Focus on Energy Efficiency Through Power Consumption Disaggregation

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Additional information is available at the end of the chapter

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1. Introduction

According to the American Council for an Energy-Efficient Economy – ACEEE, the worldwide energy consumption increases around 1% per year [1]. This is a worrying fact, since 80-90% of this energy is generated from non-renewable resources [2].

Utilities and government agencies all around the world have been implementing energy efficiency programs over the last thirty years (most significantly in the last decade) in a way to minimize depletion of resources and mitigate environmental impact.

According to [1] the cost of promoting energy efficient programs is about one third of the cost to generate the same amount of energy saved by these programs. Besides the environmental benefits, these programs also culminate in economic profits such as reducing the cost of energy generation, resulting benefits both for utilities and their customers.

An assortment of information technologies, that includes smart meters, is quickly becoming part of these programs [3]. Although those devices do not improve energy efficiency on their own, they are responsible for providing information on ways the household can reduce energy waste and improve energy savings in energy efficiency programs.

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 savings. This fact was confirmed by a research conducted during 15 years (1995-2010) in several countries by ACEEE. The result indicates that the more detailed is the information that the users receive about their energy consumption, the more significant the savings are. A better understanding of where (which device) and when (which period of the day) the energy is being used leads both to reduction of energy consumption and shift the energy consumption from peak periods to off-peak periods [4].

Recent studies have been shown that the most significant savings are achieved by providing to the households real-time information of how much energy each appliance is consuming. That can lead them to reach savings up to 19.5%, with average of 3.8% [1].

Over the last 30 years, researches all around the world has been developing systems, methodologies and algorithms to disaggregate the total energy consumption in order to assist the people on how to increase energy efficiency.

In recent years, several companies have created smart metering solutions that allow discrimination of power consumption and nowadays companies such as myEragy Energy Monitoring, Opower Home Energy Report, Open Energy Monitor, People Power, Smart Energy Groups, ThingSpeak, among others are offering services of smart metering.

(a) (b)

Figure 1. (a) myEragy Energy Monitoring and (b) Open Energy Monitor

These services allow the user to track their residential energy consumption, generate consumption reports and receive information on how they can save energy, but, as for now, despite the wealth of information offered by these services, none informs the individual amount of power consumed by every single appliance in a residence.

Detailed energy consumption information is not only important for customers but for energy service companies (ESCOs) as well. It can be used to resourcefully manage the supply-demand chain and accurately forecast the needs of investments in distribution systems.

Despite the variety of techniques and technologies used, the energy consumption monitoring systems can be divided in two main groups: Plug Level or Decentralized Load Monitoring Systems and Non-Intrusive Load Monitoring (NILM) Systems.

This chapter presents the major concepts of power consumption disaggregation techniques, given special attention to Non-Intrusive Load Monitoring Systems and the concept of Load Signature.

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2. Plug level load monitoring

Plug Level Load Monitoring Systems, Decentralized Load Monitoring Systems, Intrusive Load Monitoring Systems or even Traditional Load Monitoring Systems are the names given to systems in which the power consumption of an appliance is individually measured by a smart meter that connects the appliance to the power outlet. The Plug Level Load Monitoring terminology was chosen to designate this section since the term itself properly illustrates the whole concept.

In this approach, each meter is able to monitor only one appliance at a time; thus, the use on every single appliance in a building turns to be extremely costly to install and maintain, although it is able to precisely provide the power consumption of each monitored load.

It is possibly the simplest way to gather information of the power consumption of an appliance on its own. Yet, this approach can still be a good option in cases where the information regarding the power consumption of a building doesn't need to be exceptionally detailed and/or when focusing on the power consumption of only a few targeted loads aggregates enough information for the household.

There are many power meters for plug level load monitoring available in the market. Even though the majority of these meters only present the power consumption of the monitored appliance on a LCD display, models like “Watts up? Pro” [5] can record the power consumption over time and then send the data to a computer via USB, while other models like “Watts up?.Net” [6] allow the recorded data to be reached via wired Internet. There are also models that send the data wirelessly to a central device that shows the information on a LCD display, like the “Kill A Watt CO2 Wireless” [7], and even make the information available to a computer wirelessly connected via Wi-Fi, like the “Ecobee Smart Plug” [8].

Figure 2. (a) Watts up? Pro, (b) Watts up?.Net, (c) Kill A Watt CO2 Wireless and (d) Ecobee Smart Plug.

Researches in this field show that different types of Wireless Sensors Network (WSN) can be used to improve plug level load monitoring. It facilitates the data retrieve process, saves time and eliminates reading errors. The most used wireless communication protocol in this area is the ZigBee /IEEE 802.15.4, followed by Wi-Fi/IEEE 802.11; notwithstanding, hybrid networks can also be found in the literature as presented by [9] in which the use of ZigBee along with Power Line Communications (PLC) is shown.

In the end of the process, regardless of the communication method adopted to retrieve the information from the sensors, a computer application is used to process the data and report it to the user.

3. Non-intrusive load monitoring

Non-Intrusive Load Monitoring (NILM) is a term widely spread in the literature to address systems that are able to quantify the energy consumption of more than one appliance by measuring the power consumption at the utility service entrance or at the circuit box. It is also known as Non-Intrusive Appliance Load Monitoring (NALM / NIALM). The terminology comes from the fact that no access to the individual components is necessary for installing sensors or making measurements [10]. Since the technique uses only one power meter at the entrance or just a few power meters after the circuit breaks it is also called Centralized Load Monitoring and Building Level/Circuit Level Load Monitoring.

This approach is in general cheaper and easier to install and maintain than the intrusive ones [11-14]. However, NILM systems are, for now, unable to identify the power consumption of loads that exhibit non-discrete changes in the power and larger oscillations in the steady state, as some fluorescent lamps, refrigerators, AC variable speed drivers and other non-linear loads [15].

