Techniques for Efficient Implementation of Firmware in Microcontroller's Based Energy Consumption Breakdown Smart Meters

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Abstract

We present in this paper the firmware of a residential power meter capable of measuring the total energy consumption and the electrical parameters needed for power consumption breakdown. The developed system is capable of measuring the active, reactive and apparent powers, power factor, rms voltage, rms current and the first five odd harmonics in current signal. Thanks to the use of advanced embedded systems programming techniques and right design decisions, we developed a high-precision, low-power and low-cost smart meter using a low-cost microcontroller. The smart meter can calculate all the electrical parameters for each power line cycle (16.67 ms), enabling its use for transient analysis.

Keywords - Harmonics, Smart Meter, Algorithms, Microcontroller

Introduction

According to the American Council for an Energy-Efficient Economy – ACEEE, the energy consumption increases around 1% per year (York *et al.*, 2013). This is a worrying fact, since 80-90% of this energy is generated from fossil fuels combustion (Solomon, 2007), what causes a number of environmental problems. Seeking to change this scenario, utilities and governmental agencies all around the world have been implementing over the last thirty years (most significantly in the last decade) energy efficiency programs. These programs aim to develop solutions that help customers to manage the energy use and save money on their energy bills (Duarte *et al.*, 2012).

It has been shown that the effectiveness of an energy efficiency program depends strongly on the feedback that the consumers receive about their energy use. A good knowledge of where the energy is going is fundamental for the customers to decide how it is possible to reduce energy waste and to maximize energy bill savings. This fact was confirmed by a research conducted during 15 years (1995-2010) in several countries by ACEEE (Ehrhardt-Martinez *et al.,* 2010). The result indicates that real-time information of the energy consumption per appliance culminates in savings up to 12%. Another recent study indicates that information in real-time results up to 19.5% savings, average of 3.8% (York *et al.*, 2013).

Many smart metering solutions that allows energy consumption breakdown through single point measurement, known as Non-Intrusive Load Monitoring Systems – NILMS, has been proposed. These systems are composed of two basic components: the measuring module (smart meter) and the load discrimination algorithm. The data acquired by the smart meters is send to the discrimination algorithms that perform the energy breakdown based on the principle of load signature.

Load signature is defined as a set of distinct electrical characteristics that can be used to identify a load. Almost all electrical parameters derived from voltage and current waveforms can be treated as load signatures. The most used are the power (active, reactive and apparent), power factor, the rms voltage, rms current and the odd harmonics of the current signal (Bouhouras *et al.,* 2012; Baranski and Voss, 2004; Srinivassan *et al.,* 2006; Patel, 2007; Chang, 2012; Moro *et al.,* 2013; Huang *et al.,* 2011; Chang *et al.,* 2012; Liang *et al.,* 2010).

The smart meter is a critical part of the NILM systems. An accurate measurement of the electrical parameters needed for NILM systems is essential for their performance (Bouhouras *et al.,* 2012). Therefore, for the evolution of the NILM systems, it is mandatory the evolution of the monitoring modules.

A variety of equipment can be used for measuring the electrical parameters used in NILM systems. In Baranski and Voss (2004) the authors used commercial electronic power meters to obtain the active power. In Srinivassan *et al.* (2006), a harmonic analyzer was used for acquiring the harmonic components of the current signal. In Bouhouras *et al.* (2012), a three-phase power quality recorder was used to measure the harmonic components of the current signal. An oscilloscope and a Data Acquisition Module (DAQ) was used in Patel (2007) to obtain the frequency spectrum of the current signal. In (Chang, 2012) the author used an oscilloscope to sample the voltage and current curves and post process them in a Matlab script. In Moro *et al.* (2013) the author used an energy meter IC to measure the active and apparent power in a circuit. The smart meter proposed in Huang *et al.* (2011) was build using a microcontroller. It is capable of calculating the real and reactive powers, and 2nd and 3rd harmonics of the current signal.

Each of these approaches have advantages and disadvantages. Electronic power meters are easy to install, but can measure only the active power. Power quality recorders, harmonic analyzers, oscilloscopes and DAQs can measure a large number of electrical parameters; however, due to the high cost and physical dimensions they are suitable only for laboratory experiments. Energy metering ICs present low cost and small size, but they are not flexible regarding the electrical parameters which can be measured.

