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Support Framework For Building's Electrical Consumption Assessment

Dissertação para obtenção do Grau de Mestre em Engenharia Electrotécnica e de Computadores

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"Events in life are not negative or positive. They are completely neutral. The universe does not care about your fate; it is indifferent to the violence that may hit you or to death itself. Things merely happen to you. It is your mind that chooses to interpret them as negative or positive. And because you have layers of fear that dwell deep within you, your natural tendency is to interpret temporary obstacles in your path as something larger - setbacks and crises.
(...) Understand: you are one of a kind. Your character traits are a kind of chemical mix that will never be repeated in history. There are ideas unique to you, a specific rhythm and perspective that are your strengths, not your weaknesses. You must not be afraid of your uniqueness and you must care less and less what people think of you."

Robert Greene

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Abstract

Predictions state that energy demand will rise about 53% until 2030. This fact, aligned with the problem of the on growing scarce nature of fossil fuels represents a serious issue because as it's well known, energy sectors world wide face serious problems when the topic is energy production. To tackle this problem, the most commonly appointed solution is a sustainable energy development, or in other words, energy efficiency.

When energy efficiency is the topic, what comes to mind is energy efficiency in buildings. With that being said, solutions that allow the monitoring of the energy consumption of a building, or that allows the visualization of the behavior of specific electrical devices, are a necessity.

With that in mind, a solution that has the purpose to relate the Active Power of specific circuits from an electrical switchboard, to the total Active Power of that electrical switchboard is proposed. This will be achieved by the development of a module that has the capability of monitoring a number of electrical devices that are connected to an electrical switchboard using current and voltage sensors. All the data collected will then be processed with the help of Computational Intelligence (CI) methods, so the relation between the Active Power of specific circuits versus the Active Power from the entrance of the electrical switchboard can be established and then analyzed.

It's important to note that the developed module will be a non-intrusive system, which is a great advantage when compared to other similar products already in the market.

Keywords: Sustainable energy development, energy efficiency, energy consumption, electrical switchboard, Active Power, current and voltage sensors, CI methods, non-intrusive system

Resumo

Previsões indicam que a procura energética a nível global vai aumentar cerca de 53% até ao ano 2030. Este factor aliado ao facto de que os combustíveis fósseis são cada vez mais escassos representa um assunto muito sério, pois como é sabido, os sectores energéticos em todo o mundo têm graves problemas nos dias de hoje quando o assunto é produção de energia. Para resolver este problema, a solução mais apontada tem sido um devenvolvimento de energia sustentável, ou por outras palavras, eficiência energética.

Quando a eficiência energética é o tópico, é costume pensar-se em eficiência energética em edifícios. Assim o desenvolvimento de soluções que permitam a monitorização do consumo da energia de um edifício, ou que permitam a visualização dos comportamentos de certos equipamentos eléctricos, são uma necessidade.

Desta forma, é proposta uma solução capaz de relacionar a potência activa de certos circuitos de um quadro eléctrico, com a potência activa total desse mesmo quadro. Para tal, é necessário o desenvolvimento de um módulo capaz de monitorizar circuitos eléctricos ligados a um quadro eléctrico através de sensores de corrente e de tensão. Todos os dados recolhidos são posteriormente processados com a ajuda de métodos computacionais inteligentes, para que a relação entre a potência activa de circuitos específicos de um quadro eléctrico versus a potência activa total desse quadro eléctrico possa ser estabelecida e depois analisada.

É importante referir ainda que o módulo que irá ser desenvolvido é um sistema não-intrusivo, o que é uma grande vantagem quando comparado com outros produtos semelhantes que existem no mercado.

Palavras-chave: Devenvolvimento de energia sustentável, eficiência energética, consumo energético, quadro eléctrico, potência activa, sensores de corrente e de tensão, métodos computacionais inteligentes, sistema não-intrusivo

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Acronyms

AC Alternating Current

ANN Artificial Neural Networks

CFL Compact Fluorescent Light

CI Computational Intelligence

CT Current Transformers

EC Evolutionary Computing

FFT Fast Fourier Transform

HVAC Heating, Ventilation and Air Conditioning

I2C Inter-Integrated Circuit

LCD Liquid Crystal Display

NILM Non intrusive Load Monitoring

PSO Particle Swarm Optimization

RTC Real Time Clock

RMS Root Mean Square

SCL Serial Clock

SDA Serial Data

SI Swarm Intelligence

1

Introduction

1.1 Background and Motivation

Energy, as a whole, is a key element to modern civilization, and its consumption raises continuously due to several factors like the population growth or the increase of the standards of life [1]. The energy consumption raises in such a continuous way, that predictions state that the energy demand will rise about 53% until the year 2030 [2]. This means that an increase in available energy is a necessity, which represents a problem because energy sectors world wide face serious problems when the topic is energy production, with the most commonly appointed solution being a sustainable energy development, mainly because this solution takes into account some of the most important factors, like the fight against climate changes, and also the increasingly scarce nature of fossil fuels [3, 4].

It's mainly because of the on growing scarce nature of fossil fuels, and the impact of their applications on the environment, that governments worldwide are implementing energy saving measures, and so the need to implement new sources of energy increases [5, 6]. With this in mind, it's important to tackle subjects like sustainable energy development, because its foundations are based on energy efficiency, and it's widely agreed that energy efficiency is the most effective, and better way, to impact today's environmental issues [3].