NILM systems perform the power consumption disaggregation based on the concept of load signature. Load signature consists in a set of characteristics regarding its electrical consumption behavior that are unique for each load. Almost all electrical parameters derived from voltage and current waveforms can be considered load signatures. Active power, reactive power, apparent power, power factor, rms voltage, rms current are the most commonly used parameters adopted to distinguish the loads. These parameters can be represented in the time domain, in the frequency domain, or even mathematically in terms of wavelets and, eigenvalues or singular value decomposition (SVD). Since every load has got a distinct electrical characteristic, by measuring and comparing these parameters, the system is able to recognize the loads in the circuit.

Regardless of the method used to represent the signatures, the recognition algorithm can operate considering the transient characteristics (the period of time in which the load is turned on or off), the steady state characteristics, or a combination of both.

The first NILM system was proposed in the 80's by MIT researchers [10]. Although the simplicity of the proposal compared to recent works, it is quite useful for exemplifying the use of load signatures in load identification. In the developed technique, the operating schedules of individual loads were determined by identifying the instants where the power consumption changed from one steady state to another. These steady-state changes, known as events, correspond to the load either being turning on or off, and can be characterized by the magnitude and sign of active and reactive power values. In this approach, only the steady state brings the useful information and therefore the transients are eliminated in the analysis. A database of the operating schedules of each load must be obtained prior to the load identification. Figure 3 shows the power consumption curves of a refrigerator and a microwave oven, where two distinct signatures are overlapped. Knowing the frequency of each on and/off event and the magnitude of the power steps it is possible to identify when the refrigerator and the microwave oven are on in each instant and consequently determine the total energy consumption of each one.

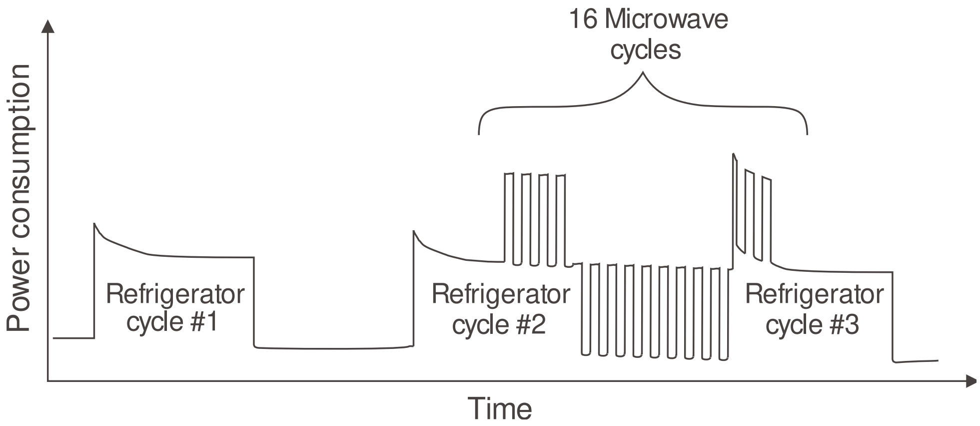

Figure 3. Characteristic signatures of a refrigerator and a microwave measured on the same circuit [16].

This method does not allow load identification in several cases: (i) when there are loads that overlap ambiguously in the ΔP-ΔQ plane, (ii) when two or more loads are switched on/off simultaneously, (iii) when the load is switched on/off faster than the power meters can capture the steady-state, and (iv) when a new appliance, not referenced in the database, is used [17].

In the 90's researchers introduced transient event detection to non-intrusive load monitoring. The MIT PhD thesis defended in 1993 [11] proposed a prototype of a multiscale event detector for residential NILM implemented in a digital signal processor. This system uses transient characteristics in the real and reactive power signature space to differentiate the loads. The paper in [18] presents a NILM for commercial buildings based on steady-state and transient load-detection algorithms. The developed prototype is able to differentiate appliances with near-simultaneous start-ups and similar power levels. Other techniques for load disaggregation based on transient were later proposed in [15, 19-21].

Researchers presented in 2000 the first approach for load identification using the harmonic content [15]. In this paper, they proposed a NILM system for three-phase environment that uses the first eight odd harmonics of the current signal of the loads both in transient and steady-state. Other proposes of systems that use harmonic features are presented in [14, 19, 22-25].

According to [17], harmonic analysis is very useful to distinguish loads that ambiguously overlap in the ΔP-ΔQ plane, suitable for non-linear loads identification.

In 2010 researchers presented a NILM system installed in the electrical panel after the circuit breakers that makes use of one power meter per electric circuit [26]. This method minimizes the number of loads the power meter has got to discriminate, facilitating the process of load recognition. This system also makes uses Bayesian network in order to take in account the user behavior in the recognition process. Another NILM system based on measurement at circuit level was proposed in [27]. The hardware of this system is composed basically of energy meter ICs that are responsible to acquire the electrical information from the circuits and a microcontroller used to send the collected data to the clouds. Embedded firmware running in the microcontroller performs the load identification and presents the amount of energy consumed by each appliance in web pages.

4. Electrical parameters used to define load signatures in NILM systems

Many papers presenting novel NILM systems [14, 19] and load identification algorithms [23, 28-32] have been published. However, none presents a detailed study about which electrical parameters derived from voltage and current curves are adequate for load identification.

The researchers diverge regarding which parameters are the best for load disaggregation. Most use the active power and current for defining load signatures, some use reactive power [13, 14, 22, 23, 29] other use power factor [27] and harmonic components in the current signal [14, 15, 19, 22-25, 30].

The choice of which electrical parameters are used to define load signature is a critical factor in the performance of NILM systems. The use of just a few parameters can reduce the accuracy on the load identification, particularly for complex loads such as computers, refrigerators, etc. On the other hand, the use of numerous parameters requires more complex algorithms and therefore more computational power. Since most of the NILM systems are designed as embedded systems with low power microcontrollers/DSP, the computational complexity to calculate the electrical parameters is a limiting factor for the development of these systems.