Many energy metering ICs (for example, the ADE7763 from Analog Devices and the CS5463 from Cirrus Logic) can be used for measuring voltage, current, active, reactive and apparent power and power factor. Some more complex ICs, such as the ADE7880 from Analog Devices are also capable of measuring the harmonic in the voltage and current (Analog devices, 2011). However, these circuits can measure only the magnitude of the harmonics; they do not get phase information. As harmonics are complex numbers, the magnitude and phase information are needed for the breakdown algorithms.

The smart meters based on microcontrollers, are in general cheaper, can be small, and allows the designer to choose which electrical parameters will be measured. Moreover, unlike energy metering ICs, microcontrollers can be programed to measure module and phase of the harmonics.

We developed a smart meter capable of measuring all the electrical parameters needed for NILM systems. The smart meter was developed using a low-cost microcontroller, the MSP430AFE253 from Texas Instruments. The firmware of this smart meter will be presented in this paper.

Electrical Parameters

The proposed smart meter is capable of measuring the active, reactive and apparent powers, power factor, voltage and current and the first five odd harmonics in current signal. In this section, we present the formulas used to calculate these electrical parameters.

The effective voltage is calculated using the following equation:

$$V_{RMS} = \frac{G_v}{N}\sqrt{\sum_{n=1}^{N} v[n]^2} \quad \ldots (1)$$

Where V_{RMS} is the rms voltage, G_v is the voltage gain, n is the sample index, $v[n]$ is the nth voltage sample and N the sample number. The rms current is obtained by an analogous equation.

Equation (2) is used to calculate the active power.

$$P = \frac{G_i * G_v}{N}\sum_{n=1}^{N}(i[n] * v[n]) \quad \ldots (2)$$

In this equation, P is the active power value and G_i and G_v are, respectively, the current and voltage gains.

The apparent power is calculated from the effective values of voltage and current using Equation (3):

$$S = V_{RMS} * I_{RMS} \quad \ldots (3)$$

The reactive power is calculated from the active and apparent powers using Equation (4):

$$Q = \sqrt{S^2 - P^2} \quad \ldots (4)$$

The power factor corresponds to the ratio of active power by the apparent power, as shown in Equation (5):

$$PF = \frac{P}{S} \quad \ldots (5)$$

The effective values of the harmonic components of the current signal are calculated using a formula based on the classical equation of the Discrete Fourier Transform, presented in Equation (6):

$$|I[k]_{RMS}| = \frac{\sqrt{Re\{I[k]\}^2 + Im\{I[k]\}^2}}{N} * G_i * \sqrt{2} \quad \ldots (6)$$

The phase is calculated using Equation (7):

$$\angle I[k] = \mathrm{arctang}\left(\frac{Im\{I[k]\}}{Re\{I[k]\}}\right) \quad \ldots (7)$$

Where k is the index of the harmonic component, $|I[k]_{RMS}|$ is the rms value of the module of the kth harmonic, $\angle I[k]$ is the phase of the kth harmonic and $Re\{I[k]\}$ and $Im\{I[k]\}$ are, respectively, the real and imaginary parts of the kth harmonic component. Equations (8) and (9) present the formulas used to calculate $Re\{I[k]\}$ and $Im\{I[k]\}$.

$$Re\{I[k]\} = \sum_{n=1}^{N} i[n] * \cos\left(\frac{2\pi kn}{N}\right) \quad \ldots (8)$$

$$Im\{I[k]\} = \sum_{n=1}^{N} i[n] * \mathrm{sen}\left(\frac{2\pi kn}{N}\right) \quad \ldots (9)$$

Power Meter Firmware

Observe that, except equation (3), (4) and (5), the other equations presented have a summation term. Observe also that the calculation of the electrical parameters can be separated in two steps: (i) calculation of the summation terms and (ii) calculation of the electrical parameters from the accumulators. Figure 1 presents the flowchart of the algorithm used to calculate the electrical parameters. This algorithm is the core of the smart meter firmware.

The smart meter firmware is divided into two parts: Initialization and Infinite Loop. The procedures present in the Initialization are executed only once, after the system is powered on, and only run again if the microcontroller restarts. The procedures described in Infinite Loop are periodically and indefinitely executed. The electrical parameters are calculated at this stage.

The first task performed in the Initialization phase is the hardware configuration. The microcontroller's hardware (clocks, inputs/outputs, A/D converters, SPI communication, flash memory, watchdog, etc.) is set up at this moment.