With this, it can be said that energy efficiency takes into account not only the processes of energy production and energy consumption, but also energy flow and its losses, which can occur in a variety of processes, ranging from the energy transformation process, transmission and distribution, to the point where the energy is actually used, i.e. end-use. Although the end-use process is complex, because it has to take into account all the end-uses of energy, it's easier to tackle energy efficiency in the end-use because ultimately changes in consumers behavior, whether industrial, commercial or domestic are easier to perform than to change entire systems already in place, because for instance, reducing the losses in the transformation processes is more of a technological problem (e.g. switching from fossil fuels to renewable energies, or improving the existing renewable energy sources to better outputs) [3]. For instance, in studies like the one performed in [7], results showed that there is a lack of information with building users about how much energy is consumed by a building, or even by a specific electrical device, which is a big deal taking into account the fact that between 1997 and 2008, residential and industrial buildings accounted for 56% of the European Union electrical consumption [8]. Nonetheless, it is easier to "educate" people, than to change entire systems that are already in place, as it was mentioned. Off course that changes in those two processes - educating people and changing/improving the systems that are already in place, is the ideal solution, but because technological setbacks prevents the enhancement of say for instance, a better usage and harnessing of renewable energies, it's easier to provide solutions regarding energy efficiency on its end-use.

1.2 Objectives

With the objective of improving the energy efficiency in buildings, and to facilitate energy readings of those same buildings, this thesis has as its main objective the development of a module that, with the help of CI methods, has the ability to relate the Active Power of specific circuits from an electrical switchboard, to the total Active Power of that electrical switchboard.

In order to do this, the proposed solution is performed taking into account the following steps:

- Development of a module - hardware and software - that has the ability to not only collect data like the Active Power of a circuit, but that also has the ability to know at which time and day of the week the data is being collected;
- After the data is collected, there is a need to rearrange that data so it can be applied to the chosen CI method;
- Once the data is rearranged, the chosen CI method is applied, along with simulations to the results from the CI method applied, to see if a correlation between the total Active Power of an electrical switchboard and the Active Power of a circuit (or circuits) from that electrical switchboard can be established;

In order to achieve all that was proposed, a module with the described capabilities was developed, and installed in a household environment, in order to determine the potential of the developed system.

1.3 Thesis Organization

Aside from this introductory chapter, this document is organized as follows:

Chapter 2:

In this chapter, an approach of the state of the art on subjects such as relevant factors in energy consumption in buildings, energy auditing, Non intrusive Load Monitoring (NILM) systems, electricity monitoring systems and CI methods is performed.

Chapter 3:

In chapter 3, the proposed solution is presented as a whole. In other words, chapter 3 describes all that was necessary to develop the proposed module, as well as the CI method chosen.

Chapter 4:

Chapter 4 describes the implementation of the proposed solution. Most specifically, this chapter describes in detail the case study performed to validate the proposed solution.

Chapter 5:

In this chapter, the obtained results are compared and discussed in detail.

Chapter 6:

Finally, in chapter 6, the work that was developed is resumed. Approaches on how this work can be further improved are also tackled.

2

State of The Art

This chapter has the purpose of reviewing a number of topics that are important to the developed work, such as relevant factors that influence energy consumption in buildings, energy audits, the analyses of similar products that can be found in markets, as well as several CI methods that can be applied to this specific work.

2.1 Relevant Factors in Energy Consumption in Buildings

Energy consumption in buildings depends on a number of factors, ranging from the weather conditions, to the direct consumption systems in the buildings (e.g. Heating, Ventilation and Air Conditioning (HVAC)), to the building's characteristics (e.g. characteristics of the building's structure), to the usage of the building itself (e.g. whether the building is commercial, residential, industrial or an office building), to the economical and environmental factors (e.g. electricity prices, environmental issues).

2.1.1 Economical Factors and Environmental Issues

No matter which country in the world, nowadays energy production depends mainly on the use of fossil fuels, like coal, natural gas or petroleum, among others. Due to the fact that the prices of this resources are almost always fluctuating, energy production, and consequently energy prices also fluctuate [9]. Not only are electricity costs affected by the price fluctuation of the resources necessary for energy production, but they're also affected by the environmental impact that energy production will have, i.e. CO2 emissions and the Green House Effect. It is with this in mind that energy efficiency is becoming an increasingly major topic worldwide [10].

2.1.2 Building's Characteristics

Another topic that influences energy consumption in buildings, is the building itself. In other words, the way the building is built, and also the materials used in it, affect energy consumption [11]. For instance, the better the heat storage capacity of an exterior wall of a building is, the less energy is going to be needed for heating because solar radiation can be stored during the day [12]. The building's envelope also plays an important role in the energy consumption, because if the building's envelope has an air leakage, people tend to raise or lower the temperature inside the building, depending on the time of the year. Another factor to be taken into account, is the fact of whether the building has a significant portion of its exposed surface covered by windows, in which case replacing the windows for more energy efficient windows (e.g. airtight, high-R value windows) has a significant effect on the building's energy consumption [9, 13–15].

