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Monitorização Fina do Consumo de Energia Eléctrica

Fine Grained Monitoring of Electric Energy Consumption

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Fine Grained Monitoring of Electric Energy Consumption

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Electrónica e Telecomunicações, realizada sob a orientação científica do Professor Doutor Paulo Bacelar Reis Pedreiras, Professor Auxiliar do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro e do Professor Doutor Alexandre Manuel Moutela Nunes da Mota, Professor Associado do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro.

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Palavras-chave

Monitorização Não Intrusiva de Cargas, Redes de Sensores sem Fios, Medição Indirecta de Potência

Resumo

Hoje em dia assistimos a uma grande pressão e esforço no sentido de estimular a conservação de energia, seja devido a limitações económicas, preocupações ambientais, ou normas regulatórias. No topo do consumo de energia está a energia sob a forma de electricidade

Para se conseguir incentivar a utilização eficiente da energia é necessário fornecer consciencialização energética. Se os consumidores de elecricidade tiverem acesso a informação detalhada sobre como, quando e que aparelhos estão a consumir energia, estes poderão tomar boas e bem suportadas decisões e anuir mudar os seus hábitos de modo a reduzir o consumo de energia, e por fim, gastar menos dinheiro.

O projecto aqui apresentado desenvolve as bases para um aparelho que fornece informação detalhada sobre o consumo de energia eléctrica para uma casa. A informação a ser fornecida deverá ser separada individualmente para *virtualmente* cada aparelho singular presente.

A técnica escolhida para desenvolver o aparelho foi *Monitorização Não Intrusiva de Cargas de Aparelhos*. A partir de um único ponto de medida o sistema deverá identificar as cargas individuais na casa, o que faz com que o *hardware* tenda a ser simples e minimal, recaindo a complexidade para o *software*. O sistema desenvolvido deverá ser de baixo custo e de fácil instalação.

O sistema que foi desenvolvido foi capaz de identificar individualmente e com grande sucesso os aparelhos presentes num ambiente controlado. Ao contrário de outros sistemas deste tipo, o sistema apresentado nesta dissertação é capaz de distinguir cargas eletricamente idênticas, através do uso da técnica de *Medição Indirecta de Potência* implementada através de uma *Rede de Sensores Sem Fios*.

Keywords

Non-Intrusive Appliance Load Monitoring, Wireless Sensor Networks, Load Disambiguation, Indirect Power Sensing

Abstract

Nowadays we witness a great pressure and effort in order to stimulate energy conservation, either due to economic constraints, environmental concerns, or regulatory pressures. At the top of the energy consumption is the consumption of energy in the form of electricity.

The first step to improve energy utilization efficiency is energy awareness. So if there is some manner to provide the average person information about how he is consuming electricity, he may take it by its own interest, and In fact, if electricity consumers have access to detailed information about how, when and by which devices energy is consumed, they can make good and well supported decisions on how they can change their habits to spend less energy and ultimately spend less money.

The project hereby presented, develops the basis for a device that provides detailed information on electrical energy expenditure for a home. The information to be provided aims to be disambiguated for *virtually* every individual appliance present.

The chosen technique to develop such a device was *Non-Intrusive Appliance Load Monitoring*. The system identifies individual loads from a single measurement point. That makes that the hardware tends to be simple and minimal, passing the complexity to the software. The system aims to be very low cost and easy to deploy.

The system developed was able to identify with great success individual appliances in the total load on a *controlled* environment. Unlike other systems of this type, the system presented in this dissertation has the ability of disambiguating electrically identical loads, by the use of the technique of Indirect Power Sensing deployed with a Wireless Sensor Network

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List of Acronyms

NIALM	Non-Intrusive Appliance Load Monitoring
WSN	Wireless Sensor Network
NILM	Non-Intrusive Load Monitoring
FSM	Finite State Machine
SFD	Start of Frame Delimiter
EFD	End of Frame Delimiter
MSb	most significant bit
MSB	most significant byte
GUI	Graphical User Interface

Chapter 1

Introduction

1.1 Motivation

Nowadays we witness demanding economical and regulatory pressures for the deployment of energy efficient technologies, to promote energy's conservation. The reasons behind this interest are the reduction of carbon dioxide emissions as in *Kyoto's Protocol*, the reduction of costs, and ultimately the ambient conservation, by reducing the consumption of fossil fuels.

One of the most, if not the most, used energy form is electrical energy, thus it arises the need to reduce the electrical energy being spent in industrial, commercial and home environments.

One way of promoting this reduction is giving energy awareness to electricity consumers, giving them feedback on how and where the energy is being spent. Some studies state that direct feedback on energy consumption can lead to savings between 10 to 15% in the electrical bill [20].

To provide energy awareness there's the need of a *fine grained* energy monitor capable of monitoring the majority of appliances within a household environment, individually. There are two main ways of accomplishing this. The first consists in deploying one sensor at each appliance to be monitored and measure directly the power being spent by it, recording the desired data. This technique presents the drawbacks of being very expensive and difficult to install, as it requires intrusion and modification of the house's electrical circuit. Further it can be very difficult to monitor appliances that don't allow direct physical access, such as embedded ovens. The second is a concept introduced in 1992 by George W. Hart, that is *Non-Intrusive Appliance Load Monitoring* a technique for monitoring the electrical consumption of individual appliances of a household facility without the necessity of installing individual sensors for each appliance. By sophisticated analysis of current and voltage of the total load, ideally at the main panel circuit breaker, it is estimated the number and nature of the individual loads and their individual energy consumption, as well as other relevant statistics. The hardware cost of this implementation is comparatively very low, turning the complexity to the software [18].

1.2 Proposition

It is hereby proposed the development of a *fine grained* energy monitor capable of monitoring the majority of appliances within a household environment based on *Non-Intrusive*

Appliance Load Monitoring. The system ought to provide direct feedback, in *real time*, by showing the total power being spent as well as what appliances are turned *ON*, and historical feedback by doing with electricity what is done with the telephone bill, *i.e.*, discriminating in detail how the energy was spent, what appliances were in function and when, and how much energy they were spending and its cost.

Although a *Non-Intrusive Appliance Load Monitoring (NIALM)* system may identify different appliances within the total load, there is a clear limitation in distinguishing identical loads, such as lamps or other appliances that may be equal, in different rooms of a house. To address this limitation it is also proposed the deployment of a *Wireless Sensor Network (WSN)* that monitors environmental and physical parameters (*e.g* light, temperature, vibration, magnetic field), that allow the identification of appliances that cannot be disambiguated with NIALM. The data gathered by the WSN is used to augment the data for the NIALM monitor, to distinguish similar/equal appliances. The simplicity of the network and the inexpensiveness of the sensors make the installation costs lower than the deployment of a network of single power measurement equipment, turning it cost effective and advantageous.

1.3 Document Outline

The document outline is as follows:

- ***Chapter 2***: Presents a theoretical and technical exposition of the *Non-Intrusive Appliance Load Monitoring* branch of research, analysing its deployment, advantages and limitations. Addresses the problem of disambiguating electrical identical loads, presenting the concept of *Indirect Power Sensing*;

- ***Chapter 3***: Presents a High-level description of the system's architecture and discusses its *hardware* implementation concerning development, material selection and deployment. It is described the implementation of the *Data-aquisition system* that monitors the parameters of an electrical installation, the *communication interface* between the *Data-acquisition system* and the *computational system* and the hardware for the deployment of the *WSN* for *Indirect Power Sensing*;

- **Chapter *4***: Presents a discussion of the system's algorithms and software logical components, namely the *Load Disambiguation and Appliance Classification* algorithms in the *Fine Grained Electricity Monitor* and its integration with the *Indirect Power sensing WSN*. The system's output and user interface are also discussed;

- ***Chapter 5***: Presents the methods and tests that enabled the validation of the system. The description of the test-bed and the calibration of the system is performed in order to guarantee the desired performance. The results of tests to the various components of the system are presented and analysed.

- ***Chapter 6***: Presents the conclusions regarding the implementation of the system and future work to be considered in the improvement of the system.

- ***Appendices***: Present complementary information about the development of the system.

Chapter 2

Analysis of Non-Intrusive Appliance Load Monitoring

This chapter aims to give the reader a full-depth analysis of the *Non-Intrusive Appliance Load Monitoring (NIALM)*, examining all the needed details underlying this technology and all the requirements to deploy *load disambiguation* of *total load.*

This chapter will be greatly based on George W. Hart's paper "*Nonintrusive Appliance Load Monitoring*" [18], as it is the most comprehensive article in this matter, to my knowledge.

2.1 Definition

Considering a typical household electrical circuit, we may find various and different appliances/devices that work independently, consuming energy from the mains power. It is then possible to measure the total energy being spent in the circuit, loading the power source. Lets call the resulting load *aggregated load.*

NIALM is a technique that, by analysis of current and voltage waveform of the total load, is able to disaggregate it in the components of each appliance present, at any time in the circuit. The data provided by load disaggregation can then be used to compute the energy consumption of any appliance, and build relevant statistics about power consumption, cost, variation *etc.*.

Being only the total load monitored there's only the need to install sensors at one point of the circuit, ideally immediately after the power source, measuring *voltage* and *current.*

2.2 Total Load Model

In order to be able to disambiguate appliances in the aggregated load it is a requirement to know how it combines and behaves. A straightforward and intuitive representation of load in a typical household electric circuit is *power*, as it appears as a combination of the appliances wired in parallel. At a first approximation assuming the loads to be linear, the power consumed is additive.

For simplicity assume the model of Figure 2.1, where the appliances are labelled as Z_i. It is clear that the total load depends on which appliances are switched *ON* at any given time. So the total load can be described with a *boolean* switch process $\vec{a}(t)$. Suppose there

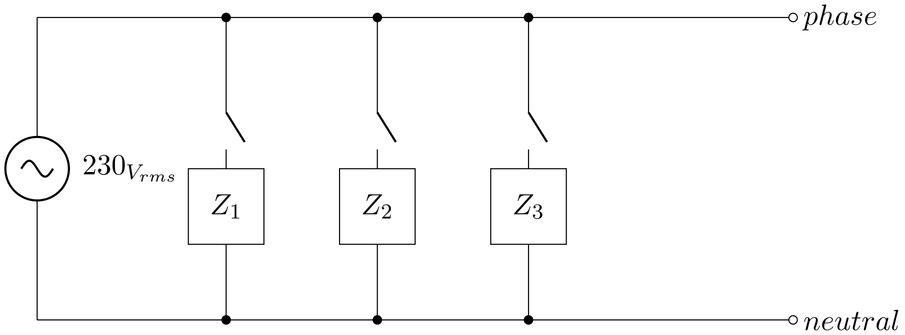


Figure 2.1: Simple representation of home's electrical circuit

are n appliances numbered 1 to n and let $\vec{a}(t)$ be a n-component boolean vector describing the state of the n switches at time t: [18]

$$a_i(t) = \begin{cases} 1, & \text{if appliance } i \text{ is ON at time } t \\ 0, & \text{if appliance } i \text{ is OFF at time } t \end{cases} \tag{2.1}$$

The total power is then the sum of the individual power per appliance, being the power $\vec{P_i}$ a vector representing the real and the imaginary power of the ith appliance,

$$P(t) = \sum_{i=1}^{n} a_i(t) P_i + e(t), \tag{2.2}$$

where $P(t)$ is the total power seen at the utility power source at time t, and $\vec{e}(t)$ a small noise or error term.

This model may suggest a straightforward criterion for estimating the state of the appliances. Assuming that all the appliances in the circuit are known and the measured $P(t)$ is given, the solution reduces finding the vector $a(t)$ that minimizes $|e(t)|$,

$$\hat{a} = arg_a \, min \left| P(t) - \sum_{i=1}^{n} a_i(t) P_i \right| . \tag{2.3}$$

While this may seem very attractive, since it is a very well-studied combinatorial optimization problem, being able to be solved computationally by exhaustive techniques, those may be proven impractical for growing values of n. This model is not suitable for the project's objective either because the complete set of appliances may not be entirely known, nor is acceptable to model a household electric circuit by a finite set of appliances, as the presence of unknown appliances may cause the attempt of describing it by a combination of the others [18].

Another problem that may prove that the solution of equation 2.3 is not suitable for the project is that a small change in the measured $P(t)$ can be solved as a big change in the switch process, $a(t)$, with a number of appliances switching simultaneously in order to better describe the measured $P(t)$. Assume that all P_i are known, for example $P_1 = 100,\ P_2 = 200,\ P_3 = 300,\ P_4 = 401\ W$. If the measured load is 500 W at a time t, the best estimate is $\hat{a} = [0, 1, 1, 0]$, as it solves to $e(t) = 0$ in equation 2.2. If the measured aggregated load at time $t + \Delta t$ increases to 501 W the best estimate would then be $\hat{a} = [1, 0, 0, 1]$, resulting again in $e(t) = 0$. But it implies that every appliance switched state in a short interval Δt However normal household environment, a change of state of all appliances is very unlikely and improbable. From this it comes the suggestion of a criterion for describing the changes in the load model:

Switch Continuity Principle: In a small time interval, we expect only a small number of appliances to change state in a typical load[18].

As it will be shown in the following chapters, this principle will be the basis of the system's NIALM implementation. This principle introduces a very important notion, that is, in a small enough interval it is expected that the number of appliances changing state to be usually zero, and sometimes one, and very rarely more than one.

From this section it is important to retain the importance of the Power measurement. As it will be a representation of the circuit's load, it is also of the highest value the *Switch Continuity Principle* as it will be the concept which we will build up the project.

2.3 Appliance Models

Having a brief view on how the appliances combine and how they may behave, it is important to know how they can be modelled taking into account their function and behaviour.

Here it will be discussed three classes of appliances models:

- *ON/OFF*
- *Finite State Machine (FSM)*
- *Continuously Variable*

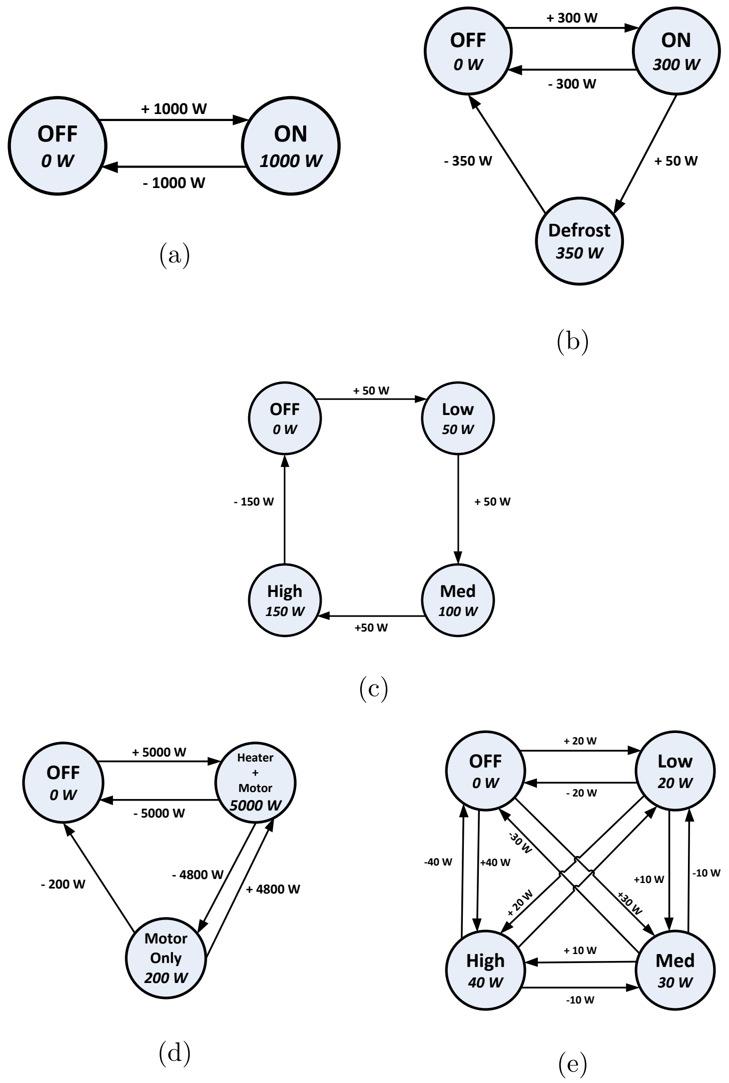
ON/OFF model

The ***ON/OFF*** model is the simplest model, assuming the form of a *Boolean Switch Function* allowing an appliance to be either *ON* or *OFF* at a given time t. This model suits almost all appliances in a household environment with great accuracy.

FSM model

The ***Finite State Machine Model (FSM)*** model is suitable to appliances with more than two different *ON* states, *i.e*, states of function which have different power consumption, as it allows for an arbitrary number of states and state transitions. Some representations of *FSM* models for common appliances are shown in figure 2.2. The circles denote the states, identified by name and operating power. The arcs denote the allowed state transitions and are labelled with the correspondent signature change in power that occurs in that state transition. For simplicity power is only represented with scalar real power, but it is here advised that following in this document power will be identified with a vector of *real* and *imaginary* power, i.e., *active* and reactive power. As one can see the *ON/OFF* model is a particular case of the *FSM* model, one with only two states, what makes this model more robust and ideal for modelling appliances.

An important notice to this model is that the signatures labelling the arcs cannot be chosen arbitrarily. As one can see in figure 2.2 (a) and(b), the transition from ON to OFF is the negative of the transition form OFF to ON, and furthermore the sum of the signatures of the cycling of the states in (c) is zero. Generalizing, the following constraint can be stated:



(a)

(b)

(c)

(d)

(e)

Figure 2.2: Finite State Appliance Models: (a) generic 1000 W two-state appliance; (b) no frost refrigerator; (c) three-way Lamp; (d) clothes dryer; (e) three-speed fan. Based on figure 4 of [18]

Zero Loop-Sum Constraint(ZLSC) : The sum of the power changes in any cycle of state transitions is zero [18].

Anyone with background in electric circuits will see that this constraint is analogous to *Kirchoff's voltage law*, being the discrete-space analogue to the constraint that the curl of conservative vector field is zero.

Another valuable constraint that may be used in *FSM* models, in order to simplify the build of models for the appliances is:

Uniqueness Constraint(UC): Distinct states in a FSM appliance model have distinct operating power levels [18].

Being the analysis of *FSM* important to the subject of NIALM, in order to correctly build methods and algorithms for learning the appliances in the circuit, it wont be that important in this project, because it's complexity wont bring much performance improvements. For this reason the project will be focused in the *ON/OFF* model.

Continuously Variable

At last, comes the *Continuously Variable* model, which arises from a generalization of the *FSM* model, in such a way that a continuously variable appliance is one which has an infinite number of states, and is suitable for few appliances such as light dimmers, sewing machines or variable speed drills which have a continuous range of power levels, and so do not generate step-change signatures, not fitting in *ON/OFF* or *FSM* models [18].

Again this model wont be used in this project, not only due to its complexity, but also the existence of appliances that are described by this model is small, and though not very significant in household environments.

2.4 Signatures

Knowing what are the models of appliances suitable to be found in the load, it is needed a consistent way of identifying the appliances in the aggregated load. The previous sections used power steps, solemnly, as signatures, but as it will be explained later in this chapter, that may not be the most effective way of identifying appliances in the load, nor the only one.

We start then by the definition of signature:

Signature - A signature is a measurable parameter of the aggregated load that gives information about the nature or operating state of an individual appliance in the load [18].

Now that the reader understands what a signature is, it is important to refer that this concept is the fundamental basis for *NIALM*, as *signatures* are the pieces of data that allow for load disaggregation.

The signatures can be subdivided in *Non-intrusive Signatures* and *Intrusive Signatures*, which will be now discussed.

2.4.1 Non-intrusive Signatures

Non-intrusive Signatures are those that can be measured passively by sensing the aggregated load. The previously mentioned *power steps* qualify as non-intrusive signatures. This non-intrusiveness is such that there's no need to observe individual loads or to modify the loads in any way. Within the non-intrusive signatures we can also classify the observed signatures according to its nature. The *steady-state signatures* have information about the appliances state of operation that it is is continuously present in the aggregated load. The *transient* signatures have information about appliance's state changes, which is only present for brief moments at the times of transition.

Steady-State Signatures

Steady-State Signatures arise from the difference of steady-state properties between appliance's states of operation, and can be measured in different parameters, that will be discussed further ahead. Besides, they have some interesting properties that are worth taking in to account.

They are continuously present in the load indicating the appliance's operating state, which turns it easier to assess consistency of appliance's detections.

They are the signatures that satisfy *ZLSC*, taking a very important place in detecting appliance's modelled with *FSM* models.

They are additive when two or more happen coincidentally.

Fundamental frequency signatures: The measurements available at the utility's fundamental frequency[1] are *power, current, and admittance* of the aggregated load (all these parameters may be expressed in the complex form). From this parameter's we may search for *step changes* as signatures. The most intuitive parameter to use, for someone with electric circuits background, is power, as it is widely used and gives a quick perception on energy being spent by the appliance. But as this parameter and as current, are dependant of *voltage*, and there are some vicissitudes that make these inadequate for use. The utility's voltage, $V(t)$, is time varying and the power provider only guarantees it within a fluctuation of $\pm 10\%$ of its nominal $230\,V$ [27], which will consequently make the power drawn by *linear devices* to vary over $\pm 20\%$. In addition there is also a variation in voltage at the load depending on the load itself due to the *power source* not being ideal, by having an equivalent internal resistance.

Basing *NIALM* in the detection of changes around a parameter that can varies $\pm 20\%$ due to external factors is not acceptable. *Admittance* is preferable since it is independent from voltage and it is additive, since the appliances are all wired in parallel as suggested in figure 2.1. Let $P(t)$ the power and $V(t)$ the *RMS* voltage, *Admitance* $Y(t)$ is

$$Y(t) = \frac{P(t)}{V^2(t)}. \tag{2.4}$$

While this may be the adequate parameter for the signature, it lacks intuitive meaning, therefore it is be preferable to handle this parameter through a linear transformation called *"normalized power"*:

$$P_{norm} = V_{nom}^2\, Y(t) = \left(\frac{V_{nom}}{V(t)}\right)^2 P(t). \tag{2.5}$$

where P_{norm} is the power that would be spent by a linear load with admittance $Y(t)$ if the voltage supply is stable at its nominal voltage V_{norm}, $230\,V_{RMS}$ in Portugal.

Another model to best fit the normalization should arise by the non-linearity of some appliances [18], but this analysis is not relevant for the project.

For better understanding of the concepts here stated, it is presented in figure 2.3 a *signature space* in *real* and *reactive* power, of the *steady-state* signatures of some appliances.

Harmonic frequency signatures: Assuming that the loads are linear, it is expected that if the supplied voltage waveform is sinusoidal, the response current should also be sinusoidal. But, as one may observe, this is false for many appliances, being them non-linear in this aspect. This non-linearity may express itself as the presence of some power in some harmonics of the base frequency. It is possible to consider that inductive motors may have triangular current waveform containing power in third, fifth and other low-order odd harmonics.

[1] $50Hz$ in Portugal

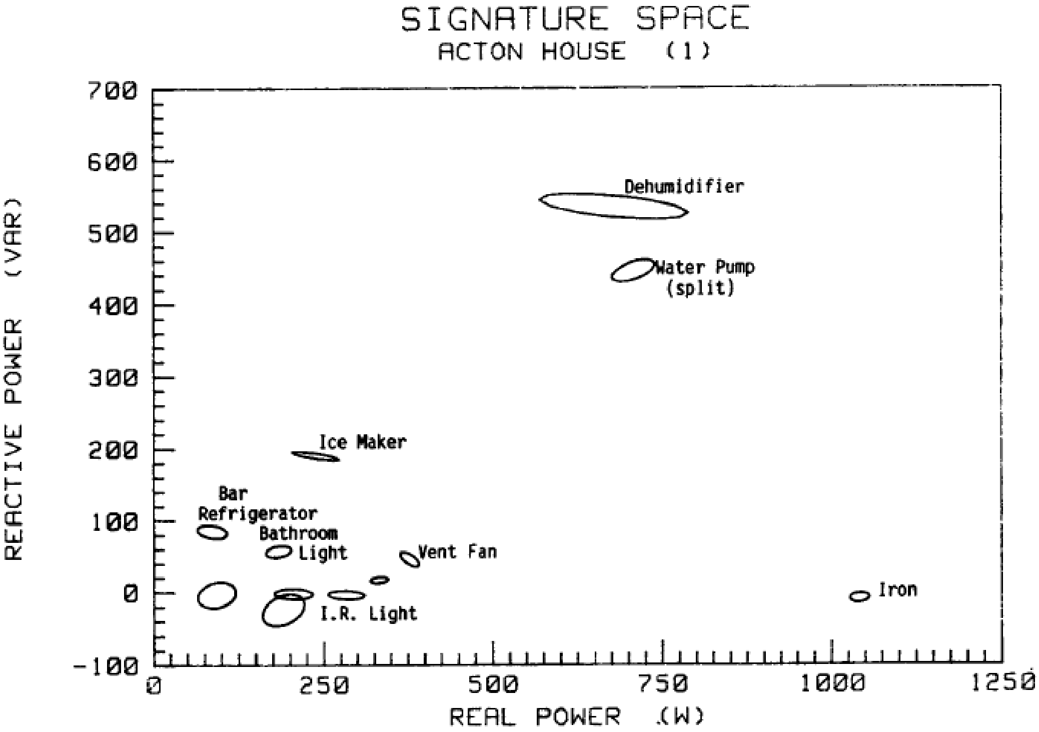


Figure 2.3: Steady-State complex power signature space of some household appliances [18]

Other electronic devices with switched supplies may have power at higher frequencies such as in the range of the ultrasounds ($[20;40]kHz$), almost all appliances other than resistive heaters and incandescent lights have power in various harmonics [18].

One way of building data with this informations is by using a structure called *spectral envelope* and gathering the powers of the harmonics. A *spectral envelope* may be a vector of the powers at a predetermined number of harmonics [24].

This characteristic can also be used as signature for *NIALM* by augmenting the *power vector* for the *steady-state signatures.* This signature may be useful to disambiguate some appliances that are electrically identical in the utility's frequency, but different at other harmonics.

Direct current signatures: In sequence of the non-linearities there may be some appliances that have *DC* components different from zero. This behaviour may be noted on some small heating appliances in which manufacturers may put a diode in series with the heating element to create a two level system, having the rectified operation as the *low* setting. This *half-wave* rectification produces a significant *DC* level in the current waveform[18].

While this type of signature is very uncommon, it has the potential of aiding in some appliance disambiguation.

Transient Signatures

As stated before transient signatures are electrical signals that are only present in the load for a short duration of time at the changing states of operation. Since they exist only for a short duration they are more difficult to detect, and are less informative.

Transient signatures however, may provide valuable information for load disambiguation as they are intimately related to the physical task being performed [24]. They allow the distinction of appliances otherwise electrical identical, since, as stated in [24], most observed loads have repeatable transient profiles or at least sections of it.

Transients have also the potential of being incorporated in *FSMs* by labelling each arc with the transient relevant for the corresponding state-change. Transients may be parametrised by:

- shape;
- duration;
- time constants;
- parametric variables of fitting curves of observed *waveforms*.

These parameters should be allowed to be shifted and transformed in order to fit better the detected events.

Other Non-intrusive signatures

There are other types of signatures able to be used by *NIALM* for *e.g. low frequency ripples* or *ramps in power consumption*, but they are not very much significant and won't be analysed here.

2.5 NIALM Process

Diverse approaches, presenting different compromises in terms of simplicity, accuracy and easiness of deployment, may be employed to carry out load disambiguation. Due to its simplicity and capability of modeling a vast range of appliances, it was decided to use an algorithm derived from the one presented in section *IX* of [18], but slightly modified to be simpler, and more generic. The signature is based in the normalized power and the appliances are modeled by the ON/OFF model. The signature steps of the appliances are assumed to be known a priori.

A global view of the whole process is represented in figure 2.4. Each step will be discussed in the remainder of this section.

2.5.1 Data Acquisition

An adequate sensory system attached to the main power source of the home measures voltage and current and computes digitally the *complex power* and the *RMS voltage* at a predetermined sampling frequency. The sampling frequency needs to be wisely chosen since it affects the system's time granularity, i.e. the ability of the system to detecting various appliances and appliance features in a short period of time.

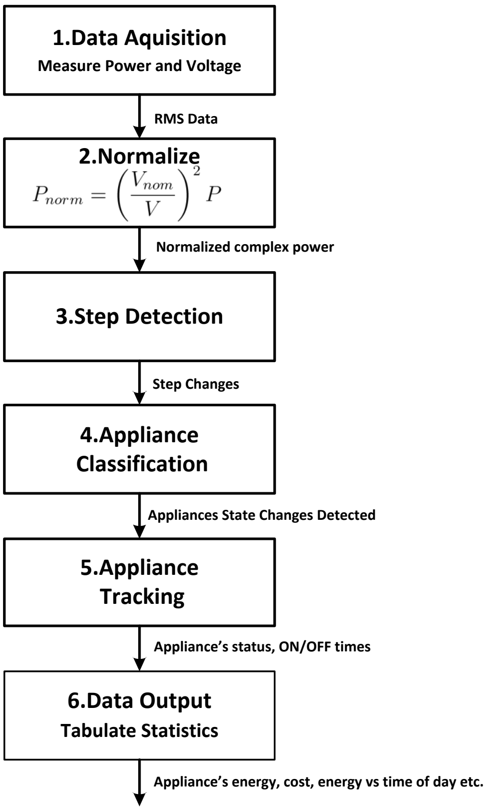

1.Data Aquisition
Measure Power and Voltage
RMS Data
2.Normalize
$P_{norm} = \left(\frac{V_{nom}}{V}\right)^2 P$
Normalized complex power
3.Step Detection
Step Changes
4.Appliance Classification
Appliances State Changes Detected
5.Appliance Tracking
Appliance's status, ON/OFF times
6.Data Output
Tabulate Statistics
Appliance's energy, cost, energy vs time of day etc.

Figure 2.4: NIALM process

2.5.2 Normalize

Taking *complex power* $\vec{P}$ and *RMS voltage* V, we compute *normalized power* P_{norm} by:

$$P_{norm} = \left(\frac{V_{nom}}{V}\right)^2 P, \tag{2.6}$$

where V_{nom} is the utility's *nominal voltage*[2]. It is created then a voltage-independent signature to vitiate the problems of the fluctuation of utility's voltage as stated in subsection 2.4.1.

2.5.3 Step Detection

Taking normalized power as an input, this block implements an algorithm that detects *step-like changes* and finds their times and sizes. For this, the *power flow* is decomposed in *steady* and changing periods. A *steady-period* is defined as a sequence with a *minimum number of samples* in which they do not vary more than predetermined *tolerance* in both of the power components. All the other periods in between are said to be *changing periods.* Having the steady periods been defined the *steady-state* power of that period is the average of the

[2] In Portugal the nominal voltage is commonly 230 V for homes with BTN("Baixa Tensão Normal")

samples in that period, in order to minimise the noise. Lets call these values the *steady-states*. Having the *steady-states* defined the *steps* are calculated by the differentiation of consecutive *steady states*, with this value comes too a time-stamp that allows the identification of the time of the step. The output of this block is a sequence of time-stamped *step-change complex power* values.

An illustration of a possible instance of the algorithm is figure 2.5 where it is represented the power and a measure of how much the power is changing, that is used to sequence the power flow in *steady* and *changing* periods. There we may also see the detected steps represented in the center of the *steady* periods. This may not be the most correct way to represent the steps, but as long as the steps are always represented in the middle of the period, the time coherency is maintained.

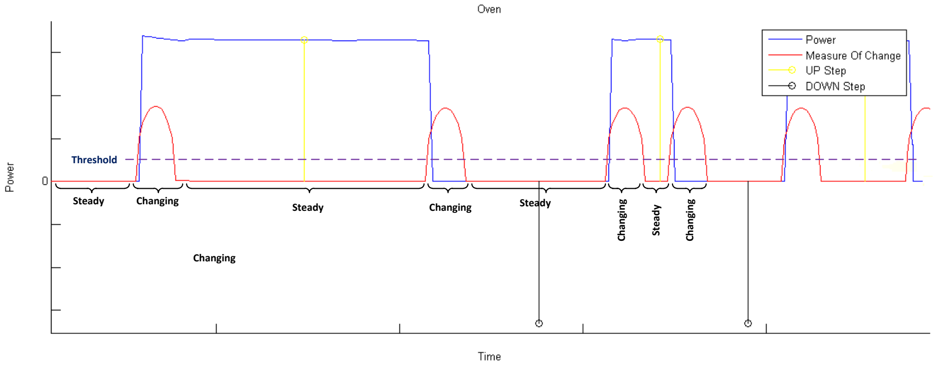


Figure 2.5: Detection of Steps

2.5.4 Appliance Classification

It is assumed that there is *a priori* a list or database with the appliances as well as its characterization in terms of signatures, defined by confined areas in the *complex plane*(in this case in which it's only considered *ON/OFF* models, the *OFF signature* of an appliance is the symmetric the *ON signature*). The algorithm takes each step and finds if it belongs to any of the areas of appliances' signatures, being discarded otherwise. The output is then the appliance and the state change, i.e. an *ON* or an *OFF*.

2.5.5 Appliance Tracking

Here the information about the appliances changes is used to update and maintain its state on a *database* of the registered appliances, guaranteeing coherency of data, avoiding and detecting anomalies such as repeated events, such as two *ONs* or two *OFFs* in a row.

2.5.6 Data Output/ Tabulate Statistics

Lastly, once we have the information about how the appliances are behaving, i.e. their power and their times of changing state, and consequently the periods on which they are consuming energy or not, we can produce a big number of statistics and other valuable information. The system shall be able, with little effort, to:

- compute how much energy is being spent by any individual appliance at any time;
- compute the cost of any appliance within the total bill;
- tabulate the variation of energy consumption with time of day, temperature ...

One of the aims of this block is to produce a detailed bill of appliances' consumption, such as the one that is common at the phone bills. Here we would have the times at which the appliances were on, for how long and how much they cost.