The smart meter uses two A/D converters, one for voltage and other for current sampling. These converters were configured to sample at a frequency of 1.92 kS/s, resulting in 32 samples in one cycle of a 60 Hz power line. Both the voltage and current converters were configured to perform the conversions at the same instant. An interruption is generated at the end of the conversions.

After all the hardware is configured the A/D converters are started and the program runs in an infinite loop. This loop runs periodically in the frequency of A/D converter (1.92 kHz). When an A/D conversion is complete, an interruption is generated and the voltage and current samples are processed.

As explained before, the parameters are calculated in two phases: first, the voltage and current samples are processed and stored in accumulators. Then, when an entire power line cycle is sampled, the electrical parameters are calculated from the accumulators. The left side of the flowchart corresponds to the summation processing, and the right side of the flowchart shows calculation of the parameters values.

In the microcontroller implementation, the left side of the algorithm is performed between two consecutives A/D conversions. The code that implements this algorithm runs in the A/D conversion interrupt routine, and has the biggest priority in the program. This code is executed in approximately 320 µs. Since the A/Ds run at 1.92 kS/s, the time between two conversions is 521 µs. The remaining 201 µs seconds are used to calculate the parameters (right side of the flowchart). This code runs in background and is preempted when an A/D conversion occurs. The parameters calculation must be finished before 16.67 ms, when a new power line cycle starts being sampled.

Legend

I : current sample
V : voltage sample
N : number of samples in a mains cycle
n : sample index
I_accum : current accumulator
V_accum : voltage accumulator
P_accum : active power accumulator
K : the higher harmonic calculated
k : harmonic index
Ir_accum[]: harmonic real part accumulator
Ii_accum[]: harmonic imaginary part accumulator
Irms : rms current
Vrms : rms voltage
P : active power
Q : reactive power
S : aparente power
PF : power factor
IM[] : harmonic magnitude
IF[] : harmonic phase
I_gain : current gain
V_gain : voltage gain

