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An advanced energy/power meter based on ARM microcontroller for smart grid applications

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Abstract- The Smart Grids are an electricity delivery system which monitors, protects and optimizes the operation of its interconnected elements from end to end. They include central and distributed renewable energy generators through the electrical network. Thus, it can easily be argued that they are characterized by great issues to manage the whole system and to assuring a proper energy quality. In this scenario the possibility to have advanced power/energy meter with energy quality monitoring and communication capabilities is of great interest. So, in this paper the design and implementation of a wattmeter for single phase electrical systems based on an ARM microcontroller is presented. The wattmeter is composed of measurement transducers (for voltage and current), conditioning, acquisition, processing and communication sections; the last three are embedded in the microcontroller. Other than typical wattmeter tasks, the system is capable to measure some power quality parameters. Moreover communication is performed through an USB based transfer block to an Host Pc, through which it can be configured. Even if it is designed to respect on-line measurement constraint, it remains a low cost system. In the paper experimental results related to characterization are also described.

I. Introduction

Electrical energy measurement plays a crucial role not only in commercial energy transactions but also in the estimation of energy balances in industries and in the performance evaluation of machines and energy systems, both traditional and innovative. With the integrated quality certification of the electrical services the possibility to stipulate contracts for quality for the customers has been introduced. This implies the fixation of an agreed level of quality ("Custom Power"), an annual fee on the back of the customer and a reimbursement in favour of him in the case when the level of quality has not been respected.

This requires on-line determination of energy flows and a corresponding level of quality. In order to reach this goal, digital signal processing techniques can be adopted; these techniques are commonly used in today's instrumentation world, both in the scientific and industrial fields. They are mainly based on the application of mathematical operations. Most measurement algorithms, such as the discrete Fourier transform, digital filtering, or adaptive signal processing, require the extended use of arithmetic operations.

Moreover digital processing of physical-world signals requires their conversion into digital format which can be carried out by analog to digital converters (ADC). Measurement of energy flows also requires synchronous conversion of voltage and current signals. So at least two S&H and one ADC or two S&H and two ADC have to be used, in order to avoid phase errors between signals. Other requirements for such systems are portability, communication capability, to transfer or view the measurement results and the low cost, to the aim to have a spread diffusion ([1]-[3]).

Instruments for on-line measurements are characterized by an absolute time constraint to complete input, processing and output operations, which must not be exceeded. They are specifically designed to reduce:

– the time spent by the data acquisition system (DAS) to acquire the input signal;
– the time spent by the microprocessor to process data;
– the time spent by the communication interface to transfer measurement results.

Data processing time mainly depends on the required parameters, that is, on the adopted measurement algorithm and on processor performance. A suitable platform for these applications is the microcontroller, thanks to its special architecture that integrates microprocessor, permanent memory, volatile memory, I/O pins, and devices such ADCs, communication interfaces, DMA, etc. Unlike microprocessors (general purpose) a microcontroller is designed for maximum self-sufficiency and optimizing price-performance ratio for a specific application.

In this paper the design and implementation of a microcontroller based wattmeter, with the on-line measurement constraint. Other than typical quantities measured by a wattmeter, it can also evaluate harmonic distortion.

In section II there is the description of the realized measurement instrument, its hardware architecture and measurement algorithm. In section III experimental results are presented.

II. Measurement Instrument

The greatest difficulty for the designer of instrument for on-line applications is that the DSP overall computing power may be not high enough to satisfy the time constraints. In fact, apart from the DSP throughput, it must be also considered if the specific requirements, in terms of data flow, can be ensured by the memory and I/O architectures. Some devices are optimized to work with on-chip memory, even if it is always strictly limited.
Through a suitable policy for memory management and using devices such as "Direct Memory Access" (DMA), microprocessor has only to deal with measurement algorithm. This reduces processing time, increases performances, without loss of samples, keeping on-line constraints.