2.6 Known Limitations

There are some capital limitations in what concerns *NIALM.* They result primarily from the fact that this technique is only applicable to a restricted set of appliances. It's not suitable for detecting very small appliances, continuously variable appliances and appliances that operate constantly. Apart from that there is another fair limitation that is that it can't distinguish between electrically similar appliances. This limitation is quite interesting because one may have similar appliances in different rooms of a house, such as lamps, and one may be interested in knowing how much energy each one consumes.

2.7 Indirect Power Monitoring WSN

To ease some of the limitations, above mentioned, it is possible to deploy an *Wireless Sensor Network (WSN)* with *Indirect Power Sensing*, in order to get information about individual appliances, using inexpensive sensors.

Indirect Power Sensing is based on the fact that *an appliance emits measurable signals when it consumes energy.* By sensing these signals one could estimate power consumption[21]. This concept was introduced by *Younghum Kim et al* in 2009 with *Viridiscope* a *Fine Grained* Power Monitoring System for Homes[21], where he uses some inexpensive sensors, such as light, sound or magnetic sensors, to estimate the power consumption of individual appliances. These were attached in a wireless sensor network that would report the gathered information to a *PC/Fusion Center*, that makes appropriate calculations to estimate the power being spent.

Another use for this concept was documented in *ANNOT: Automated Electricity Data Annotation Using Wireless Sensor Networks* where *Schoofs et al* where the data gathered by the sensors is used to annotate the data about power consumption in order to facilitate the installation and training of a NIALM system[39].

It is hereby proposed the use of WSN with Indirect Power Sensing to augment the NIALM system, by gathering information to help distinguishing similar/identical appliances, and identify small loads. Nodes have to be attached to the appliances of interest, to identify if the appliance is *ON* or *OFF* and report it to the main monitoring system. The information gathered by the *WSN* is absolute.

The deployment of a WSN implies little intrusiveness. But nodes are small and can be integrated seamlessly. They don't need wirings for communications, neither for power supply as they can be made battery-operated and if well designed, they can have big autonomy.

2.8 Summary

In this chapter it was given an introduction and an analysis of the concepts underlying the *Non-Intrusive Appliance Load Monitoring*, identifying its main requirements and its main results.

A *NIALM* system is able to decode all the information from only one point of measurement, at the *total load*, without the need for any more sensors at any appliance. There are various appliance models, being the most important the *ON/OFF* and the *FSM* models, although the majority of the appliances are accurately described by the first. In order to detect the appliances the algorithm looks for *signatures*, being the *steady-state* the most straightforward, easy to understand and deploy and the most informative due to its permanent existence in the load. Within the *steady-state signatures* the *normalized power* is one of the best, because it provides independence from voltage fluctuations. It was shown that it can be relatively easy to deploy a *NIALM* system based on *step detection* on *normalized power*, and that such a system would permit the production of valuable information about *power consumption*, being able to disaggregate the energy in components for each appliance. One of the major limitations of this technologies is the difficulty in distinguishing *electrically similar loads*. To address this limitation it is proposed an inexpensive individual load monitoring with the deployment of a WSN based with *Indirect Power Sensing*.

Chapter 3

System's Architecture and Hardware Development

This chapter starts by giving an high-level overview of the system that was developed, being identified its building blocks and basic function. It is discussed the implementation of the hardware platform needed to perform the Energy Monitoring and the selection of components. The discussion starts with the introduction of some considerations about the requirements, it proceeds to the comparison of the available materials, devices and components, and finally its set-up and deployment.

3.1 System's Architecture

The developed system can be seen as a group of individual building blocks that perform the essential operations for the deployment of a *Fine Grained Electrical Energy Monitor*. These blocks are represented in figure 3.1 and will be described in this section.

Main Power Source and Total Load

The system targets a real household. The power source it is assumed to be $230\,V$ single-phase at $50Hz$. There are various independent appliances connected to the internal distribution infrastructure.

Data Acquisition

In order to monitor the *total load* and get the needed values of *complex power* and *voltage*, a *data acquisition system* needs to be deployed. This system will be an *integrated solution* that senses the *voltage* and the *current* and provides directly, digitally and at high sampling rates the characteristics of the the electric installation. This system has to have *PC connectivity*, to where the data must be delivered.

Load Disambiguation

In the computational system, it is deployed an application that takes the data from the *data acquisition system* identifies what appliances are turning *ON* and *OFF* in real time. Additional information from appliances of interest is fetched *via* a *WSN*, in order to distinguish

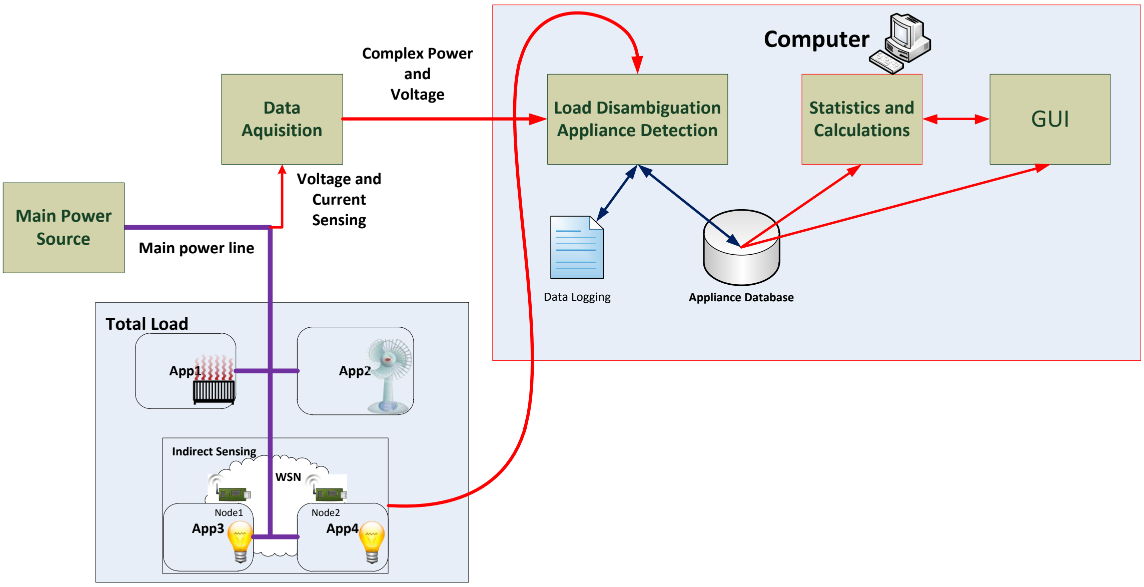


Figure 3.1: System's architecture overview

between similar appliances. The produced information is then used to maintain a *database* that reflects the state of all the appliances at any time. The *state changes* of the all the appliances are also recorded, to make possible the production of information that rely on historical data about the appliances.

Statistics and Calculations

This part of the system takes as input the *real-time* and the *historical data* on power consumption for each appliance, as well as for the total load, and computes and calculates important and interesting statistics.

This statistics shall be:

- Energy spent by each appliance with its distribution over time and cost;
- Calculations on variations of energy consumption during day/week/month;
- *etc.*

Graphical User Interface(GUI)

A *graphical user interface* gives *visual feedback* of the electric installation to the user. This GUI takes as input the *real time stats* to display:

- Graphs with circuit voltage, current and total complex power;
- Real time state of each appliance;
- Power spent by each appliance;

- Power/Cost weight of each appliance in the total power.

Historical data and statistics to display:

- Detailed Electrical Bills;
- Graphs of power consumption *versus* time;
- Any other relevant statistic worth of being displayed;

Indirect Power Sensing and WSN

To help the *Load Disambiguation Algorithm* with similar loads, it was deployed a system based on *Indirect Power Sensing* that provides, via WSN, information about individual appliances to the system. The WSN measures physical quantities that indicate that the appliance is working. The WSN system is deployed to detect changes, i.e. to detect if an appliance changes state, and then to communicate it to the computational system, to augment the completeness of its report.

3.2 Deployment of Data Acquisition System

To perform *NIALM* one has to have access to various parameters of the facility's *electric installation*, as it was stated in Chapter 2, these parameters are: *RMS Voltage* and *Instant Complex Power*. Thus it is necessary to get/deploy a system capable of being attached to a home's electric circuit and monitor these parameters.

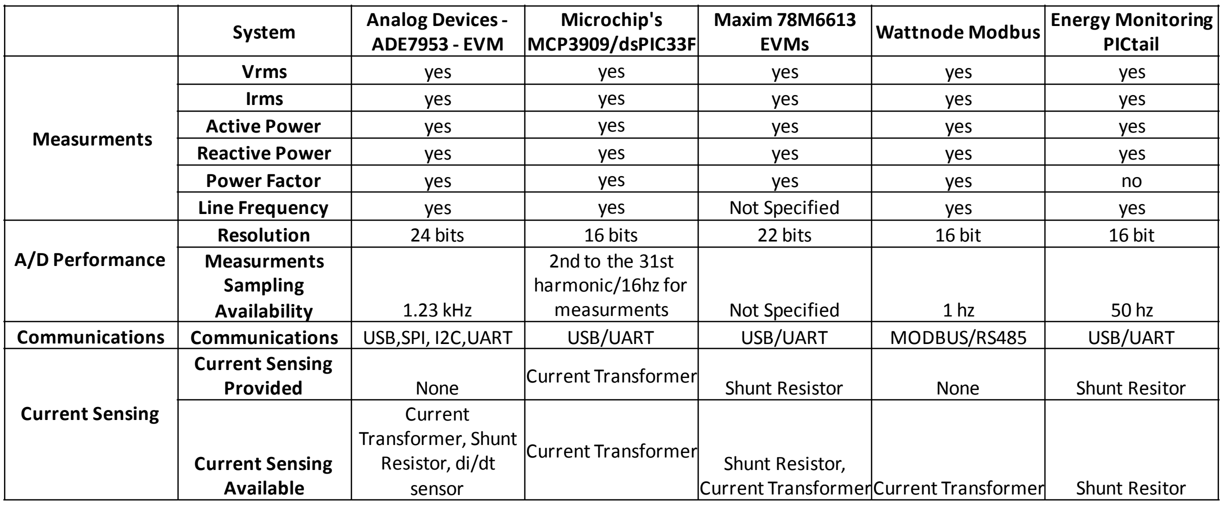
Considering the type of analysis that it's going to be developed, which is *load disambiguation* via *step-detection* on *steady-state signatures*, the requirements of this system are providing a measurement of *complex power* and a measurement of *voltage* at a sampling frequency in the range of $[2;10]Hz$, as suggested in[18]. However, the system developed in the scope of this thesis aims to be a versatile platform capable of sophisticated analysis to be used in scientific research in the field of *Load Monitoring*, so it is reasonable to consider that it necessary to develop a system capable of providing data for processing *transient analysis* and *harmonic analysis* on the various components of an electrical installation. These requirements, imply that the system has to provide measures of *voltage*, *current*, *active power* and *reactive power* at *high sampling rates*, thus a minimum sampling rate of $1.2 - 2kHz$ is suggested for *high harmonic* and *transient* analysis [45].

In order to accelerate the development process, it was decided to use an integrated solution for monitoring electrical parameters. This option is viable since, as it will be seen further on, there are available in the market diverse equipments that satisfy the specifications and that are affordable.

Market Survey and Device Selection

System's Feature Summary: It was carried out a market survey on meter equipment. The complete results are reported in appendix A, while table 3.1 presents a brief summary and comparison of the solutions found.

Analysing the data in table 3.1 is possible to conclude that the viable equipments are *Analog Devices - ADE7953 EVM Evaluation Board* and *Microchip's MCP3909/dsPIC33F*



	System	Analog Devices - ADE7953 - EVM	Microchip's MCP3909/dsPIC33F	Maxim 78M6613 EVMs	Wattnode Modbus	Energy Monitoring PICtail
Measurments	Vrms	yes	yes	yes	yes	yes
	Irms	yes	yes	yes	yes	yes
	Active Power	yes	yes	yes	yes	yes
	Reactive Power	yes	yes	yes	yes	yes
	Power Factor	yes	yes	yes	yes	no
	Line Frequency	yes	yes	Not Specified	yes	yes
A/D Performance	Resolution	24 bits	16 bits	22 bits	16 bit	16 bit
	Measurments Sampling Availability	1.23 kHz	2nd to the 31st harmonic/16hz for measurments	Not Specified	1 hz	50 hz
Communications	Communications	USB,SPI, I2C,UART	USB/UART	USB/UART	MODBUS/RS485	USB/UART
Current Sensing	Current Sensing Provided	None	Current Transformer	Shunt Resistor	None	Shunt Resitor
	Current Sensing Available	Current Transformer, Shunt Resistor, di/dt sensor	Current Transformer	Shunt Resistor, Current Transformer	Current Transformer	Shunt Resitor

Table 3.1: Systems' main features

3-Phase Meter Reference Design. The reasons for this statement are: they both are full functional systems, removing all the designing and prototyping work; they measure active and reactive power; and mainly because they provide data that makes the analysis of high frequency signals, such as transients possible: the ADE7953 provides 1.23 kHz bandwidth waveform sampling and the MCP3909/dsPIC33F provides harmonic analysis of the signals (high frequency waveform sampling could also be attained with firmware modification).

However Microchip's solution isn't available for purchase, as the product has become obsolete, therefore the *Analog Devices - ADE7953 EVM Evaluation Board* is the only choice viable.

3.2.1 Current Sensing

Having selected the electricity monitoring integrated solution, it is necessary to acquire all the necessary equipment and components in order to deploy the system.

The *ADE7953 EVM Evaluation Board* doesn't provide a direct way to measure current. Contrariwise to voltage, it is necessary to deploy a current sensor to attach to the monitoring system, in order to sense the facility's current. Again there are some requirements that need to be met. The sensor has to perform well at a certain bandwidth and be able to measure currents in the range of what a common house can consume. Regarding the bandwidth, the sensor needs to measure in a range that goes from the utility's frequency, $50\,Hz$ to various *kilohertz*, to not compromise the systems performance. In terms of current range a minimum of $30A$ of maximum current should be considered as, it will cover the majority of consumers in Portugal[6].

A survey of the *current sensing technologies* is presented in appendix B, from where table 3.2 is a summary. The *Rogowski Coil Sensor* is the most promising and accurate sensor, but the availability of this technology for the general market is scarce. So the selected solution is the *Current Transformer*, which presents the best compromise between safety and support, as it's the one of the most used technologies in energy metering.

	Shunt	**Current Transformer**	**Hall Effect Sensor**	**Rogowski Coil**
Cost	Low	Medium	High	-
Bandwidth	Low	Medium	High	High
Isolation	Low	High	High	High
Linearity	Good	Good	Medium	Very Good
High Current Measurements	Low	Good	Good	Very Good
Power Dissipation	Medium	Low	Low	Low
Temperature Drift	Medium	Low	Medium	Very Low
Saturation	No	Yes	Yes	No

Table 3.2: Comparative of the various solutions for current measurment

Equipment Selection

Having chosen the type of sensor, it was acquired the *Current Transformer* `CR8349-1500` from *CR Magnetics, Inc*, shown in figure 3.2. This sensor is a *general purpose vertical pcb mount current transformer* with small footprint. It's main characteristics are:

- maximum current to be linearly sensed, $I_r = 75\,A$;
- maximum saturation output voltage, $V_{max} = 12.8\,V_{rms}$;
- frequency range $20\ -\ 1KHz$.

Figure 3.2: CR8349 Current Transformer

3.2.2 ADE7953 Theory of Operation

3.2.3 Data Acquisition System Deployment

Figure 3.3 represents a block diagram of the *ADE7953 Evaluation Board* in terms of supplies and main inputs/outputs(I/O).

Power Supplies

As one may see in figure 3.3, the board has two separate power connections. The power in the board is in two parts, one for the "*hot part*" where the analogue front-end is, and one for the "*cold part*", dedicated to communications. The reason for this isolation is the protection

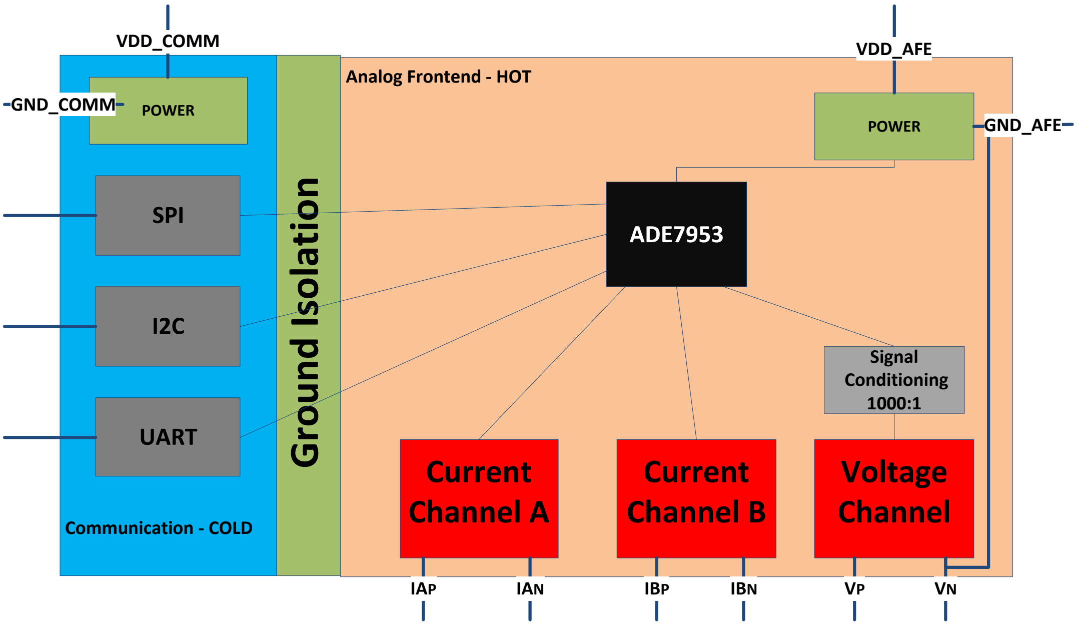


Figure 3.3: ADE7953 evaluation board I/O

of user and user-equipment connected to the communications interface, since that in the *hot-part* the ground may be coupled to *high-voltage signals*, due to the direct connection of the system's ground to one of the *voltage's inputs.*

Both power inputs are rated to have an independent $3.3V_{DC}$ ± 10% *voltage supply*[4]. The one connected to the hot part was based on a $3.3V$ regulator, a `UA78M33` from *Texas Instruments*, connected to the *lab bench supply.* The other one was deployed in conjunction with the communication by a *micro-controller development board* connected to a *PC*, that will be further discussed further ahead.

Voltage Sensing

The voltage sensing of the *board* can be directly driven by the utility's voltage signal. The V_P input shall be driven with the *Phase conductor*, while the V_N shall be driven with the *Neutral* one.

This is done by connecting the conductors of the configurations power strip *in parallel*, as depicted in figure 3.4, to the board.

Current Sensing

As mentioned before the *ADE7953 Evaluation Board* doesn't provide a direct way to sense current. One has to design sensory circuitry to allow current sensing, meeting the platform's

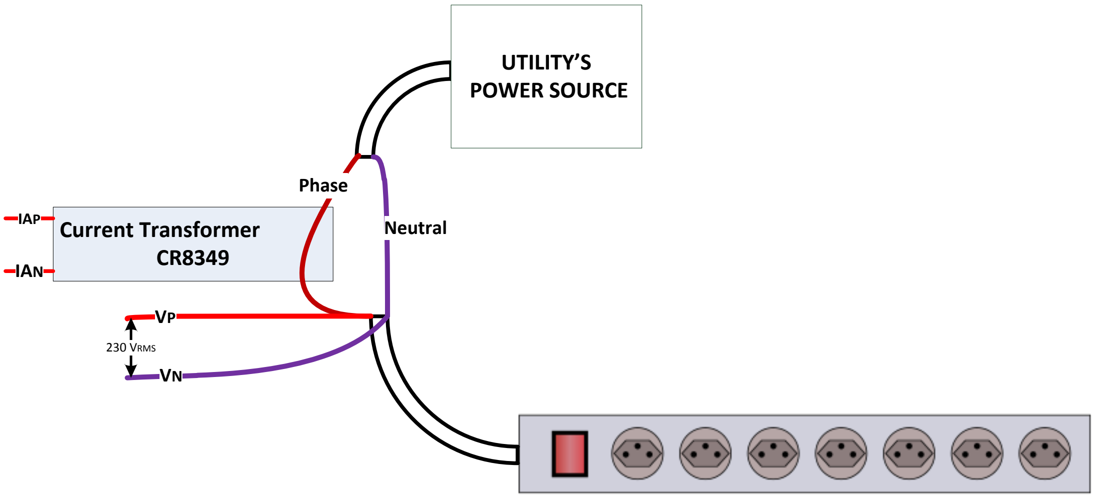


Figure 3.4: Load System Configuration

requirements.

Only one current channel needs to be used. *Channel A* was selected, since it is the most versatile[4]. Current sensing will be then made through the *current transformer* mentioned in subsubsection 3.2.1

The project of a transimpedance circuit to measure current is done in appendix C, where the *sensor circuit* was deployed with a $R_{burden} = 2.5\Omega \ \pm 1\%$. The circuit then connects to the I_{A_P} and I_{A_N} of ADE7953 Evaluation Board.

3.3 Communicating with the Data Acquisition System

3.3.1 ADE7953 Communication Model/Memory Model

Before implementing any kind of communication with the *ADE7953*, it is important to understand the underlying concepts. All of the features can be accessed through addressable registers *via* 3 distinct *communication interfaces*.

Registers are 8, 16, 24 and 32 bit long. The data in 32 bit registers is the same of that in its correspondent 24 bit registers, through signal extension. These differences are justified with the 24 bit registers being more efficient in terms of communication speed while the 32 bit registers provide easier programming with the long format [4]. All the registers are addressed with a *2 byte* value. The *most significant byte (MSB)* of the address contains an indication of the register's length, being the registers length equal to

$$\text{register length} = ((\text{address's MSB}) + 1) \times 8 \; \textit{bits} \; . \tag{3.1}$$

The registers lengths and the corresponding address format are represented in table 3.3, where `X` means *don't care*.

Register Length	Address
8 bit	`0x0XX`
16 bit	`0x1XX`
24 bit	`0x2XX`
32 bit	`0x3XX`

Table 3.3: Register's adressing scheme

The communication interfaces are three:

- 4 - pin SPI interface;
- 2 - pin bidirectional I^2C interface;
- 2 - pin UART interface [4].

Despite being carried out *via* different interfaces, the steps necessary to access the registers are generically the same consisting in read or write one register at a time in an ask/reply fashion. Figure 3.5 shows a minimal representation of a data transaction.

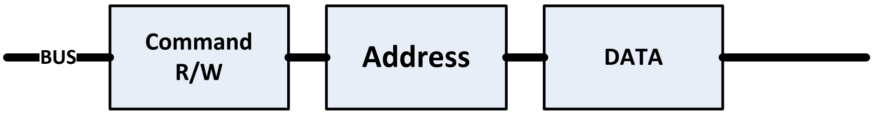


Figure 3.5: Minimal data transaction

3.3.2 ADE IO INTERFACE BOARD Z

To develop the system it is necessary to implement communication between the acquisition system and a *PC*. The *ADE7953 Evaluation Board* already comes with an interface to communicate with a *PC via USB*, emulating a *Virtual COMM*. That interface is done with a independent board, the *ADE IO INTERFACE BOARD Z* that connects to interface depicted in figure 3.3. This PC interface was developed to communicate directly to proprietary software in *LabVIEW*, and allows to test the system with all the communication technologies allowed in the *ADE7953*, *I^2C,SPI,UART*[14]. But the protocol it uses to communicate with the *LabVIEW* program is not available, nor the program's *API*, making it impossible to develop custom software around it.

It is then necessary to deploy another way of communicating with the acquisition system.

3.3.3 Communicating Directly

UART

Due to its simplicity, it was first tested the UART implementation, directly connecting the *PC* to the *ADE7953* through an *USB-UART* converter, that displayed in the PC as *virtual COMM*. Though it was possible to establish communication, it didn't provide enough performance,it was limited to a *4800bps* and the connection wasn't reliable ,the culprit is it's timing scheme, that was not easy to guarantee by general purpose *operative systems* which have scheduling granularity in the order of the of tens of *milliseconds*, while the protocol has constraints in the order of *milliseconds*[4]. Posteriorly to this test, it was found one configuration on the *virtual comm* driver that could have produced this behaviour, but another solution with much better performance was already developed.

SPI

Since the UART interface did not meet the *requirements*, communicating *via* another interface is imperative. The choice was *SPI* because it has the capability of being faster in data transactions than *I²C*. It can operate at a maximum clock of $5MHz$ with one bit *per* clock with an fixed overhead of $24bits$ *per* register access, while *I²C* can operate at a maximum clock of $400kHz$ with 1 bit *per* clock with an overhead of $16bits$ plus 1 start and 1 stop bit plus $1ack$ bit per byte written in the bus. Besides all that, *SPI* can be considered simpler than *I²C*.

3.4 SPI-PC Gateway Implementation

As normal *PCs* don't provide external *SPI* interface. To fulfil the communications implementation, it is demanded to implement a *gateway* to provide the needed communication interface. Some requirements are to be taken into account. The communication has to have high bitrates, and should be compatible, *i.e.*, should be in a connectivity interface present in the majority of computers.

3.4.1 Chipkit Max32

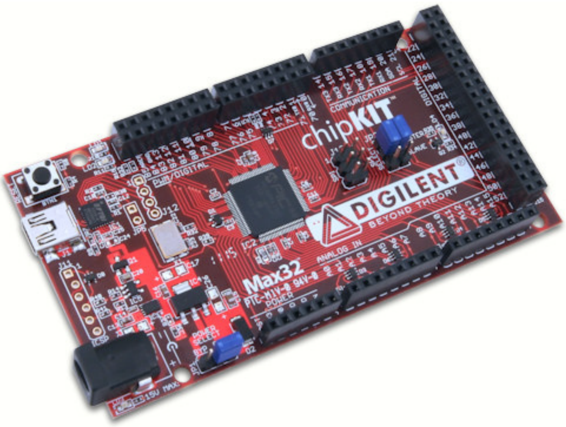


Figure 3.6: chipKit Max32 development board [7]

Again, for fast integration, it was chosen to develop the gateway with an integrated solution, in this case a *microcontroller* development board. The platform chosen was *chipKIT Max32* by *Digilent* (figure 3.6), a microcontroller board based on *Microchip PIC32MX795F512L*. For the project's interest, this platform has the following features:

- PIC32 high performance 32-bit micro-controller at 80 MHz with a 5 stage pipelined *MIPS core*[35];

- Hardware SPI driver, performing with maximum of 40 MHz clock[34];
- Hardware UART driver, with performance up to 20$Mbps$[34];
- FTDI FT232R UART to serial UART that may perform at a maximum of 3 $Mbaud$ at 7 or 8 bit symbols[7][16];
- 3.3V regulator that can provide up to 500 mA [7];

This platform meets all the connectivity and communications requirements. It exceeds the SPI specifications of the *ADE7953*, it has USB connectivity in order to communicate with a PC, that is good because that's an interface that the majority of PCs have, and the UART has high bitrates. Plus it is capable of supplying power to the communications interface of the *energy monitoring board*, without any other connection than *USB*.

3.4.2 Gateway Deployment

Figure 3.7 presents a diagram of the gateway and its interface with the rest of the system.

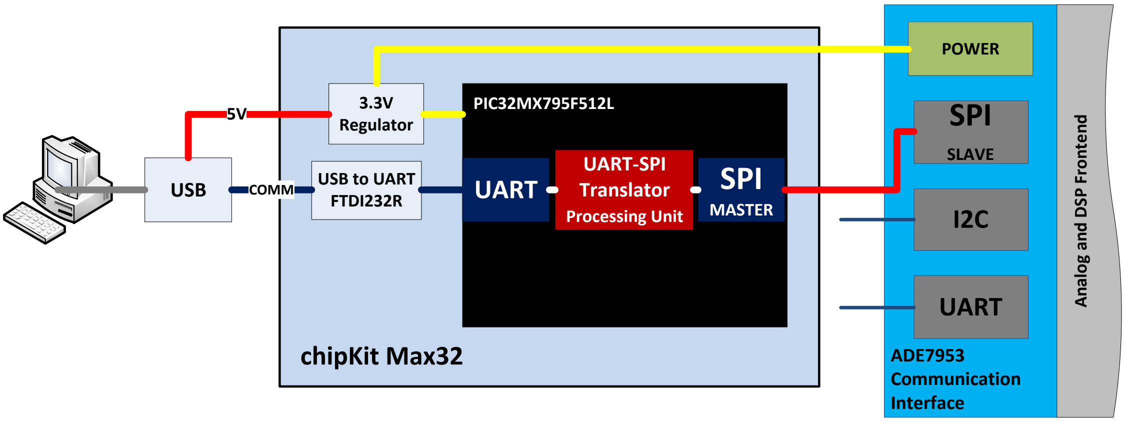


Figure 3.7: SPI gateway implementation

ADE7953's SPI interface

ADE7953's SPI interface is a fully functional SPI device that uses all four communication pins. It operates in slave mode which means that a clock must be provided by the master. This clock can be at maximum 5MHz.

As said before, registers are accessed one at a time. The access to a register is encapsulated in a *SPI* packet. Which is always initiated by the master, consisting in two initial bytes for the register's address. Then it is transmitted a command byte, to state if the access will be a *read or a write*. Finally the data is sent from *ADE7953* to the master in case of a read, or written to *ADE7953* by the master, in case of a write. All the data is sent or received MSb first [4]. A representation of a packet may be found in figure 3.8.

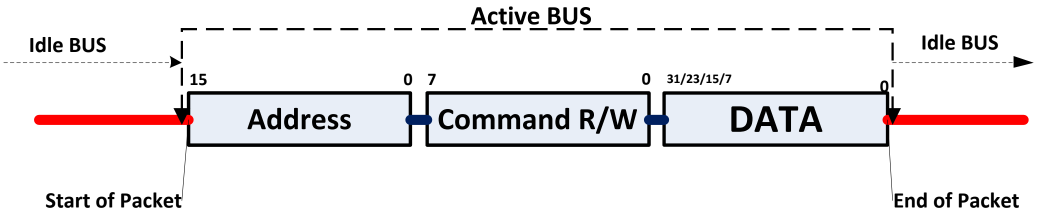


Figure 3.8: SPI Packet

PIC32 SPI Interface

The PIC32 provides a full function *SPI hardware driver*, that can provide *master* or *slave* communications. For this implementation, this interface is configured as *master*, providing a clock of 1 Mhz to the *slave* and will be responsible of managing the communications. Assuming that the system needs the data from *Voltage, Active Power* and *Reactive Power* registers at a frequency of $1.2kHz$, being the registers of 24 *bits* and having the communications an overhead of 24 *bits*, the minimum clock of the SPI has to be 173 kHz. This configuration is more than sufficient to the specified requirements.

UART Interface

An UART interface is used to connect the gateway to a *PC*. This UART interface is implemented with PIC32's *UART driver* connected to *FTDI FT232R USB-UART converter*, that connects with PC *via* USB, and is seen by *Operative System (OS)* as a virtual *COMM RS232 port*. The interface is configured to operate asynchronously at a baudrate of 115200 *bps*. Assuming that the gateway would work with an optimized protocol that sends to the PC the needed data continuously with a minimum overhead of *2 bytes*, one before the data and one after, having the system to get data from three *24 bit* registers at $1,2kHz$, the data has to arrive at the PC at a rate of 48000*bps*. Being the *UART* configured at 115200*bps*, the actual data rate is $\frac{8}{10} \times 115200 = 92160\,bps$, again the configuration is more than sufficient for the specified requirements.

3.4.3 Communication Model

The *communication model* implemented in this *gateway* is coherent with the *memory model* implemented in the *ADE7953*. The accesses are done to single registers, and issued *via* the UART to the *gateway*. A write to a register is issued by sending a packet to the gateway, with a write command, the address and the data to write. The *gateway* then is responsible to communicate with the device, and forward the write transaction, as depicted in figure 3.9. A read is issued by sending a *read command* with the register's address to the gateway. Then the gateway fetches the data, in the register, from the device and replies it via *UART*. A read transaction is depicted in figure 3.10.

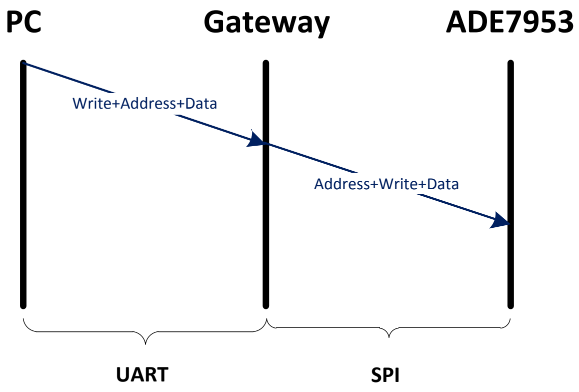


Figure 3.9: Gateway Write

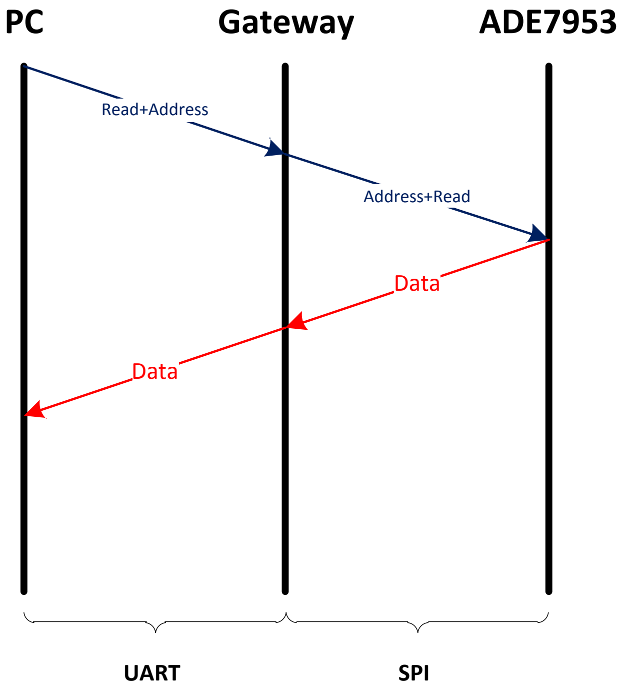


Figure 3.10: Gateway Read

This communication model was chosen by its simplicity, and it is adequate for testing and configuration purposes. However it has some limitations, namely it is not suitable for high throughput systems that need synchronized data at very high sampling rate. Considering that the PC-Gateway is much more slower than the Gateway-device, because of structural interface limitations, the overhead introduced consumes valuable bus time that may jeopardize the data synchronization, and that in other models could be used to send real data. Furthermore issuing single access to registers introduces delays that are inconvenient.