An electrical parameter suitable for defining load signatures has two basic characteristics: it presents quite different values for different appliances and gives repeated values for the same device at same operational condition. Preferably, these parameters should be obtained by simple operations requiring few computational resources to be calculated.

The analysis in the frequency domain for residential loads identification has been shown promising. However, there is no consensus regarding which harmonics are the best for this purpose. In [15] and [23] the authors used the first eight odd harmonics, in [18] the sixteen first even and odd harmonics were used, whereas in [14] only the 2nd and 3rd harmonics were taken in account. Considering the relatively high computational cost of the algorithms used to calculate the Discrete Fourier Transform (FFT, Goertzel, etc.), the calculation of many harmonic

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components in real-time may become impractical. Moreover, the use of too few harmonic components can hinder the load identification process.

Recent studies conducted by the Department of Semiconductors, Instruments and Photonics of the School of Electrical and Computer Engineering, at the University of Campinas, indicate the active power, reactive power, power factor, rms voltage, rms current and the odd harmonics of the current signal are good parameters to be used in NILM systems. These studies also concluded that the most useful information in the frequency domain for load identification is in the first five odd harmonics of the current signal [33].

5. Smart meters for NILM systems

The NILM 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 sent to the discrimination algorithm that performs the energy breakdown based on the principle of load signature.

The smart meter is a critical part of the NILM systems since an accurate measurement of the electrical parameters needed for NILM systems is essential for their performance [30].

A number of equipment can be used for measuring the electrical parameters used in NILM systems. In [21] the author used an oscilloscope to sample the voltage and current curves and post process them using a Matlab script. In [31] commercial electronic power meters were used to obtain the active power. In [23], a harmonic analyzer was used for acquiring the harmonic components of the current signal. In [5], 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 [19] to obtain the frequency spectrum of the current signal. In [27] the author used an energy meter IC to measure the active and apparent power in a circuit. In [14] the authors built a smart meter using a microcontroller capable of calculating the real and reactive powers, and 2^{nd} and 3^{rd} harmonics of the current signal.

Each of these approaches presents advantages and disadvantages. Electronic power meters are easy to install, however can measure only the active power. Power quality recorders, harmonic analyzers, oscilloscopes and DAQs can measure a large number of electrical parameters; but have high cost and big physical dimensions, making them suitable only for lab experiments. Energy metering ICs present low cost and small size, however, they are not flexible regarding the electrical parameters which can be measured [34].

Many energy metering ICs (for example, the ADE7763 from Analog Devices and the CS5463 from Cirrus Logic) are capable of 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 computing harmonics in the voltage and current [35]. Yet, these circuits can only provide the magnitude of the harmonics giving no information about the phase whatsoever. Since harmonics are complex numbers, both magnitude and phase information are needed by breakdown algorithms [34].

Smart meters based on microcontrollers are, in general, cheaper, smaller, and fully customizable, allowing the designers to decide which electrical parameters will be measured. Moreover, unlike energy metering ICs, microcontrollers can be programed to measure harmonics magnitude and phase among other desired parameters to be taken as load signatures.

6. Proposal of a microcontroller based smart meters module for NILM systems

Recently, the Department of Semiconductors, Instruments and Photonics of the School of Electrical and Computer Engineering, at the University of Campinas developed a prototype of a smart meter module for NILM systems to be used in a pilot energy efficiency program [33].

This smart meter module was developed using a low cost ultra-low power microcontroller. It is capable of measuring: active power, power factor, rms voltage and current and the first five odd harmonics of the current signal, presenting the harmonics in terms of magnitude and phase. All the measured parameters can be retrieved via SPI interface.

Shown in Figure 4, the developed module has 36 mm wide by 38 mm high. It was designed to measure the electrical parameters of home appliances at circuit level. Thus, the system needs one module for each monitored circuit. This module can be used for monitoring single-phase and two-phase circuits.

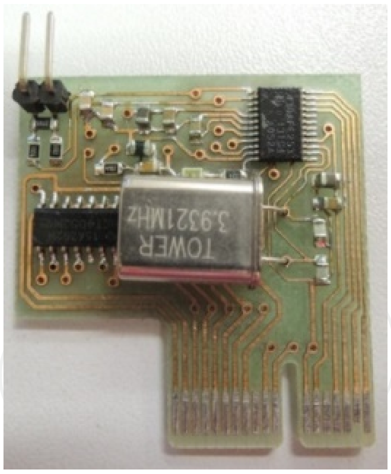

Figure 4. Prototype of the smart meter module [33].

The module on its own does not have power source neither voltage signal conditioning elements. It was designed to be very minimalistic, sharing the conditioned voltage signal and power source from a concentration module with other smart meter modules in parallel.

The concentration module can obtain the voltage signals of up to three mains phases. These signals are isolated and conditioned by transformers with 110/220 V_{RMS} nominal input and 8 V_{RMS} output, ensuring galvanic isolation to the measuring circuit. The transformer outputs are attenuated by resistive divider composed of a 24 kΩ and 1 kΩ resistors, resulting in 320 mV_{RMS} (452.5 mV peak) nominal output voltage. Using effective 16-bit A/D converters, with full scale of ± 600 mV, it is possible to measure voltages up to 145 V_{RMS} with resolution of 4.42 mV_{RMS} or voltages up to 290 V_{RMS} with resolution of 8.85 mV_{RMS}.

Two 4x1 multiplexers in the smart meter modules are used to select the voltage to be sampled, enabling the smart meter to measure six different voltage combinations: “Phase A to Neutral”, “Phase B to Neutral”, “Phase C to Neutral”, “Phase A to Phase B”, “Phase B to Phase C” and “Phase A to Phase C”. This feature allows the modules to be suitable for single-phase and two-phase circuits.