2.1.3 Building Usage

Whether the building is residential, commercial, industrial or an office, all of them are going to have different amounts of energy consumption, mainly because of what they're meant to. It's obvious that an industrial building is going to have a bigger energy consumption then a residential building for instance, mainly because industrial buildings have machinery/electrical devices that consume much more energy when compared to the typical electrical devices found in a household environment. It also becomes clear that the way in which people behave, is also going to have an impact on the building's energy consumption. Whether it is the opening or closing of windows, lighting systems, or the personal regulation of HVAC systems, everything is going to have even the slightest impact on the energy consumption [16]. One example of human factors in energy consumption can be found in [17], where it was concluded that by automating the HVAC, shutters and lighting systems, savings of about 50% can be achieved. Because people's behavior influences the building's energy consumption, the amount of people in the building also has a direct effect on the energy consumption. A study was done in [18] regarding a building's occupation, where it was concluded that the lifestyle of the occupants has an influence on the annual energy consumption of the building. For instance, the study shows that the fact that many office/factory workers aren't home during the day leads to opposite energy profiles between offices/factories and homes. Because of this, factors like what kind of day it is (whether it's a holiday, normal weekday or weekend) and also the time of the day are very important and must be taken into account.

2.1.4 Direct Consumption Systems

These are all the systems that are a part of the building that have the goal to enhance the quality of life inside the building [19]. They can be systems like HVAC, cooling systems, illumination systems, boilers, etc. Out of all the direct consumption systems, it is estimated that the HVAC systems are the ones with the most significant impact on energy consumption, typically assuming values in the range of 30-40% of a building's consumption [20]. The energy consumption of HVAC systems is itself dependent of a number of factors where the most important one is the outside temperature [15, 19]. For instance in [21] is shown that in Japan, when in peak demand period, a simple increase of 1ºC in temperature causes an increase of 4500 MW of energy demand. Because direct consumption systems depend on a large number of factors, they play a very important role in energy consumption, especially HVAC systems.

2.1.5 Weather Conditions

It is clear that the weather conditions have an impact on energy consumption [22]. Weather depends on a number of variables that have direct influence on energy consumption like [23]:

- Temperature;
- Solar light exposure;
- Rain;
- Wind velocity;
- Sky clearness;

Temperature: In a study conducted in [24], it was concluded that temperature is the most important weather factor when it comes to energy consumption. Simply put, if it's to hot, people tend to decrease the temperature inside the building. On the other hand, if it's too cold, people tend to raise the temperature. This is done using HVAC systems, fans, oil heaters, etc, and this are all systems, as shown in the previous sections, that tend do have a high energy consumption ratio.

Solar light exposure: As discussed in section 2.1.2, buildings with walls that have good heat storage capability, don't need a lot of energy for heating or cooling the building.

Rain: As shown in [25], rain can have a significant impact on relative humidity inside buildings, thus creating the need to raise temperatures indoor.

Wind velocity: Wind has a direct impact on the temperature of the walls of a building, thus affecting its energy consumption [26]. Despite this effect, wind also influences buildings that have wind turbines, because the more wind, and depending on the efficiency of the system installed, the less energy the building is going to require from the energy grid [27].

Sky clearness: On a similar note, buildings that have systems with solar panels will benefit from days that have clear skies versus days that are more clouded. Sky clearness also affects the solar light exposure that a building has, and ultimately will affect energy consumption as well.

Despite all the factors mentioned in this section, for this thesis, all the results presented will only take into account the time of the day, and day of the week, because the case study done did not had the need, or in other words, did not justified the use of more variables, as it will be explained further on. Also, this two factors are very important in the sense that without the knowledge of what time it is, or what day of the week it is, there is no way to distinguish two points of equal power for instance.

2.2 Energy Auditing

Energy audit is a widely used term and may bare different meanings depending on the energy company that provides that service, but typically, four types of audits can be performed according to [9, 28]:

- Walk-through Audit;
- Utility Cost Analysis;
- Standard Energy Audit;
- Detailed Energy Audit;

Each of them will be briefly explained next.

2.2.1 Walk-through Audit

This type of audit consists on a simple and short on site visit of the facility being audited, in order to identify small and simple actions that provide immediate energy savings, like, for instance replacing broken windows, isolating exposed water/steam pipes or adjusting HVAC systems.

2.2.2 Utility Cost Analysis

The purpose of this type of audit is to perform a detailed analysis of the operating costs of the facility. This is typically done by analyzing several years of data so that patterns of energy usage can be identified. Those patterns, as mentioned in section 2.1, depend on several factors. To perform this type of auditing, the energy auditor has to take into account for instance the utility charges in order to ensure that no mistakes were made calculating the monthly electricity bills. The energy auditor also has to identify the most important/dominant loads of the facility, because peak demand charges can be a significant part of the electricity bill, and it can be concluded by the energy auditor that the facility can downscale or renegotiate the utility charges contract.

2.2.3 Standard Energy Audit

The standard energy audit, aside from performing all the steps as the two previous types of energy audits (see subsections 2.2.1 and 2.2.2), also provides a baseline for the energy use of the facility, and also the evaluation of both the energy savings and cost-effectiveness of the energy conservation measures, through the use of simple tools like linear regression models. Also, typically a payback analysis is performed in order to determine the real cost-effectiveness of the the energy conservation measures applied.

