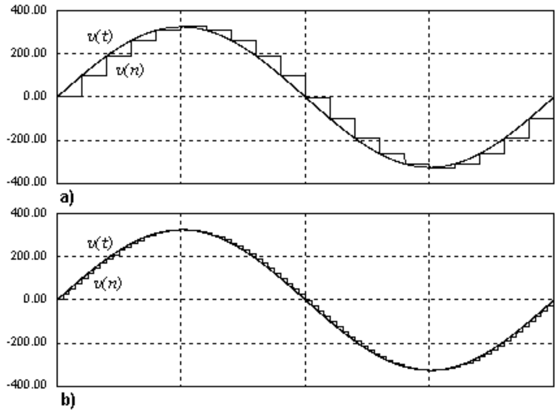

Figure 5. Effects of the ADC sampling rate: a) 1.000 samples/s b) 10.000 samples/s

Based on the acquired signals, the involved integral calculations presented in (8) and (9), are substituted by digital summations, according to the signal sampling rate. Therefore, the RMS values of voltage and current are now obtained by expressions (16) and (17).

$$V_{RMS} = \sqrt{\frac{1}{m}\sum_{n=1}^{m} v^2(n)} \tag{16}$$

$$I_{RMS} = \sqrt{\frac{1}{m}\sum_{n=1}^{m} i^2(n)} \tag{17}$$

According to previous introduced definitions, the instantaneous power corresponds to the product of the instantaneous values of voltage and current (18). The apparent power is achieved by multiplying the RMS values of voltage and current. Active energy and reactive “energy” are obtained by the continuous accumulation of the respective power signals.

$$p(n) = v(n) \cdot i(n) \tag{18}$$

The line cycle period is achieved by measuring the time between consecutive zero cross detections.

3. Developed equipment

In Figure 6 it is possible to see a photo of the laboratorial prototype of the developed equipment.

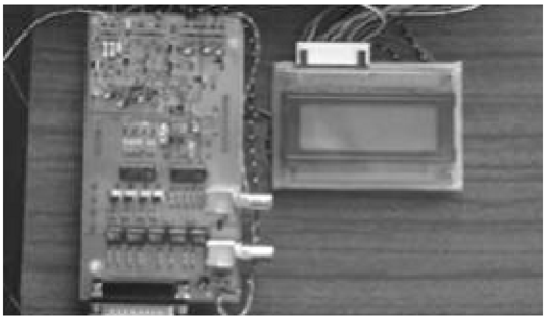

Figure 6. Digital energy meter prototype

The main device of the equipment is the microcontroller. It is responsible for the coordination of all other components. First the microcontroller executes the operations that allow the acquisition of the electrical signals to be measured. To perform this operation two high speed sigma-delta 16 bits ADCs are used to convert the signals obtained by the voltage and current transducers. After this operation, the microcontroller executes the necessary calculations to obtain the desired parameters, and finally performs the numeric to character data transformations to place the results in the LCD (Liquid Crystal Display) display. In Figure 7 it is possible to see a photo with the parameters that are presented in the LCD during normal operation.

Figure 7. Data presented in the display

In order to allow the interconnection with other computerized devices the equipment has a serial communications port. The implemented communication protocol allows two main operations: a calibration procedure and data polling. When in calibration mode, the microcontroller disables the normal operation of the equipment and allows read and write operations to the calibration registers. These registers are physically implemented in an internal EEPROM and allow the non volatile storage of gains, offsets and other constants necessary to normal operation mode.

When in normal operation, if the equipment receives a data request, an interruption is generated and the microcontroller responds immediately with the requested data. In Figure 8 is represented a communication frame according to the implemented protocol.

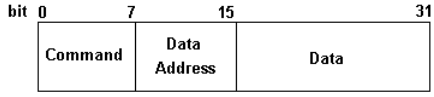

Figure 8. Communication frame

The field “Command” is used to indicate the operation that the microcontroller must execute. The field “Data Address” is used to select the parameter that is involved in the operation. Finally the field “Data” contains the information that affects the selected parameter. The “Data” field is ignored if no data is requested by the “Command” operation.

4. Conclusions

This paper presents a low cost Digital Energy Meter that allows the measurement of Power, Energy and RMS values of voltage and current. The equipment is based on a microcontroller that controls the signal acquisition and presents the measured parameters through an LCD display. In order to allow initial calibration and communication with other computerized devices the equipment has an available serial port.

In comparison to other measurement instruments the developed meter shows good results.

5. Acknowledgements

This work was supported by the FCT (Fundação para a Ciência e a Tecnologia), project funding POCTI/ESE/41170/2001 and POCTI/ESE/48242/2002. The authors are also grateful to PRIME (Programa de Incentivos à Modernização da Economia) for funding the Project SINUS.

9. References

[1] IEEE Power Engineering Society, “IEEE Trial-Use Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions”, 2000.

[2] G. N. Stenbakken, "High-Accuracy Sampling Wattmeter", *IEEE Transactions on Instrumentation and Measurement,* vol. 41, no. 6, pp. 974- 978, December 1992.