The current signal comes from a current transformer (CT) that should be installed around the hot wire after the circuit breaker. Every smart meter module is connected to an individual CT with input/output rate of 50:0.106 A, 1% accuracy and 50 A_{RMS}. A 5.6 Ω resistor is used as border resistor to match this CT. With 16-bit A/D converter operating at ± 600 mV of full scale it is possible to measure currents up to 50 A_{RMS} with 1.53 mA_{RMS} resolution.

Figure 5 presents a block diagram showing an example of how the smart meter module receives the voltage and current signals. In this example the smart meter module is monitoring the circuit #2, with the CT installed just after the circuit breaker and with the multiplexers configured to get the voltage from phase C to neutral.

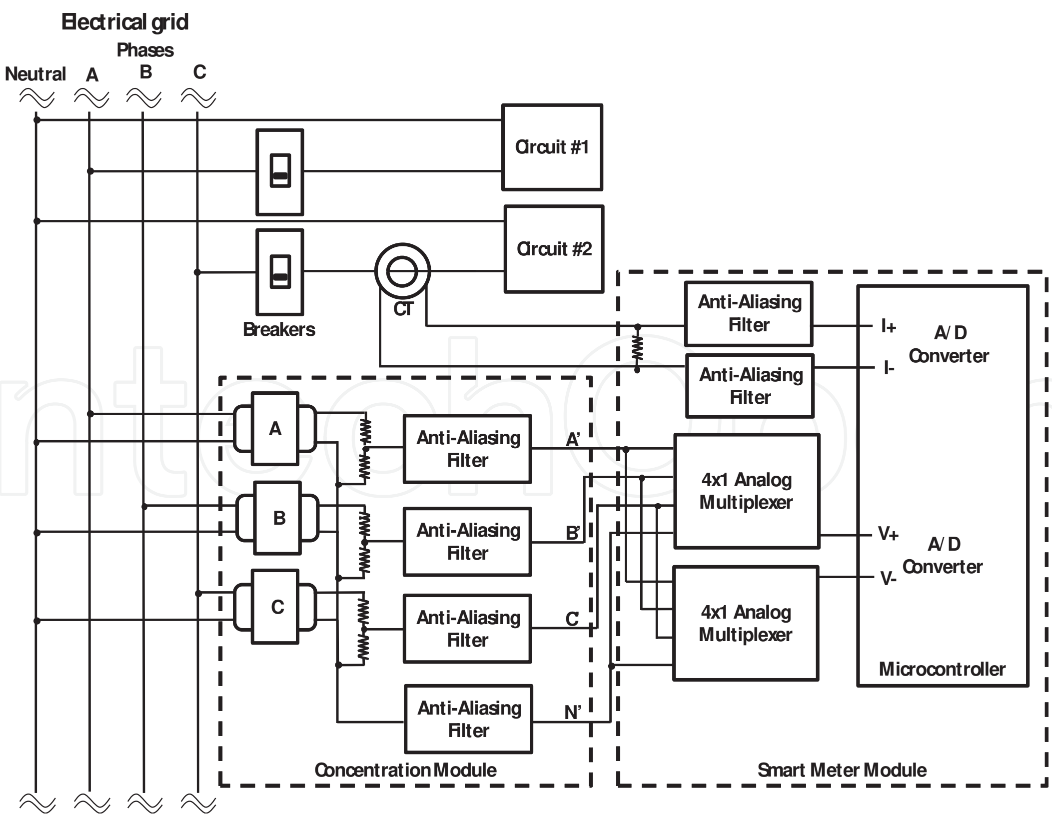

Figure 5. Block diagram of concentration module and the smart meter module sensing circuit #2.

The Texas Instruments MSP430AFE253 microcontroller was chosen as processor unit for the smart meter module. This low cost and ultra-low power consumption microcontroller is very suitable for single-phase power meters. It contains a 16-bit RISC processing unit running up to 12 MHz, 16 KB flash memory, 512 B SRAM memory, UART and SPI communication interfaces, 16-bit hardware multiplier, 16-bits TIMERS, 11 digital input/output pins and three independent 24-bit sigma-delta A/D converters that can operate in synchronized mode [36]. Moreover, they have 1.2 V internal reference voltage with 50 ppm/°C maximum variation. All these features make this microcontroller a great choice to implement a smart meter.

In this project, two A/D converters were used for simultaneously sampling the voltage and current signals. The simultaneous sampling is necessary to calculate the active power and power factor. These converters are configured to operate with 16-bit resolution, differential bipolar inputs, with ± 600 mV of full scale and unity gain.

According to [37], the A/D converters must operate with sampling rate multiple of the power grid frequency to minimize errors in the calculation of active power. With that in mind, the developed smart meter has the A/D converters operating with a sampling rate of 3.84 kS/s (64 * 60Hz). This sampling rate makes it possible to measure harmonic components up to 31st order, in accordance with the Nyquist theorem. The use of higher sampling rates results in greater accuracy in the electrical quantities calculated, especially if nonlinear loads (that have significant values of components of higher order harmonics) are plugged in the circuit.

The sigma-delta A/D converters used for sampling voltage and current signals were configured to operate with oversampling rate of 512. Thus, to read data at a rate of 3.84 kS/s the A/D operates at an effective rate of 1.96608 MS/s.

The use of sigma-delta A/D converters with high oversampling rate allows the use of low-order passive anti-aliasing filters. The anti-aliasing filters implemented are RC low-pass filters with cutoff frequency of-3 dB at 15.9 kHz. Each of them is composed of a 1 kΩ resistor and a 10 nF capacitor. In the bandwidth of interest, from 60 to 1.86 kHz (frequency of the 31st harmonic), the maximum attenuation is-0.06 dB (0.7%). Using a sampling rate of 1.96608 MS/s, these filters are able to attenuate signals at frequencies causing aliasing (1.964220 MHz above) in at least-37.78 dB (98.7%).