2.2.4 Detailed Energy Audit

This type of energy audit is the most comprehensive one, but also the most time consuming one. It includes the usage of measurement instruments to measure the energy consumption of the entire building, and/or of some energy systems inside the building, more specifically end-use systems (direct consumption systems) such as lighting or HVAC systems. There are a number of techniques that allow energy measurements. For instance, during the on-site visit, clamp-on and/or hand-held equipment is used to determine variations of some of the building's parameters, like indoor temperature, or energy usage. These are the kind of parameters that are relatively easy to obtain. When more long-term measurements are required, usually sensors are used, that are connected to data-acquisition systems in order to store all the collected data, and also to have remote access to that data. In most recent years, energy auditors began to use the NILM technique (which will be explained further ahead). Because NILM techniques are associated with a minimal effort when compared to the traditional methods, they're also a very attractive and inexpensive way to perform data-acquisition. In addition to the techniques mentioned above, sophisticated computer simulations are considered to evaluate and recommend energy savings for the building. The simulations performed by these computers provide the energy use by load type. A detailed energy audit also performs a more rigorous economic evaluation of the energy savings and cost-effectiveness measures applied.

Summing up, it is obvious that energy audits are not only a requirement for either offices, industrial and/or commercial buildings, but are also a way to improve the energy efficiency of said buildings, as it points where energy is being wasted, and provides valid solutions for the problems found.

2.2.5 Energy Audit Example

This subsection aims to explore a case of an actual detailed energy audit made in [29]. The energy audit was done in a factory in Sri Lanka. The steps already described in subsection 2.2.4 were performed, and in this case the aim of the energy audit was not only to specifically analyze and identify possible energy saving measures so that the monthly electrical bill would decrease, but also to help reduce production costs. Through the first steps of a detailed energy audit, it was possible to obtain the factory's energy consumption, both in terms of functional area and also in terms of equipment consumption (see Figure 2.1 and Figure 2.2 showed next, respectively).

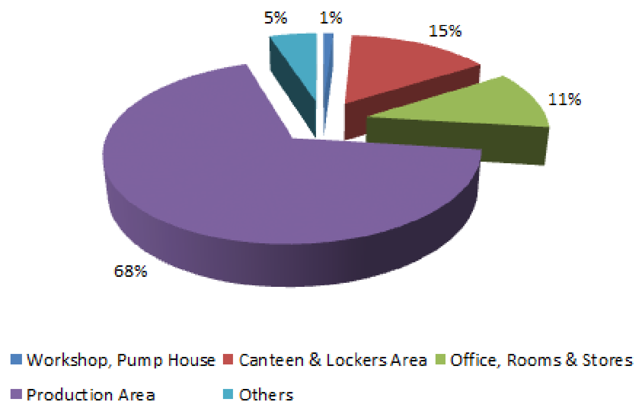


Figure 2.1: Area wise energy consumption, adapted from [29]

As expected, the production area has the highest values of energy consumption.

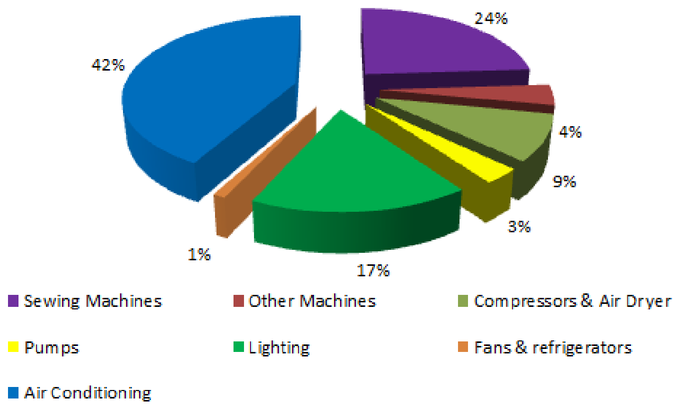


Figure 2.2: Equipment wise energy consumption, adapted from [29]

Through the analyses of Figure 2.2, some interesting results can be found, namely the air conditioning and sewing machines results. As mentioned in subsection 2.1.4, the air conditioning system is the one with the highest percentage of energy consumption, and in this case, it's followed by the sewing machines and lighting systems.

Next an evaluation was made in order to obtain the energy saving measures, and one of the points where it was found improvements could be made, despite not being the systems that showed highest energy consumption, was in the compressors and air dryer systems by minimizing the air leakages, and through the installation of both variable speed controllers and intermittent controllers. Another set of improvements was made in the lighting systems by replacing incandescent lights by Compact Fluorescent Light (CFL), or by replacing the magnetic ballasts with electronic ones, among other replacements.

The conclusions made by this energy audit are very interesting, not only from the point of view of cost reductions (seeing savings of around 3000 €), but also from a more personal point of view. For instance during the energy audit, the auditors found that employee's motivation was key to save energy without making serious investments. This can occur maybe because ultimately, all the measures proposed and implemented result in the improvement of job security, as well as working and environment conditions. Lastly, it's important to refer that all the measures suggested are of the entire responsibility of the administration panel of the factory, and in this case, they decided to go through with them.

2.2.6 Energy Audit Application

This subsection explores a software application developed in [30], so that energy auditors have a practical methodology that is able to combine a predetermined set of principles and rules in energy auditing.

When using this software, users are able to add new cases, or open an existing case. There's a tab for data collection showed in Figure 2.3.