A. Hardware Architecture

Embedded system architecture is shown in Fig. 1. Voltage and current transducers are, respectively LEM LV25-P and LA25-NP. Conditioning section adapts the signals to the input range of the microcontroller.
Devices such ADCs, S&H, DMA, μP, Memory, Communication interface USB, are enclosed in a single chip. This chip is microcontroller STM32F103RB, of ARM family.
The STM32 is based on the Cortex-M3 profile, which is specifically designed for high system performance combined with low power consumption. The heart of the STM32 is the Cortex-M3 processor. The architecture of the microcontroller is shown in Fig. 2. The Cortex M3 processor is a standardized microcontroller including 32 bit CPU, bus structure, nested interrupt unit, debug system and standard memory layout. The Cortex processor benchmarks give a performance level of 1.2 DMIPS/MHz, which is 1.2 Clock cycles per instruction. The STM32 operates up to CPU clock speeds of 72MHz, it offers FLASH ROM sizes up to 128K (Program) and 20K SRAM (Data), Dual 12bit ADC with input range of 0÷3.3 V, general purpose timers, I^2C, SPI, CAN, USB and a real-time clock. The STM32 is composed of the Cortex core which is connected to the FLASH memory by the dedicated Instruction bus. The Cortex Data and System busses are connected to a matrix of ARM Advanced High Speed Busses (AHB). The internal SRAM is connected directly to the AHB bus matrix as the DMA unit. The peripherals are located on two ARM Advanced Peripheral Busses (APB). Every APB bus is bridged onto the AHB bus matrix. The AHB bus matrix is clocked at the same speed as the Cortex core. However, the AHB busses have separate prescalers and may be clocked at slower speeds to conserve power. It is important to note that APB2 can run at the full 72MHz while APB1 is limited to 36MHz. Both the Cortex and the DMA unit can be bus masters. Because of the inherent parallelism of the bus matrix, they will only arbitrate if they are both attempting to access the SRAM, APB1 or APB2 at the same time. However, the bus arbiter will guarantee 2/3 access time for the DMA and 1/3 for the Cortex CPU. Microcontroller is a programmable system according to the specific application. STM32 can be programmed entirely in C++ code through development environments which allow debugging by JTAG interface. After Reset STM32 is able to work autonomously, being a stand-alone system.

B. Microcontroller management

In signal acquisition two ADCs with two S&H have been used. ADCs have been programmed to make simultaneous acquisition, thus no phase errors between voltage and current signals are encountered (Fig. 3).
After every single conversion cycle, ADC1 (Master) sends an interrupt to DMA device, which will transfer both ADC1 and ADC2 samples from "ADC1 Data Register" to a memory buffer. DMA fills this buffer in a circular mode (at the end of buffer, transfer continues starting all over again). Moreover it sends two interrupts to CPU, called "Half_Buffer" and "Buffer_Full", so in its service routine, CPU can always process half buffer avoiding loss of samples.
Sampling frequency and buffer length have been chosen according to the available SRAM (20 KB) and processing time, in order to respect on-line constraint. Therefore sampling frequency has been chosen as $F_S \cong 8.9\ kHz$ and buffer length as 2200 samples. Moreover it has been taken into account that [4] and [5] prescribe that an instrument for power quality measurements must synchronize with electrical system frequency in the range of 42.5 ÷ 57.5 Hz. CPU is programmed to process, every step, five periods of voltage and current: 1100 samples, i.e. half buffer, at 8.9 kHz corresponds to a little more than five cycles of a 42.5 Hz frequency signal. In this way, in a half buffer, five periods of voltage and current are always contained. So the time between two interrupts (Half – Full or Full – Half), i.e. acquisition time, is $T_A > 0.1s$. With the chosen sampling frequency, processing time $T_P < T_A$ and thus the constraint of on-line processing is respected.
Measurement results can be transferred to Host Pc via USB interface. Three communication channels called "Endpoint" have been used:

- ENDP0: used for connection to the Host and device acknowledgement.
- ENDP1 and ENDP2: used for data transferring "Device to Host" and "Host to Device" respectively.

STM32 has a 512 bytes memory area (PMA) reserved for USB-controller. The interface between µP and USB-controller is APB1 bus. For example, if a transfer "Device to Host" has to be made, data are transferred to PMA to the ENDP1 address, then "Serial Interface Engine" (SIE), which performs transfers to Host-PC, is enabled.