Figure 6 shows the power meter firmware flowchart. This program is divided in two parts: Initialization and Infinite Loop. Procedures presented in Initialization stage are executed only once, after the system is turned on, and only run again if the microcontroller restarts. Procedures described in Infinite Loop are periodically executed (until the microcontroller is off). The electrical parameters are calculated at this stage.

The first routines executed after microcontroller initialization are the ones that perform hardware configuration. These routines disable the watchdog and sets up the clocks, the A/D converters, SPI communication and digital I/O. The main microcontroller clock (Master Clock-MCLK) used by the processing unit is configured to use the signal generated internally by the microcontroller DCO (Digitally Controlled Oscillator). The DCO is configured to operate at 16 MHz. A 3.93216 MHz crystal oscillator generates the clock signal used by the A/D converters.

The voltage and current gains are retrieved from the flash memory (embedded into the microcontroller) after hardware configuration. These calibration variables are stored in non-

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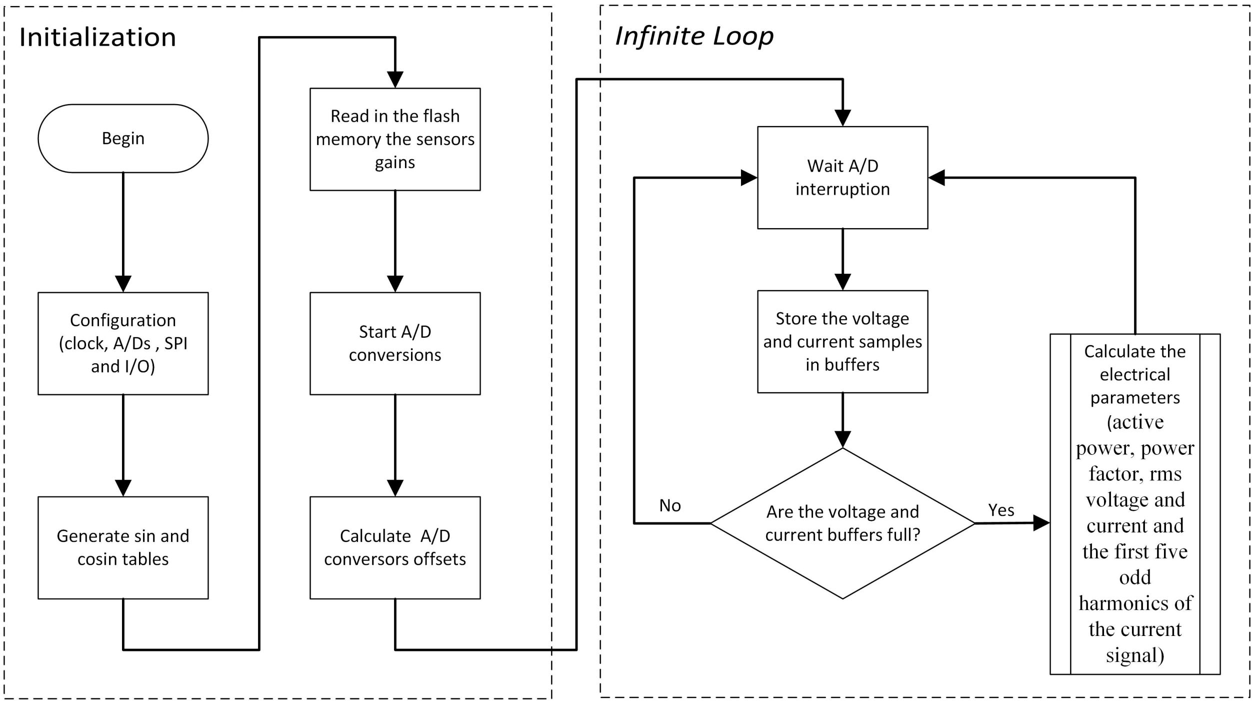

Figure 6. Smart meter firmware flowchart.

volatile memory in order to allow the modules to hold the calibration parameters even if it is turned off.

Following gain calibration, the A/D converters are started and calibrated for offset compensation. The A/D converters present in the MSP430AFE253 microcontroller have offset up to 0.2% [36] that can be almost completely eliminated by calibration.

After Initialization stage, the system goes into the Infinite Loop where the voltage and current samples are processed. Before being processed, the samples are stored in buffers (one for voltage and another for current samples). When the buffers are full (number of samples is equivalent to one power cycle) it is started the routine to calculate the electrical parameters. In the presented implementation, the A/D converters operate at 3.84 kS/s, so in 60 Hz grids, one power cycle corresponds to 64 samples.

As presented before, the electrical parameters calculated are: active power, power factor, rms voltage, rms current, and the magnitude and phase of the first five odd harmonics of the current signal.

The rms voltage is calculated using the following equation:

$$V_{RMS} = \frac{G_v}{\mathrm{N}} \sqrt{\sum_{n=1}^{N} v[n]^2} \tag{1}$$

where $\mathrm{V_{RMS}}$ is the rms voltage, $\mathrm{G_v}$is the voltage gain, n is the sample index, $\mathrm{v[n]}$is the $\mathrm{n^{th}}$ voltage sample and $\mathrm{N}$the number samples. An analogous equation is used to calculate the rms current.