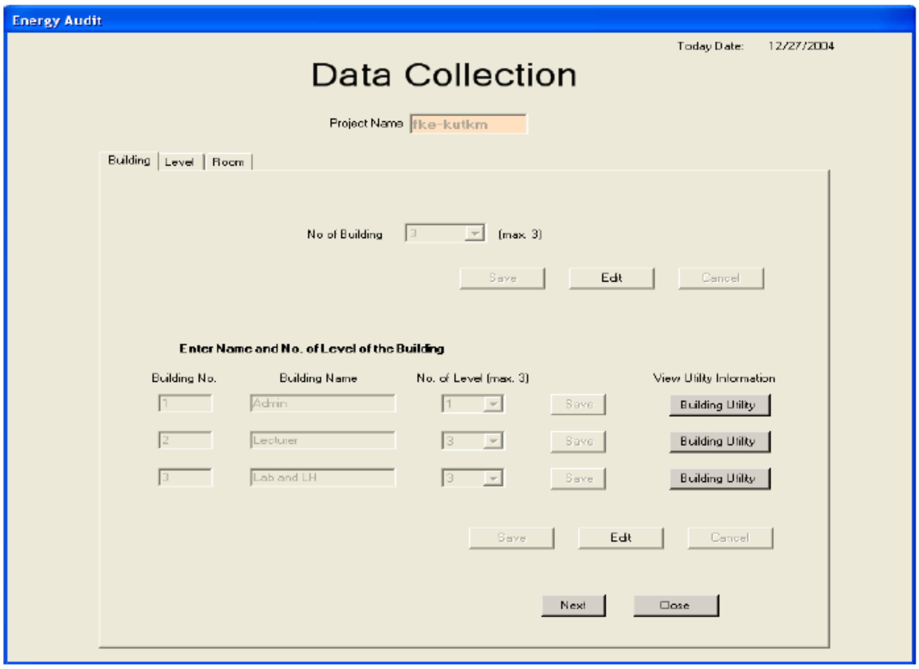


Figure 2.3: Add data collection Tab [30]

In this tab, the user is capable of inserting for instance parameters regarding utility charges of the building, or a wide number of parameters about the building's characteristics like the room's length, width and height, wall colors, windows size, etc. The user is also able to insert other important parameters like the operating conditions of major energy devices (HVAC for instance), average room temperature, among others. Summing up, this is where the user inserts all relevant information regarding the building's energy consumption, as well as relevant information gathered during the on-site visit to the facility being audited. The software is also able to provide suggestions for energy saving measures for each room audited, as shown in Figure 2.4.

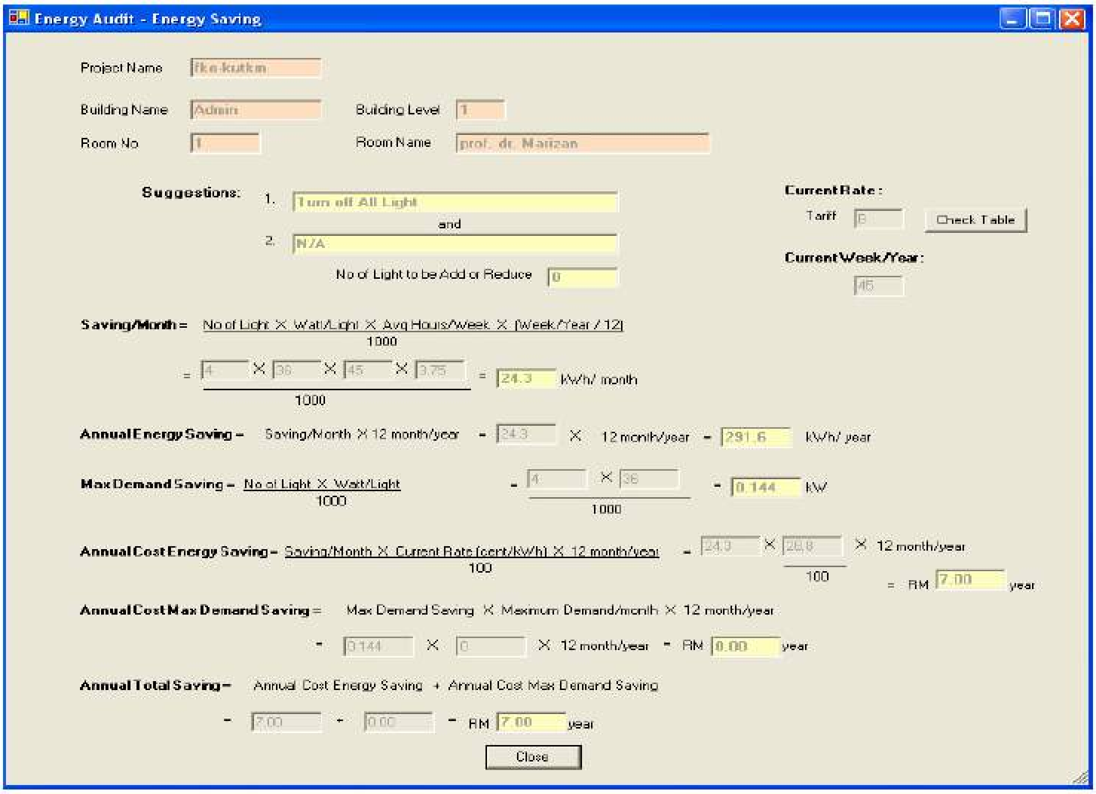


Figure 2.4: Energy savings Tab [30]

It is important to refer that the energy savings measures shown on Figure 2.4 are merely demonstrative.