A more suitable implementation would be such that, in case of *read of registers* could issue repetitive reads of a list of register cycling through them. In case of the *write of registers*, it could be also be improved by being able to write to several registers in a single access. Note that writes aren't critical since they are used almost only during the configuration phase of the device, and in sporadic maintenance. Such a model would allow for the data to be read by the *PC* at almost the maximum of the speed of the *UART*, by eliminating the overheads and the round trip times, assuming that the Gateway-Device communication is much faster than the PC-Gateway communication, which is usually true since the gateway is implemented to a single purpose, being very efficient in one task, while the PC is designed to perform a high number of tasks simultaneously, turning it mediocre in each task.

An example of an alternative method for high-performance access is represented in figure 3.11. A repetitive read is issued by a sending special command of *cycle read* and a list of registers to read, the gateway than cycles the list repetitively by issuing reads in the ADE7953, and when it has a new version of each register of the list it sends it to the PC *via* UART.

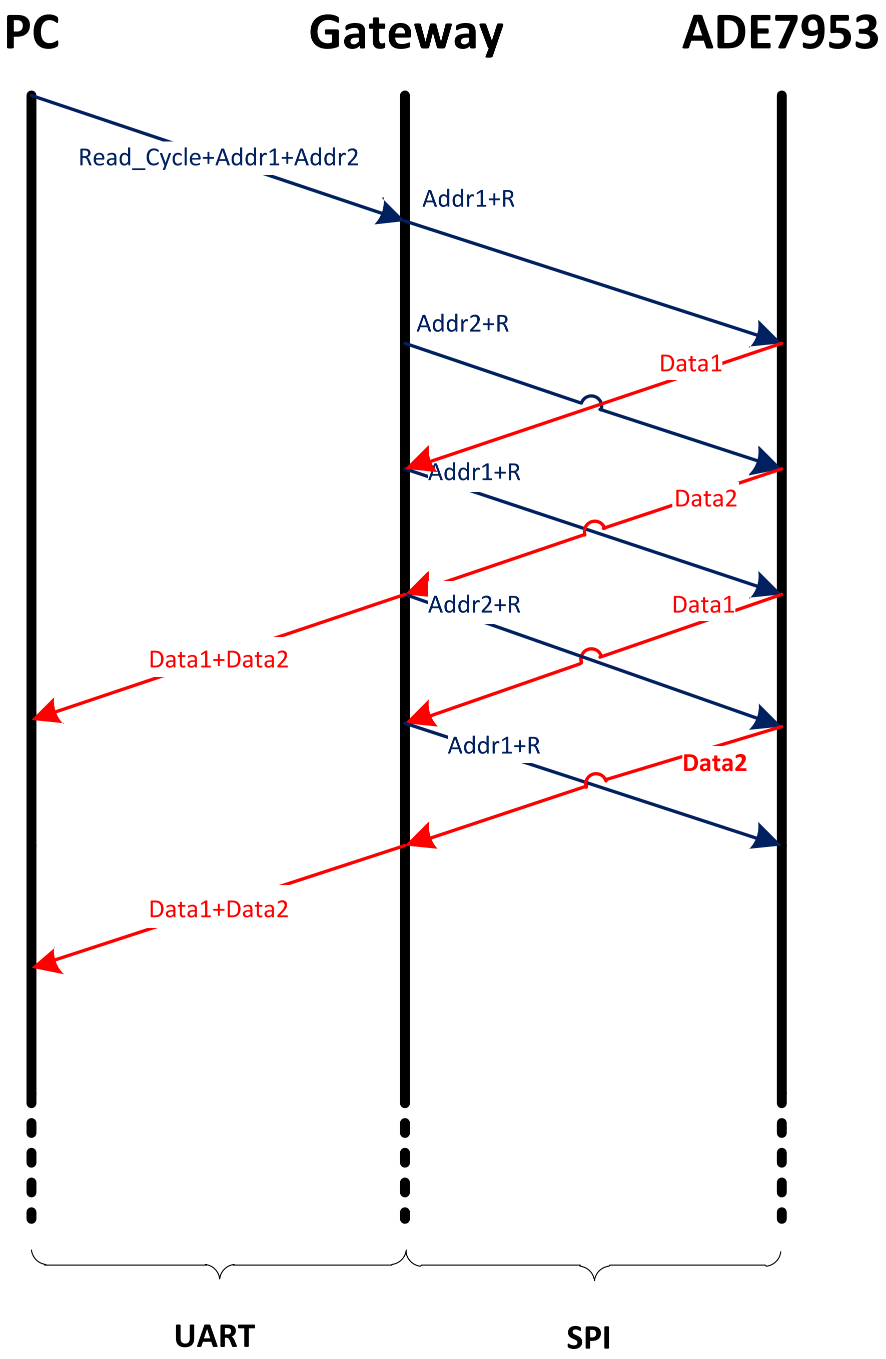


Figure 3.11: Gateway Read Alternative

3.4.4 UART Protocol

The *UART protocol* developed is based on the one for ADE7953's own protocol for its *UART* but without the time constraints [4]. A representation of a basic packet of the *UART* protocol is represented in figure 3.12. A full description of the protocol implementation is presented in appendix F.

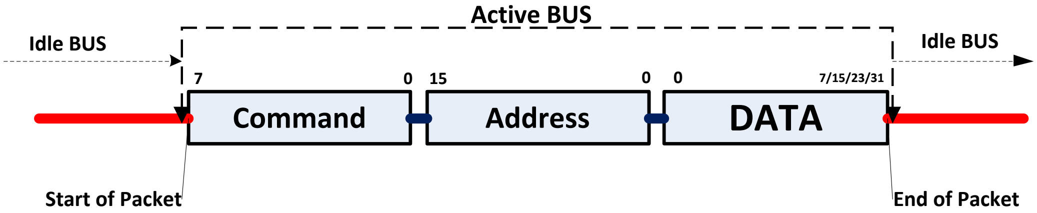


Figure 3.12: UART protocol basic packet

3.4.5 Gateway Firmware Model

Figure 3.13 presents the data-path/state machine inside the gateway, illustrating how the operations are processed and how the communications are handled.

UART Message Handling

The *handling* of *UART* messages can be considered a process and flows as follows. A start of a *new message* is detected after the *Start of Frame Delimiter (SFD)* has passed. The type of message is then fetched. A decision upon what type of message is made. If a *read* command is detected, the machine then fetches the next 2 bytes as address and finalizes the message. If a write command was issued, the next 2 bytes are fetched, again, as address. Next it is fetched the data, which length, here *N_bytes*, is found by analysis of the address's *MSB*, and finally the packet is finalized. The packet finalization depends also of the receiving of *End of Frame Delimiter (EFD)*. If any error is detected on *SFD*, *EFD*, or any other field which data is different from what is supposed to, the program flow returns to the beginning, with the start of a *new message*. After a *message* is finalized, the data is passed to the *SPI handling process*

3.4.6 SPI Handling

SPI handling starts after a complete message is received *via UART*. Upon receiving, the process decides what to do depending on the operation to perform. If a *read* was issued, the system reads *N_bytes* (again the length is found from the address) of the register, and sends the read data *out*, *via* UART, and then finalizes the command. If a *write* was issued, *N_bytes* of data coming from the data of the received packet, are written to the register, and then command is finalized.

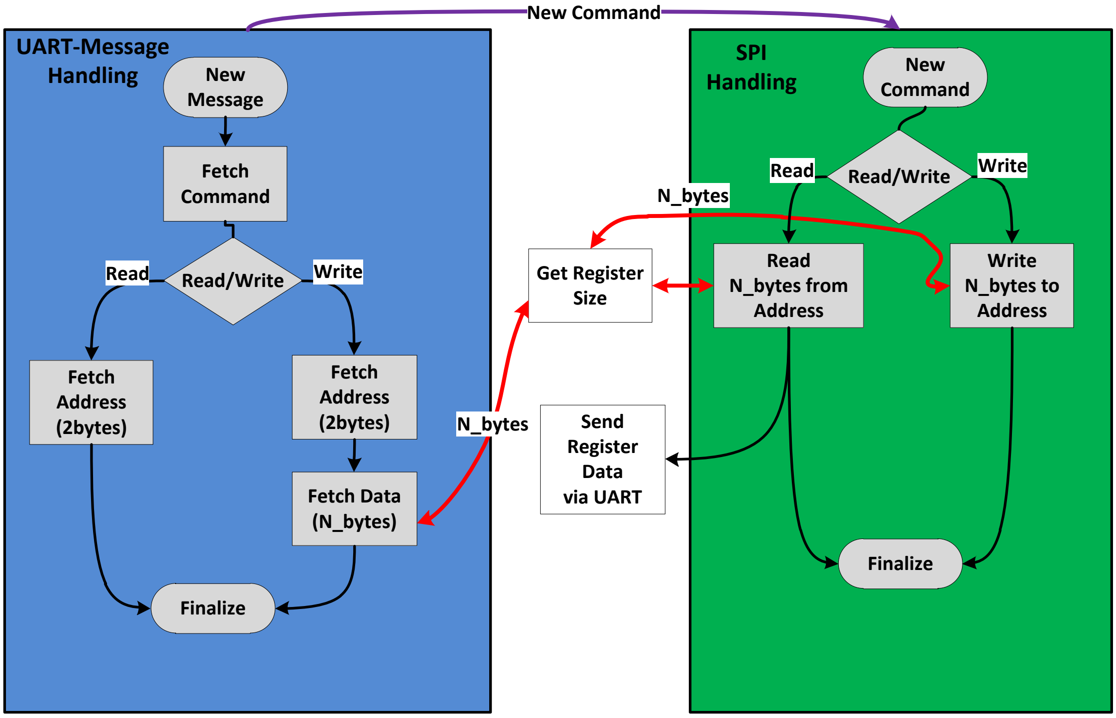


Figure 3.13: Gateway Dataflow

The system has ended the processing of a message and is ready to receive and process another.

3.5 Wireless Sensor Network Nodes

The project's proposition demands the deployment of a *complementary WSN*, to perform *Indirect Power Sensing* of individual appliances, in order to augment the *data* available for *load disambiguation*. These *WSN* has, too, some requirements. It has to cause the minimum intrusion to customer's space, has to be quick and easy to install, and preferably cheap. This implies that the *wireless sensor nodes* need to be, small, battery-operated, and have to have low power consumption for high autonomy.

3.5.1 uMRFs

The *WSN nodes* used were the the *uMRFs*, provided by *Micro I/O Serviços de Electrónica*, figure 3.14. They are developed for embedded solutions with wireless applications and they satisfy the needed requirements. The nodes are compact and have small profile, they are battery operated by a rechargeable *Li-Ion battery*. The processing capabilities are provided by a 8-bit low power micro-controller from microchip, PIC18F26K20 with *nanowatt XLP*. The wireless capabilities are provided by *IEEE 802.15.4* compliant radio transceiver MRF24J40MA, which protocol is designed for low power applications. They provide USB

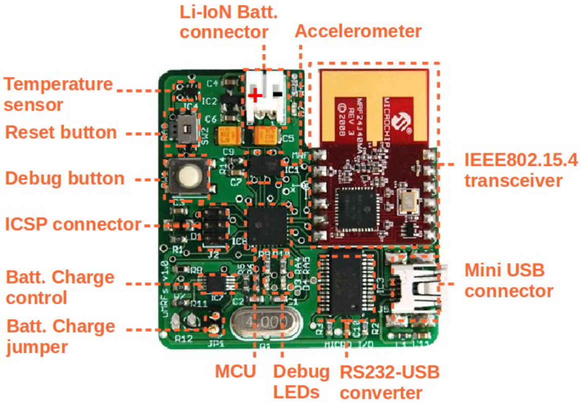


Figure 3.14: uMRFs wireless node[5]

connectivity by a USB-UART converter. The USB connection can also be used to provide power to the node and to recharge batteries[5].

The nodes provide direct digital input/output to the micro-controller *via* connection pins, which will be used to interface to external sensors, sensing the environment[5].

3.6 Deployment of Indirect Power Sensing

The indirect sensing method is based on the fact that appliances may emit measurable physical signals when consuming energy [21].

To indicate if some appliances are *ON/OFF*, according to the appliance model followed in the project, it is necessary to implement sensory circuitry which output is directly correlated with the appliance's power state. Since there is no need to estimate the power consumption from this, the circuits output was chosen to be digital, indicating only an *ON* or an *OFF* state. The circuits developed were based on *light sensors* and *magnetic sensors*. Operation and implementation details will follow.

3.6.1 Ambient Light Sensing Circuit

Lamps emit light when consuming power. Sensing the light intensity near a lamp is a way to discriminate its internal state.

There exist such sensors called *ambient light sensors*. Ambient light sensors are photodetectors designed to perceive the power emitted in the visible spectrum. These sensors shall be ideal for the end here demanded, as they can sense the most important output of a lamp, which should be the easiest to detect.

There exist essentially two types of light sensors:

Light Dependant Resistors, CdS Cells - Commonly known as *LDRs*, these sensors vary their impedance with the intensity of light, in a phenomena called *photocondutance*. These sensors have Cadmium in its composition, not being suitable for consumer products having a *RoHS* prohibition.

Photo-diode/Photo-transistor - these detectors are semiconductor based, with p-n junctions that convert light in electricity, capturing photons, creating a photo current in phenomena called photoelectric effect. The main difference between *Photo-diodes* and *Photo-transistors* its the output/input gain, which is much greater in *Photo-transistors*

The selection of photo-transistor's comes naturally, as they are *RoHS* compliant and are easy to use.

The sensor used for light sensing was the *TEPT5600* from Vishay, this is an *ambient light sensor* based on a silicon NPN planar photo-transistor. It is sensitive to visible light much like the human eye having its peak sensitivity at $570\,nm$[43].

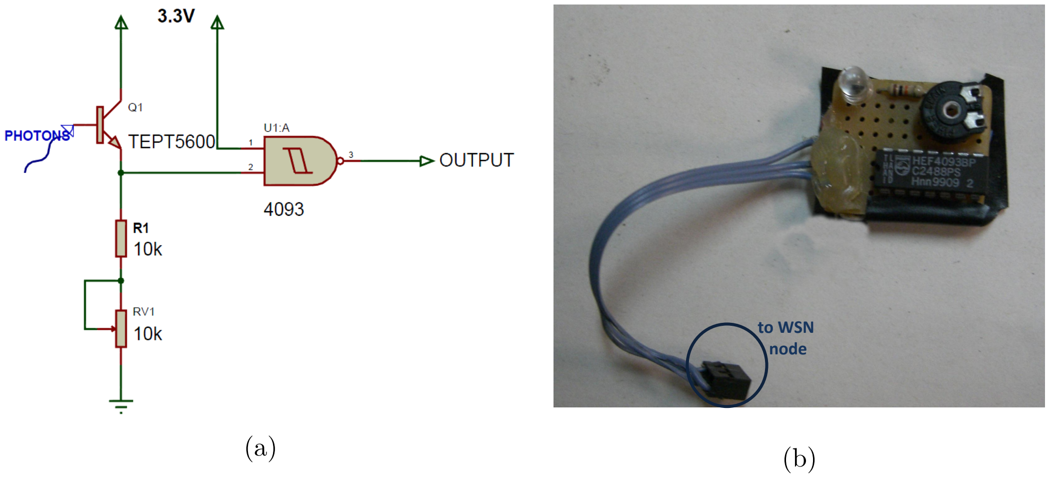
The transistor is placed in a transparent case, capturing photons in the *base-collector junction*, imposing a current flowing from *collector* to *emitter*,(*photo-current*).

Sensor Circuitry

The circuit to develop is a digital discriminator of presence of light, so it is wanted to put the sensor in saturation. It's then necessary develop a transimpedance circuit to convert *photo-current* in voltage.This sensor circuit is to be attached to *uMRFs* where it will output its digital value, and from where it will get its power supply of $3.3\,V$.

The circuit developed is presented in figure 3.15a, where it is represented the transimpedance circuit attached to a *Schmitt-trigger*, to output digital levels regarding the appliance's state, *ON* or *OFF*. The design and analysis of the *light sensor circuit* is presented in appendix D.

The sensor is designed to be placed near a lamp, where the light intensity is very high. A final assembled version of the developed circuit/device can be seen in figure 3.15b.



(a)

(b)

Figure 3.15: Light Sensor: a) - Light Sensor Circuit Schematic; b) - Assembled Sensor Circuitry

3.6.2 Magnetic Hall Effect Sensing

Proposition: one could measure/detect current flowing through a current carrying conductor by measuring the magnetic field around it, with a magnetic *hall effect sensor*.

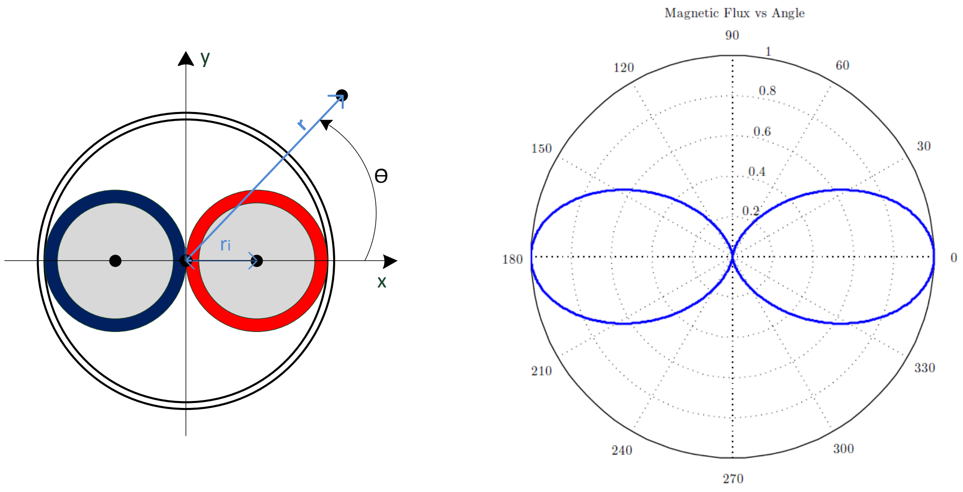
Hall effect sensors are semiconductor based devices that when subjected to a magnetic field, output a voltage proportional to the field strength [19].

Taking into account that this project aims to detect household appliances non-intrusively, the place where one could place the sensor is attached to the electric cable of the appliance, which generally is a two wire cable as represented in figure 3.16a.

From the *Ampere's Law*, which an analysis is presented in appendix E, it was derived the dependence of the magnetic flux at a distance r of the center of a fixed position two conductor cable. The magnetic flux varies with the angle(θ) as expressed in equation 3.2. A normalized plot of such equation is shown in figure 3.16b.

$$B(\theta) = \frac{I\mu}{2\pi\|(r\ \cos(\theta) - r_i)\hat{\mathbf{x}} + (r\ sen(\theta))\hat{\mathbf{y}}\|} - \frac{I\mu}{2\pi\|(r\ \cos(\theta) - (-r_i))\hat{\mathbf{x}} + (r\ sen(\theta))\hat{\mathbf{y}}\|}\ (T) \tag{3.2}$$

The first term of the equation corresponds to the component of one of the conductors and it is additive. The second term corresponds to the component of the other conductor and it is subtractive because the current flow is in the inverse direction and so the field is symmetric to the first.



(a)

(b)

Figure 3.16: Magnetic Flux around a two Conductor Cable: a) -Cut-section of a generic two conductor cable; b) - Magnetic Flux vs Angle

From the plot, one can infer that the function maximum is obtained int $\theta \in \{0^{\text{o}}, 180^{\text{o}}\}$ with the value

$$B_{max} = \frac{I\mu}{2\pi(r - r_i)} - \frac{I\mu}{2\pi(r + r_i)}\ (T)$$

and is minimum at $\theta \in \{90, 270\}$ with the value

$$B_{min} = 0\ (T)$$

since at that points the contribution of the magnetic flux of each conductor is equal in norm but with inverse directions and so they cancel themselves.

If a *hall effect* sensor is to be attached to a power chord of an appliance, it should be possible to extract information about the current being carried in that conductor. This method can be used to detect and measure the current flowing in the chord, but the uncertainty in the cable placement and the possible sensor position drift, makes it only viable to detect if the appliance is *ON* or *OFF*.

In conclusion, if one can find a sensor with sufficient sensitivity to sense magnetic fluxes around a conductor and have special care with the sensor placement, it is possible to detect if an appliance is consuming energy or not, and with sufficient training it could be even possible to differentiate *ON* states, for *multi-state* appliances.

SS49E - Linear Hall-Effect Sensor IC

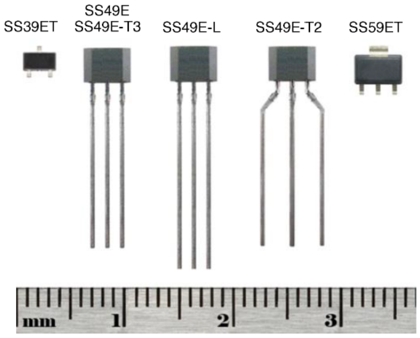


Figure 3.17: SS39 Series Linear Hall Effect Sensors[42]

The sensor selected was the SS49E *Linear Hall-Effect Sensor IC*, figure 3.17. This sensor is a *low cost* and *compact linear hall-effect sensor*. The sensor aims to be used for basic current sensing and for position/displacement sensing with a sensibility of $1,4mV/Gauss$[42]. Its main electrical characteristics are:

- Low voltage capability ranging from 2.7 to $6.5\,V$;
- Analog Output with $1,4\,mV/Gauss$ sensibility;
- Maximum magnetic range of $\pm 1000\,Gauss$;
- Wideband frequency response up to tens of *kilohertz*.
- Output voltage, $V_{out} = 2.5\,V$ at $0\,Gauss$

Detecting Appliance's Power State

The objective is detecting the power state of the appliance by detecting the current flowing in the cable. The aim is then to develop a circuit which output is a logical digital value indicating the presence or not of current in a cable.

To perform the above mentioned function it is necessary to perform certain operations. Figure 3.18 shows a simple diagram of the implemented circuit for indirect current sensing. Further details of the development of this circuit are described in appendix G.

The output of the sensor, to our interest, is a sinusoidal wave at $50Hz$ with few *millivolts* of amplitude.

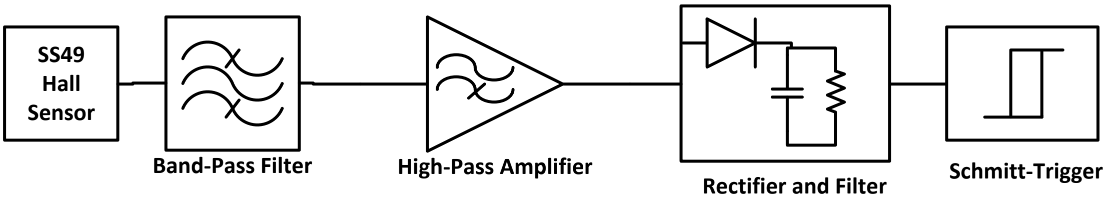


Figure 3.18: Block Diagram for indirect current sensing

The sensor's output passes then through a *band-pass filter* to remove other frequencies than that of interest. High frequency noise may appear due to radio signals.

The signal has very low amplitude, so it passes through an *amplifier* with high-pass characteristic, in order to amplify the desired signal and reject any type of DC.

Being the signal at an amplitude in the order of the units of *Volt*, it is necessary to convert it to a *DC* signal in order to further convert it to the digital signal. The signal is passed then through a *Rectifier and Filter* that generates a *DC* voltage corresponding to the maximum voltage of the *Steady-State* sinusoidal wave. In correct function the output here is a *high dc voltage* when there's current flowing in the cable, and *null voltage* otherwise.

The signal passes then through a *Schmitt Trigger* that converts the signal into a digital value indicating the presence or not of current. It functions as a comparator with hysteresis. A fully assembled version of the circuit can be seen in figure 3.19.

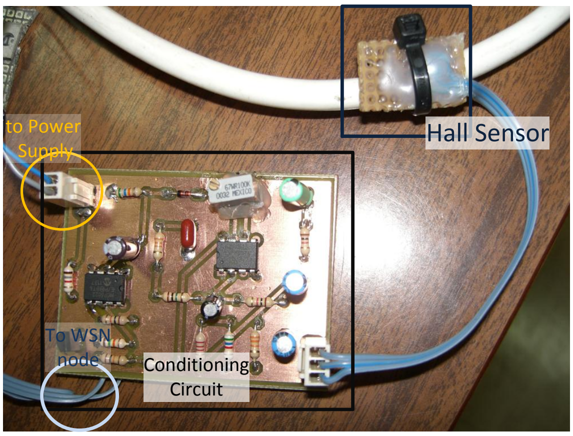


Figure 3.19: Fully Assembled Version of Indirect Current Sensor Circuit

3.7 Summary

This chapter presented the architecture solution and the hardware for the project.

The *data acquisition system* is based on *ADE7953 Evalutation Board*, a system that monitors an electricity facility, returning at *high sampling rates* various characteristics of the electric circuit.

The communication between PC and data acquisition system is intermediated by a *gateway* that communicates with the PC *via* virtual COMM and to *ADE7953 via* SPI.

The indirect sensing WSN is deployed by *uMRFs* nodes, using PIC 8-bit micro-controllers for processing and will communicate wirelessly *via* radio using `IEEE 802.15.4` protocol.

Indirect Power Sensing is deployed by circuits attached to *uMRFs.* The sensors are be based on photo-transistor for light sensing, and hall-effect sensors for current sensing. The sensing is deployed in such a way that the circuits output digital values indicating *ON* or *OFF* states.

Chapter 4

Software Implementation

4.1 Load Disambiguation and Appliance Classification

Before presenting the software solution for the *Fine Grained Electricity Monitor* it is important to acknowledge the underlying methods that will be in use. Following the *NIALM analysis* presented in Chapter 2, it will be here described the main algorithm for *load disambiguation and appliance classification*, depicted in figure 4.1.

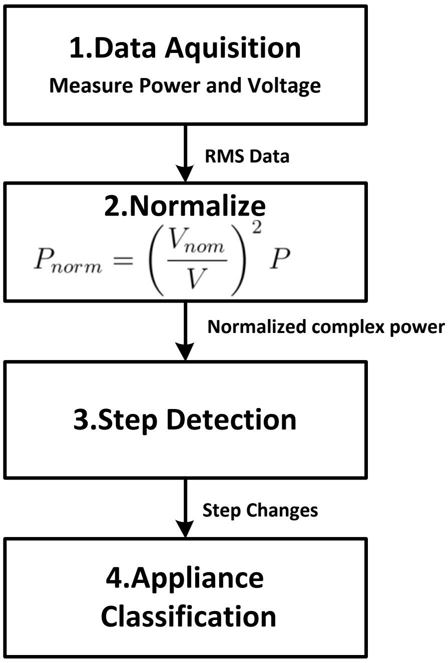

1.Data Aquisition
Measure Power and Voltage
RMS Data
2.Normalize
$P_{norm} = \left(\frac{V_{nom}}{V}\right)^2 P$
Normalized complex power
3.Step Detection
Step Changes
4.Appliance Classification

Figure 4.1: Load Disambiguation Algorithm Representation

4.1.1 Initial considerations

To develop the algorithm it is necessary to choose the *signature* type that will be used to detect the *appliances*, as well as their model.

The *signature* type used is the *steady-state* with n*normalized complex power*, which is tolerant to variations in voltage supply

The *model* in use will be the *ON/OFF* model , where each appliance has unique steady state *ON* and *OFF* signatures, and where the *OFF* is the symmetric of the *ON* signature. For identification purposes each appliance has a tolerance within its signature, which results in the signatures being characterized by circles in the *P-Q plane*(in Phase-Quadrature, same as Real-Imaginary) for each state. The circles must not overlap for any appliance signature.

4.1.2 Pseudo-code Implementation

In this subsection it is described the Load Disambiguation Algorithm in *Pseudo-code* to complement the block diagram of figure 4.1

```

/* Data Acquisition and Normalization*/

at(sampling frequency Hz)
{
  Vrms = get RMS Voltage();
  Power = get Complex Power();

  Norm_Power = ((Nominal Voltage)/(V))^2 * Power;
  New_Norm_Power_Value(Norm_Power)
}


/* Step Detection */

  /* Steady State Detection */

last_window_steady = false;
at(sampling frequency Hz)
{
  power_window.push(Norm_Power);

  if(power_window.STD < STD_Threshold)
    if(last_window_steady == false)
    {
      /* New Steady State Detected*/

      state.power=power_window.get_mean_Power();
      state.time = System.get_Time();
      new_Steady_State(state);
      last_window_steady = true;

    }
  else
  {
    power_is_changing();
    last_window_steady = false;
  }
}

  /* Step Calculation */

for(each new Steady State)
{
  Step = (old Steady State) - ( new Steady State);
  new_Step_Detected(Step);
}

/* Appliance Classification */
  for(each New Step Detected)
{
  /* Comparison by euclidean distance*/
  Closest_App_Signature = step.find_closest_signature();
  if(step.is_within_tolerance(Closest_App_Signature)
  {
    /* A Change of State in an Appliance has been detected;*/

    Appliance=Closest_App_Signature.getAppliance();
    Event = Closest_App_Signature.getEvent();
    newEventDetected(Appliance,State);
  }
  else
  {
    No Operation();
  }
}
```

4.1.3 Data-acquisition

By sensing the installation's current and voltage it is computed the RMS *Voltage* and *Power* which are sampled for further processing.

4.1.4 Normalize

Normalize takes *Voltage* V and *Power* P as inputs and normalizes P through

$$P_{norm} = \left(\frac{V_{nom}}{V}\right)^2 P \ , \tag{4.1}$$

where V_{nom} is the nominal voltage of the load being monitored. Following there is a pseudo-code representation:

4.1.5 Step-Detector

The *step-detector* takes the normalized power as an input flow and sequences it into changing periods and steady periods. The power values are inserted in a finite moving window of length N. The operations of *standard deviation* and *mean* values are computed through the window. A representation is shown in figure 4.2.

Standard deviation is used as a measure of how much the power is changing in the window. If greater than the threshold *STD-Threshold* the power is considered to be changing at that

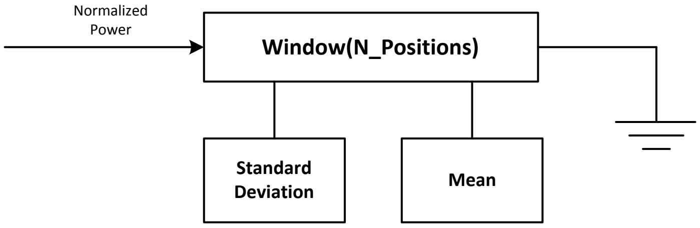


Figure 4.2: Representation of the filter for step detection

moment. Once it goes below the threshold the power is considered to be *steady*. A time-stamped sample of the *mean power* of the window is taken and registered as a *steady-state*.

The difference between *steady-states* is calculated and is considered to be a step. Not all steps are to be considered because some of them may be too small, so they are compared to a minimum threshold *Step-Threshold*. If greater, the step is registered and passed for further processing, otherwise is discarded. Following there is a pseudo-code representation:

4.1.6 Appliance Classifier

Once a step is detected, it follows the identification of the appliance that changed state. To achieve this goal, steps are compared with the signatures of the list of all known appliances to find the closest one. Once the closest signature is found it is computed if it fits within the appliance's own tolerance. If it does it is registered a detection of an appliance change of state, otherwise is discarded.

For illustration purposes, in figure 4.3 are represented *detected steps* and *appliance signatures* in the *P-Q plane*. *Step-1* is detected, the closest signature is *App2 ON*. *Step-1* is contained in *App2 ON* tolerance, so *Step-1* is classified as the *Appliance 2* turning *ON*. *Step-2*'s closest signature is *App1 ON*, but its not contained in the tolerance, so it is discarded.

This algorithm represents the basic operations needed to deploy, in order to provide NIALM. However it isn't supposed to provide a detailed solution for *Load Monitoring*, because it lacks appliance tracking, energy calculations and user interfaces. Following there is a pseudo-code representation:

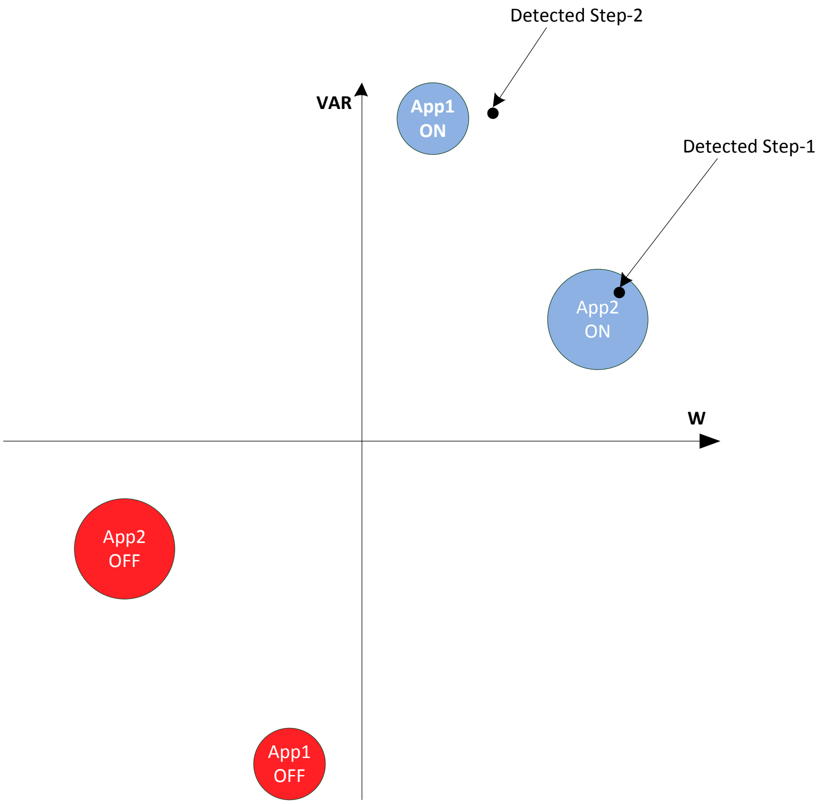


Figure 4.3: Steps and Signatures on the P-Q plane

4.2 Preliminary Validation of the Load Disambiguation Algorithm

Before implementing the system based on the algorithm presented, it is good practice to assess if it can perform as it is supposed, *i.e.*, if it provides a correct output, provided a correct input.