Equation 2 is used to calculate the active power.

$$P = \frac{G_i * G_v}{\mathrm{N}} \sum_{n=1}^{N} \left(i[n] * v[n] \right) \tag{2}$$

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

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

$$S = V_{RMS} * I_{RMS} \tag{3}$$

The power factor corresponds to the ratio of active power by the apparent power, as shown in Equation 4:

$$PF = \frac{P}{S} \tag{4}$$

The effective value of the harmonic components of the current signal is calculated using a formula based on the classical equation of the Discrete Fourier Transform, presented in Equation 5:

$$\left| I[k]_{RMS} \right| = \frac{\sqrt{Re\{I[k]\}^2 + Im\{I[k]\}^2}}{N} * G_i * \sqrt{2} \tag{5}$$

The phase is calculated using Equation 6:

$$\angle I[k] = arctan\left(\frac{Im\{I[k]\}}{Re\{I[k]\}} \right) \tag{6}$$

where kis the index of the harmonic component, $|I[k]_{RMS}|$is the rms value of the module of the k^{th} harmonic, $\angle I[k]$is the phase of the k^{th} harmonic and $Re\{I[k]\}$and $Im\{I[k]\}$are, respectively, the real and imaginary parts of the k^{th} harmonic component. Equations 7 and 8 present the formulas used to calculate $Re\{I[k]\}$and $Im\{I[k]\}$.

$$Re\{I[k]\} = \sum_{n=1}^{N} i[n] * cos\left(\frac{2\pi kn}{N} \right) \tag{7}$$

$$Im\{I[k]\} = \sum_{n=1}^{N} i[n] * sin\left(\frac{2\pi kn}{N} \right) \tag{8}$$

Observe that all equations, except 3 and 4, 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 7 presents the flowchart of the algorithm used to calculate the electrical parameters. This algorithm is the core of the smart meter firmware.

After the hardware configuration 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. When an A/D conversion is complete, an interruption is generated and the voltage and current samples are processed.

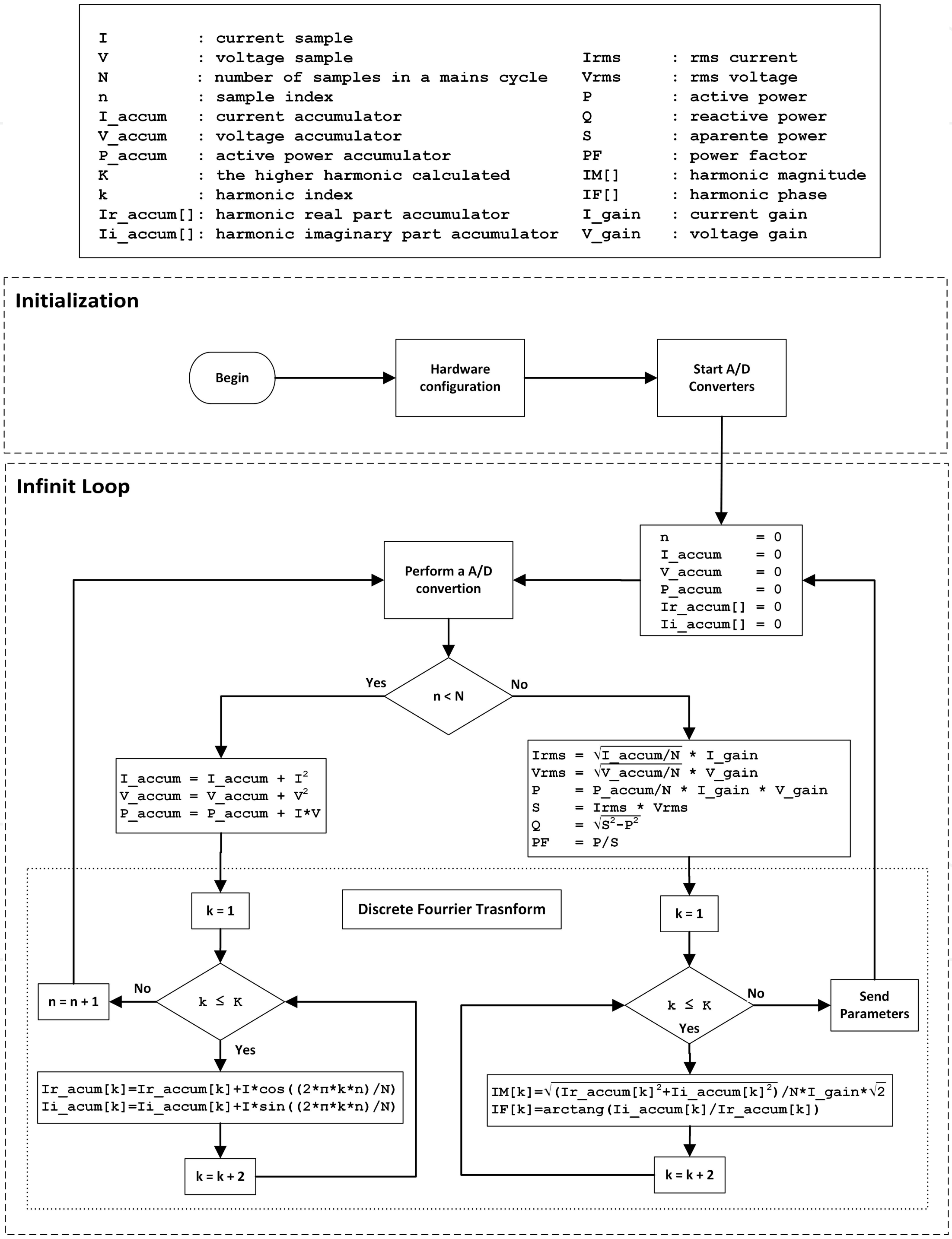

Figure 7. Smart meter core algorithm.

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. The electrical parameters calculation (right side of the flowchart) runs in background and is preempted when an A/D conversion occurs.

7. Commercial NILM solutions

In recent years, several companies have created smart metering solutions that allow discrimination of consumption per appliance by measurement at a single point. We can cite as examples, the American: Bidgely (former MyEnerSave), LoadIQ, PlotWatt, Verdigris and Verlitics (former Emme); the British: Navetas and Onzo; the French: Fludia and Wattseeker; the Irish: Powersavvy and Wattics (former Veutility) and the German Yetu.