The software is also able to perform a detailed summary containing all the information inserted by the user, and more importantly, containing all the calculations/steps done for the energy audit. It is concluded by the authors that this type of software greatly facilitates the energy auditors job by making the energy audit more effective and efficient [30].

2.3 Non Intrusive Load Monitoring

The first NILM system was developed by G. W. Hart in 1980. The origins of the first NILMs, or in other words, their purpose, was to monitor loads in residential buildings in order to get an insight about the final use of electricity [31–35]. Because G. W. Hart was "stuck" with the existing limitations of the computing power of that time, those systems were initially designed to detect whether an appliance was plugged or unplugged (ON/OFF states) [32].

Basically, NILMs are systems that rely on external sensors or meters, which measure Apparent, Reactive and Active Power. Those were the more rudimentary types of NILMs, or in other words, the first generation of NILMs. Next generation NILMs were the ones capable of processing the instantaneous voltage and current at the entry of where the energy is being measured [32].

For monitoring systems, it is possible to analyze measured data in steady state and in transient state [31, 33]. In the steady state analysis, individual load (or group of loads) are determined by analyzing and identifying the times where the electrical power measurement changes from a steady state value to another value [31]. In other words this type of method monitors the Active and Reactive Power, and then computes their differences whenever a current variation occurs [33]. The transient state analysis relies on the behavior of the load to perform the load identification. In other words, the shape of the transient represents a specific class of loads, and then corresponds them to their electrical behavior. For a more efficient identification, this type of analysis compares each of the transient identified to a data base through the least squares criterion [31]. A simple diagram between this two types of states can be viewed in Figure 2.5.

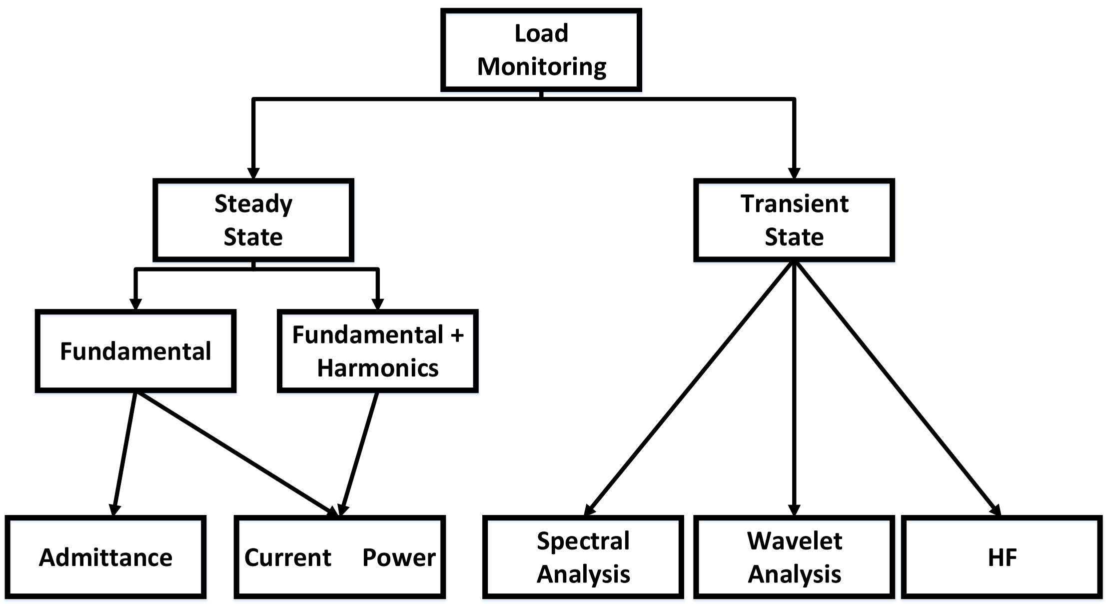


Figure 2.5: Comparison between steady state and transient analyses, adapted from [31]

2.4 Electricity Monitoring Systems

This subsection has the purpose of analyzing systems already in the market that are capable of monitoring and provide feedback about electricity consumption. Research showed that a variety of these types of devices exist, from the ones that monitor a single device, to the ones capable of monitoring the energy consumption of an entire residence or a building, etc. The monitoring systems will be briefly reviewed next.

2.4.1 Socket Monitoring Systems

Kill a Watt P4400 and Power Monitoring for Dummies P4455:

On Figure 2.6 it's possible to visualize two devices developed by P3 International that are socket monitoring systems [36]. The system shown in Figure 2.6(a) was the first device developed by P3 International. It is capable of tracking the overall power consumption of a device connected to it. It is also capable to check the quality of power by monitoring Voltage, Power Factor and line frequency. It has an additional interesting feature that is the ability to show the operating cost of the appliance connected to it with a 0,2% accuracy. The device shown on Figure 2.6(b) is an upgrade of the first one. Aside of having all the features of the first system, it is also capable of calculating the cumulative electrical expenses of the appliance connected to it and forecast usage by day, week, month or year. These systems costs go for approximately 20 € and 35 € respectively.