4.2.1 REDD - A Public Data Set for Energy Disaggregation Research

Reference Energy Disaggregation Dataset (REDD) is a publicly available dataset containing detailed information on power usage from real household environments. It was created to provide valuable data to research on energy disaggregation[22].

The data provided consists of *whole home* and *device specific* power consumption from various houses over several months.

For each house it was recorded the whole home electricity signal at high frequency ($15kHz$). For every recorded home the dataset provides data about up to 24 individual circuits. These circuits are normally for categorized appliances. Data is provided at $0.5Hz$. The dataset also provides data about up to 20 individual appliances, that were monitored via plug-level monitors. This data was recorded at $1Hz$[22].

The only data that is useful in this project is that of the low frequency. In case of *whole home* data, it is available the *Real Power* at a frequency of $1\,Hz$ samples. In the case of single appliance data it is provided again *Real Power*, but at $\frac{1}{3}Hz$. The sampling frequency is different from the frequency it was recorded because it is the result of some processing and not *raw* data.

For each monitored home there are individual files with data from aggregated load called *mains*, and files for individual appliances.

4.2.2 Testing the Algorithm in MATLAB

The platform chosen to assess the algorithms validity was MATLAB, due to its flexibility in programming and by making it easy to handle large quantities of data.

Single Appliance Characterization

A script that characterizes an appliance by executing the *disambiguation algorithm* upon the *data-flow* of power of a single appliance was developed in MATLAB, and it performs the algorithm as follows:

1 - Standard Deviation - The first step is pass the whole *Real Power* signal through a finite length *moving standard deviation.* Figure 4.4 illustrates this step. In this case it was passed a window of 4 samples through the data. As one can see the *standard deviation signal* only rises when a step change in the power flow occurs, otherwise is steady near 0. This is the first argument in favour of the algorithm.

2 - Steady State Identification - After passing the standard deviation, a threshold is passed to its result to find where the signal is steady, and where the signal is changing. Once the threshold is passed it is found the middle of the steady-periods, and taken a sample. That sample is called a steady state. It is assumed that on the middle of a period the signal is steady enough. Figure 4.5 shows the result of *steady-state* identification with the red bullets indicating the middle of a steady state.

3 - Step Detection and Classification - Now that the *steady-states* are known it is simple to calculate the *step-changes.* A differentiation of the consecutive *steady-states* is performed, resulting in the *step-changes.* Not all step changes may qualify as steps of an appliance as they may be too small. A threshold is passed through the step-changes in order to eliminate false positives. Figure 4.6 represents the step identification. Positive steps(turn *ONs*) are represented as represented in the middle of the *steady-states* as *yellow-stems*; and the negative steps(turn *OFFs*) are represented as *black stems.*The *step threshold* used in this case was of $100\,W$.

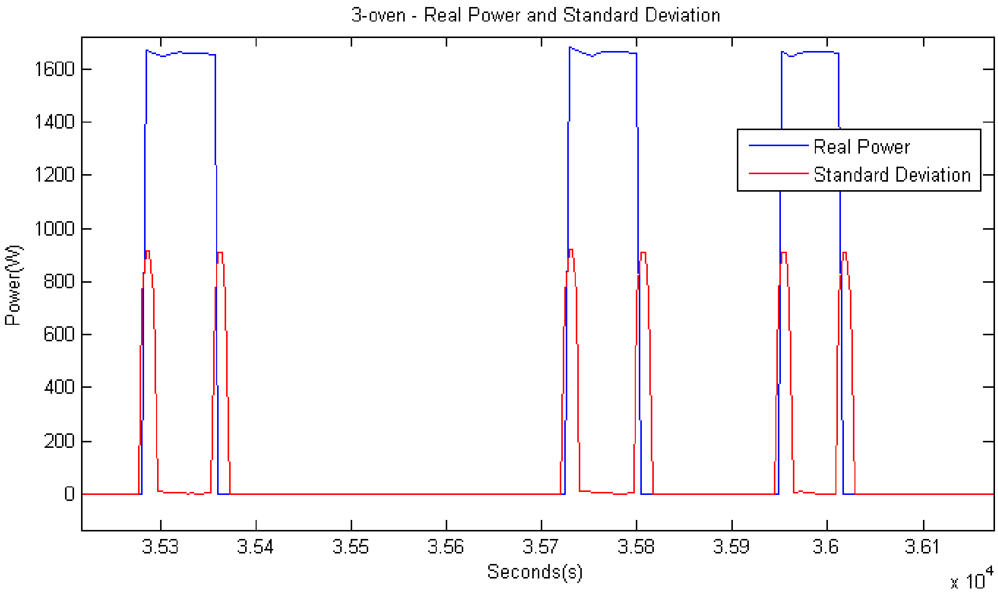


Figure 4.4: Pass of Standard Deviation window through the Real Power of an Oven

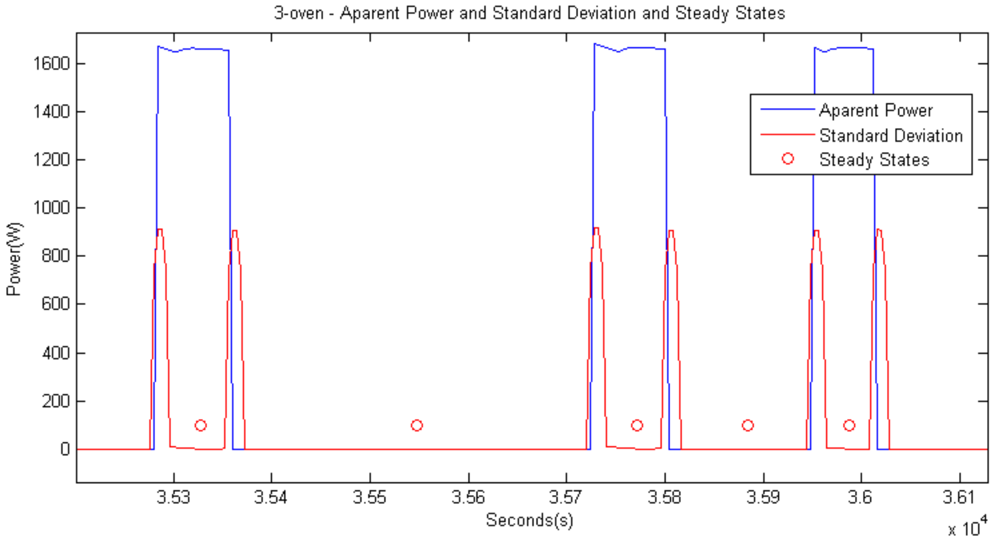


Figure 4.5: Representation of Steady State Identification

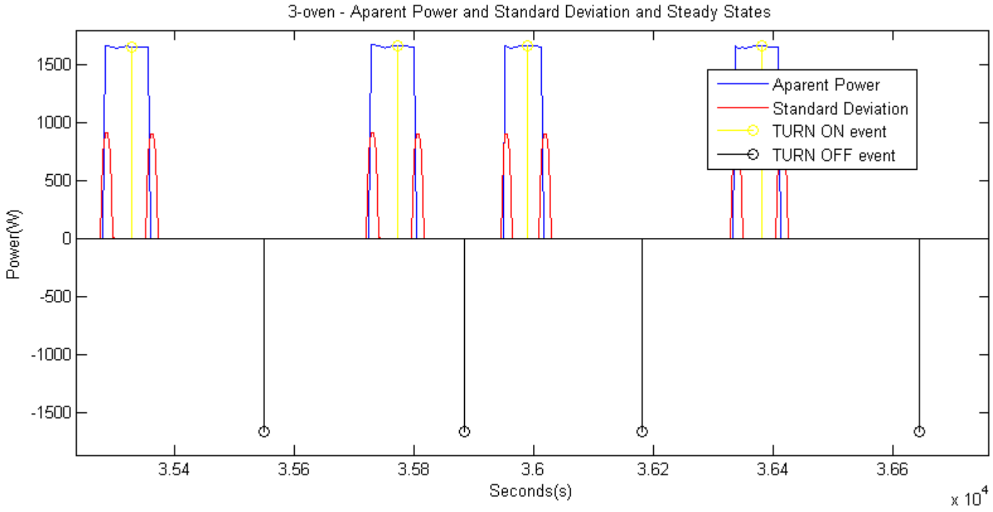


Figure 4.6: Representation of Step Identification

4.2.3 Results

Some of the appliance files of the REDD database were selected to validate the algorithm. After analysing the individual power flows of the various appliances it was possible to characterize some. The parameters of the analysis were:

- Time interval: 3134061 seconds;
- Window Size: 30 seconds;
- Standard deviation threshold: 50 Watts;
- Step Threshold: 100 Watts.

Table 4.1 shows the results of the appliance characterization, *Sig* is the mean of the steps detected, and *STD* is their standard deviation, *Num events* is the number of steps detected for that state.

	Turn ON			**Turn OFF**		
Appliance	*Sig(W)*	*STD(W)*	*Num Events*	*Sig(W)*	*STD(W)*	*Num Events*
Oven	1640	24	46	−1639	24	46
Refrigerator	186	13	662	−192	42	642
Dishwasher	545	350	107	−452	291	126
Lighting	235	51	28	−241	46	27
Microwave	1524	44	241	−1514	100	242
Bathroom GFI	1607	21	43	−1607	21	43
Washer Dryer	2706	32	107	−2706	32	107

Table 4.1: Single Appliance Characterization of some appliances in REDD

Analysing the results one can verify that the algorithm is indeed capable of discriminating *step-like* changes in well behaved *power flows.* Thus the *standard deviation* of the steps is very low in the majority of the appliances detected. The *OFF* signatures are very close to the symmetric of *ON*, apart from a small error, thus satisfying *Zero Loop-Sum Constraint.* And the number of detections of *ON* states is coherent with the number of detections for *OFF* states, satisfying in this way the *Uniqueness Constraint* described in section 2.3.

One of the appliances, the dishwasher, stands out having big *Standard Deviation* and signatures very different in absolute and even not coherent in the number of detection. The reason for this is that the appliance is not well described by the *ON/OFF* model for which the algorithm was designed, because it is multi-state, being only possible to described by the *FSM* model.

4.3 Preliminary Algorithm's Software Implementation

Now that the algorithm was verified in MATLAB it is necessary to implement it in a general purpose programming language. The programming language chosen was *JAVA*, for its easiness integration and portability.

The implementation here is a bit different than that on Matlab, since the data is processed iteratively as it is pushed into the processing, instead of being processed as a whole.

4.3.1 Step Detector

The heart of this implementation relies in the *stepDetector* class/interface, where are implemented the structures and functions to perform *step detection.*

Firstly the structures:

Processing Window - This is the *window* for signal processing, where the power flow is pushed to be analysed by the operations of *standard deviation* and *mean.*

Steady States Queue - This is a *FIFO queue* for *steady-states*, where they are pushed after being identified. The data in this structure are *states* that are defined by a *steady-state power signature* and a *epoch time-stamp.*

Non Steady-States Queue - Alongside the queue for *steady-states* there is a queue for *non-steady states* which the only data of value to push in is the time-stamp of the identification of a start of a *changing period.*

Steps Queue - This is the queue where the detected steps are pushed into, for passing to further processing.

The methods:

Push into Window - This is a method to push one *power sample* to the window in order to slide the power flow. Once the window is full, at each push the oldest sample is discarded.

Steady Power Discrimination - This is a method to discriminate if the power in window is steady, by comparing the *standard deviation* to a pre-determined *STD Threshold.*

States Identification - This is a method that by observing the succession of steadiness, or not, of the power flow, identifies and pushes a *steady-state*, a power sample with the mean of the window at the time of the detection and the time-stamp, to the *Steady-State Queue.* The *non steady-states* are also identified and pushed to the *Non Steady-State Queue* with a dummy power sample and the time stamp.

Step Detection - This is a method that takes at each time the two least recent *steady-states* and finds the distance between them comparing it to a *step-threshold*, and classifying if they are steps, pushing a power sample of the difference between the steps and a time-stamp for that sample.

4.3.2 Preliminary Appliance Classifier

Having the steps been identified, another important part of the system is the appliance classifier. For that there is another class/interface implemented, that is responsible by identifying the appliances that are turning *ON* and *OFF*, given the step changes.

There is an *Appliance* structure for registering what appliances are in the system, in which the classifier relies to perform the classification. In a preliminary implementation this structure has the parameters:

- ***Name*** - The name of the appliance;

- ***ON Signature*** - Complex power Steady-State Signature of the *ON* state;
- ***OFF Signature*** - Complex power Steady-State Signature of the *OFF* state;
- ***State*** - Flag indicating if the appliance is *ON* or *OFF*;

There is also a database where the data about all the appliances is stored, in order to be further accessed.

The **classification** starts with the computing of the minimum *euclidean* distance between a given step to every signature of all the appliances in the database, with the goal of identifying the closest signature and consequently the appliance and the event, an *ON* or an *OFF*, that is candidate to have occurred. The identification ends by the verification if the *step* is contained within a predetermined tolerance. If so, the step is classified with the *event* and the *appliance.* The state data of the appliance in the *database* is also updated.

4.3.3 Process data-flow

Having the methods and structures been defined, it can now explained the processing flow of the data.

The power samples are pushed into the *window.* Next, the *steady power discriminator* takes the *standard deviation* and the mean from the window, and discriminates the *steady-states* from the *non steady-states.* After the discrimination the *step identification* is made taking into account the consecutive steady states. The *steps* are then taken into appliance classification, where the appliances being turned *ON* or *OFF* are identified and the database is updated. Summarizing the dataflow must pass through this steps in order:

1. Steady State Discrimination
2. Step Identification
3. Appliance Classification

4.3.4 Validation

With the software implementation defined it is necessary to assess its accuracy and correctness. For this it was taken the *aggregated load* of some data from REDD and the characterization of some appliances from table 4.1, and it was performed load disambiguation in order to find the *Refrigerator* and *Oven* appliances. The parameters used for the process were:

- *Window* - 15 seconds for single appliance, 5 seconds for mains data ;
- *Standard Deviation Threshold* - 5 W;
- *Step Threshold* - 25 W;
- *Fixed Appliance Tolerance* - 40 W;

The results presented are from the first 800000 seconds of the records. Table 4.2 compares the number of detections made by detection of appliance in single appliance file, with detection of appliances in the aggregated load in the mains file, by the algorithm implemented in Java.

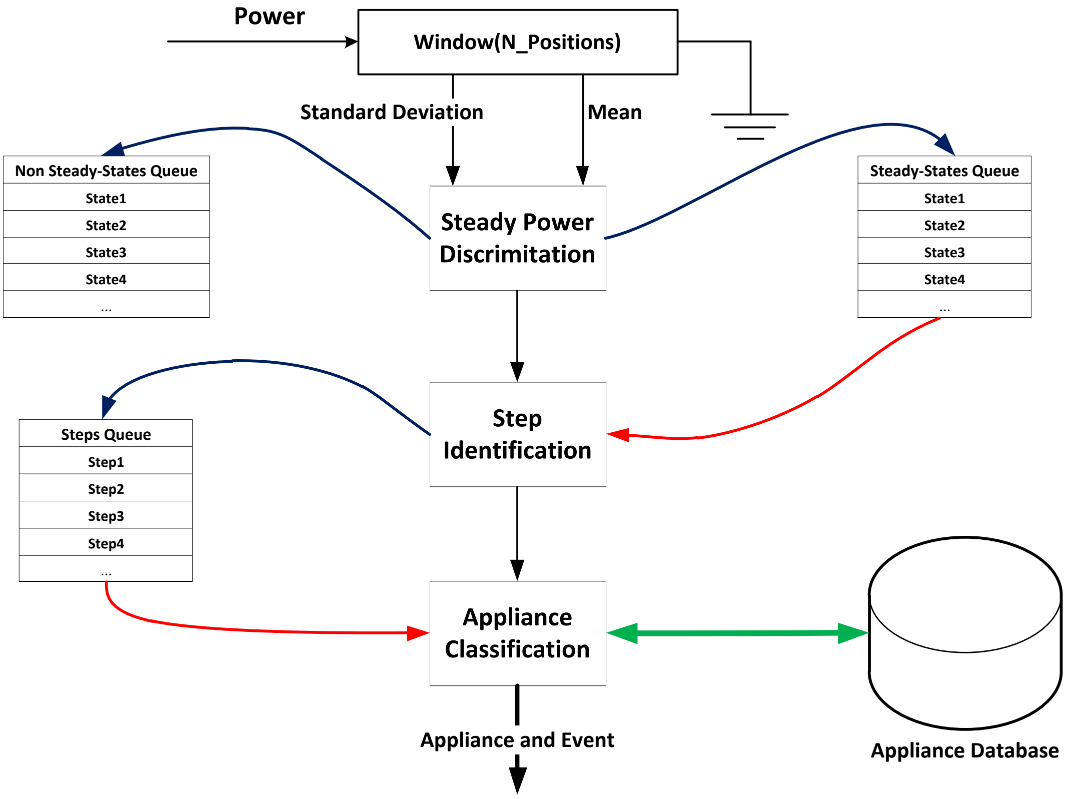


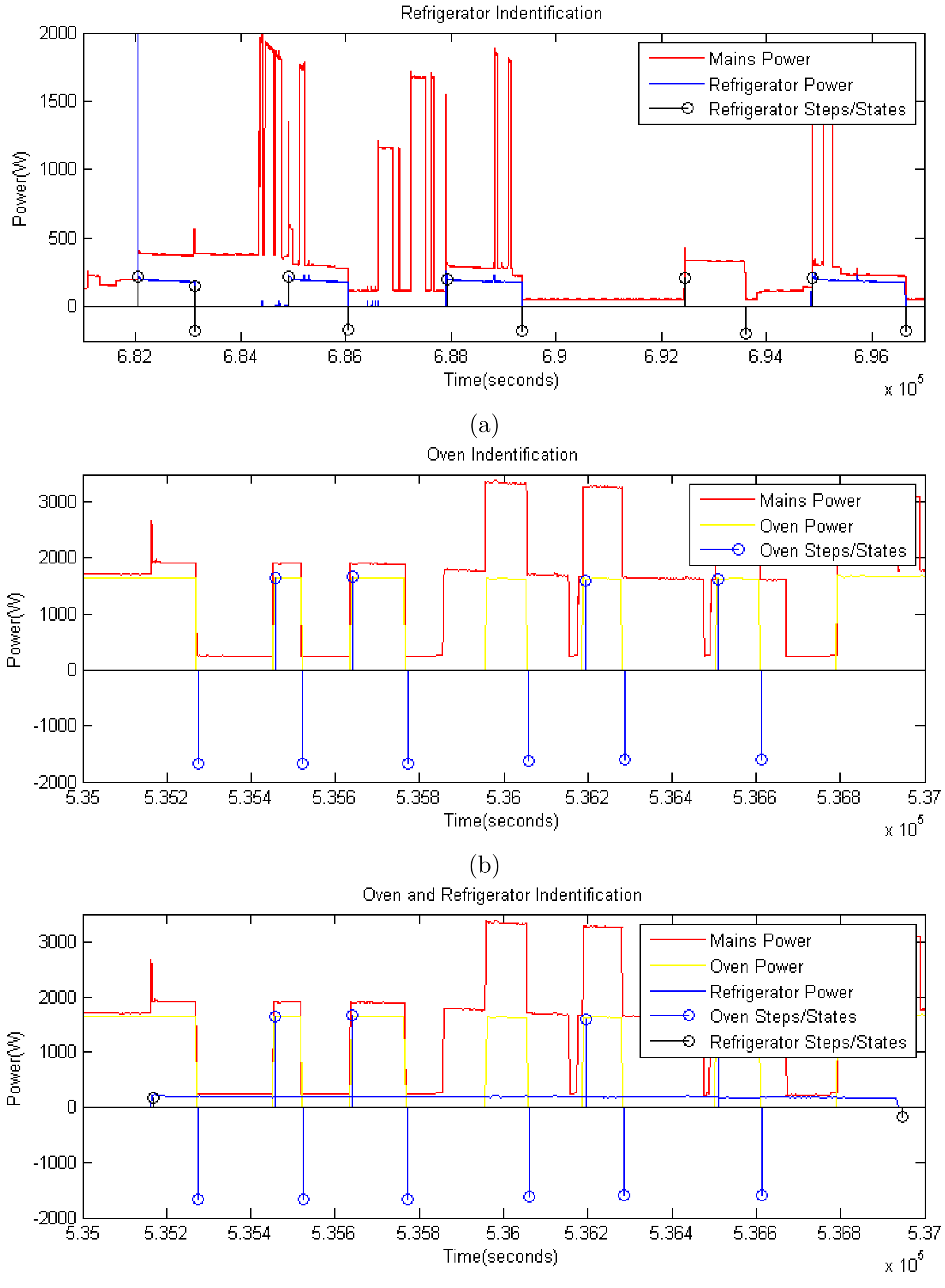
Figure 4.7: Preliminary Implementation of the NILM system

Appliance	**Single Appliance**		**Mains**	
	ON	*OFF*	*ON*	*OFF*
Oven	13	13	17	20
Refrigerator	173	179	165	128

Table 4.2: Comparison of detection in single appliance files to detection in aggregated load mains file

Analysing table 4.2 one can see that the number of *ON/OFF* events detected are close but not equal. These errors arise from the low sampling frequencies on the power flows and the big number of appliances on the mains file. That two characteristics result in overlapping events that are seen as noise by the system, causing the miss of detections of some events.

Figure 4.8 represents identification of appliances in the mains file by the *JAVA* routine, the power flow of *total load* and the power flows of individual loads. In figure 4.8a it is represented the identification of a *refrigerator* in the total load. The refrigerator is identified well even when there are other appliance events happening along the function of the *refrigerator*, but it is also seen a false identification caused by a signature very close to that of the *refrigerator*. In figure 4.8b it is represented the identification of an *oven*. The same observations made for



(a)

(b)

(c)

Figure 4.8: Appliance Identification in mains aggregated load: a) - Refrigerator Detection; b) - Oven Detection; c) - Refrigerator and Oven Detection

refrigerator apply in this case, although here it is shown a miss of an identification caused by the events that are very close, due to low sampling frequency. In figure 4.8c it is represented the simultaneous detection of *refrigerator* and *oven*. From the figures here presented and the data in table 4.2 it's established the correctness of the suggested algorithm. It is important, now, to develop the infrastructures and interfaces to apply the algorithm to real data acquired by the *data acquisition system*, and to develop a full functioning *Monitoring system*.

4.4 Fine Grained Electricity Monitor

With the proposed algorithm verified it is now opportune to develop the *Fine Grained Electricity Monitor*. The system developed can be decomposed in various logical entities, which are represented in figure 4.9

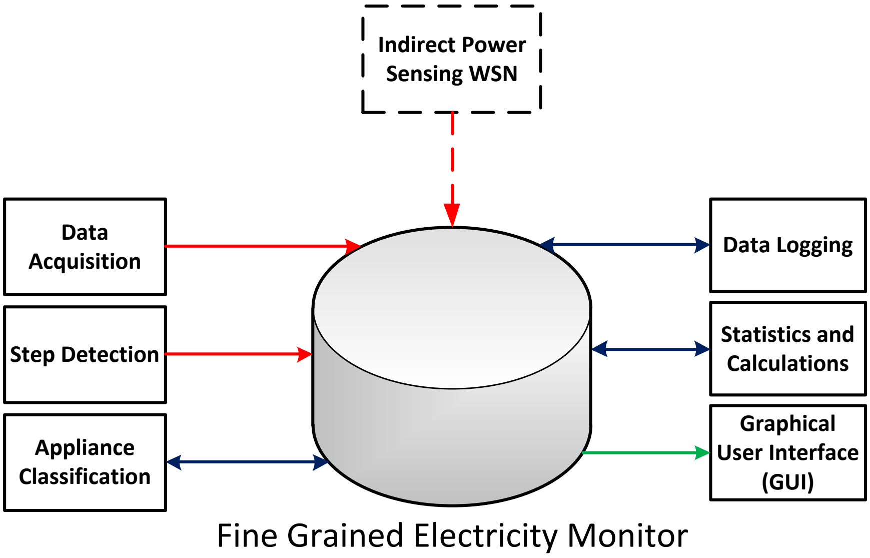

Indirect Power Sensing WSN
Data Acquisition
Step Detection
Appliance Classification
Data Logging
Statistics and Calculations
Graphical User Interface (GUI)
Fine Grained Electricity Monitor

Figure 4.9: Fine Grained Electricity Monitor and its logical entities

Data Acquisition - Obtains *raw data* and manipulates it to *normalized power*;

Step Detection - Takes *normalized power* and identifies *steps* within it;

Appliance Classification - From identified *steps* classifies it in meaningful appliance events;

Data Logging - Records and saves any data valuable for processing and statistics;

Statistics and Calculations - Takes historical and real time data to produce meaningful statistics and figures;

Graphical User Interface - Shows real-time data and historical statistics about *power consumption* in order to deliver valuable data to the user;

Indirect Power Sensing WSN - Provides individual state data about appliances of interest, to help in disambiguation of similar loads;

In the center of the system there is a logical database which holds all the valuable data for the systems function, where all the data, either externally fetched or internally computed or, is stored.

4.4.1 Data Acquisition

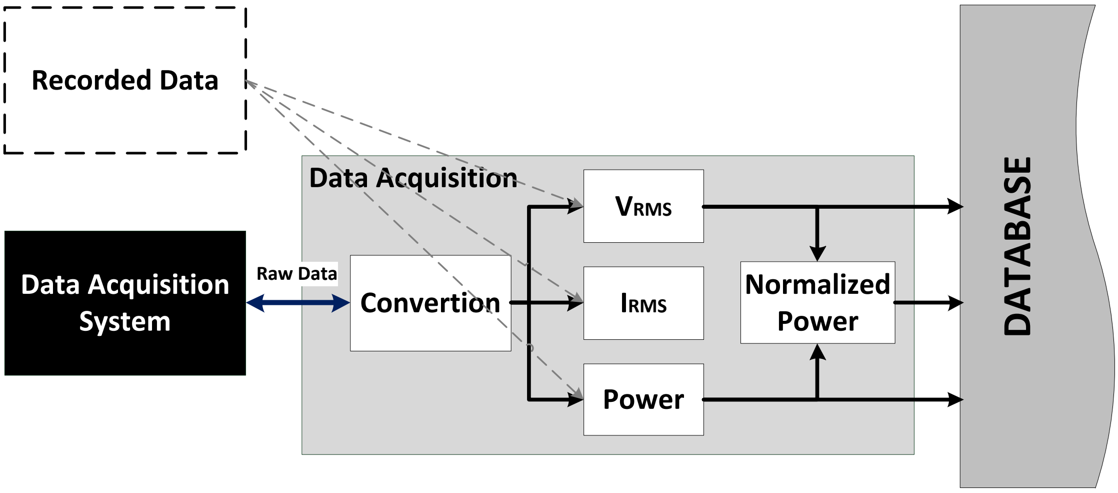


Figure 4.10: Data Acquisition Logical Entity

The *data acquisition entity*, depicted in figure 4.10, is responsible of communicating with the *data acquisition system* already described. Its basic function is to *read* and write *registers* from the *ADE7953*. The data in the registers doesn't have a direct physical meaning, thus it is considered to be *raw data*. So this part of the system is also accountable for converting *raw data* into meaningful physical values, *i.e. Volts*, *Amperes*, *Watts*, *Watt Hour etc.*

The *data acquisition layer* obtains repeatedly at a frequency of $50\,Hz$ the following values:

- V_{RMS} - RMS Voltage;
- I_{RMS} - RMS Current;
- P - *Complex Power*, it is composed by two values: *active power* and *reactive power*;

The values of V_{RMS} and P are used to compute a sample of normalized power at the same frequency as of that of the sampling of those values. Alternatively to the sampling of the values of power consumption from the data-acquisition system, there is also the possibility of providing the system with data recorded previously by the system, by the *data-logging entity.*

All the obtained and computed values are timestamped and pushed into the database.

4.4.2 Step-Detection

The *Step-Detection entity*, depicted in figure 4.11, takes the samples of *normalized power* from the *logical database*, and sequences the flow in *steady-periods* and *changing-periods.* Then identifies *step-change* events in the *power-flow*, that are the difference of the *average power* of consecutive *steady-periods* intercalated with *changing periods.* The *steps* are identified by its characteristic value of *Power* and its *time-stamp* of occurrence. The steps are then pushed to the *database.* No further discussion on this aspect is needed since this subject has already been thoroughly discussed.

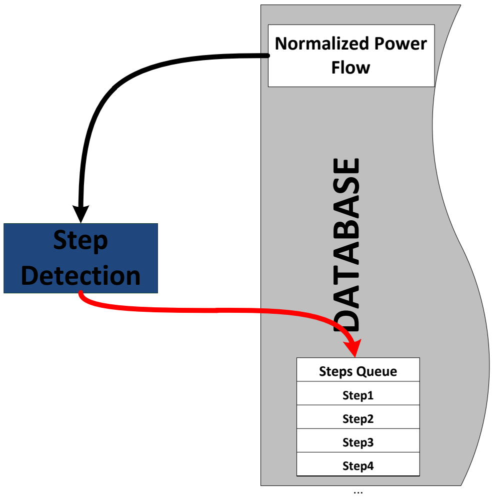


Figure 4.11: Step-Detection entity

4.4.3 Appliance Classification

Although *appliance classification* has been already discussed, in concept and implementation, the implementation that will be here presented is different from the one previously exposed.

Before presenting the actual implementation of the algorithm it is important to present some concepts on the database that are necessary for the *appliance disambiguation*.

Appliance Database

The system here developed only identifies appliances known *a priori*. This means that the all appliances passive of being detected must be first identified and catalogued with their characterization. Therefore it was implemented in the *database* an *appliance database* in which all the appliances of interest must be described, in order to provide sufficient data for *appliance detection* and tracking of *operating state*. An entry of the *appliance database* has the following parameters:

- ***Name*** - Name of the appliance for identification;
- ***ON Signature*** - Complex power-steady state signature of *ON* state;
- ***OFF Signature*** - Complex power-steady state signature of *OFF* state;
- ***Tolerance*** - Scalar value of tolerance in for identification of steady-state signatures;
- ***State*** - Indicator of the appliance's current state, *ON* or *OFF*;
- ***Sensor Address*** - Physical address of the node monitoring the appliance. This parameter will only exist for the appliances monitored *via Indirect Power Sensing WSN*, and will be explained later.

Appliance Classification Process

A *step* is fetched from *logical database* and then compared with all signatures of all appliances in the *appliance* database. Once the closest signature, by euclidean distance, is found, it is assessed if it is contained within the appliance's signature tolerance, as in figure 4.3. If so, it is then checked if the event is coherent with the appliance's *current state*, since a *turn ON* can't occur if the appliance is already *ON* neither a *turn OFF* if the appliance is already *OFF*. Provided that all the information is consistent, the appliance state is updated, and the detection of an appliance event is signalized in the *database*. The appliances monitored by *Indirect Power Sensing WSN* are discarded from this process. This process is illustrated in figure 4.12

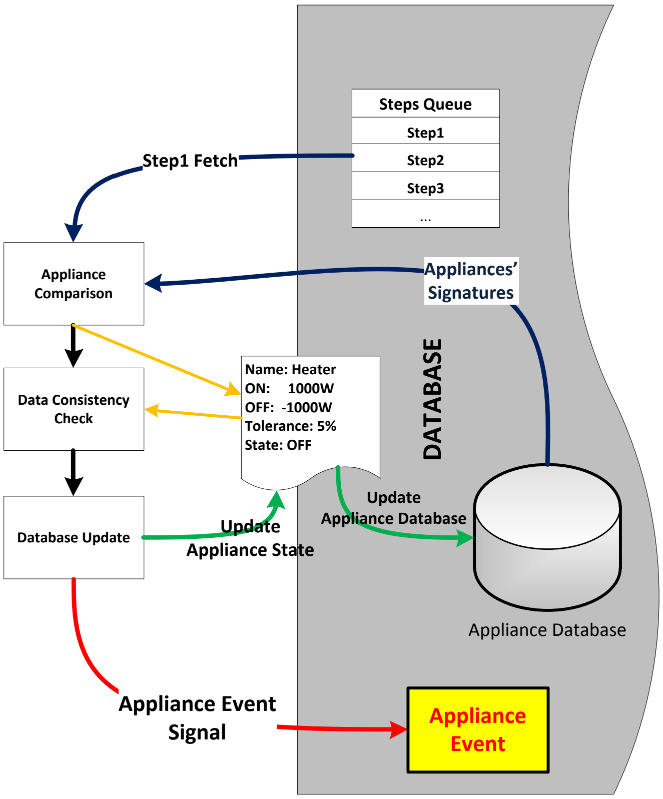


Figure 4.12: Appliance Classification Process

4.4.4 Data Logging

Despite the system being designed for *real-time monitoring*, not all data expected to be produced is real time data. Historical data for *statistics* and other *calculations* are of the highest importance. There is also interest in improving the system, by the development of more sophisticated algorithms.

To satisfy these requirements it was developed a *Data Logging module* that records the data that may be of interest to further experiences and processing. Figure 4.13 represents the *data-logging entity.* The entities recorded in the database are:

- ***Data Acquisition*** - V_{RMS}, I_{RMS} and *Normalized Power*;
- ***Step Detection*** - *steady-states* and *steps*;
- ***Appliance Classification*** - events associated with every *appliance* individually in separate files and all appliances together in a single file;
- ***Estimated Power*** - the power resulting from the sum of power being spent by all the appliances detected to be *ON*;
- ***Indirect Power Sensing WSN*** - all the detected changes of state of the monitored appliances.