C. Measurement Algorithm
The microcontroller is programmed to measure:

- Frequency;
- Voltage and Current root mean square (rms) values (V_{RMS} and I_{RMS});
- Active (P) and Apparent (S) Powers and Power Factor (PF);
- Voltage and Current Total Harmonic Distortions (THD_V and THD_I).

Frequency is measured evaluating zero crossings of voltage signal, after that the DC component, added by conditioning stage, has been cancelled. V_{RMS}, I_{RMS}, P, S and PF are calculated as it is prescribed by [6]. THD_V and THD_I are evaluated from Fast Fourier Transform (FFT) of voltage and current signals, after that they are resampled to analyze a number of samples equal to 256, i.e. a power of 4.
In the **Errore. L'origine riferimento non è stata trovata.** a flow chart of the implemented algorithm for measurement and transfer is shown:

III. Experimental Results

In order to prove reliability of the implemented instrument some experimental tests have been performed. These tests have been carried out without sensing and conditioning sections, using as reference values the measurement results of a PXI platform with high performance data acquisition system.
The first test has been aimed to verify performance of AD converters. Eleven dc values have been generated in the input range of the ADCs, i.e. 0÷3.3 V, and the mean relative deviations with respect to full scale (F.S.) range have been measured. The results are shown in Fig. 5: deviations are included in the range -0.1÷0.7 %.
Linear characteristics in almost all of voltage range is shown. Only around 0 V, ADCs transfer characteristics is not linear. However, according to IEC 61000-4-30, the peak voltage must be equal to half of full scale: voltage range in which ADCs have to work is $\Delta V = 1.65 \pm 1.65/2 = 0.825 \div 2.475\ V$. So, in order to compensate ADCs gains and offsets, ADCs transfer characteristics have been fitted with linear functions considering only input range of the ADCs 0.33÷3.3 V. The results are shown in Fig. 6: deviations are included in the range -0.01÷0.01 %.The corrected sample values are therefore used to calculate all the measurement quantities.
In the second test, RMS voltage and current, active power, apparent power and frequency measurements have been verified. Sinusoidal waveforms, with frequency in the range of 42.5÷57.5 Hz and peak-to-peak amplitudes of 1.65 V, have been generated. The results of frequency deviation are shown in Fig.7. In the same figure the range of standard deviation is also shown: it is included in the range of ±0.07 %. Deviations on measurement of V_{RMS}, I_{RMS}, P, S, with relative standard deviations are shown in Fig. 8, Fig. 9, Fig. 10, Fig. 11, Fig. 12: they have been calculated as percentage of instrument full scale; their mean relative deviation are in range ±0.01 % F.S.
In the third test, THD measurement has been verified. Deformed waveforms, composed by two spectral tones have been generated: fundamental harmonic with frequency of 50 Hz and a harmonic with frequency in the range 100÷1250 Hz. Peak-to-peak amplitudes are 1.65 V,. The results of voltage and current THD with relative standard deviations are shown in Fig. 12 and Fig. 13: deviations are included the range of ±0.2 %.
In the fourth test, THD_V, THD_I, V_{RMS}, I_{RMS}, P, S and frequency measurements in distorted conditions have been verified. Distorted waveforms, composed by a fundamental harmonic component with frequency in the range of 42.5÷57.5 Hz and peak amplitude to 0.825 V, and third harmonic component with peak amplitude of 10% of fundamental harmonic (0.0825 V) have been generated. The results of frequency deviation are shown in Fig.14 . in the same figure the standard deviation, included in the range of ±0.3 %, is also shown. The results of V_{RMS}, I_{RMS}, P, S measurements are shown in Fig. 15, Fig. 16, Fig. 17: they have been calculated as percentage of instrument full scale.