(a) Kill a Watt P4400 [37]

(b) Power Monitoring For Dummies P4455 [38]

Figure 2.6: Examples of socket monitoring systems

2.4.2 Full "household" Monitoring Systems

Next, some monitoring systems capable of fully monitoring the electricity consumption of a house, or a small commercial, industrial or an office building are reviewed.

Wattson Solar Plus:

Figure 2.7: Wattson Solar Plus [39]

The Wattson Solar Plus [39], shown in Figure 2.7 is a system designed for residential or small commercial buildings that have some kind of renewable energy system [39]. This system relies on sensors that are clamped on the electrical switchboard which in term transmit data to the Wattson panel shown on the Fig. 2.7. The clamps have to be put on the main feeder from the grid to the house (or small commercial building). If the house (or small commercial building) has any type of renewable energy system, a clamp can be put on the feeder that goes from the renewable energy system to the electrical switchboard. The system is capable of showing energy usage history, not only on the panel, but also on a computer, mobile phone or tablet. Perhaps the most interesting feature of this system is the colors display. For instance, when the panel shows the color green it means that there's a surplus of energy. The system also knows how much of the surplus energy one can use, and so by knowing that there's more energy being produced than energy being consumed, it is possible to increase savings and financial return. The panel is capable of showing three more colors, which are blue, meaning that energy consumption is below average, purple, which means that the energy being consumed is the normal/typical value of consumption for that building, and finally red, which means that the energy consumption is above the average use. The price for the Wattson Solar Plus is approximately 195 €.

2.4.3 Energy Meters and Energy Analyzers

Algodue UPT210 and UPM307 Energy Analyzers:

Figure 2.8 shows two energy analyzers developed by Algodue [40]. On Figure 2.8(a) is a simpler energy analyzer. It is capable of measuring single-phase or three-phase systems (but it's mainly used for three phase systems). It is also capable of reading more than 35 electrical parameters through true Root Mean Square (RMS) metering. Information can be viewed in real-time through the high contrast Liquid Crystal Display (LCD). Although information can be accessed in real-time, this analyzer has communications

(a) Algodue UPT210 Energy Analyzer [40]

(b) Algodue UPM307 Energy Analyzer [40]

Figure 2.8: Two different energy analyzers developed by Algodue

ports that provides the user means to connect it to a computer so data can be stored and then processed. The analyzer also has diagnostic capabilities like, for instance, the capability of detecting over/under-voltage or over-current which can indicate incorrect working conditions.

Figure 2.8(b) shows a more complex energy analyzer. Aside from having all of the capabilities of the Algodue UPT210, the Algodue UPM307 is capable of reading more than 100 electrical parameters. It also offers Fast Fourier Transform (FFT) analysis up to the 15^{th} or 31^{th} order according to the accuracy. Among several more differences between the two analyzers, the ones that standout more are maybe the fact that this analyzer is able to perform temperature readings, the fact that it possesses a high contrast graphic LCD, and also the fact that it provides the ability to download real-time waveform via communication ports.

Despite all the capabilities of this two analyzers, their prices are quite elevated, going from approximately 155 € to approximately 325 € respectively [41].

It's important to refer that this two analyzers are prepared to be integrated with CTs, like the ones shown on Figure 2.9.

(a) Hinged Split-Core Current Transformer - 30A:333mV Ratio [42]

(b) Hinged Split-Core Current Transformer - 250A:333mV Ratio [43]

Figure 2.9: Two different types of current transformers developed by Ram Meter Inc

These CTs come with great advantages because not only do they provide even more analyses power, as some of these CTs are capable of grouping multiple feeding cables at a time, but they're also very easy to install on an electrical switchboard. There is a large number of these type of CTs, going from rigid ones (like the ones on Figure 2.9) to flexible Rogowski coils for instance. Their price goes for approximately 20 € to approximately 35 €, respectively [42, 43], which are relatively cheap when compared to the prices of the flexible Rogowski coils that go for approximately 140 € [44].

Chauvin Arnoux Qualistar+ 8331:

The Chauvin Arnoux Qualistar+ 8331 [45] shown in Figure 2.10 is one of the most advanced portable (and relatively compact) test and measurements instruments in the market nowadays. It is specifically designed for test and maintenance departments working in industrial and/or office buildings.

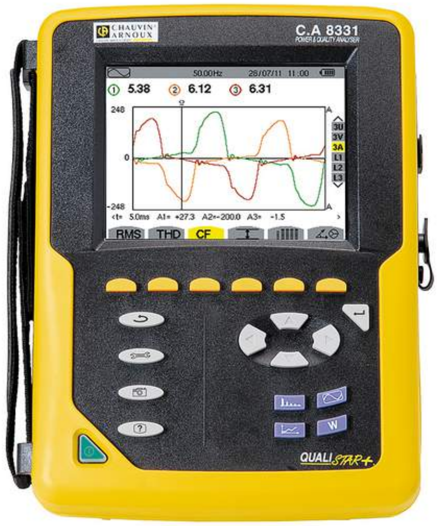


Figure 2.10: Chauvin Arnoux Qualistar+ 8331 [45]

It is extremely easy to handle and it offers a wide number of calculated values and processing functions. It is capable of performing all the features of the systems reviewed above, and then some more. It offers the possibility to connect current sensors to it, which it recognizes automatically and in term allows the direct reading of the measurements. Aside from being able to directly view the measurements done, the Chauvin Arnoux Qualistar+ 8331 allows the storage of those measurements, which can later be processed. This is possible because this device permits USB communication. With all its features, the Chauvin Arnoux Qualistar+ 8331 is the perfect tool to perform an energy audit.