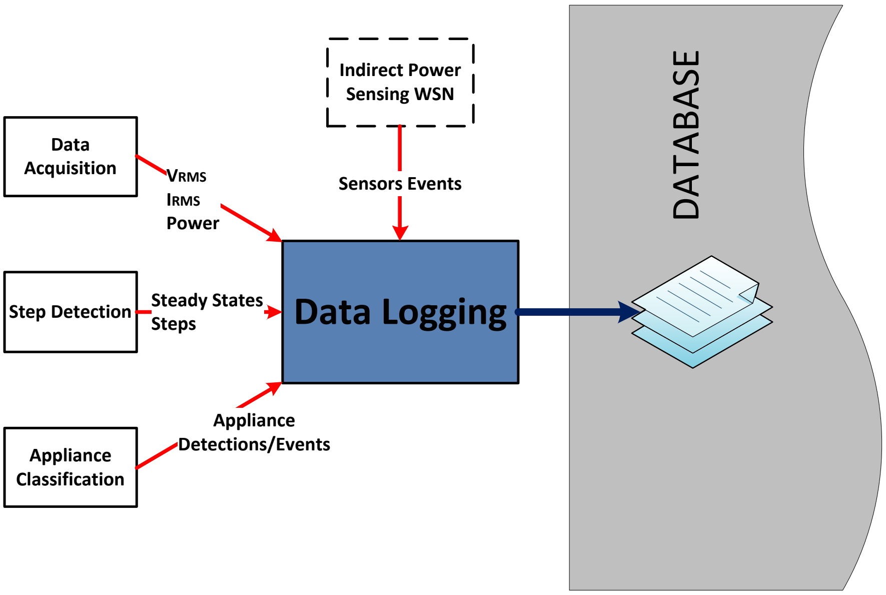


Figure 4.13: Data-logging entity

4.4.5 Indirect Power Sensing WSN

The *Indirect Power Sensing WSN* is a *Wireless Sensor Network* designed to monitor individual appliances and provide its internal power state to the *Monitor.* It is demanded to be easy to configure and have low power consumption.

The network was developed with the following principles in mind:

Star Topology - There is one master node responsible for network maintenance and coordination;

Self Configuration - The network configures itself when deployed, favouring easiness of installation;

Event Driven Communication - The network tends to communicate only when there is new information on the nodes, using minimum energy when not in function;

An in depth analysis of the WSN development and operation is documented in the report of the project *"Monitoring System [17]"* developed in the course of *Redes de Comunicação em Ambiente Industrial(Communication Networks in Industrial Environment).*

Network Topology

The network is deployed in a *logical star topology* with a *master node* in the center, connected to a *PC*, and the slaves attached to the appliances to monitor. Communication only occurs between *master and slaves.*

Network Self Configuration

The network configures it self at start-up. The *slave* requests the *master* for registering in the network and awaits for reply. The *master* receives the *request*, acknowledges the presence of the *slave* in the network, and sends a reply to the *slave* indicating that it has been registered. Once the *slave* receives the reply of the registering phase, its is ready to work normally.

Network Maintenance

The network has detection of failures, for *slaves*, by an "*I'm Alive*" mechanism. This detection of failures mechanism is implemented by the imposition on the slaves of a periodical transmission to the master(an "*I'm Alive*" message), to indicate that it is working. The master detects if there is any problem with a slave, by detecting failure in receiving the "*I'm Alive*" messages from the slave.

WSN System Function

The *master* is in the center of the network. It has full knowledge of all the *slaves* in the network, as well as the *states* of the sensors monitoring the appliances. The master is responsible for coordinating the network, and to communicate with the *PC* informing it of all the states of sensors and signalize when a state change occurs in any of the appliances.

The *slaves* are at the ends of the *network* and attached to the appliances being monitored. The *slaves* must inform the master every time their sensors detect a state change in an appliance.

In figure 4.14 it is represented the network and a sequence of events that occur when one appliance changes state. *Slave 1* detects a *state* change in the appliance that it monitors, and informs the master of that occurrence. After checking the information's coherency, the master informs the *PC* of the change of state in the sensor.

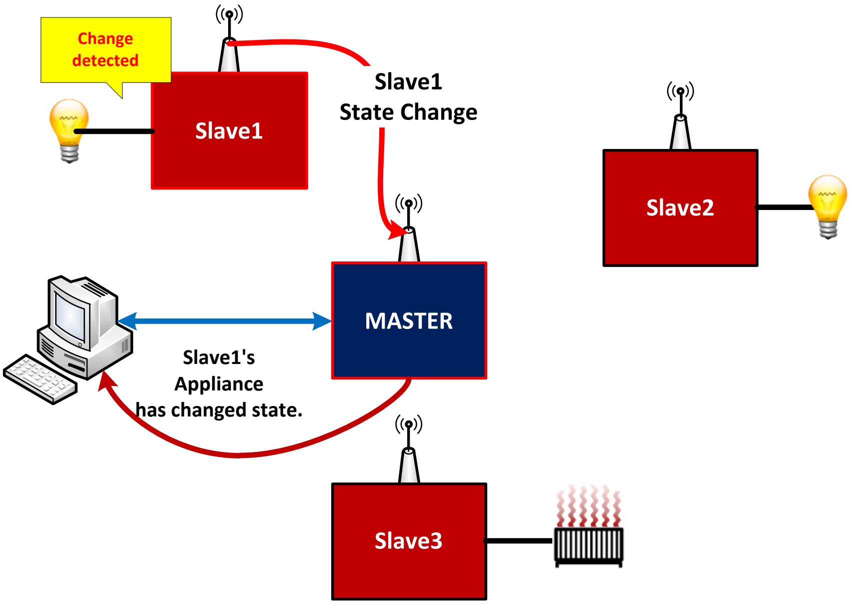


Figure 4.14: WSN Representation

4.4.6 WSN entity

Before describing the *WSN entity* function specificities, it is necessary to present some concepts about the abstraction here developed. The *WSN* monitors individual appliances with sensors, that are used to infer the *internal power state* of the appliance. To that matter there is a *Sensor Database* inside the *WSN entity* that holds information about the individual sensors present in the *WSN*. The entries of the database have the following parameters:

- ***Sensor Address*** - Physical address of the *WSN* node;
- ***Status*** - State of the sensor. It can be *ON* indicating the attached appliance is on, *OFF* indicating that the appliance attached is off, or *Disconnected* indicating that the *WSN* node is malfunctioning.

The *WSN entity* role can be seen as two different *tasks*. The *WSN Interface*, that is responsible for communicating directly with the *network*, retrieves information about the sensors. The *WSN Classifier/Tracker* is responsible by treating the *state* changes on the sensors and relate them with the changes in the *appliance database*. These tasks are linked in the access to the *Sensor Database*. Figure 4.15 illustrates the *WSN entity* architecture.

WSN Interface

The *WSN interface* is responsible for managing the communications between the *WSN* and the *Electricity Monitor*. This interface provides an abstraction layer that is agnostic with respect to the *network*, the *Indirect Power Sensing WSN* is seen as a simple data device.

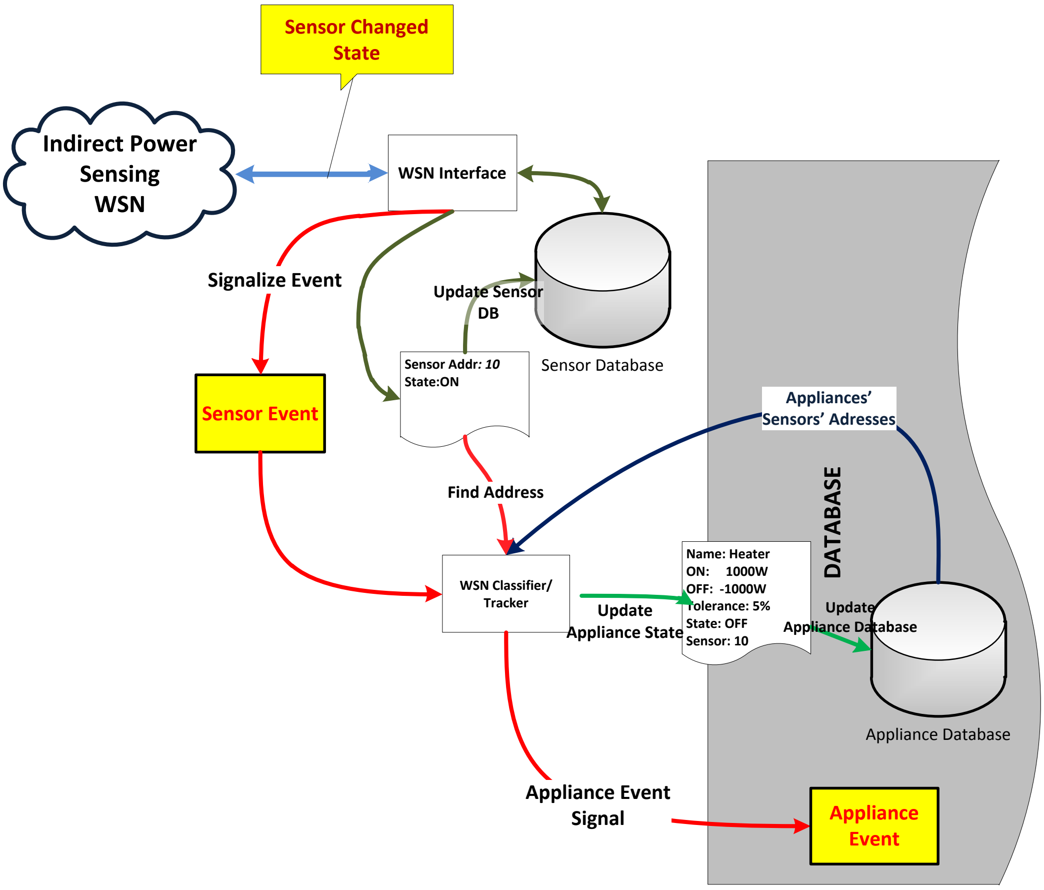


Figure 4.15: Indirect Power Sensing WSN entity representation

Thus it provides a notification mechanism that fires, asynchronously, notifications every time a state change is detected in any sensor. Additionally, it also permits the access to information about the sensors available and their status, by request.

At start-up the interface builds the *sensor database* with all the sensors and their current state. Then, at normal operation, it waits for messages from the *WSN* with information about state changes on sensors. Once a message about a change in a sensor is received, it is checked if the change is allowed, taking into account the current state of the sensor. If so, the information on the database is updated and a notification for the *WSN classifier* with the information about the occurrence of state change on a sensor is fired.

WSN Classifier

The *WSN Classifier* waits for an *event notification* on state change of a sensor. Then, by the *Sensor address*, it fetches the correspondent appliance from the *Appliance Database*. It checks if the announced change is valid. If so, the appliance entry in the *Appliance Database* is updated, and a notification is fired in the *Logical Database* signalizing an appliance state change event.

4.4.7 Statistics and Calculations

Having power consumption and times of state changes for every appliance available, it is possible to compute some very interesting statistics. Those may be Energy Spent/Cost by appliance, variation of power consumption by time of day/weekday/weekend, duration of time each state is visited *etc.*

None of this statistics are currently computed, but with the data provided by the *logging system* it could be achieved with minimum effort.

Nonetheless there are some calculations made by the system. The system computes the *estimated power*, that is the sum of the characteristic power of the appliances that are on the *ON* state at each moment. Recalling from *boolean switch process* $a(t)$ of equation 2.1 the estimated power, $P_{estimated}$, is:

$$P_{estimated}(t) = \sum_{i=1}^{N} P_i a_i(t) \ , \tag{4.2}$$

where P_i is the power consumed by the ith appliance when in *ON state.*

Another calculation made is the *residual power*, $P_{residual}$, which is the difference between the *total measured power* and the *estimated power*, which is analogous to $e(t)$ in equation 2.2 and can be interpreted as a measure of completeness and accuracy of the system[18].

$$P_{residual} = P_{Total} - P_{estimated} \ . \tag{4.3}$$

4.4.8 Graphical User Interface

The *Graphical User Interface(GUI)* is designed to provide to the user all the system's data of interest, being it real time and historical.

The *GUI* is connected to the *database*, fetching the the following data about the electric circuit in:

- RMS Voltage;
- RMS Current;
- Normalized Complex Power in active and reactive components.

It also fetches the following the computed *real time* data:

- Expected Power, in the active and reactive components;
- Residual Power, in active and reactive components.

The *GUI* should also fetch the historical and the computed statistics data, but that isn't implemented and should be considered for short term future work. Apart from that, the *GUI* listens for the events of the appliances changing states, as well as it fetches information about the *appliance database.* A representation of the data transactions of the *GUI* is represented in figure 4.16.

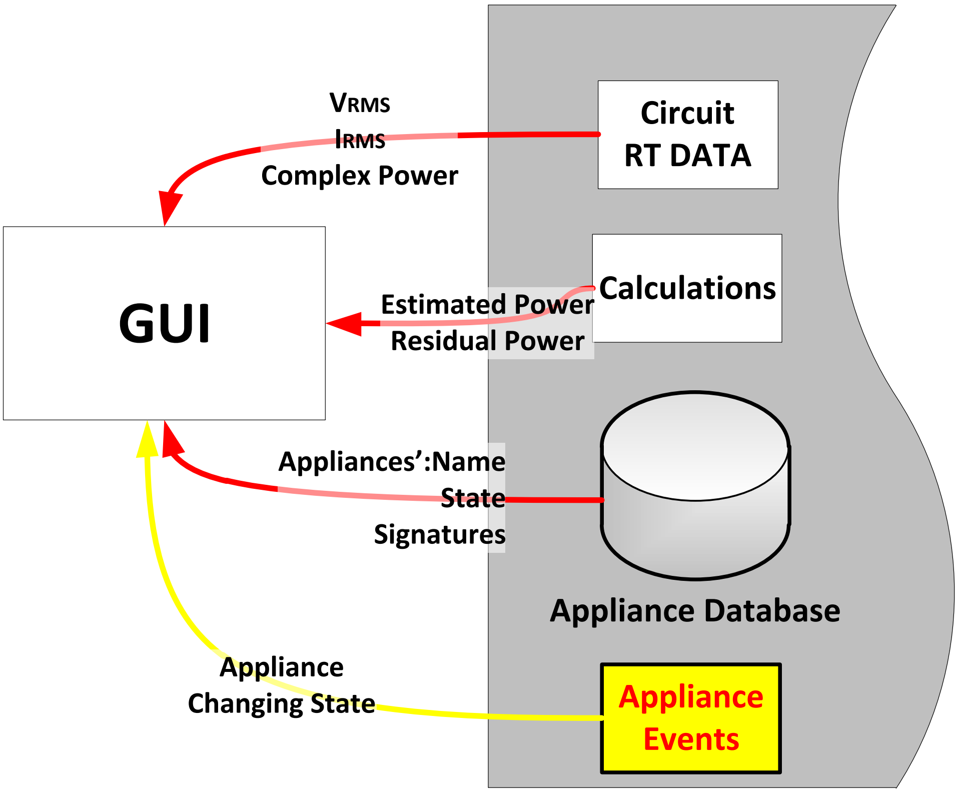


Figure 4.16: Graphical User Interface entity

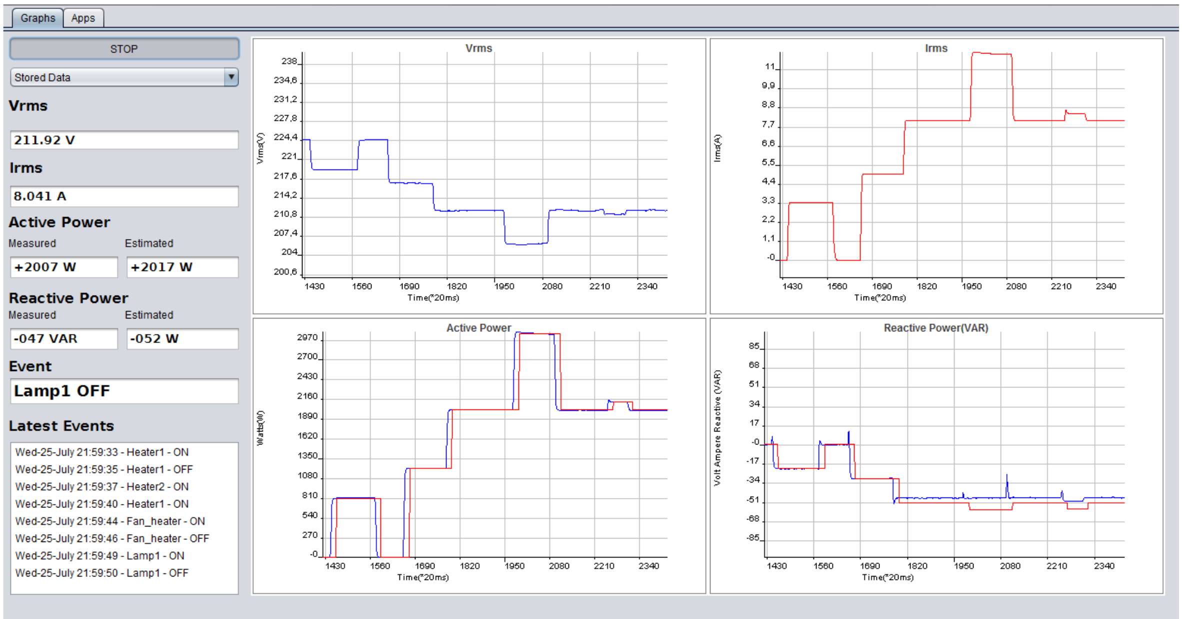
Figure 4.17 represents the default aspect of the *GUI*. The *GUI* is divided in two tabs. The *Graphs tab* is oriented to display the data about the electric installation and plotting the graphs of interest. The *Apps* tab displays the data about the appliances in the circuit.

Graphs Tab

The graphs tab shows *real time* traces of *RMS Voltage* and *RMS Current*, as can be seen in figure 4.18.

It is also shown *real time* traces of the components of power. As it can be seen in figure 4.19, both the measured *total power*(blue trace) and the *estimated power*(red trace) are present.

All the traces are updated at 50 Hz.



Vrms

211.92 V

Irms

8.041 A

Active Power

Measured: +2007 W

Estimated: +2017 W

Reactive Power

Measured: -047 VAR

Estimated: -052 W

Event

Lamp1 OFF

Latest Events

Wed-25-July 21:59:33 - Heater1 - ON
Wed-25-July 21:59:35 - Heater1 - OFF
Wed-25-July 21:59:37 - Heater2 - ON
Wed-25-July 21:59:40 - Heater1 - ON
Wed-25-July 21:59:44 - Fan_heater - ON
Wed-25-July 21:59:46 - Fan_heater - OFF
Wed-25-July 21:59:49 - Lamp1 - ON
Wed-25-July 21:59:50 - Lamp1 - OFF

Figure 4.17: Graphical User Interface default appearance

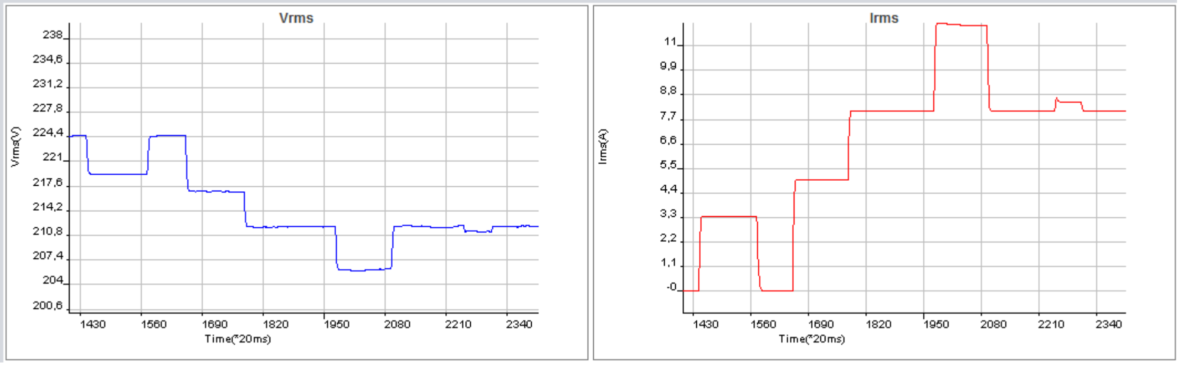


Figure 4.18: Graphics with traces of RMS Voltage and RMS Current

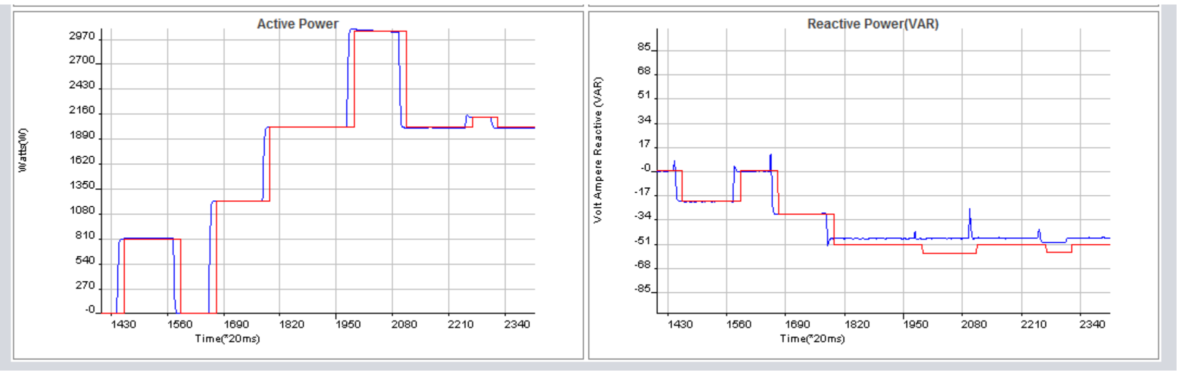
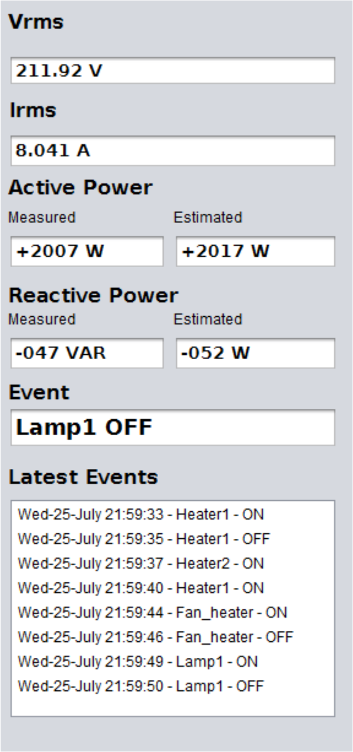


Figure 4.19: Graphics with traces of the components of complex power of Total Power and Estimated Power

In parallel with the graphs, it is also displayed some information in text form about the electric installation and about the events that are happening in the appliances. As shown in figure 4.20 it is displayed the values of:

- V_{RMS} - RMS Voltage;
- I_{RMS} - RMS Current.
- Complex power components in the measured total power, and in estimated power.

There is also a field called *Events* that is updated at the detection of an *appliance* event and flashes, so it can get the user's attention. Under that field there is also a scrolling list of the last 10 events that have happened, appended to their time-stamp.



Vrms

211.92 V

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8.041 A

Active Power

Measured: +2007 W

Estimated: +2017 W

Reactive Power

Measured: -047 VAR

Estimated: -052 W

Event

Lamp1 OFF

Latest Events

Wed-25-July 21:59:33 - Heater1 - ON
Wed-25-July 21:59:35 - Heater1 - OFF
Wed-25-July 21:59:37 - Heater2 - ON
Wed-25-July 21:59:40 - Heater1 - ON
Wed-25-July 21:59:44 - Fan_heater - ON
Wed-25-July 21:59:46 - Fan_heater - OFF
Wed-25-July 21:59:49 - Lamp1 - ON
Wed-25-July 21:59:50 - Lamp1 - OFF

Figure 4.20: Informations about the electrical installation

Apps Tab

The *Apps Tab* was designed to provide visual information about the appliances. Not only the current state but some historical data and other calculations should be displayed. But in the current implementation it only shows the appliances in the system and their detected states. Figure 4.21 shows the *Apps Tab* in operation. As one may see, there are three types of states for appliances. *ON* and *OFF* are self explanatory. The *Undetermined* state is the default for the appliances at *start-up*. Since the appliances states are detected at their changes, if no state change is detected one should not infer the appliance's state, although it may be possible for special cases, such as no power being drawn which means all appliances are *OFF*, their state is left *Undetermined*.

One feature that was projected to have but is missing is that, when clicked on any of the appliances, historical statistics and data on appliances power consumption, such as the times of operation and the energy cost of its usage, was to be shown. This feature should be considered for future short-term implementation.

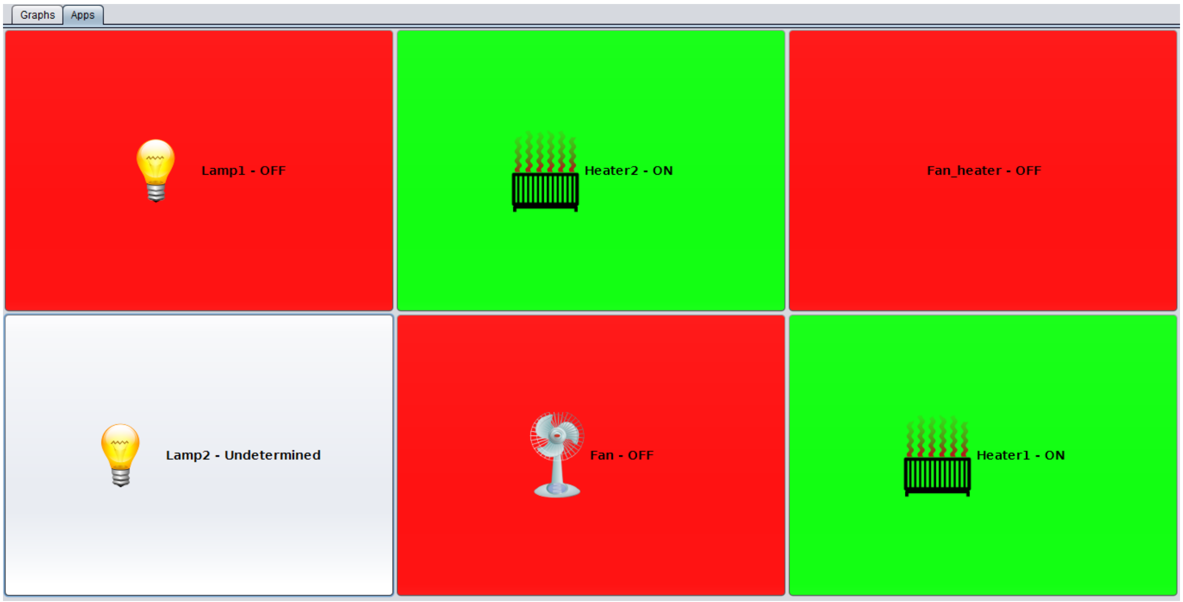


Figure 4.21: Apps Tab of Graphical User Interface

4.5 Summary

In this chapter it was presented the *algorithms* and structures for a *Fine Grained Electricity Monitoring* system. The algorithms were tested and validated. This led to a preliminary implementation in software that was also tested and validated.

The algorithm's preliminary implementation in software was the basis for the development of the system's implementation.

The implementation consists in:

- Data Acquisition;
- Appliance Classification;
- Indirect Power Sensing WSN;
- Statistics and Calculations;
- Data Logging;
- Graphical User Interface.

To the *Indirect Power Sensing WSN* it was seen that it is self configurable, and that it integrates with the PC like a data-device. Thus it notifies the system about the changes of state in individual appliances.

In terms of inputs/outputs the system gets *RMS Voltage, RMS Current and Complex Power* from the *Data Acquisition System* and gets individual states of some appliances from the *Indirect Power Sensing WSN*. It produces as output appliance disambiguation, calculations and statistics on historical data and logging of all data of interest.

Finally it was presented the *Graphical User Interface(GUI)*, the ultimate output for user's feedback. It shows *real-time data* on the electric installation(V_{RMS}, I_{RMS}, *Power*) and the *calculated Expected Power*. On the appliances side the GUI shows the appliances present in the circuit as well as their operating state.

Statistics and calculations on historical data are not yet implemented. But the data logger already records data in a way that make the future implementation very easy.

Chapter 5

Tests, Results, Validations and Calibrations

This chapter presents a set of tests that have been carried out to validate the system. In addition it is also presented the calibration methodology.

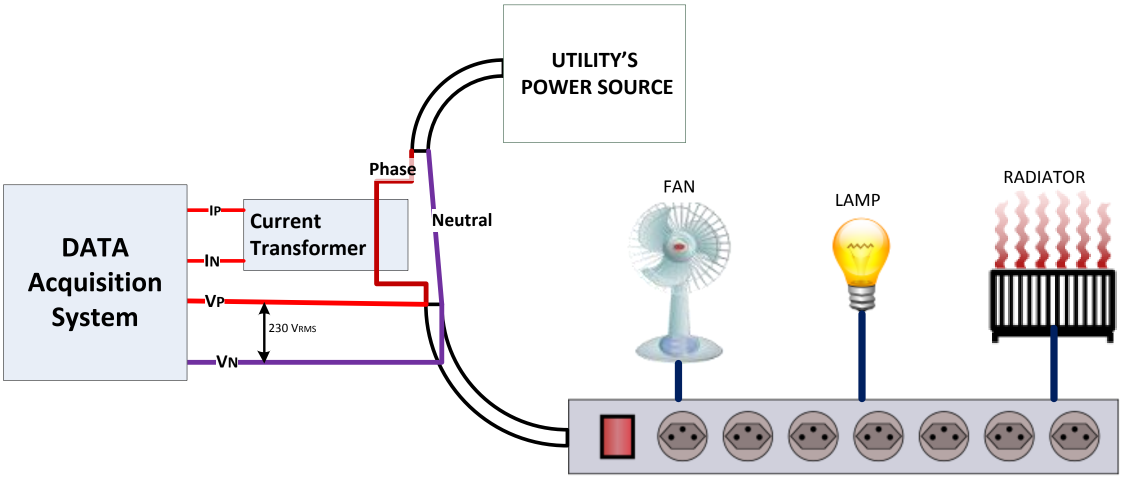
5.1 Test-bed

Taking into account that the system should monitor a household electrical installation, it was developed a *test-bed* that simulates the electric circuit of a house.

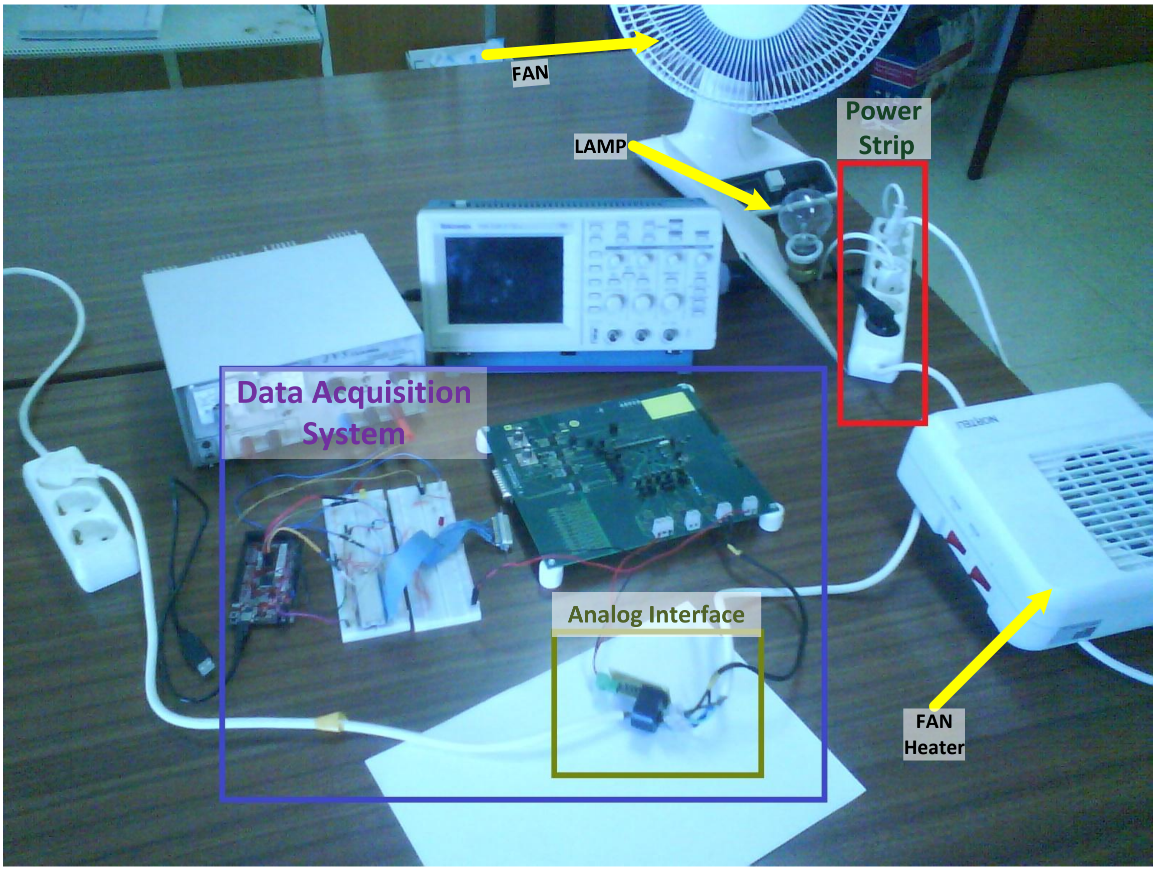
The electrical power source is taken from a *standard* $230\,V_{RMS}$ power outlet to a 6 outlets *power strip*. The voltage signal is directly fed to the *data acquisition system* through a connection in parallel with the power strip, while the current signal is fed to the *data acquisition system* through a *current transformer* in the phase conductor of the *power strip*. Figure 5.1 shows the most important components of the test-bed's electrical installation.