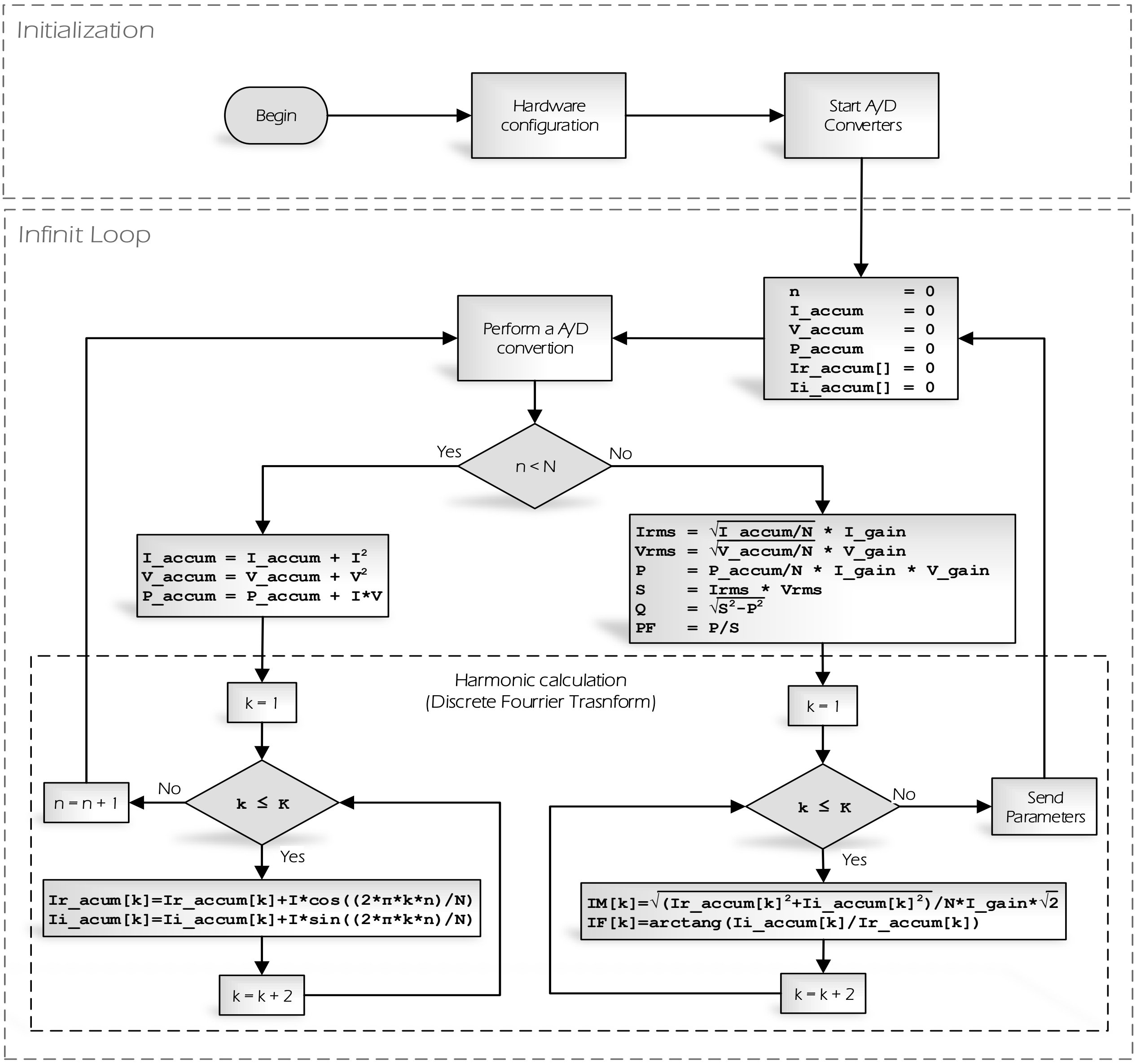

Figure 1: Smart Meter algorithm.

Efficient Calculation of the Electrical Parameters in MSP430AFE253 Microcontroller

As could be seen in the previous section, the execution time is a scarce resource in the proposed system. Thus, some design decisions and programming techniques had to be used in order to make possible calculate all electrical parameters uninterruptedly. These design decisions and techniques are discussed in this section.

Most of the firmware was implemented using fixed point variables. Fixed point programs are considerably faster than float point programs, at least in low-cost microcontrollers that has no dedicate hardware for float point operations. To get an idea of the performance gain, consider the multiplication operation in the MSP430AFE253 microcontroller. A multiplication of two floats takes 395 clock cycles, while an integer multiplication using the hardware multiplier consumes only eight cycles (Texas instruments, 2011), about 50 times faster. Considering that the electrical parameter are calculated for each power line cycle (16.67 ms), and that the computation of each parameter requires at least 32 multiplication operations, the use of integer variables instead of floats results in a considerable reduction in the execution time.

The MSP430AFE253 contains three independent A/D converters that can operate with 24 bits resolution each. In this project two A/Ds were used, one for voltage and other for current sample. Both converters were configured to operate with 16-bit resolution. Since the MSP430 has a 16-bit architecture, the use of variables larger than 16 bits makes the firmware execution slower. Moreover, with 16 bits of precision is possible to measure, for example, voltages up to 250 VRMS with 7.6 mVRMS resolution and currents up to 100 ARMS with 3.1 mARMS resolution.

The current harmonics calculation is done using the Discrete Fourrier Transform (DFT) formula, unlike (Bouhouras *et al.,* 2012; Baranski and Voss, 2004; Srinivassan *et al.,* 2006; Patel, 2007; Chang, 2012; Moro *et al.,* 2013; Huang *et al.,* 2011) that used FFT algorithms. The DFT equation, despite having bigger computational complexity than FFT algorithm, can be used to calculate a few points of the frequency spectrum, while FFT algorithms can be used only to calculate the full spectrum. Since we are interested only in the 1st, 3rd, 5th, 7th and 9th harmonics, there is no need to calculate the whole spectrum. The execution of the classic DFT formula for these few points is faster than the FFT algorithms. Even the Goertzel algorithm, which can be used to calculate few points of the frequency spectrum, in general, with lower computational cost than the FFT and DFT algorithms, has worse performance than the DFT formula in the MSP430AFE253 microcontroller. As this microcontroller has hardware multiplier, the advantages of the Goertzel algorithm (fewer multiplication operations) does not overcome its disadvantages (highest number of sums, subtractions and assignments).