The American company Bidgely, founded in 2011 with the name MyEnerSave, has received until July 2013 eight million dollars funding through the venture capital company Khosla Ventures. Other companies that developed energy consumption breakdown technologies, such as PlotWatts, also received substantial investments through venture funding. The emergence of a large number of start-ups focusing on residential energy consumption monitoring systems and the massive investment in these companies clearly indicate the degree of interest in this area.

The system developed by Bidgely allows real time monitoring (at intervals from one second to one minute) of energy consumption in device level [38]. By using disaggregation algorithms based on the concept of load signature, this system is capable of measuring energy consumption of some residential appliances, identify energy-inefficient appliances and, when applicable, suggest behavioral changes that culminate in power savings. The disaggregation algorithm uses only the active power as input information. The active power is periodically obtained through a monitor module connected to the conventional power meter. The Bidgely monitor module is not compatible with all power meters used in USA. Another limitation of this system is the fact of it is not able to disaggregate the consumption of all devices present in a home. Only the following loads can be identified: refrigerator, heater, air conditioner, clothes dryer, heater and pool pump. The consumption of the other loads is classified as devices that are always connected, or others.

The solution proposed by the company PlotWatt is very similar to the one created by Bidgely, requiring the installation of a monitoring module along with conventional power meter. The following loads can be monitored: water heating, light, refrigerator, heater and air conditioning, water and light, electric vehicle charging, "always on" and others [39].

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The French company Flundia, as well as the American PlotWatt and Bidgely, use monitoring modules connected to the conventional power meter through optical interface to obtain the instantaneous power consumption. Figure 8 presents the monitoring module Flundiometer; it is comprised of optical interface (white piece installed in front of the power meter) and data recorder (black box over the power meter).

(a) (b)

Figure 8. Flundiometer: (a) monitoring module for electromechanical power meters (b) monitoring module for electronic power meters [40].

Flundia offers two different versions of optical interfaces, one for electromechanical and another for electronic power meters. This system has the advantage of allowing quick and easy installation, but is not compatible with all power meters [40]. Unlike the solutions proposed by Bidgely and PlotWatt the Flundiometer has no remote communication and therefore does not allow real-time monitoring. The data loggers have a USB interface for system configuration and also to retrieve the stored information. The loads disaggregation algorithm developed by Fludia, the Beluso, is able to distinguish the consumption of the following loads: lighting, refrigerator, washing machine, stand-by equipment, water heaters and other machines.

The system Enable.EI developed by the LoadIQ allows real-time energy consumption monitoring using the non-intrusive smart meter EI.Monitor, available in two versions: two-phase and three-phase. The three-phase EI.Monitor, shown in Figure 9, is able to measure rms voltage and current, active and apparent powers, power factor and phase unbalance [41]. This meter is provided with three communication interfaces: Ethernet RJ-45, WI-Fi and GSM.

The company Verlitics developed a smart meter module able to monitor each electrical circuit present in the house individually [42]. This module is provided of 4G/LTE communication.

As can be noticed, the commercial solutions of NILM systems, mostly just make use of active power for load discrimination. So far, there is no record of commercial solutions using harmonic information, or transient analysis to identify loads, despite the potential of these approaches.

Figure 9. Smart meter EI.Monitor [41].

8. Conclusions

This chapter presented a compilation of several studies regarding systems that are able to report detailed information about the power consumption of a residence, discretizing the consumption of each appliance and providing information the households can rely on to change their behavior towards energy efficiency. Both Traditional Load Monitoring systems and Non-Invasive Load Monitoring systems were cited as techniques able to provide this kind of information.

The literature has shown that Traditional Load Monitoring systems are complex to deploy and maintain and tends to be prohibiting expensive as the number of monitored appliances increases, although they can provide very precise information. It has also shown that Non-Invasive Load Monitoring systems are cheaper and much easier to deploy and maintain, even though, for the time being, they are not able to discriminate all the appliances in a residence. Despite of that, commercial solutions of both techniques have been emerging in the market and the current major players are hereby mentioned.

As a key part, the chapter presented the major concepts of power consumption disaggregation techniques, given special attention to Non-Intrusive Load Monitoring Systems and the concept of Load Signature. It presented the technologies adopted by energy meters in NILM systems and also detailed a proposal of a microcontroller based smart meter for NILM systems, developed by researchers at the University of Campinas.

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References

[1] York D. et al. Next Generation Programs Reach for High Energy Savings. Washington D.C.: ACEEE; 2013.

[2] Solomon, S. et al. Climate Change 2007: The physical science basis. Cambridge: Cambridge University Press; 2007.

[3] York D. et al. Frontiers of Energy Efficiency: Next Generation Programs Reach for High Energy Savings. Washington D.C.: ACEEE; 2013.

[4] Herhardt-Martinez K., Donnelly K. A., Laitner J. A. Advanced Metering Initiatives and Residential Feedback Programs : A Meta-Review for Household Electricity-Saving Opportunities. Washington D.C.: ACEEE; 2010.

[5] Watts Up? https://www.wattsupmeters.com/secure/products.php?pn=0&wai=200&more=4 (accessed 17 September 2014).

[6] Watts Up? https://www.wattsupmeters.com/secure/products.php?pn=0&wai=0&more=2 (accessed 17 September 2014).

[7] P3 International. http://www.p3international.com/products/p4250.html (accessed 17 September 2014).

[8] Ecobee. http://www.ecobee.com/solutions/accessories (accessed 17 September 2014).

[9] Duarte L. F. C. et al. Characterization and breakdown of the electricity bill using custom smart meters: A tool for energy-efficiency programs. International Journal of Circuits, Systems and Signal Processing 2011; v. 5 p. 116–123.

[10] Hart G. W. Nonintrusive appliance load monitoring. Proceedings of the IEEE 1992; v. 80, n. 12, p. 1870-1891.

[11] Leeb S. B. A conjoint pattern recognition approach to nonintrusive load monitoring. PhD. thesis. Department of Electrical Engineering and Computer Science – MIT; 1993.