Along with the electrical installation it is deployed the *WSN based Indirect Power Sensing* that aims at disambiguating similar appliances. There are *sensor nodes* with light sensors,to monitor 2 equal lamps,which cannot be disambiguated solely by the normal algorithm. It is also deployed one *sensor node* with a magnetic sensor coupled to a fan heater. The reasons for this are that it showed to have a rather slow transient, what made the detection through load disambiguation difficult, while the detection through indirect power sensing WSN showed to be more reliable.

Connected to the *data-acquisition system* and to the *Indirect Power Sensing WSN* there is a *PC*, which executes the all necessary tasks to perform the *Electricity Monitoring*.



(a)



(b)

Figure 5.1: System's electric installation testbed: a) - block diagram, b) - physical instalation

5.2 Calibration

Calibration is very important in systems that depend on measurements and sensing of environment quantities. Furthermore, from the nature of load monitoring system, that aims to be an energy meter, it is expected that it is a device with great accuracy and correctness, so that it meets or exceeds the common household revenue meter.

The main measurement system is the *ADE7953 - Evaluation Board*, in which the measures of *Voltage* and *Current* need to be calibrated. To calibrate a system one needs references. The reference used for *voltage measurement* was *Fluke 287 True RMS Multimeter*, while for *current measurement* the reference used was *Tektronix A622 AC/DC Current Probe* connected to a *Tektronix TDS 210 Oscilloscope.*

5.2.1 Calibration of Measurement System

ADE7953 ADC Gain error Calibration

The *gain error* is defined as the *per*-channel difference between the ADC output code and the ideal output code. Thus *ADE7953* provides *gain error* calibration for each of its ADC channels. The gain adjustment allowed is in the range of $[0.5; 1.5]$. The gain adjustment is set in appropriate registers and is regulated by equation 5.1.

$$Output = Input \times \left(\frac{GAIN}{\text{0x400000}}\right), \tag{5.1}$$

with $\text{0x200000} \leq GAIN \leq \text{0x600000}$.

The gain error calibration for *voltage* and *current* channels can be performed using the values of *VRMS* and *IRMS* from the registers of *ADE7953* and with the measurements of RMS voltage at ADC's channels' input. Knowing that the ADC has a full scale input of $500mV$ and that the expected value in the registers of *VRMS* and *IRMS* at full scale input, $\frac{500}{\sqrt{2}}mV_{RMS}$, is 9032007d[4], the calibration equation becomes

$$GAIN = \text{0x400000} \times \left(\frac{\text{Value Expected}}{\text{Value Actual}}\right), \tag{5.2}$$

which can be modified, in order to be applied iteratively, to

$$GAIN_i = GAIN_{i-1} \times \left(\frac{\text{Value Expected}_i}{\text{Value Actual}_i}\right), \tag{5.3}$$

with i the order of the iteration. The first iteration assumes $GAIN_{i-1} = \text{0x400000}$.

The calibration method for any of the ADC channels is:

1. Get VRMS or IRMS registers from ADE7953 during an interval of 10 seconds at a sampling frequency of $10Hz$. Compute the mean value to get Value Actual$_i$. Parallelly, measure the mean value of V_{RMS} at ADC's channel input with *multimeter* during the same 10 seconds interval, with that value find Value Expected$_i$;

2. Apply equation 5.3 to calculate $GAIN_i$;

3. Apply $GAIN_i$ to the system;

4. Repeat *step* 1 and check current accuracy;

The calibration method is to be repeated for any of the channels until one gets the desired accuracy.

Checking Voltage Channel Accuracy

Let $V_{measured}$ be the mean value of RMS voltage at the *data acquisition*'s voltage input measured in 10 seconds intervals. Let V_{actual} be the mean value of samples of the *VRMS register* taken at $10Hz$ during the same interval.

Knowing that between the Voltage input of the *data acquisition system* and the *ADE7953*'s voltage ADC channel is a 1 : 1000 voltage divider, it is easy to compute the voltage at the ADC's input, disregarding any error in the voltage divider which should be very small. It is possible to compute the value that was expected in the *VRMS register*, namely $V_{expected}$, that is

$$V_{expected} = V_{measured} \times \frac{\sqrt{2}}{500} \times 9032007 \ . \tag{5.4}$$

Thus the gain error is

$$error_{gain} = 1 - \frac{V_{expected}}{V_{actual}} \ . \tag{5.5}$$

The *Fluke 287 True RMS multimeter*'s accuracy is

$$accuracy = \pm([\% \text{ of reading}] + [\text{number of least significant digits}]). \tag{5.6}$$

For the range of the measurements used, which was $500V$ AC for a signal at $50Hz$ is

$$accuracy = \pm([3\% \text{ of reading}] + [25 \times 0.01V]) \tag{5.7}$$

Table 5.1 shows the results of the assessment of the *gain error*, comparing it to the *accuracy* of the reference. $error_{gain}$ represents the ratio in percentage of the gain error of the ADC to V_{actual} and *accuracy* represents the *accuracy* of *reference multimeter* regarding $V_{measured}$. It may be observed that the gain error is always smaller than the reference's accuracy, which means that the calibration may exceed the *reference*'s performance, therefore it is not possible to improve the calibration with this reference.

$V_{measured}[V]$	$V_{expected}[LSB]$	$V_{actual}[LSB]$	$error_{gain}[\%]$	$accuracy[\%]$
211.05	5391562	5412301	0.38	0.42
213.93	5465136	5483521	0.34	0.42
218.70	5586992	5617941	0.39	0.41
219.13	5597977	5617941	0.36	0.41
221.93	5669507	5689227	0.35	0.41
224.60	5737716	5768089	0.53	0.41
225.36	5757131	5777579	0.35	0.41
227.96	5823551	5845952	0.38	0.41
228.24	5830704	5849892	0.33	0.41

Table 5.1: Assertion of gain error following the calibration of voltage channel

Checking Current Channel Accuracy

Let $Iv_{measured}$ be the mean value of RMS voltage at the *ADE7953*'s current ADC channel input measured in 10 seconds intervals. Let I_{actual} be the mean value of samples of the *IRMS register* taken at $10Hz$ during the same interval.

Following the same principles as those on the ADC's voltage channel. $I_{expected}$ is the expected value at the *IRMS register* for $Iv_{measured}$ and is computed as

$$I_{expected} = Iv_{measured} \times \frac{\sqrt{2}}{500 \times 10^{-3}} \times 9032007 \ , \tag{5.8}$$

and so the gain error is

$$error_{gain} = 1 - \frac{I_{expected}}{I_{actual}} \ . \tag{5.9}$$

The range of measurement used in the multimeter was $50mV$ AC with a signal of $50Hz$. The accuracy is

$$accuracy = \pm([0.3\% \text{ of reading}] + [25 \times 0.001mV]) \tag{5.10}$$

Table 5.2 shows the results of the assessment of the *gain error* comparing it to the *accuracy* of the reference. $error_{gain}$ represents the ratio in percentage of the gain error of the ADC to I_{actual} and *accuracy* represents the *accuracy* of *reference multimeter* regarding $Iv_{measured}$. It may be observed that the gain error is always smaller than the reference's accuracy, which means that the calibration may exceed the *reference*'s performance. Once again it is not possible to improve the calibration with this reference.

$Iv_{measured}[mV]$	$I_{expected}[LSB]$	$I_{actual}[LSB]$	$error_{gain}[\%]$	$accuracy[\%]$
5.326	136060	135535	-0.39	0.77
5.328	136111	135618	-0.36	0.77
5.350	136673	136792	+0.09	0.77
12.702	324490	325841	+0.41	0.50
12.777	326406	326448	+0.01	0.50

Table 5.2: Assertion of gain error following the calibration of current channel

RMS Voltage and RMS Current Meter Constants

The data obtained from ADE7953 registers doesn't have direct physical meaning, as it is relative only to the values sampled in the ADCs. Thus it is necessary to convert the *raw* values into meaningful values in *Volts, Amperes, Watts, etc.*. These values that convert the register data to physical values are called *Meter Constants*. All the values needed to the project, that are related to the electrical installation are related RMS *Voltage* and *Current*, so it is only necessary to find *Meter Constants* for these. The others can be subsequently derived.

These relationships may be expressed as

$$V_{constant} = \frac{\text{Voltage Input}\,[V]}{\text{VRMS}\,[LSBs]} \ , \ I_{constant} = \frac{\text{Current Input}\,[V]}{\text{IRMS}\,[LSBs]} \tag{5.11}$$

The meter constants ought to be calculated under *Steady* conditions and with very precise loads. It was observed that voltage varies with the load in the circuit. In addition the test-bed is connected to the installation of a large building where numerous appliances are always working and switching, so one cannot guarantee the steadiness of voltage. For this reason a simple measure of V_{RMS} or I_{RMS} does not suffice to accurately find the meter constants.

The *meter constants* will be computed with the *linear regression* of various points of current and voltage observed with different loads.

Method of calibration for Voltage Meter Constant

A list of ordered pairs $\{\text{VRMS}[LSBs], \text{Voltage Input}[V]\}$, *Voltages List*, needs to be obtained by the following steps:

1. Set System's load;

2. Get VRMS register from ADE7953 during an interval of 10 seconds at a sampling frequency of $10Hz$. From the values obtained compute the mean to get one VRMS$[LSBs]$ value. Parallelly, measure mean value of V_{RMS} at the Electric Installation input with the *multimeter* during the same 10 seconds interval to get one value of Voltage Input$[V]$;

3. Store ordered pair in *Voltages List*;

The previous steps are to be repeated until the needed number of values are obtained.

Next a *linear regression* of Voltage Input$[V]$/VRMS$[LSBs]$ must be made to get the *Voltage Meter Constant.*

The linear regression result was a *voltage meter constant* of

$$V_{meterConstant} = 3.887799914 \times 10^{-5}\,[V_{RMS}/_{LSB}] \tag{5.12}$$

with a correlation factor

$$R^2 = 0.9995 \tag{5.13}$$

the *offset* was

$$b = 0.6726\,V_{RMS} \tag{5.14}$$

that represents an error of $error_{offset} \approx 0.3\%$ which is very small and lower than the reference meter's accuracy. For being so small, and for system's simplicity, this error was not taken into account.

Table 5.3 compares the value of *RMS voltage* at the utility's electrical installation measured by the *reference multimeter*, V_{RMS}, with the measurements by the data acquisition system, $V_{RMSactual}$. The error of *the data acquisition system* in relation with the *reference measurements* is lower than the provided accuracy and is mainly due to the discarding of offset on the calibration.

Method of calibration for Current Meter Constant

A list of ordered pairs $\{\text{IRMS}[LSBs], \text{Current Input}[A]\}$, *Currents List*, needs to be obtained by the following steps:

1. Set System's load;

$V_{RMS}[V]$	$V_{RMSactual}[V]$	$error_{Mconstant}[\%]$	$accuracy[\%]$
211.05	210.42	0.30	0.42
213.93	213.19	0.35	0.42
218.70	218.06	0.29	0.41
219.13	218.41	0.33	0.41
221.93	221.19	0.34	0.41
224.60	224.25	0.16	0.41
225.36	224.62	0.33	0.41
227.96	227.28	0.30	0.41
228.24	227.43	0.35	0.41

Table 5.3: Results of the voltage meter constant fitting

2. Get IRMS register from ADE7953 during an interval of 10 seconds at a sampling frequency of $10Hz$. From the values obtained compute a the mean to get one IRMS$[LSBs]$ value. Parallelly, measure I_{RMS}, at the phase cable of the Electric installation with the *current probe* attached to an *Tektronix TDS210 Oscilloscope* to get Current Input$[A]$. It was not possible to measure accurately the mean current in the interval, so the current input is taken as a sample of instant peak current, which, is then transformed into a RMS value.

3. Store ordered pair in *Currents List*;

The previous steps are to be repeated until the needed number of values are obtained.

Next a *linear regression* of Current Input$[A]$/IRMS$[LSBs]$ must be made to get the *Current Meter Constant.*

The linear regression result was a *current meter constant* of

$$I_{meterConstant} = 2.392182902 \times 10^{-5}\,[A_{RMS}/_{LSB}] \tag{5.15}$$

with a correlation factor

$$R^2 = 0.9998 \tag{5.16}$$

the *offset* was

$$b = -0.0219\,A_{RMS} \tag{5.17}$$

The accuracy of the *Tektronix A622 AC/DC* current probe at the scale measured, that was $100mV/A$, is

$$accuracy_{probe} = (3\% \text{ of measurment}) + (50\,mA). \tag{5.18}$$

The accuracy of the *Tektronix TDS210* oscilloscope on the function used, that was *Delta Volts*, is

$$accuracy_{osciloscope} = (3\% \text{ of reading}) + (0.05 \text{ div}). \tag{5.19}$$

Table 5.4 shows a comparison between the current measured by the *current probe* and the *oscilloscope*, I_{RMS}, with the current measured in the *data-aquisition system* when scaled by the *current meter constant* $I_{RMSactual}$. One can see the accurate fitting of the values from the *data- acquisition system*, with the error, $error_{Mconstant}$, always smaller than the measurements' accuracy, *accuracy*. This means the system meets the accuracy of the reference and that discarding the offset in the scaling of the values is not significant.

$I_{RMS}[A]$	$IRMSactual[A]$	$error_{Mconstant}[\%]$	$accuracy[\%]$
0.188	0.182	-3.42	29.82
3.230	3.299	2.14	5.14
7.920	7.922	0.04	4.78

Table 5.4: Results of the current meter constant fitting

5.2.2 Calibration of Sensors in Indirect Power Sensing WSN

Because the nodes in the Indirect Power Sensing WSN perform measurements, it is also necessary to guarantee that they produce the correct outputs to the designated inputs. To this matter it is necessary to calibrate them in site to check its proper function.

Light Sensor Nodes Calibration

The sensor should be placed near the lamp to be monitored. An example of a correct placement is shown in figure 5.2.

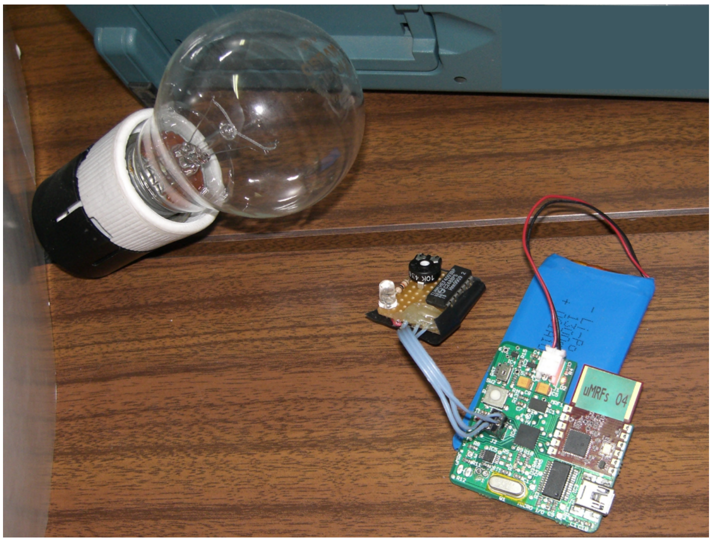


Figure 5.2: Light Sensor Placement

Calibration Method

1. Place *sensor node*;
2. Turn the *Lamp ON*;
3. Check if sensor's output reflects *Lamp's* state. If not:
    - Tune potentiometer on board until the sensor's output is correct;
4. Turn the *Lamp OFF*;
5. Check if sensor's output reflects *Lamp's* state. If not:

- Tune potentiometer on board until the sensor's output is correct;

This method is to be repeated until the sensor node outputs the correct information about the *Lamp's* state;

Magnetic Sensor Nodes Calibration

The sensor placement requires it to be very close to the supplying cable. Figure 5.3 shows an example of correct placement of the magnetic sensor, in which the sensor is in direct touch with the cable and strapped with a nylon clamp.

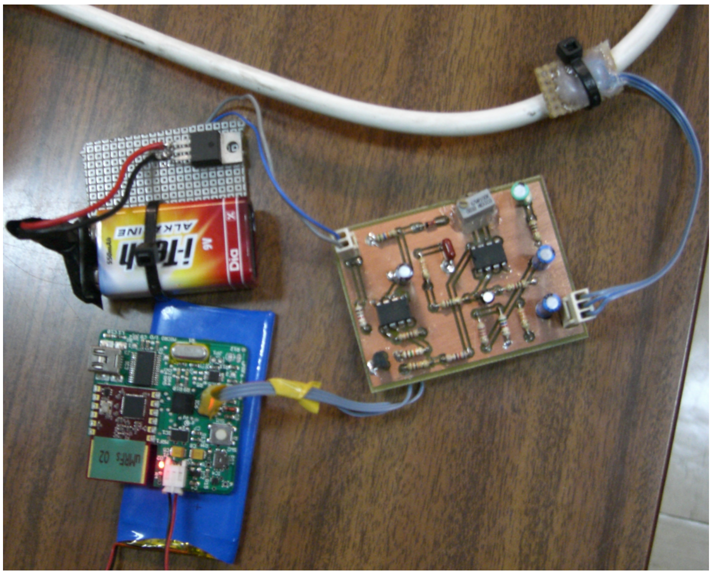


Figure 5.3: Placement of magnetic sensor

Calibration Method

1. Tune potentiometer on board to approximately mid position;
2. Attach sensor to the cable of the appliance to be monitored, and supply it;
3. Turn the appliance *ON*;
4. Install oscilloscope probe on the output of the second amplifier;
5. Rotate sensor around the cable and find the position where the signal has maximum amplitude;
6. Fix sensor position;
7. Check signal's amplitude, tune potentiometer until the amplifier outputs a signal with amplitude close to $3V$, in order to put the system in saturation, to guarantee correct operation;
8. Check sensor's digital output and verify if it is stable, and if reflects appliance's state. If not:

- Some tuning in the potentiometer may be needed;

9. Turn the appliance *OFF*;

10. Check sensor's digital output and verify if it is stable, and if reflects appliance's state. If not:

    - Some tuning in the potentiometer may be needed;

This method is to be repeated until the results are satisfactory.

5.3 Appliance Characterization

Before presenting the results and tests to the system it will be presented the appliance characterization. This is done here to justify the values of power detected in the system while testing its accuracy and validity.

The appliances were characterized by *steady-state* and by *turn ON* and *turn OFF* transients in *normalized power* consumption, recorded by the acquisition system at a sampling frequency of $50Hz$ for approximately 10 seconds.

The *steady-state signature* was found by taking one sample of the power consumption of the appliance after approximately 10 seconds of being turned *ON* on a cold start, assuming that all the transients are over after that period. The *rise time* is the time that the appliance's power consumption takes to rise from 1% to 99% of the *steady state signature* after being turned *ON*. The *fall time* is the time that the appliance's power consumption takes to fall from 99% to 1% of the *steady state signature* after being turned *OFF*.

The appliances available in the *test-bed* are:

- *Two-Level Radiator Heater* - this appliance is categorized in two appliances *Heater1* and *Heater2*, since the system is incapable of treating multi-state appliances.

- *Two* $100W$ Lamps - These lamps were specifically introduced for having 2 identical appliances in the system, in order to exploit the problem of identification of similar loads with the *Indirect Power Sensing WSN*. Only one will be characterized, it is assumed that the other to be equal.

- *Desk Fan*

- *Fan Heater*

the characterization of the appliances is summarized table 5.5.

Appliance	**Signature(W)**	**Rise Time(s)**	**Fall Time (s)**
Heater1	$806.75 - 21.32i$	0.14	0.16
Heater2	$1210.49 - 30.31i$	0.14	0.16
Fan	$39.78 - 0.80i$	8.46	6.11
Lamp	$106.62 - 4.72i$	0.22	0.18
Fan Heater	$1030.64 - 5.60i$	1.56	0.18

Table 5.5: Appliance's Characterization

Analysing the results from table 5.5, it is clear that the appliances that should be mainly resistive, such as the *radiator heater* and the *lamp*, have faster transients than those that have inductive element and high mechanical inertia, have slower transients, such as the *fan heater* and the *fan*. Furthermore, the values obtained for the *rise and fall times* for the *fan* are much higher than the others. This comes from the fact that it is a *very small load* in which its transient may be confused with noise present in the system. The reactive power measurements of the system seem to be disconnected from reality by a systematic error that is shifting them negatively. However, this error does not affect the detection of loads, as the algorithm only requires that the signatures are separated in the *P-Q space*;

5.4 Testing the Load Disambiguation Algorithm

5.4.1 Step-Detector

For testing the *step-detector*, *step-like* waveforms were introduced to the system by switching *ON* and *OFF* the appliances in the *test-bed*, and analysing the *step-detector* output, which is provided by the *data-logging entity*, and is characterized by a *time-stamp* and a *steady-state signature* in *complex power*.

Here it is tested the ability of the system to detect steps of the different appliances individually.

For each appliance a test was performed, by turning *ON* the system, and introducing a sequence of 21 consecutive switches with a period of approximately 4 seconds between switches, to let the power stabilize. The *step-detector* parameters used were $window\_size = 10$, $step\_threshold = 25\,W$ and $STD\_Threshold = 5W$.

In the results of the test, it was analysed the deviation of the detections from the *steady-state signature*, as well as the number of detections. Table 5.6 presents the results of these tests. For each appliance tested *Nr Detections* is the number of steps detected, *Mean Deviation* is the mean of the deviations from the steps detected to the *steady-state signature* with *Value* being the norm of the *Mean Deviation* and *Ratio*, the ratio between the *mean deviation* and the *appliance's signature. Max Deviation* represents the *maximum deviation detected. Value* and *Ratio* values have the same meanings as stated before.

		Mean Deviation		**Max Deviation**	
Appliance	**Nr Detections**	$Value[W]$	$Ratio[\%]$	$Value[W]$	$Ratio[\%]$
Heater1	21	3.09	0.38	4.41	0.54
Heater2	21	3.78	0.31	6.02	0.49
Fan	21	6.95	17.48	9.35	23.49
Fan Heater	21	28.26	2.74	32.52	3.15
Lamp	21	0.46	0.43	1.39	1.30

Table 5.6: Results of Single Appliance tests on *step-detector*

From table 5.6, it can be concluded that all the steps were detected for all the appliances, which can be interpreted as a measure of correctness of the step detector.

Due to the nature of the system it is necessary to detect the appliances in *real-time*, thus the system cannot delay its processing in order to wait that the transients of the appliances to end. There is, so, an inherent notion of the signal being sufficiently stable to be detected as a *steady-state*. This notion is expressed by the detection of *steady-state* upon a threshold on the *standard- deviation* of the processing window. This can affect the *step-detection* in a way that the steps detected may not be exactly equal to the appliances *steady-state consumption*, though they shall be close.

The appliances that should be mainly resistive, such as the *radiator heater* and the *lamp*, have very fast transients and the detections are very close to the *steady-state signature*, being the most straight forward to detect.

Appliances that by nature of the physical task present slow transients, such as the *fan* and the *fan heater*, which have motors that require long times to stabilize the spinning speed, present greater deviations from *steady-state signature*. Another effect worth to notice in this type of appliances is that the detected signatures may differ greatly if a *turn ON* is performed by *cold start*, *i.e.* the motor is stopped, where the transient will be the slowest and the deviation will be big, or if a *turn ON* is performed briefly after a *turn OFF* while the motor is still spinning, where it can be observed that the detected step deviation is almost as small as those of the *resistive loads*.

From the above discussion it follows immediately that a certain amount of time must elapse between the occurrence a state change and the identification of the appliance that experienced that change. This latency is defined as the *detection time*.

It was verified that the *step-detector* also performs well when there are various sources of *steps* in the system and even when the *steady state* of the system is not *null*. The conclusions are the same of those of when the system is tested with single appliances.

The Analysis of the deviation from *steady-state signatures* will allow the existence of a starting point in defining the tolerances for appliance detection in the *Appliance Classifier*

5.4.2 Appliance Classifier

The *appliances* were catalogued in the *Appliance Classifier* with the *steady-state signatures* from table 5.5 and with tolerances with the immediate unit upper-bound in percentage of the *maximum deviation* as described in table 5.6.

It was found that some of the appliances were not being detected correctly in the total load. For this reason the tolerances were tuned in order that all the appliances were identified and correctly classified, taking into account that none of the intervals corresponding to the *signatures* would overlap. The tolerances were tuned to those on table 5.7,

Appliance	$Tolerance[\%]$
Heater1	5
Heater2	5
Fan	25
Fan Heater	5
Lamp	5

Table 5.7: Appliance classification tolerances

In figure 5.4 is represented the classification of the appliances in the *complex power* plane. The ellipses limit the intervals where the appliances are detected while the *dots* represent the scatter of the identification of the appliances.

Figures 5.5 and 5.6 show a scatter of detections of the appliances within their tolerances.

Big loads, such as the *Radiator Heater(Heater1 and Heater2)* and the *Fan Heater*, show small *scatters*, being well defined within their intervals. The *Fan heater* seems to have a larger scatter, which is mainly due to the effects of the motor.

Small loads, such as the *Lamps* and the Fan, have greater scatters since they are more prone to the inherent errors of the system and load variation. The *Fan* seems to have the greater scatter. This may be caused by being the smallest load detected, and also because of the effects of the slow transient of its motor. Moreover, the effect of switching the appliance *ON* in *cold start* or while the motor is still spinning seems to have a very relevant effect.

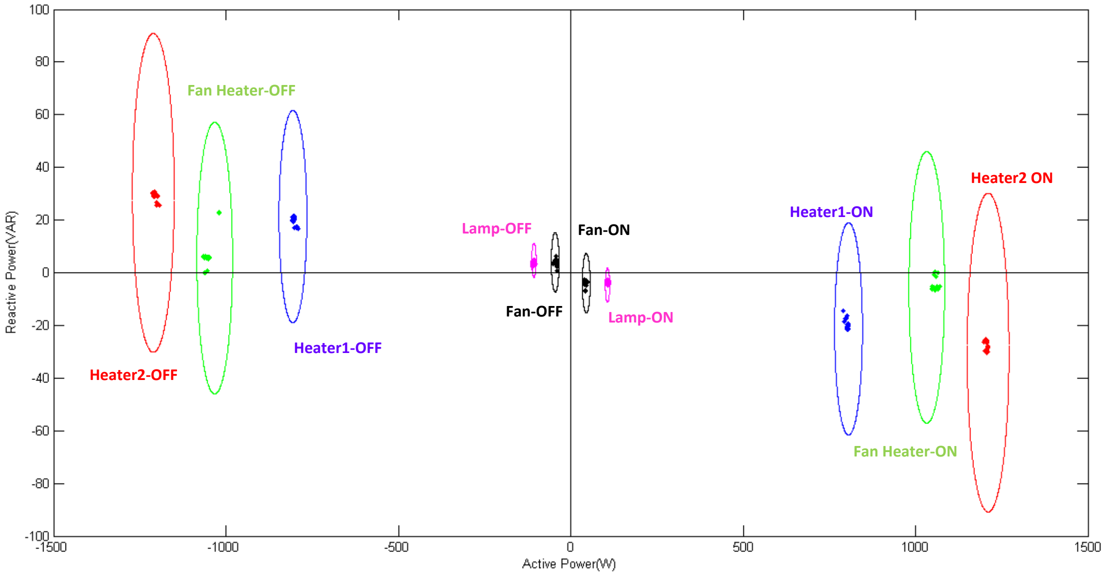


Figure 5.4: Appliance Classification in *I*-*Q* plane

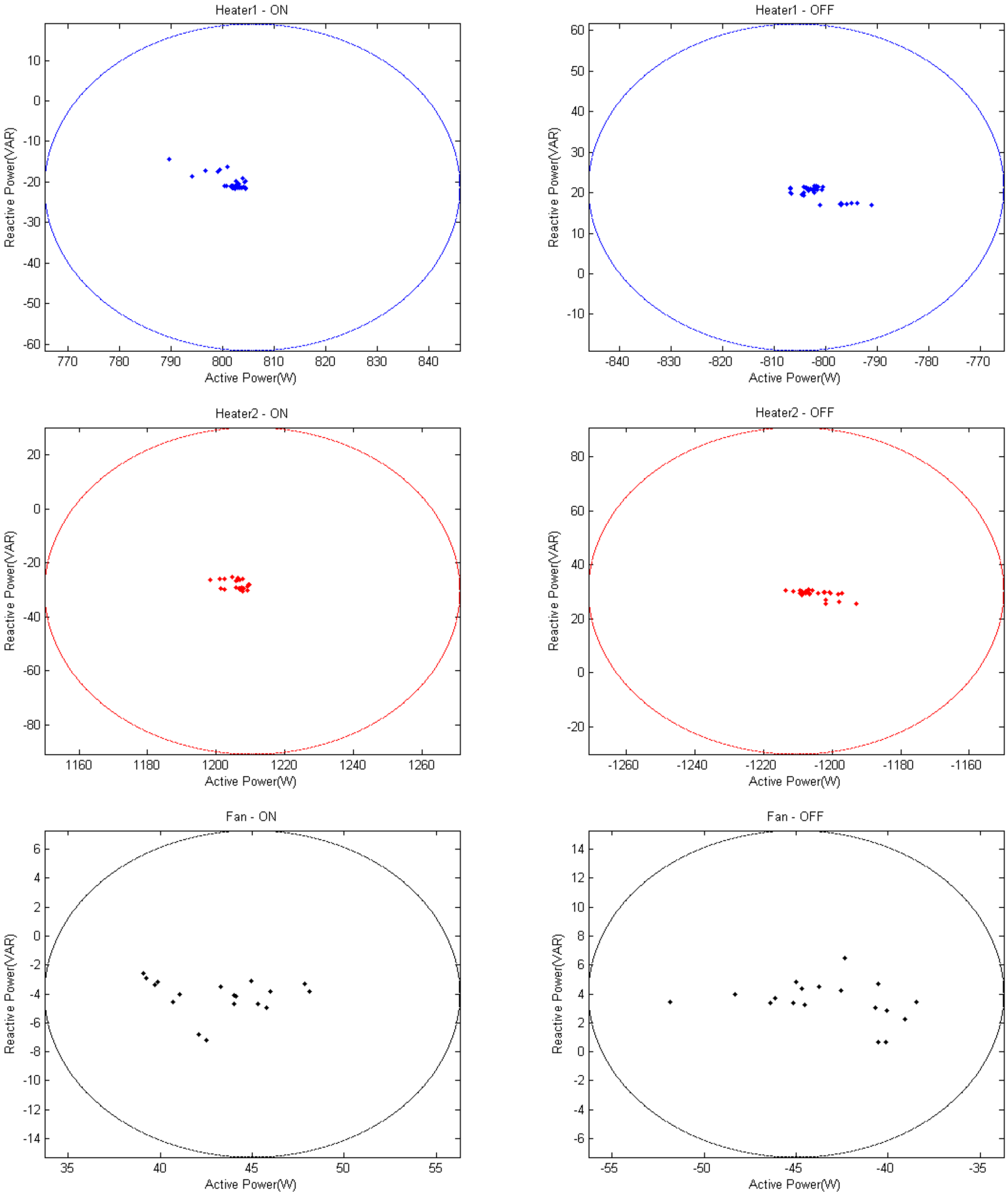


Figure 5.5: Appliances' Individual Interval of identification - a

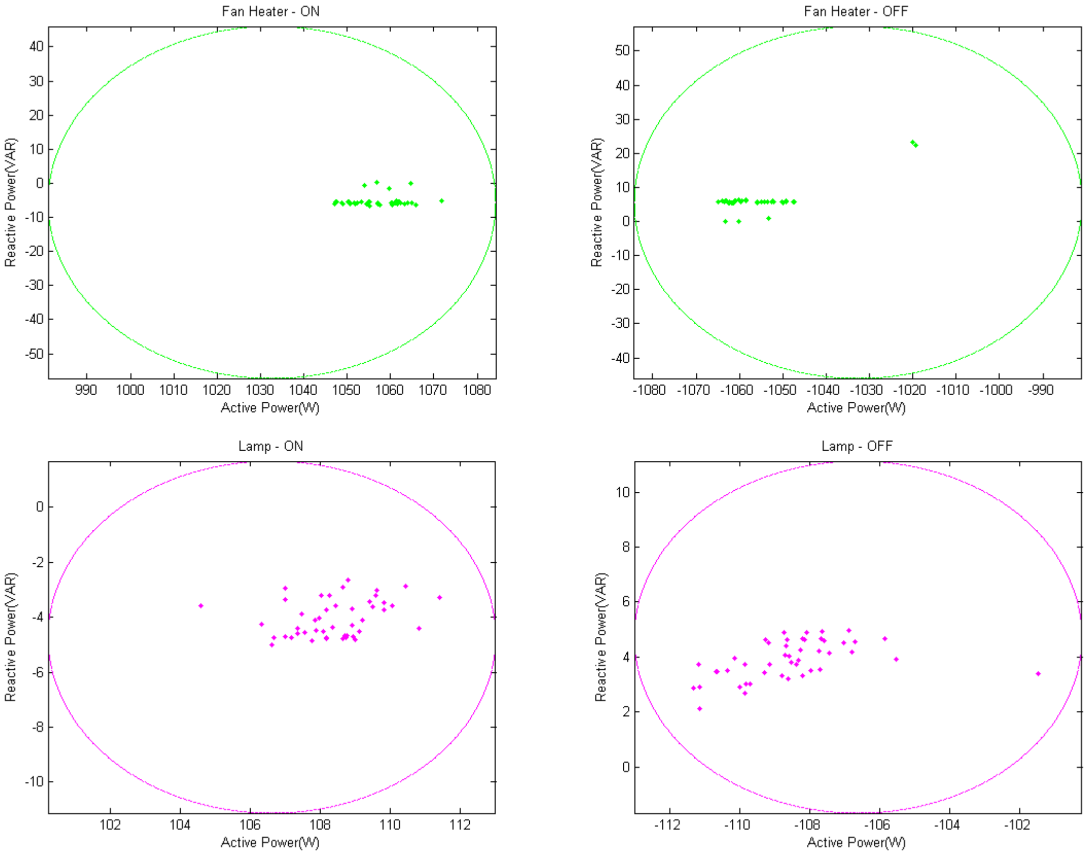


Figure 5.6: Appliances' Individual Interval of identification - b

5.4.3 Indirect Power Sensing WSN

The *WSN* is monitoring *two lamps* by *light sensors* and the *fan heater* with a hall sensor. When put to function it was observed that the *WSN* detected almost all performed events. It was not possible to characterize the detection accuracy, due to lack of time for thorough tests.