IV. Conclusion

In the final paper a wattmeter based on an ARM microcontroller will be presented. It is composed of measurement transducers (for voltage and current), conditioning, acquisition, processing and communication sections; the last three are embedded in the microcontroller. Other than typical wattmeter tasks, the system is capable to measure some power quality parameters. Moreover communication is performed through an USB based transfer block to an Host Pc, through which it can be configured. Even if it is designed to respect on-line measurement constraint, it remains a low cost system. Experimental characterization has proven its reliability even in distorted operating conditions.

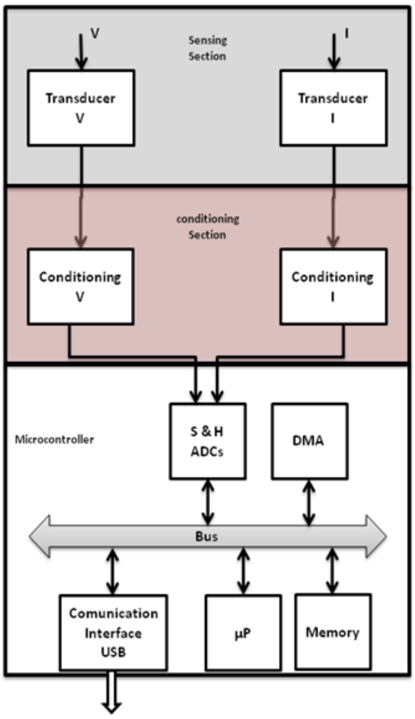


Figure 1. Architecture of the realized system.

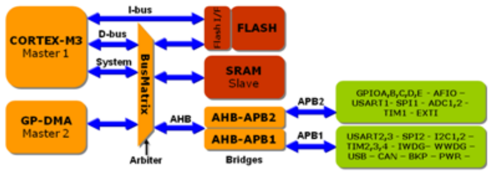


Figure 2. Architecture of the STM32 microcontroller.

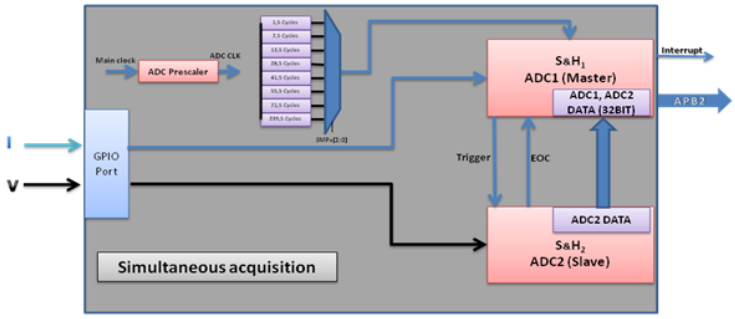


Figure 1. Block scheme of the acquisition section.

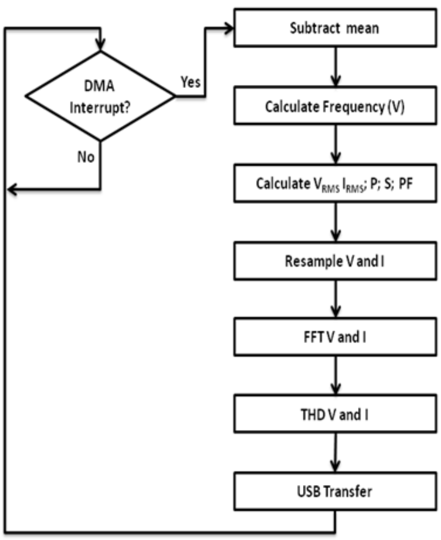


Figure 2. Flow chart of the measurement algorithm.