As can be seen in Equations (8) and (9), the computation of the Discrete Fourrier Tranform requires the sin and cosine values of many angles. Considering the sample rate used, the calculation of one harmonic component requires 32 sin operations and 32 cosine operations. The sin and cosine calculation in embedded systems is done iteratively, using Taylor or Maclaurin series, which are relatively slow. The sin and cosine operations consumes around 5550 clock cycles each (using math.h library of the IAR C/C++ Compiler for MSP430 v5.40.1). Therefore, for the calculation of the first five odd harmonic components, it would be necessary 1,776,000 clock cycles only for the sin and cosine operations. These operations, with the MSP430AFE253 microcontroller running at maximum frequency (16 MHz), would take 111 milliseconds. To solve this problem, the values of sins and cosines required for calculation of the Discrete Fourier Transform were saved in a lookup table in the program memory. Thus, the calculation of sins and cosines at runtime is not necessary anymore.

Observing Equations (1) to (9), is possible realize that the calculation of most electrical parameters involves a division by the number of samples processed. Since we used 32 samples, a number which is a power of two (25 = 32), we can replace division operations by bit shifting. A division by 32 can be replaced by a five bits right shifting with considerable processing time reduction. In the MSP430AFE253, a division by 32 takes 6500 clock cycles, whereas the same operation performed using bit shifts takes only 50 clock cycles, more than 100 times faster.

Conclusion

Thanks to the programming techniques and design decisions describe in this paper, it was possible to build a smart meter using a simple microcontroller capable of calculating active, reactive and apparent power, power factor, voltage and current and the first five odd harmonics in current signal for each power line cycle (16.67 ms).

References

Analog devices. Polyphase Multifunction Energy Metering IC with Harmonic Monitoring. *ADE7880 Data Sheet*, 2011.

Baranski, M., Voss, J. 2004. Genetic algorithm for pattern detection in NIALM systems. In the proceedings of IEEE International Conference on *Systems, Man and Cybernetics*, 3462 – 3468.

Bouhouras, A.S., Milioudis, A.N., Andreou, G.T., Labridis, D.P. 2012. Load signatures improvement through the determination of a spectral distribution coefficient for load identification. *European Energy Market (EEM), Florence*, 1-6.

Chang, H.H. 2012. Non-intrusive demand monitoring and load identification for energy management systems based on transient feature analyses. *Energies*, (5), 4569-4589.

Chang, H.H., Chen, K.L., Tsai, Y.P., Lee, W.J. 2012. A new measurement method for power signatures of nonintrusive demand monitoring and load identification. In *IEEE Transactions on Industry Applications*,764-771.

Duarte, I. F. C., Ferreira, E.C., Dias, J.A.S. 2012. Measurement techniques for energy efficiency programs. In Energy efficiency - the innovative ways for smart energy, the future towards modern utilities, Eds. Eissa, M., (1), 193-208.

Ehrhardt-Martinez, K., Donnelly, K.A., Laitner, J.A. 2010. Advanced metering initiatives and residential feedback programs: a meta-review for household electricity-saving opportunities. *ACEEE Report number E105*.

Huang, S.J., Hsieh, C.T., Kuo, L.C., Lin, C.W., Chang, C.W., Fang, S.A. 2011. Classification of home appliance electricity consumption using power signature and harmonic features. In the Proceedings of the 9th international conference on *Power Electronics and Drive Systems*, 596-599.

Liang, J., Ng, S., Kendall, G., Cheng, J. 2010. Load Signature Study—Part I: Basic Concept, Structure, and Methodology. *IEEE Transactions on Power Delivery*, (25), 551 – 560.

Moro, J.Z., Duarte, L.F.C., Ferreira, E.C., Dias J.A.S. 2013. A home appliance recognition system using the approach of measuring power consumption and power factor on the electrical panel, based on energy meter ICs. *Scientific Research Circuit and Systems*, 245-251.

Patel, S.N.E.A. 2007. At the flick of a switch: Detecting and classifying unique electrical events on the residential power line. In the Proceedings of the 9th international conference on *Ubiquitous computing*, 271-288.

Solomon, S. 2007. Climate Change 2007 - The physical science basis. *Cambridge University Press*.

Srinivasan, D. Ng, W.S., Liew, A.C. 2006. Neural-network-based signature recognition for harmonic source identification. *Power Delivery, IEEE Transactions*, (21), 398 – 405.

Texas instruments. MSP430AFE2x3, MSP430AFE2x2, MSP430AFE2x1: Mixed signal microcontroller. *Texas Instruments*, 2011.

York, D., Molina, M., Neubauer, M., Nowak, S., Nadel, S., Chittum, A., Elliott, N., Farley, K., Foster, B., Sachs, H., Witte, P. 2013. Frontiers of energy efficiency: Next generation programs reach for high energy savings. *ACEEE*, 57-66.