5.4.4 Simultaneous detection of appliances

The system was configured to try to identify the loads simultaneously by the *WSN* and by the *Load Disambiguation Algorithm*. It was found that the WSN only failed to detect the *lamps*' events 1 time out of 54 events that were introduced in the test. More, the *WSN* hasn't failed to detect the *Fan heater* in a test of 60 events.

From the data obtained it was possible to compute the relative delay between the the detection of the events on the *load disambiguation algorithm* and the detection on the *WSN*. In the following the detection by the *load disambiguation algorithm* is being used as the time reference. Figure 5.7 shows histograms of the delay in bins of $50ms$. From the figure, it can be concluded that the most common delay in *Lamp* detections is in the interval of $[200; 250[ms$, while the most common delay for *Fan heater* detections is in the interval of $[100; 150[ms$.

From the results in figure 5.7 and from table 5.8 and from the fact that the *WSN* detection

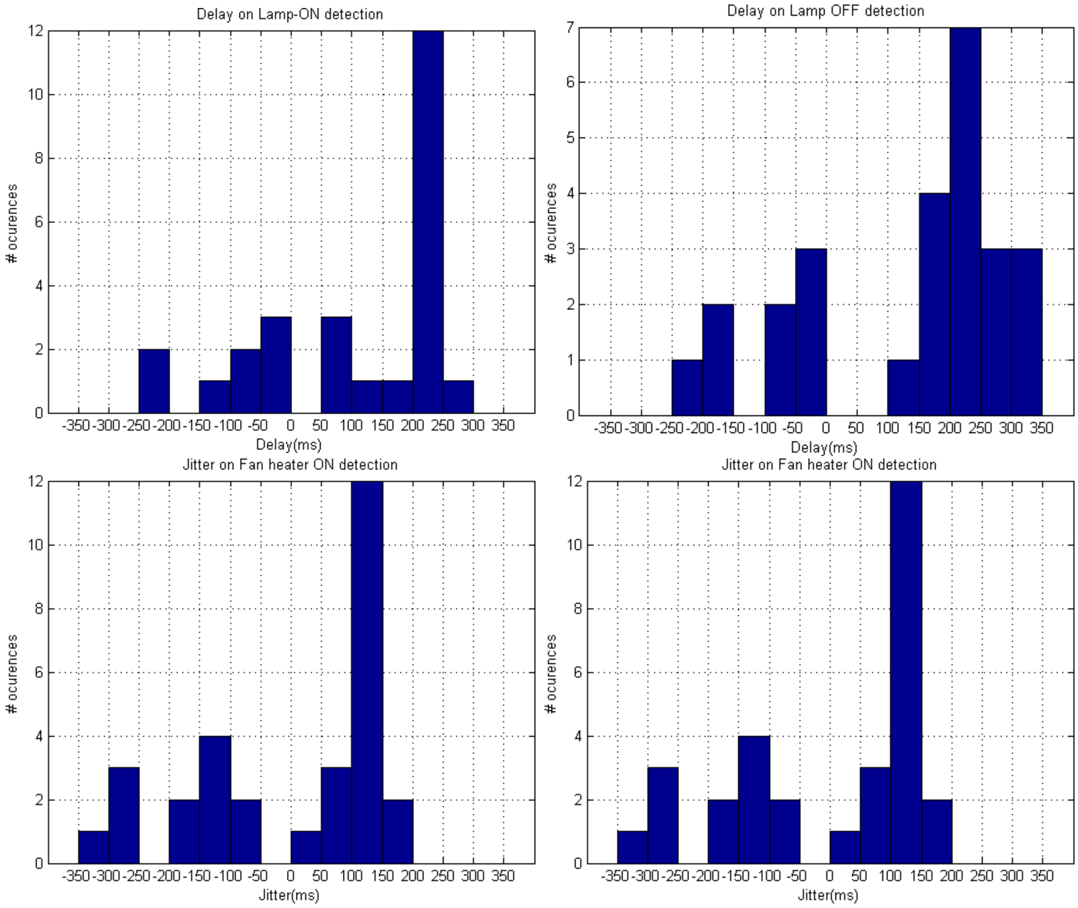


Figure 5.7: Histograms of the *delay* between the detection by the WSN and by the *load-disambiguation algorithm*

	ON			**OFF**		
Appliance	*Min*[*ms*]	*Mean*[*ms*]	*Max*[*ms*]	*Min*[*ms*]	*Mean*[*ms*]	*Max*[*ms*]
Lamp	-220	+97	+265	-240	+131	+300
Fan heater	-325	+1	+160	-240	+57	+180

Table 5.8: Analysis of the delay in the WSN detection

only failed once in the realized tests, it can be inferred that the *Indirect Power Sensing WSN* is reliable in detection of the desired events, and has a performance that is comparable to the appliance detection in the *Non-Intrusive Load* technique. It can be concluded that the the detecting of appliances *via* WSN does not compromise the accuracy and correctness of the system, and can be used as true detector for single appliances without the requirement of correlating information about the power of the electrical installation.

5.5 Complete System Test and Validation

To verify the correctness and accuracy of the developed system, it was simulated the function of a home environment with all the appliances switching *ON* and *OFF* independently from one another.

The system was set-up to detect the *Fan* and the *Two-level radiator* by the *load disambiguation algorithm* and the 2 *Lamps* and the *Fan heater* individually by the *Indirect Power Sensing WSN*

A sequence of 100 switch events was performed by switching *ON* and *OFF* the appliances. To avoid introducing dependence upon *switching*, *events* were performed following a random sequence of numbers from `random.org`[37] website. The periodicity of the switches was *30* seconds to guarantee that the power is steady, thus it is expected that all the transients are over, and to be physically possible by manual operation.

The following data was collected:

- *Measured Power*;
- *Expected Power*;
- *Residual Power*;
- *Events detected for each Appliance*;

Table 5.9 presents the events *performed* and those which were *detected* by the system.

Appliance	**Performed**		**Detected**	
	Turn ONs	*Turn OFFs*	*Turn ONs*	*Turn OFFs*
Heater1	9	9	10	10
Heater2	5	5	5	5
Fan	8	8	5	5
Lamp1	8	7	9	8
Lamp2	8	8	12	12
Fan heater	13	12	13	12

Table 5.9: Detection of appliances in a random sequence of events

The *two level Heater Radiator* has shown to be the most easy and straightforward load to detect, being detected correctly all the times in the test. The extra detections denoted in the table were due to human error during the execution of the sequence of events. The *Fan* is not one of the best appliances to detect via *NIALM* because it is very small and any noise and variations on the load have great impact in its correct detection. Thus it was noted during the tests that every time that the *Fan* was switched *ON* after the *Fan heater* was switched *ON* the system would fail to detect the fan. It is believed that this behaviour is due to the slow transients of the *fan heater*, and it is affecting the detection of the *Fan*, preventing its *step* from being detected. The *Lamps* were noted to be detected well by the *WSN* during the tests. The extra detections noted in the table were due to some *cross-talk* between lamps, and also between the environment, due to non optimal conditions. The *Fan heater* was detected correctly by the WSN.

From the *Measured Power*, *Estimated Power*, and the *Residual Power*, one can verify the accuracy of the system by characterizing the quality of the estimation. Figure 5.8 shows plots of the above referred power flows. From figure 5.8 it can be seen that *Estimated Power* follows the *Measured Power* very closely. The *Residual Power* is most of the time close to *zero*.The peaks are due to the delay on the detection.

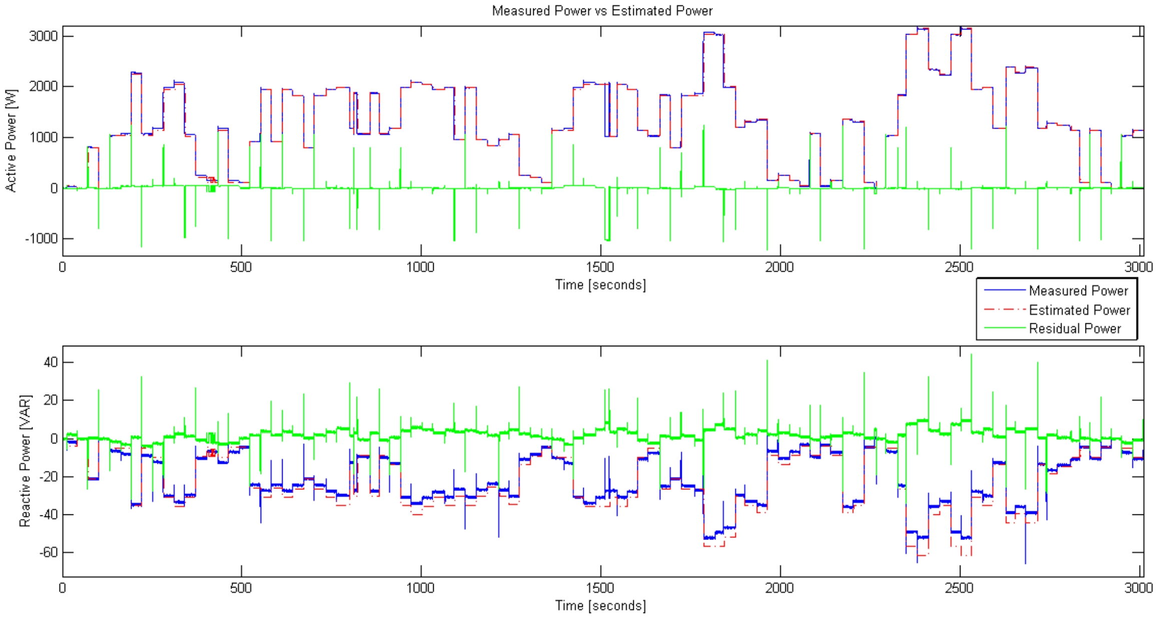


Figure 5.8: Comparison of Measured Power with Estimated Power

A characterization of the error of the system can be quantified by the norm of the *Residual Power*, compared with the *Measured Power*.

Value	**Mean**$[VA]$	**Standard Deviation**$[VA]$
Norm of Measured Power	1306.44	834.61
Norm of Estimated Power	1305.96	836.84
Norm of Residual Power	20.91	96.15

Table 5.10: Comparison of Norms of Power Values

From table 5.10 it can be seen that the *Measured Power* and the *Estimated Power* values are very close and consequently the *Residual Power* value is low.

Knowing the values of power, it is straightforward to get the values of energy by integration. Table 5.11 shows the energy of the different *power flows*.

Value	**Energy**$[J]$	**Energy**$[kWh]$
Measured Energy	3883990.521 -63343.642 i	1.078886 -0.017595 i
Estimated Energy	3882473.341 -68701.747 i	1.078465 -0.019084 i
Residual Energy	1515.048 +5358.200 i	0.000421 +0.001488 i

Table 5.11: Energy Values by integration of *Power Flows*

The values of *Measured Energy* and *Estimated Energy* are very close and consequently the *Residual Energy* is low. In terms of absolute ratio the *Residual Energy* is 0.143% of the *Measured Energy.* This value is the error of the system. This result is very good as a measure of the completeness and accuracy of the developed system.

5.6 Summary

This chapter addressed the evaluation of the system's *correctness* and *accuracy.* It started by presenting the *test-bed* that would allow the system's test and its calibration. Tests were performed on some individual components of the system, the *Step-Detector*, the *Appliance Classifier* and the *Indirect Power Sensing WSN*, which results have shown their correct implementation. To finalize, the system was tested as a whole and results were presented in order to provide indicators of *completeness* and *correct function.* It has been verified that the system detects the appliances with great success, and that the mean error on the energy by integration of power was 0.143%.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

A system capable of monitoring a household electrical installation was successfully implemented. The system disambiguates and identifies individual appliance loads within the aggregated load, recurring to *NIALM* techniques.

The problem with identifying electrically identical loads was successfully tackled with the *Indirect Power Sensing WSN*. It was shown that it was possible to detect the *internal power state* of some appliances by using simple sensors that sense physical quantities in the vicinity of the appliances. It was possible to detect lamps with *light-sensors* placed near the luminous source. It was also possible to detect *large loads* by sensing the magnetic field created by the current flux in their supply cable with a *hall-effect sensor* attached to it, without the need of breaking the circuit.

The gathered information is used to find the state of the appliances in the circuit, being able to tell what appliances are *ON* or *OFF* in *real time*, and historically. This information is believed to be useful for improving the user's awareness of how he is spending electrical energy, and hopefully for providing insight to reduce his consumption habits in order to reduce the expenditure.

The overall cost of the *data-acquisition system* system is low. Although the *ADE7953 Eval-Board* was expensive, its cost doesn't reflect the material value, and it can be made very cheap. Thus, considering the availability of small, low-cost computers such as the *Raspberry Pi*, in my opinion a system like the one here developed , even if without the *Indirect Power Sensing* module, could be very easily deployed in every home, without a representing big cost to the costumer, and it would pay itself in short term, if the user would be willing to change its consuming habits, based on the report on the consumption of the domestic appliances.

For more advanced monitoring and appliance classification/disambiguation, the *Indirect Power Sensing WSN* can be also deployed at a relatively low-cost. It is, however, less cost-effective mainly because of the cost of the wireless nodes components, namely the *micro controller* and the *radio-interface* and batteries. Thus the sensors used are inexpensive, and present nearly no cost footprint to the system.

Nevertheless, the system here developed is far from being a *commercial system* ready to be manufactured. Further research on *Appliance Models* and automation of *Appliance Cataloguing and Naming* is needed to provide the end user an easy to use and deploy system, with minimal set-up effort and calibrations.

6.2 Future Work

Concerning *future work* there are plenty of ways one can improve the system to perform better and provide more valuable information, in terms of either end consumer data or data that enables more sophisticated appliance disambiguation and classification.

Thus there are certain objectives that are to be deployed immediately and others that may be delayed to further implementation.

The most immediate need is the deployment of an improved communications interface, as stated in *Section 3.4.3* of *Chapter 3*, in order to enable higher data throughput.

There may arise the need for improving the *appliance model* in order to support *multi-state appliances*, as there are already various examples of such appliances in any home. That solution would pass through implementation of an *appliance model* based on *finite state machines* as suggested in *Nonintrusive appliance load monitoring*[18].

As the appliance pool rises there may be the need of deployment of other techniques for *appliance identification*, so it's proposed augmenting the appliance detection with transient analysis, as documented in *Power signature analysis*[24], harmonic signatures as suggested in *Nonintrusive appliance load monitoring*[18] and probabilistic and stochastic analysis of appliance's usage as in *Circuit-Level Load Monitoring for Household Energy Management*[28].

To account with the augmented parameters for *appliance detection and identification* there could be implemented *Artificial Neural Networks* with the previously mentioned data as inputs, that through sophisticated functions and *self-learning* could output the states of the appliances in the system, as documented in *Real-Time Recognition and Profiling of Appliances through a Single Electricity Sensor*[38].

One aspect of the current system that needs to be improved is the use of the computed data to produce valuable statistics on energy consumption, such as detailed electrical bill discriminating the appliance's cost, intervals of consumption, variance of consumption on a time-basis or temperature-basis etc.. That may be one of the easiest parts to implement and one of the most important features for a finalized product.

Other features that may have to be considered concern the automation of the system, in order to make it easy to use and install. This could be implemented by building a large database of appliances were the deployed system would go and look for signatures for the features it has found. This database would be on-line, to allow remote access and would grow with data gathered by user's experiences, as in the *RECAP* system[38].

Appendices

Appendix A

Available Electric Monitoring Integrated Solutions

Here it is presented a market survey of the most adequate solutions of integrated systems on electrical energy monitoring.

A.1 Analog Devices - ADE7953

The ADE7953 is a high accuracy electrical energy measurement IC intended for single phase applications. Analog Devices sells it a single IC, and has also an Evaluation board for consumers to evaluate its performance. In the following sub-subsections we present the main features of these platforms.

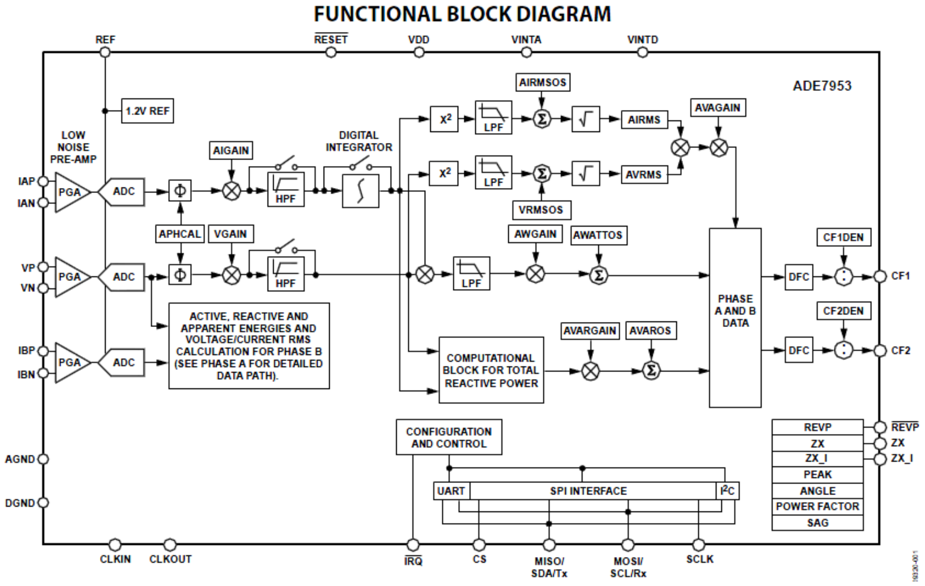


Figure A.1: ADE7953 functional block diagram [4]

A.1.1 ADE7953 - Single Phase, Multifunction Metering IC with Neutral Current Measurement

The ADE7953,functional block diagram presented in figure A.1. It has one voltage channel and two current channels, and measures line voltage and current and calculates active, reactive, apparent energy over programmable periods, plus is capable of waveform sampling in over a 1.23 kHz bandwidth in the measurements:

- V_{rms}
- I_{rms}
- *Active Power*
- *Reactive Power*
- *Power Factor*

The IC measures some power-line figures with voltage sag detection and period measurement, *no load* detection and zero crossing detection is also provided.

A variety of current sensors are supported, such as are *Rogowski Coil Sensors*, current transformers or low value shunt resistors, due to its PGAs and Integrators in the current channel path.

All ADE7953 features can be accessed via a three different communication interfaces:

- 4-pin SPI interface
- 2-pin bidirectional I2C interface
- 2-pin UART interface

[4]

A.1.2 ADE7953 – Evaluation Board

The ADE7953 evaluation kit includes two boards that together allow the performance of the ADE7953 single phase energy metering IC to be evaluated, (ADE7953 Interface Board and ADE7953 Evaluation Board)

- The interface board handles the communication from PC to the ADE7953.
- The Evaluation board includes the ADE7953, the needed isolation for high voltage inputs and anti-aliasing filters(figure A.2).

All features available in the *ADE7953* are available through supplied software, or directly using SPI, I2C or UART communication [14].

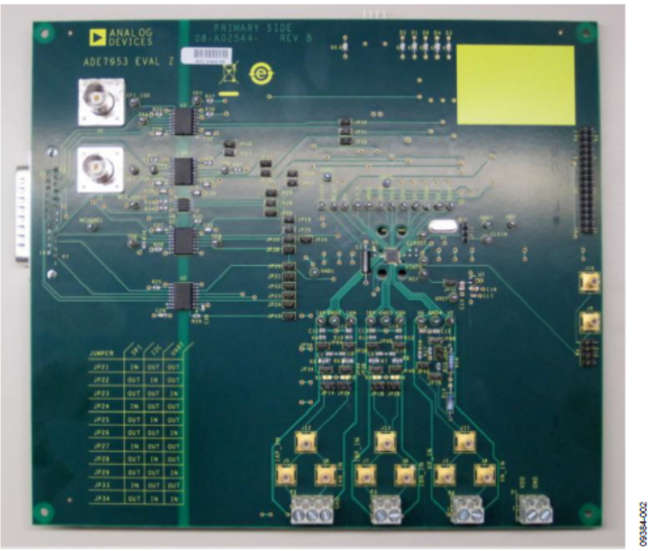


Figure A.2: ADE7953 Evaluation board [14]

A.2 Microchip's MCP3909

A.2.1 MCP3909 Energy Metering IC with SPI Interface and Active Power Pulse Output

The MCP3909 is an energy-metering IC designed for standard metering applications, the functional block diagram is presented in figure A.3. Its architecture is based on two 16-bit second order delta-sigma Analog-to-Digital Converters(ADCs) and it has Programmable Gain Amplifiers in order to allow different types of current sensors.

The IC is capable of making waveform measurements and output them digitally via SPI. The IC is capable of waveform sampling Current and Voltage over a bandwidth of $14kHz$ and output the digital data *via* SPI [30].

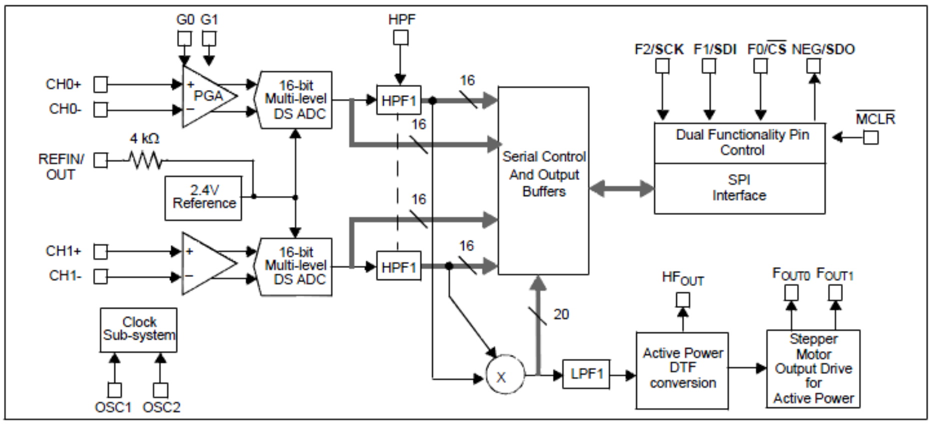

G0 G1
HPF
F2/SCK F1/SDI F0/$\overline{CS}$ NEG/SDO
CH0+
CH0-
PGA
16-bit Multi-level DS ADC
HPF1
16
16
$\overline{MCLR}$
4 kΩ
REFIN/ OUT
2.4V Reference
Serial Control And Output Buffers
Dual Functionality Pin Control
SPI Interface
16
16
CH1+
CH1-
16-bit Multi-level DS ADC
HPF1
HF_{OUT}
F_{OUT0} F_{OUT1}
20
Clock Sub-system
Active Power DTF conversion
Stepper Motor Output Drive for Active Power
X
LPF1
OSC1 OSC2

Figure A.3: MPC3909 Functional block diagram [30]

A.2.2 Microchip's MCP3909/dsPIC33F 3-Phase Meter Reference Design

Microchip supplies various energy-metering designs for evaluating MCP3909's performance, being the *Microchip's MCP3909/dsPIC33F 3-Phase Meter Reference Design* the most interesting to this project.

The Microchip's MCP3909/dsPIC33F 3-Phase Meter Reference Design is a energy-meter with many advanced features(figure A.4). It's based on the MCP3909 for waveform sampling of power line and dsPIC33F for signal processing and calculations. The current sensing is done by *current transformers*.

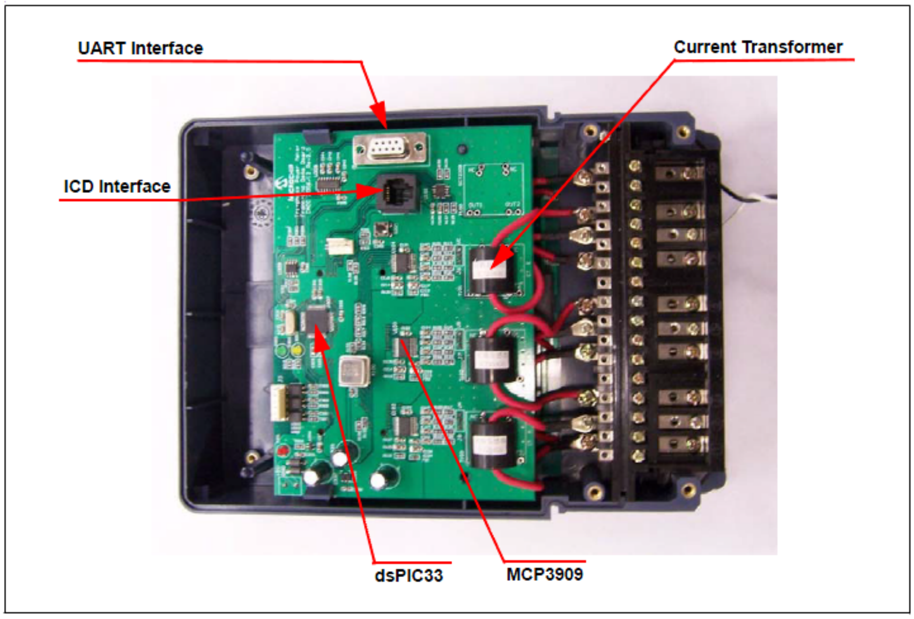


Figure A.4: MCP3909/dsPIC33F 3-Phase Meter Reference Design [29]

This meter is ready for 3-phase metering with neutral current and it produces the following data for each of 3-phases and to its total:

- line frequency
- V_{rms}
- I_{rms}
- real power
- reactive power
- power factor
- fundamental active power
- fundamental reactive power
- harmonic component measurement for voltage from the 2^{nd} to the 31^{st} harmonic

- harmonic component measurement for current from the 2^{nd} to the 31^{st} harmonic

Each of these measurements and calculations are based on frequency analysis(DFT based) are updated every 3 line cycles and accessible via UART, which can provide, at it's best, a sampling frequency of $16\,Hz$ of the desired parameters [29].

A.3 Maxim's 78M6613

A.3.1 78M6613 Single-Phase AC Power Measurment IC

The 78M6613 is a single phase AC power measurement IC designed for simplified metering of power supplies and smart appliances.

Its architecture is based in four analogue input channels, a 22-bit sigma-delta ADC, a 32-bit dedicated Computational Engine for calculations and a programmable 80515 at 5MIPS for memory access, SFR control and communications. It has digital I/O ports for interfacing with other devices, with its functional block depicted in figure A.5.

With appropriate firmware the IC is capable of the following measurements:

- V_{rms}
- I_{rms}
- apparent power
- real power
- reactive power
- phase angle
- power factor
- line frequency

The communications are done via UART, with a maximum baud-rate of $38.4\,kbit/s$ [2].

A.3.2 78M6613 Evaluation Boards

Maxim provides two evaluation boards to assess 78M6613 performance:

78M6613 - EVM - Evaluation Board - figure A.6a, is a system designed to perform measurements up to two single AC loads. The current sensing is done by current resistor shunt and the communication is made *via* USB emulating a serial port. The measurement capabilities are the same as the single IC [1].

78M6613SP - EVM - Split Phase Evaluation Board - figure A.6b, is a system designed to perform measurements to a single electrical outlet. The system provides two independent phases measurement, since in the US each outlet has two $120V_{rms}$ phases and one neutral. The current sensing is done through current transformers and the communication is made *via* USB emulating a serial port. The measurement capabilities are the same as the single IC [3].

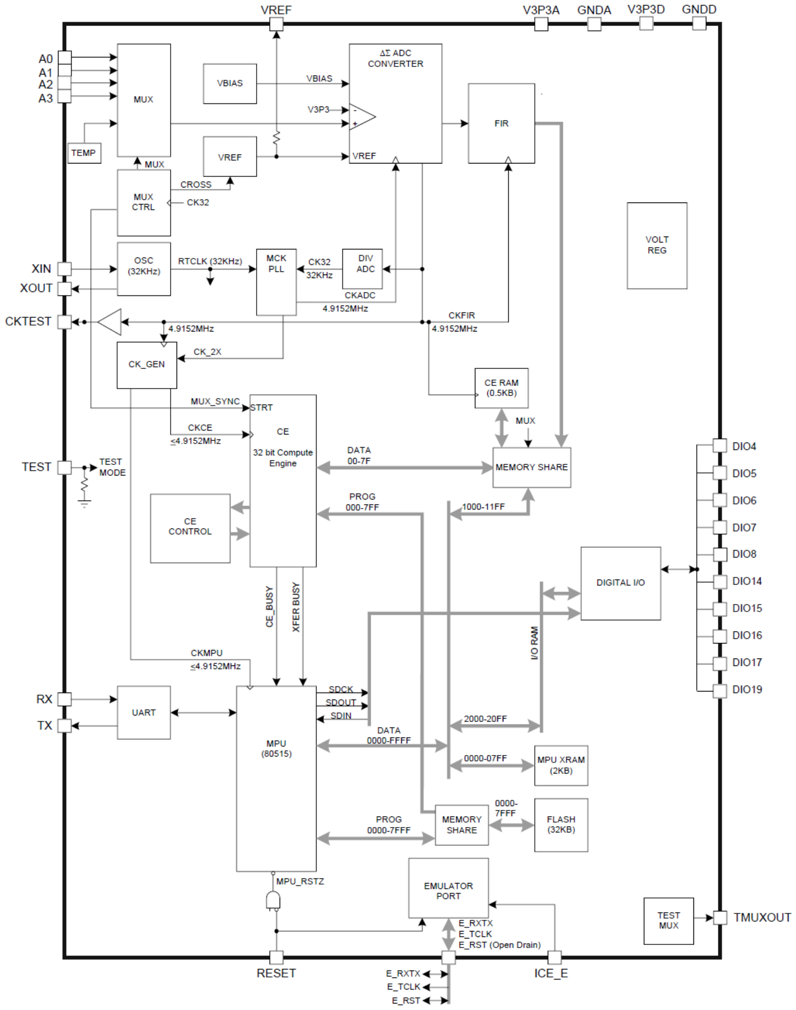
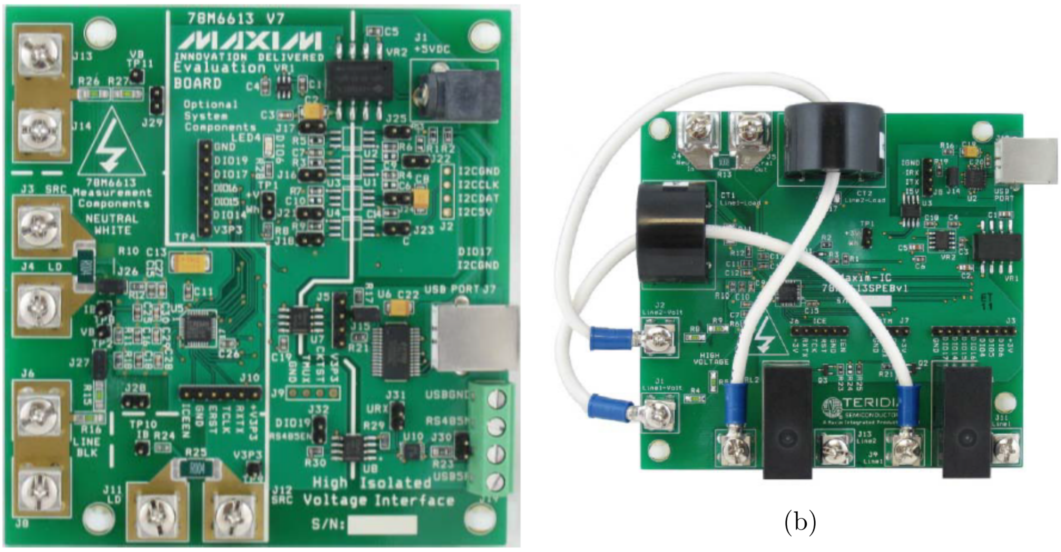


Figure A.5: 78M6613 Functional block diagram[2]



(b)

(a) 78M6613 - EVM - Evaluation Board[1]

Figure A.6: **78M6613 Evaluation Boards**:(a)78M6613 - EVM - Evaluation Board[1], (b)78M6613SP - EVM - Split Phase Evaluation Board[3]

A.4 Continental Control Systems - WattNode ModBus

WattNode ModBus is a kilowatt energy and power meter designed to monitor up to three phases. A schematic of the *WattNode* connected to one phase is represented in figure A.7.

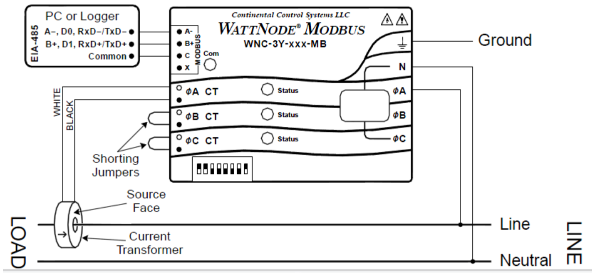


Figure A.7: *WattNode* connection schematic [44]

It provides for each phase and for the total load the following measurements:

- V_{rms}
- I_{rms}
- true RMS power
- reactive power
- power factor
- true RMS energy
- line frequency

This measurements are updated at every second *via* EIA RS-485 with ModBus. The current sensing is done by Current Transformers [44].