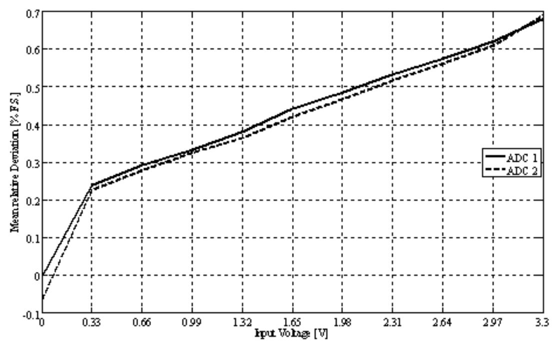
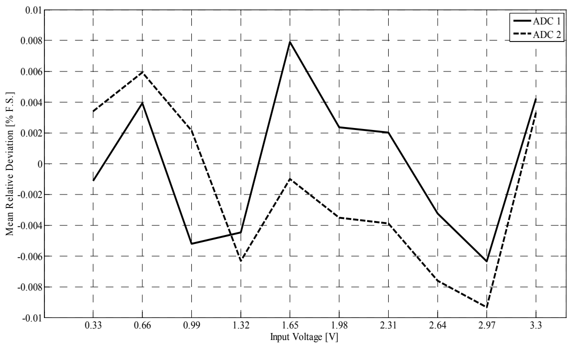


Figure 3. Static characteristics of the two ADCs of the microcontroller



. Figure 1. Static characteristics of the two ADCs of the microcontroller after Fitting

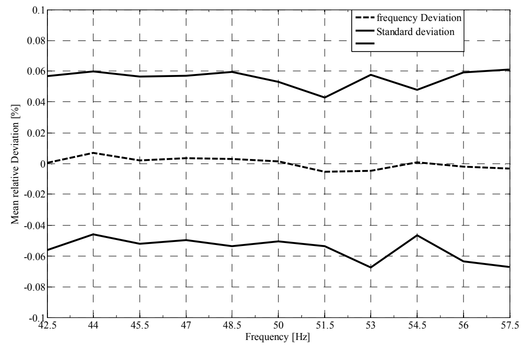


Figure 2. Mean relative deviation on frequency measurement.