[12] Chang H. H. Load identification of non-intrusive load-monitoring system in smart home. Wseas Transactions on Systems 2010; v. 9, p. 498-510.

[13] Chang H. C. et al. A New Measurement Method for Power Signaturesof Nonintrusive Demand Monitoring and Load Identification. IEEE Transactions on Industry Applications 2012; v. 48, p. 764-771.

[14] Huang S.-J. et al. Classification of Home Appliance Electricity Consumption Using Power Signature and Harmonic Features. In: IEEE PEDS, Singapore, p. 596-599; 2011.

[15] Cole A., Albick, A. Nonintrusive identification of electrical loads in a three-phase environment based on harmonic content. In: Instrumentation and Measurement Technology Conference, 2000-IMTC 2000: Proceedings of the 17th IEEE, Baltimore, v. 1, p. 24 – 29; 2000.

[16] Duarte L. F. C., Ferreira E. C., Dias J. A. S. Measurement Techniques for Energy Efficiency Programs. In: EISSA, M. Energy Efficiency-The Innovative Ways for Smart Energy, the Future Towards Modern Utilities. 1. ed. InTech, v. 1, p. 193-208; 2012.

[17] Najmeddine H. State of art on load monitoring methods. In IEEE Second International Conference on Power and Energy-PECon, pp. 1256-1258; 2008.

[18] Norford L. K., Leeb S. B. Non-intrusive electrical load monitoring in commercial buildings based on steady-state and transient load-detection algorithm. Energy and Buildings 1996; v. 24, n. 1, p. 51 – 64.

[19] Patel S. N. et al. At the Flick of a Switch: Detecting and Classifying Unique Electrical Events on the Residential Power Line. In: Proceeding UbiComp '07 Proceedings of the 9th international conference on Ubiquitous computing, p. 271-288; 2007.

[20] Robertson D. C. et al. Wavelets and electromagnetic power system transients. Power Delivery, IEEE Transactions, v. 11, n. 2, p. 1050-1058, Apr 1996. ISSN 0885-8977.

[21] Chang H.-H. Non-Intrusive Demand Monitoring and Load Identification for Energy Management Systems Based on Transient Feature Analyses. Energies 2012; v. 5, p. 4569-4589.

[22] Liang J. et al. Load Signature Study—Part I: Basic Concept,Structure, and Methodology. IEEE Transactions on Power Delivery 2010; v. 25.

[23] Srinivasan D., Ng W. S., Liew A. C. Neural-network-based signature recognition for harmonic source identification. IEEE Transactions on Power Delivery 2006; v. 21, n. 1, p. 398-405.

[24] Lee K. D. et al. Estimation of variable-speed-drive power consumption from harmonic content. IEEE Transactions on Energy Conversion 2005; v. 20, n. 3, p. 566-574.

[25] Shaw S. R., Laughman C. R. A Kalman-Filter spectral envelope preprocessor. IEEE Transactions on Instrumentation and Measurement 2007; v. 56, n. 5, p. 2010-2017.

[26] Lin G. et al. Applying Power Meters for Appliance Recognition on the Electric Panel. In: Proceedings of the 5th IEEE Conference on Industrial Electronics and Applications-ICIEA, Taichung, 15-17 June 2010, pp. 2254-2259; 2010.

[27] Moro J. Z. et al. A Home Appliance Recognition System Using the Approach of Measuring Power Consumption and Power Factor on the Electrical Panel, Based on Energy Meter ICs. Circuits and Systems 2013, v. 4 n. 3, pp. 245-251; 2013.

[28] Farinaccio L., Zmeureanu, R. Using a pattern recognition approach to disaggregate the total electricity consumption in a house into the major end-uses. Energy and Buildings 1999; v. 30, n. 3, p. 245–259.

[29] Rahimi S., Chan A. D. C., Goubran R. A. Usage Monitoring of Electrical Devices in a Smart Home. In: 33rd Annual International Conference of the IEEE EMBS, Boston; 2011.

[30] Bouhouras A. S. et al. Load signatures improvement through the determination of a spectral distribution coefficient for load identification. In: European Energy Market-EEM, Florence, p. 1-6; 2012.

[31] Baranski M., Voss J. Genetic algorithm for pattern detection in NIALM systems. In: Systems, Man and Cybernetics, 2004 IEEE International Conference, v. 4, p. 3462 – 3468; 2014.

[32] Marceau M. L., Zmeureanu R. Nonintrusive load disaggregation computer program to estimate the energy consumption of major end users in residential buildings. Energy Conversion Manage 2000; v. 41, p. 1389-1403.

[33] Bacurau R. M. A smart meter for energy consumption breakdown using power signatures. Master’s thesis. University of Campinas. 2014.

[34] Bacurau R. M. et. al. Techniques for Efficient Implementation of Firmware in Microcontroller's Based Energy Consumption Breakdown Smart Meters. VIVECHAN International Journal of Research 2014; v.5.

[35] Analog Devices. Polyphase Multifunction Energy Metering IC with Harmonic Monitoring. ADE7880 Data Sheet; 2011.

[36] Texas Instruments. MSP430AFE2x3, MSP430AFE2x2, MSP430AFE2x1: Mixed signal microcontroller; 2011.

[37] Clark F. J. J., Stockton J. R. Principles and theory of wattmeters operating on the basis of regularly spaced sample pairs. Journal of Physics E: Scientific Instruments 1982; v. 15, p. 645-652, 1982.

[38] Bidgely. www.bidgely.com (accessed 3 January 2014).

[39] Plotwatt. www.plotwatt.com (accessed 3 January 2014).

[40] Fludia Smart Energy Components. www.fludia.com (accessed 3 January 2014).

[41] LoadIQ. www.loadiq.com (accessed 3 January 2014).

[42] Vertilics. www.verlitics.com (accessed 3 January 2014).