A.5 Microchip's PIC18F87J72 Single-Phase Energy Meter - Energy Monitoring PICtail Plus Daughter Board

Microchip's Energy Monitoring PICtail Plus Daughter Board is a low cost power monitor based on the PIC18F87J72 single chip as the energy meter IC(figure A.8). Being a low cost design the current sensors are shunt resistors. The system relies on the microcontroller's 16-bit sigma-delta ADCs, and in its computational in order to do the measurements:

- V_{rms}
- I_{rms}
- active power
- reactive power

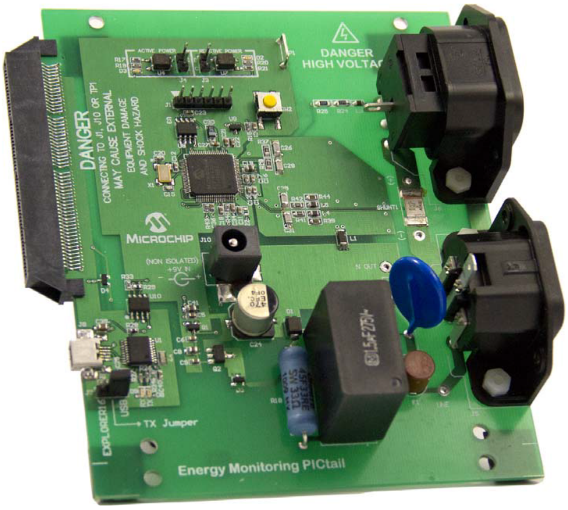


Figure A.8: Microchip's PIC18F87J72 Energy Monitoring PICtail[33]

- active energy
- reactive energy
- line frequency

The measurements are available at every line period, corresponding to a 50 Hz sampling frequency, *via* USB, emulating a serial port [13] [33].

Appendix B

Current Sensing Technologies Survey

In the current days the most used technologies in current measurement are *low resistance current shunts*, *current transformers*, *Rogowski coils* and *Hall effect based current sensors.* In this section it is presented a survey of the main characteristics of each solution, in order to choose the most adequate.

B.1 Low Resistance Current Shunts

Current shunts are the most cheap and simple solution to measure current. They can be accurately modelled by a series connection of a *low resistance shunt* and a *parasitic inductance* with the load, with the total current to be measured passing through it, being its output described by the transfer function of equation B.1,

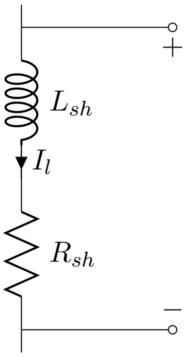


Figure B.1: Current shunt simple model

$$V = R_{sh} I_l + j\omega L_{sh} I_l \ , \tag{B.1}$$

It must be taken into account when designing the sensor, a phase mismatch due to the parasitic inductance.

As there is no galvanic isolation of the hot parts of the circuit the *shunts* are normally used in *low*, *ground referenced* currents in the order of the tenths of *Amperes*[32]. It must be also noted that these kind of sensors dissipate high amounts of power which cause the need for thermal dissipation, increasing the sensor's footprint and cost.

Figure B.2 shows some examples of *shunt resistors*.

Figure B.2: Examples of Current Shunt Resistors[9]

B.2 Current Transformer

One of the most used and most reliable solution for measuring current is using current transformers. These rely on the transformer's magnetic coupling between two coils, being the primary provided by the user, being commonly only one turn. A simple model of a *current transformer* is shown on figure B.3. And the input/output current relation is represented by equation B.2,

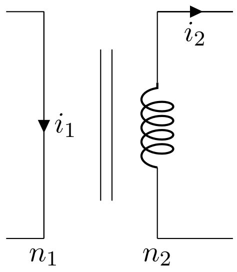


Figure B.3: Simple model of a Current Transformer

$$\frac{n_1}{n_2} = \frac{i_2}{i_1} , \tag{B.2}$$

that can be generalized to equation B.3.

$$i_2 = \frac{i_1}{n2} , \tag{B.3}$$

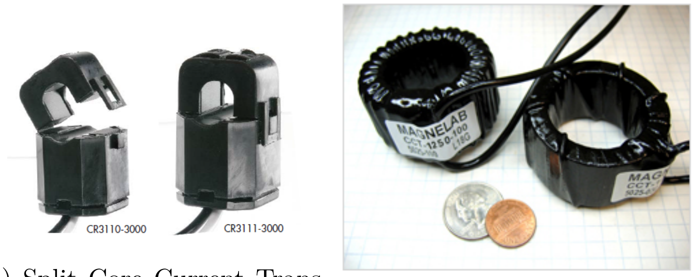
The number of turns on the secondary must then be designed to suit the application's need.

As one may see, this sensor provides galvanic isolation, making it safe for measuring high currents. This solution is very precise over a wide range of frequencies, up to hundreds of *kilohertz* but it suffers of the problem of not being able of measure nor admit *DC* due to saturation of the magnetic core. Also current transformers can introduce phase shift and special care should be taken to compensate this error.

Considering power, one can say that it consumes little power compared with the *current shunt* as it introduces nearly a null load to the system.

In terms of price it has a higher cost than resistance shunts, but it can be cheap if made small.

Some examples of current transformers are presented in figure B.4



(a) Split Core Current Transformer[8]

(b) Solid Core Current Transfomer[10]

Figure B.4: Examples of Current Transformers

B.3 Hall Effect Current Sensor

Hall Effect Current Sensors are high performance current sensors based on the *Hall effect*. The theory behind *Hall effect* states that "when a current carrying conductor is placed into a magnetic field, a voltage will be generated perpendicular both to the current and the field"[19]. So the elementary sensing system based on hall effect is based on a thin semiconductor sheet(*Hall element*) which has a current passing through it, (figure B.5).

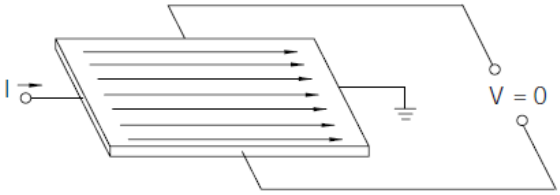


Figure B.5: Hall effect principle[19]

When a perpendicular magnetic field passes through the *Hall element* a *Lorentz force* is exhorted and a perpendicular *Hall voltage* proportional to the magnetic flux is generated[19](figure B.6).

$$V_H \propto I \times B \tag{B.4}$$

As one may see, a *Hall effect current* sensor doesn't measure the current directly, measuring the magnetic flux generated by it instead. So it's common to see *Hall effect sensors* coupled with flux concentrators in order to have better measurements. In figure B.7 there is such a configuration in which the sensor is inserted in the *air gap*.

Characterizing the *Hall effect current sensor* it is a simple sensor that provides galvanic isolation, making it safe when measuring high currents. It is possible to measure *AC* and *DC* currents with it over a wide range of values, ranging from few *milliamperes* to hundreds of

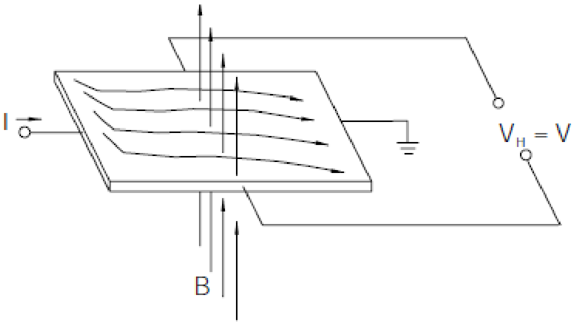


Figure B.6: Hall effect principle, magnetic field present[19]

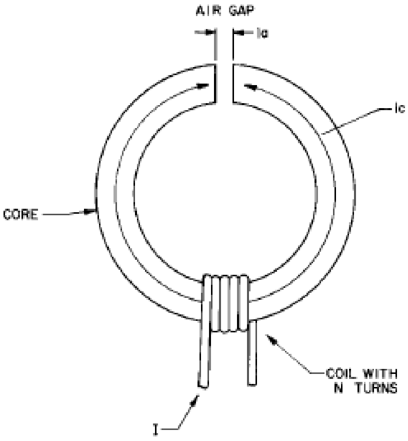


Figure B.7: Simplified linear current sensor[19]

amperes. The frequency response is said to be outstanding. There is also virtually no danger of damaging the magnetic circuit by high currents. One may have special care since these devices can have large temperature drift if not compensated.

In figure B.8 is presented an example of a *Hall effect linear current sensor*.

Figure B.8: Hall effect linear current sensor[41]

B.4 Rogowski Coil Sensor

A *Rogowski Coil Sensor* is an air cored coil with mutual inductance with the conductor carrying the primary current.

Its theory of operation is based upon the Faraday's Law that states " The total electromotive force induced on a closed circuit is proportional to the time rate of change of the total magnetic flux linking the circuit" [40]

Normally, the coil is in a toroidal shape and measures the magnetic field passing through the toroid, figure B.9. Since the magnetic flux is proportional to the current, according to Faraday's Law, the sensor's output can be described as the equation B.5

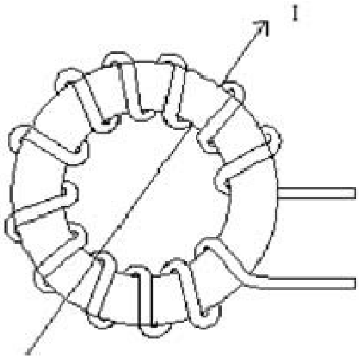


Figure B.9: Rogowski Coil current sensor, simple representation[11]

$$V_L = L\frac{di}{dt}\ , \tag{B.5}$$

As it can be observed, a current flowing through a *Rogowski Coil* induces a voltage that is proportional to the time derivative of the primary's current. There's the need of an integration for recovering the original current signal.

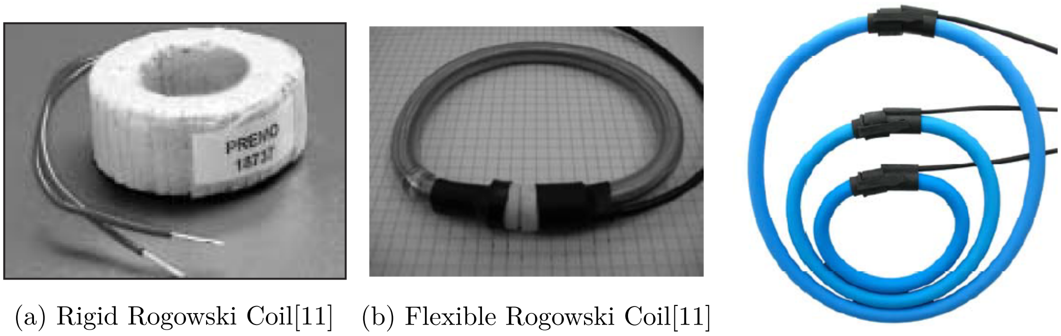
As one can notice, Rogowski coils are, by definition, incapable of measuring DC, but oposing to current transformers, these can tolerate its presence, since theoretically there is no hysteresis or saturation on the magnetic core, the device should be fully linear.

So it is safe to say that it has a very wide current operating range due to its linearity, a very good frequency response may be also seen, for the same reason. Adding to that there is galvanic isolation, making this solution very good for measuring high currents.

In its early uses(1912) it wasn't very widespread in energy metering, as the technologies for handling small output signals and for developing integrators weren't powerful enough. But with today's digital technologies it is possible to build very powerful digital integrators easily, with an outstanding accuracy[23].

Following up, nowadays it can be observed a certain effort of the manufacturers of silicon solutions for energy metering, of supporting *Rogowski Coil Sensors*, by developing energy metering ICs with already *built-in* digital integrators for these sensors.

Some examples of *Rogowski Coil Sensors* may be found in figure B.10.



(a) Rigid Rogowski Coil[11] (b) Flexible Rogowski Coil[11]

(c) Flexible Rogowski Coil[31]

Figure B.10: Examples of Rogowski Coil current sensors

B.5 Prices Survey

In the development of a technology project one must not forget about the total system cost so it is important to choose the most cost effective solution, bringing a balance through price and functionality. So a minor survey on current sensors was conducted which lead to the following findings:

Current Shunts - The *current shunts* are widely available in general components market. For the project's range international standard `IEC 61036` for energy metering, states that the power consumption per channel cannot exceed $2W$. Regarding that, to allow headroom , considering $3W$ *low resistance current shunts* it was found that it is possible to find a good set of products for a price range from 0.5 to 2 $ `US` dollars[12];

Current Transformer - The *current transformer* are also available for the general components market but in less options and quantity, as they many times customized for each project, though it is possible to find general purpose current transformers with ranging ratios from 1:1000 to 1:2000 in a price ranging from 6 to 15$ `US` dollars [12];

Linear Hall Effect Current Sensor - There are viable solutions in the general market with prices ranging from 15 to 100 $ `US` dollars[36].

Rogowski Coil - Despite being a very interesting solution for energy metering the availability of the Rogowski coils in the general components market was too scarce, so there wasn't enough information to reach conclusions about its price.

Appendix C

Transimpedance Current Sensor with Current Transformer

The maximum full scale input at the terminals IA_P and IA_N of the ADE7953 current channel is $\pm 250mV$, and a common mode of less than $\pm 25mV$ is recommended[4].

Current sensing will be made through the *current transformer* mentioned in subsubsection 3.2.1, which has the following characteristics:

- $Te = 1520$ - effective number of turns;
- $IR = 75A$ - rated current for which output is linear;
- $DCR = 80\Omega$ - DC resistance.
- $V_{MAX} = 12.8V_{rms}$ - maximum voltage at saturation;

The transimpedance circuit will be dimensioned to the *Current Transformer's*(CT), rated current and a schematic of that circuit is in figure C.1. The output is:

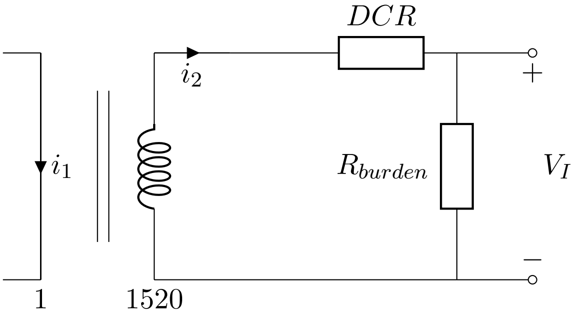


Figure C.1: Simple model of a Current Transformer

$$V_I = \frac{i_1}{Turns} \times R_{burden} \, . \tag{C.1}$$

A method of calculating R_{burden} is suggested in [15].

The burden resistor depends on the maximum current to be sensed, the maximum input range of the ADC channel and the number of turns of the CT.

Part	Value	Device	Package	Description
CT1	CR8349	CR8349	CR8349	CR8349 Current Transformer
R1	10	R-EU_0207/15	0207/15	RESISTOR, European symbol
R2	10	R-EU_0207/15	0207/15	RESISTOR, European symbol
R3	10	R-EU_0207/15	0207/15	RESISTOR, European symbol
R4	10	R-EU_0207/15	0207/15	RESISTOR, European symbol
X1	MC2	MC2	MC2	Mini-Combicon 3.81mm horizontal 2-polig

Table C.1: Current Sensor Circuit Bill of Materials

The voltage level at the current channel at maximum current on the input signal, should be at half full scale to allow headroom.

$$V_{oMax} = \frac{\text{Full Scale}}{2} = \frac{250mV_{peak}}{2} = 125mV \tag{C.2}$$

applying equation C.1:

$$R_{burden} = \frac{V_{oMax}\,CTRN}{I_{max}} = \frac{125mV \times 1520}{75} = 2.5333(3)\Omega\ ; \tag{C.3}$$

The implementation of a transimpedance circuit for current sensing. The circuit to be deployed is that of the figure C.1, with the current transformer `CR8349-1500` [8],a vertical mount pcb current transformer, and a $R_{burden} = 2.5333(3)\,\Omega$.

Taking into account that the system is to be deployed for accurate measurements, it must be taken special care with its design. The system must be very stable and accurate. It was chosen to deploy R_{burden} with *metal film resistors*,`MR25`, because they have good temperature stability, and have a tolerance of 1%. The range of `MR25` resistors doesn't have resistors with values close to the one required. So the solution was to combine resistors in order to produce a suitable resistor. The resistor was then chosen to be deployed by the combination of four $10\Omega \pm 1\%$ in parallel,

$$R_{burden} = 10 \parallel 10 \parallel 10 \parallel 10 = 2.5\Omega \pm 1\%, \tag{C.4}$$

The circuit needs now to be deployed in a *PCB*. The design was developed in *EAGLE CAD*, with the schematic depicted in figure C.2, with the layer board in figure C.3, and the *bill of materials* in table C.1.

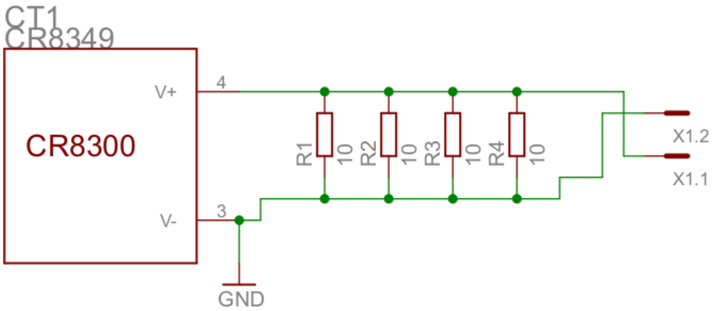


Figure C.2: Current Sensor Circuit

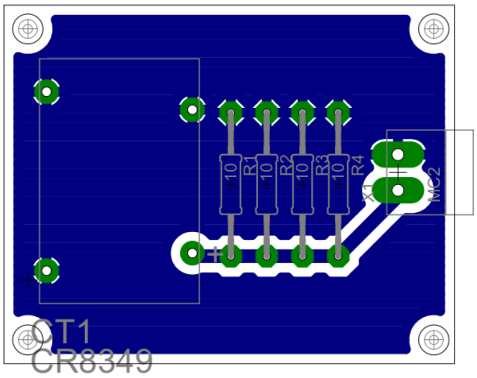


Figure C.3: Current Sensor Board

Appendix D

Light Sensor Circuit

The circuit to develop is a digital discriminator of presence of light, so it is wanted to put the sensor in saturation. It's then relatively easy to develop a circuit to convert light in voltage, sufficing to supply the transistors *collector*, and to put a resistor in the *emitter*, to the ground.

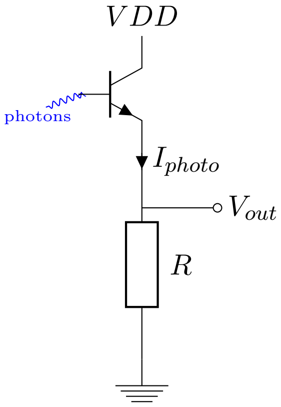


Figure D.1: Light Sensor basic Circuit

It's easy to see that the output of the circuit is:

$$V_{out} = I_{photo} \times R \tag{D.1}$$

Taking that into account, and that the sensor placement is uncertain it is necessary to deploy some sort of adjustment mechanism to the circuit. In series with R will be a *potentiometer*, in order to adjust in site, the sensor's sensitivity to the environment. As the circuit output must be digital, at the previous circuit's output it is put a *schmitt trigger* in order to force the digital levels.

This sensor circuit is to be attached to *uMRFs* where it will output its digital value, and from where it will get its power supply of $3.3\,V$. The schmitt trigger was deployed by one gate of *HEF4093 Quad Nand Schmitt Trigger* by driving one of its inputs to $3.3V$ and the other to the sensor output. The resulting schematic may be seen in figure D.2.

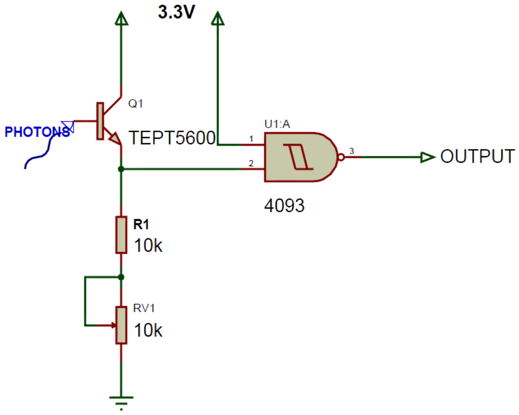


Figure D.2: Light Sensor Circuit Schematic

Circuit Analysis

By analysis of HEF4093's datasheet, it can be found that its hysteresis if supplied by $3.3\,V$ is

$$V_{iH} = 2.243\,V \ , \ \ V_{iL} = 1.415\,V \ .$$

So, the sensor has to exceed V_{iH} when detecting light and has to go below V_{iL} when the appliance is off. To guarantee correct operation and simplify calculations, it will be considered a greater threshold for V_{iH} and a smaller for V_{iL} at the sensor's output. Let them be:

$$V_{iH} = 2.5\,V \ , \ \ V_{iL} = 1.3\,V \ ,$$

Now, to make the correspondence with light it must be first calculated the current,

$$I_{photoH} = \frac{V_{iH}}{R + R_p} \ , \tag{D.2}$$

for high threshold and

$$I_{photoL} = \frac{V_{iL}}{R + R_p} \ , \tag{D.3}$$

for low threshold.

After some calculations and conversions to light according to TEPT5600's datasheet[43], the light thresholds for $R + R_p = 10k\Omega$ are

$$Photo_{high} = 70\,lux \ , \ \ Photo_{low} = 40\,lux \ ,$$

For $R + R_p = 20k\Omega$ the light thresholds are

$$Photo_{high} = 40\,lux \ , \ \ Photo_{low} = 20\,lux \ ,$$

which falls around living room lighting[25]. The tuning isn't very good, but that can easily be arranged by changing R to a more suitable value. It is here suggested that changing R to a smaller value, in order to be able to raise the thresholds, as they may be too low for normal use. Taking into account that the sensors would be placed near the lamps, the light intensity is much greater than the assumed.

A final assembled version of the developed circuit/device can be seen in figure D.3,

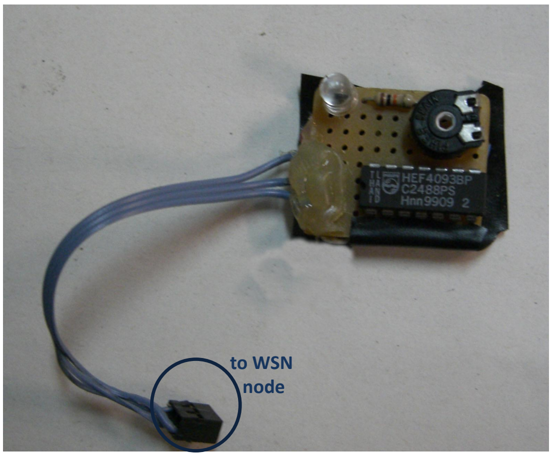


Figure D.3: Assembled Sensor Circuitry

Appendix E

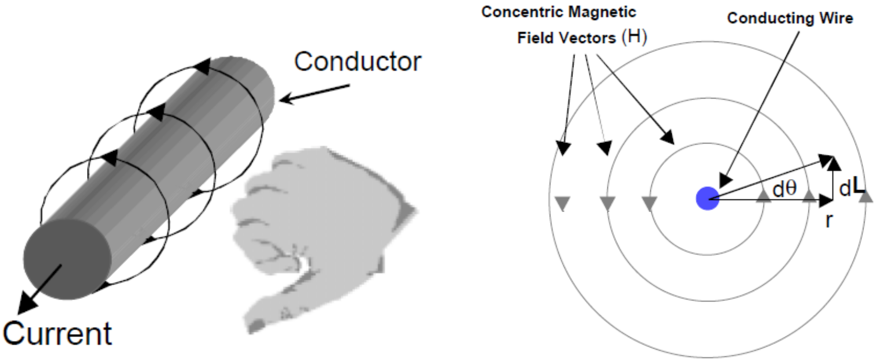
Current and Magnetic Field

The *Ampere's Law* that states: "The line integral of the magnetic field intensity (H) about any closed path is equal to the current(I) enclosed within that path" [26].

That can be stated mathematically as:

$$\oint H \bullet dL = I \ (A) \tag{E.1}$$

which, for a infinite round conductor, as in figure E.1, can derive the relationship of the equation E.2 between the current(I) and the magnetic flux(B), where $B = \mu H$ and μ is the magnetic permeability of the material.



(a) Magnetic Field vs Current directions[26]

(b) Magnetic Fields around a current carrying conductor[26]

Figure E.1: Current carrying conductor

$$B = \frac{\mu I}{2\pi r} \ (T) \tag{E.2}$$

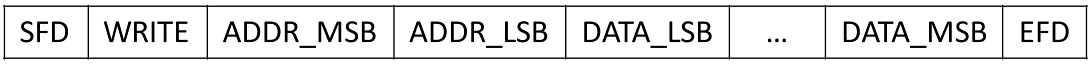
r is the radius of the equi-magnetic-flux circumference to the center of the conductor.

Appendix F

UART Protocol

Taking advantage of the software developed to test the *UART* interface, the *protocol* here developed is very similar to the one in ADE7953's datasheet[4], but without the time and baudrate constraints. Communication is byte oriented and each field in following figures represent a byte. The protocol is constituted by 3 types of messages/frames:

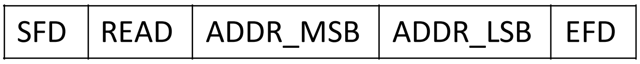
Write - This message, represented in figure F.1, is sent to gateway to issue a write in the ADE7953. *SFD* and *EFD* are *Start of Frame Delimiter* and *End of Frame Delimiter* and are used for frame consistency check and synchronization. Next there is a *WRITE* command to signalize that the PC is issuing a write. Next there are the 2 bytes of the *register address*, *MSB first*. After the address comes the *data* which the number of bytes is dependant of the register to write. The data is sent *LSB first*.



SFD	WRITE	ADDR_MSB	ADDR_LSB	DATA_LSB	…	DATA_MSB	EFD

Figure F.1: UART Write Message

Read - This message, represented in figure F.2, is sent to gateway to issue a read of a register of *ADE7953*. Again *SFD* and *EFD* are used for the same as before. Following comes a byte of command that signalizes the gateway that the PC is issuing a *read* of the register which address follows as in previous message. After this message, there will be a reply message with the data from the register addressed.



SFD	READ	ADDR_MSB	ADDR_LSB	EFD

Figure F.2: UART Read Message

Data Message - This message represented in figure F.1, is sent from gateway to PC *via* UART(figure F.3) and represents the data in the register from the *read* immediately issued before. Its length is variable with the size of the register and is sent *LSB first*. There is a lack of consistency check in this message, that can make the protocol unreliable in case of transmission errors. But its simplicity turns the coding in the PC easier, this is acceptable since the error probability is very low.

DATA_LSB	...	DATA_MSB

Figure F.3: Gateway Fata Message

The *protocol itself* may lack some error detection mechanisms. But that could be easily implemented with a *checksum* at the end of every message.

Appendix G

Indirect Current Sensor

It is not intuitive what values to expect at the hall sensor's output, so lets take by hypothesis a load of $P_{load} = 1\,kW$ connected to the power outlet at $V = 230\,V_{RMS}$, with a generic two round conductor cable with the dimensions: $d_i = 2\,mm$ for the conductors and $d_e = 5\,mm$ for the whole conductor.

Assuming that the sensor is directly put in contact with the cable, at $\theta = 0$ from equation 3.2, and from the sensor's sensibility $\dfrac{\partial V}{\partial Gauss} = 1.4mV/Gauss$ the sensor output will be $V_{out} = 4.64\,mV_{RMS}$. The sensor output is a sinusoidal wave because the *current* is sinusoidal, generating also a sinusoidal *magnetic flux*.

The *SS49E* linear hall sensor's output is a *sinusoidal voltage* with few *millivolt of amplitude* standing on a approximate $V_s = 2.5\,V_{dc}$ value when sensing current near a current carrying cable. To transform this waveform onto the desired output, one has to pass the signal through various filtering and amplification stages.

The objective of indirect sensing is detecting the power state of the appliance. With the *hall-effect sensor* it is possible to do so, by detecting the current flowing in the cable. The aim is then to develop a circuit which output is a digital value indicating the presence or not of current in a cable. The circuit will be attached to uMRFs so the digital levels of the circuit must be $0\,V$ and $3.3\,V$.

The solution developed contemplates the stages represented in the figure G.1.

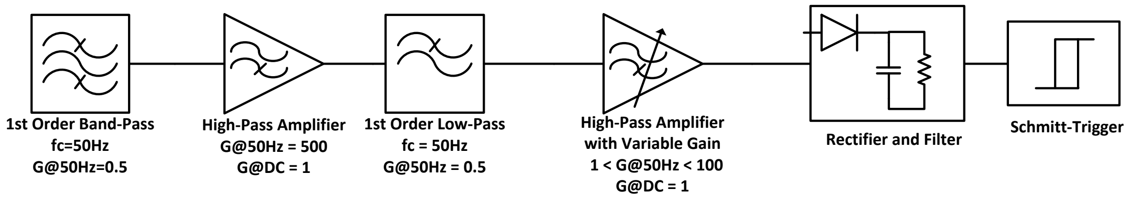


Figure G.1: Hall-Effect Sensor Conditioning Circuit

1**st **Order Band-Pass Filter - This stage implements a *band-pass filter* with central frequency $f_c = 50\,Hz$. It eliminates the DC of the sensors output and filters *high-frequency noise* due to electromagnetic interferences. It passes the only component of interest that is the $50\,Hz$ sinusoidal wave corresponding to the current.

High-Pass Amplifier - This stage implements an *Amplifier* with *High-Pass characteristic*, with the gain at $50\,Hz$ equal to $G_{50Hz} = 500$, and gain at DC equal to $G_{dc} = 1$. The need for high gain comes from the low amplitude of the signal at sensor's output of *units of millivolt*, while comparing to the desired output is a digital value of $3\,V$. The need for *no gain* at *dc* comes from that as we are dealing with such high gains, any undesired offset could saturate the amplifiers.

1**st **Order Low-Pass Filter - This stage implements a *low-pass filter* with *corner frequency* at $f_c = 50\,Hz$, to filter any *high-frequency noise* amplified by the previous stage.

High-Pass Amplifier with Variable Gain - This stage implements an *Amplifier* with *High-Pass characteristic.* The gain at $50\,Hz$ equal varies from 1 to 100, and the gain at DC is always equal to $G_{dc} = 1$. The need for variable gain comes from the ignorance *a priori* about the appliance to monitor and its power. The gain is tunable *via* a potentiometer in order to manually adjust to environment's characteristics. The need for *no gain* at *dc* comes from the same reason as the previous amplifier.

Rectifier and Filter - This stage rectifies and filters the amplified signal corresponding to the current, generating a DC voltage corresponding to the maximum voltage of the sinusoidal signal. In correct function the output here is a *high dc voltage* when there's current flowing in the cable and *null voltage* otherwise.

Schmitt Trigger - This stage aims to convert the dc voltage supplied by the previous stage to a digital value indicating the presence or not of current. It works as a comparator with hysteresis.

G.0.1 Physical Considerations

The circuit was developed to interface directly with *uMRFs*, being designed to be supplied by a $3.3V_{dc}$ source. It was found that the supply of *uMRFs* when connected to the circuit generated noise, that made the circuit unusable, causing false detection of states. To eliminate this problem the circuit is supplied externally by a $3.3V$ supply deployed by a $9V$ *battery* and a `UA78m33` *linear voltage regulator*

The schematic of the circuit is represented in figure G.2. Which fully assembled version of system is shown in figure G.3. As it can be seen the sensor was attached to the cable *via* nylon clamp.

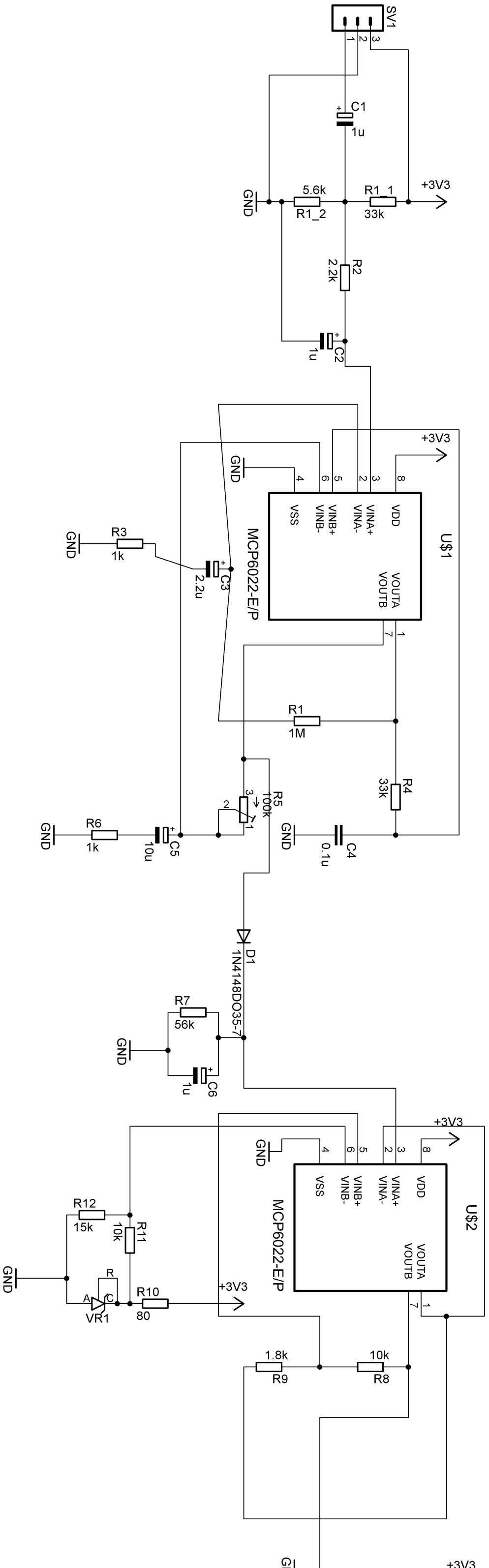


Figure G.2: Schematic of the Indirect Current Sensor Circuit

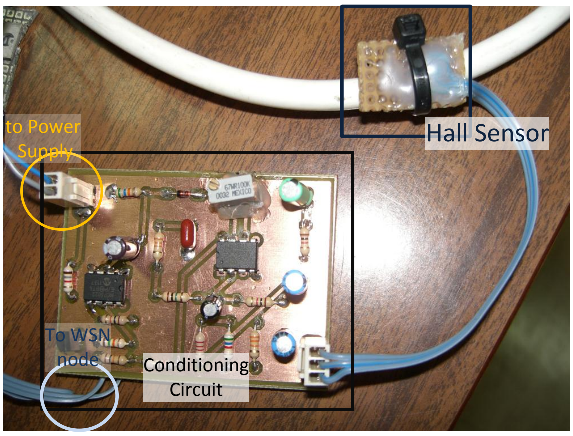


Figure G.3: Fully Assembled Version of Indirect Current Sensor Circuit

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