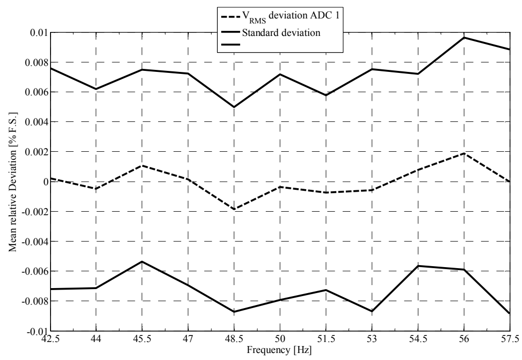


Figure 3. Mean relative deviation on V_{RMS} measurement

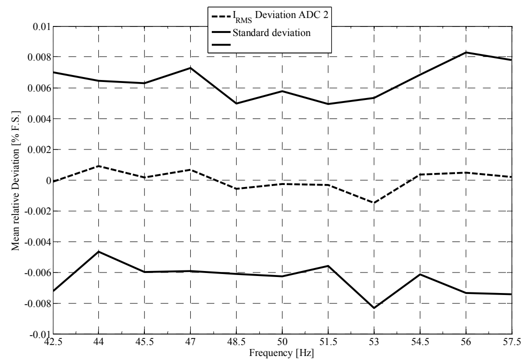


Figure 4. Mean relative deviations on I_{RMS} measurement

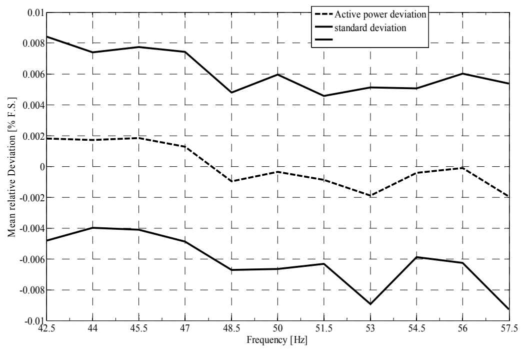


Figure 5. Mean relative deviations on active power measurement

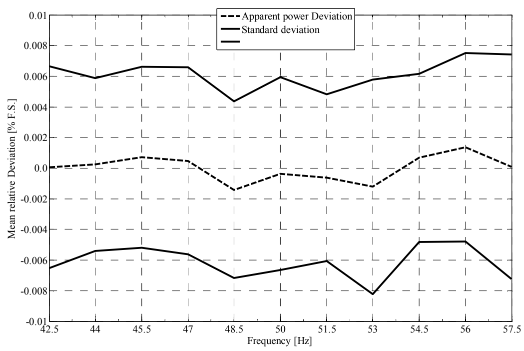


Figure 6. Mean relative deviations on apparent power measurement

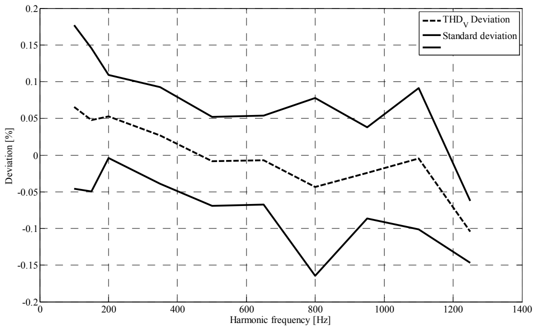


Figure 7. Mean deviations on THD_V measurement

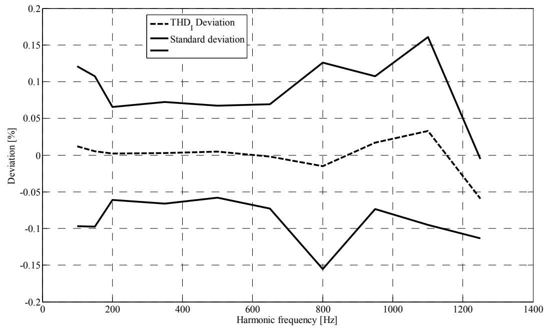


Figure 8. Mean deviations on THD_I measurement

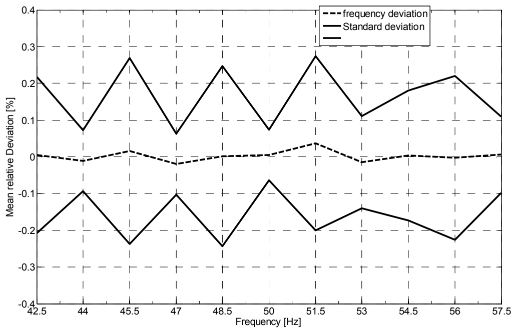


Figure 9. Mean relative deviations on frequency measurement

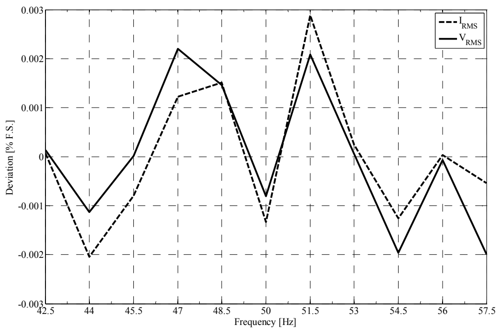


Figure 10. Mean relative deviations on V_{RMS} and I_{RMS} measurement

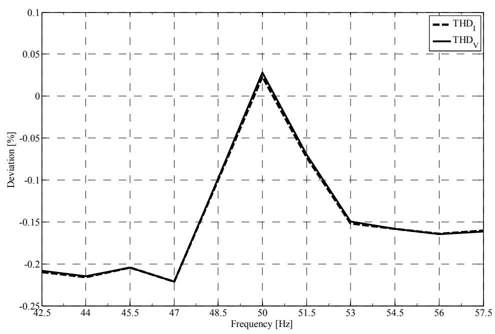


Figure 11. Mean deviations on THD_V and THD_I measurement

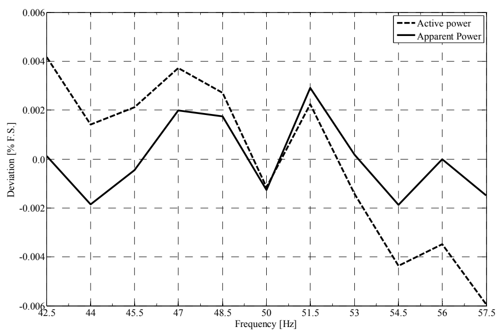


Figure 12. Mean relative deviations on active and apparent power measurement

References

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