With all it's qualities aside, one major problem with this instrument is the way it has to be setup, because the voltage input terminals have to be connected to the circuit breakers, which is a somewhat delicate procedure. Another problem is its price, that is around 1790 €, which makes it an instrument not in the price/financial range of everybody.

2.5 Computational Intelligence Methods

CI is a somewhat complex term, and over time has been interpreted in many different ways. Nonetheless, the most broad definition for CI according to [46] is that "CI is a branch of science studying problems for which there are no effective computational algorithms." These problems occur when trying to solve ill-defined vision tasks where formulating an exact and analytic algorithm is either impossible or computational wise, very demanding [47]. Another widely used definition of CI is: " CI is the study of adaptive mechanisms to enable or facilitate intelligent behavior in complex and changing environments. As such, CI combines ANN, Evolutionary Computing (EC), Swarm Intelligence (SI), and fuzzy systems." according to [48]. In the work developed in this thesis, the CI method used was the ANN, but nonetheless, it's important to review some of the other existing CI methods.

2.5.1 Evolutionary Computing

EC is a research area within computer science. Its inspiration, as the name implies, comes from the process of natural evolution. So, according to [49], EC relates fundamentally to a particular style of problem solving, which is trial and error. Basically, EC is based on evolutionary algorithms, which has a very common idea behind it: survival of the fittest. In other words, when given for instance a quality function to be maximized, it is possible to create a random set of candidate solutions, i.e. elements of the functions domain, and then apply the quality function to determine a fitness measurement. Based on the results obtained when the quality function is applied (the higher the results, the better), the best candidates are selected to pass on to the next generation by applying recombination and/or mutation to them. Basically recombination is when an operator is applied to two or more candidates and that results in a new candidate, while mutation is when a change is made to a better candidate and that results in a new candidate. The new candidates "compete" and the process is repeated until a candidate considered fit enough is found, or until the computational limit is reached [49]. An example of an evolutionary algorithm can be seen in 2.11.

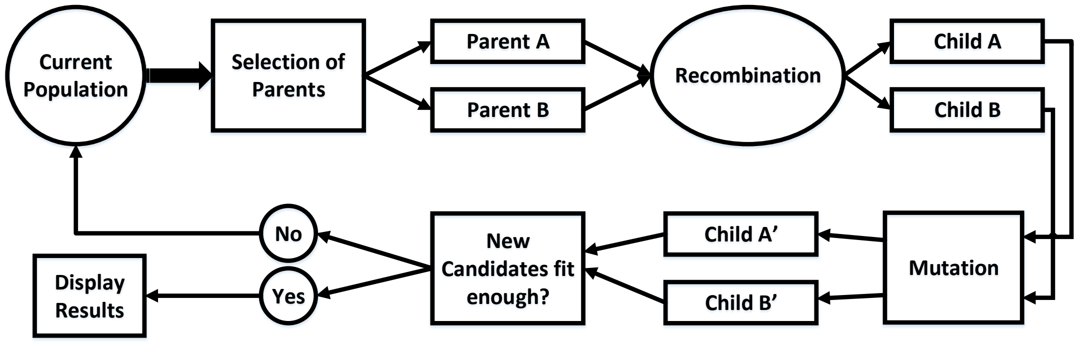


Figure 2.11: Example of an Evolutionary algorithm applied to a population

2.5.2 Swarm Intelligence

SI derives from swarming behaviors of groups of organisms. This concept is interesting because it's well known that group living enables problem solving that for a single individual are either very difficult or in some cases impossible. SI has the ability to manage very complex systems of multiple interacting individuals using minimal communication among them. They rely only on communications between local neighbors to produce a common, global behavior [50]. One of the most known types of SI is the Particle Swarm Optimization (PSO) method. It was inspired by swarming behaviors shown by flocks of birds. It has many resemblances with EC and the evolutionary algorithms, but it's much faster and easier to implement a PSO method than an evolutionary algorithm because PSO does not have operators like mutation for instance [51]. Like the evolutionary algorithms in EC, PSO requires a fitness evaluation so the best solution can be assessed. Basically PSO methods use computational entities that are distributed among the search/-work space, and in that space, each position represents a possible solution to the problem being analyzed. Each one of those computational entities is initialized in a random position and with random velocity in the work space. With every increment of the system, the computational entities "travel" through the work space checking the fitness of each position that they traveled through, retaining information about the best location they visited. Because they're capable of communicating with other computational entities, it is possible to compare the fitness of each location every computational entity visited, and then assess which one is the better one, so the swarm can converge upon that location, which represents the best possible solution among all the available solutions in that work space [50, 51].

2.5.3 Fuzzy Systems

Fuzzy systems, or fuzzy logic as it's most commonly known, maps a set of input variables to a set of output variables. The concept is very interesting because it has the capability to interact, or to reason precisely with imperfect information [52]. In other words, fuzzy logic can be interpreted as an extension of conventional (boolean) logic, that only deals with two sets of values, 0 or 1, i.e. truth or false, while fuzzy logic is capable of dealing with the values between 0 and 1, i.e. the partially truth or the partially false. It is also important to refer that fuzzy logic is capable of dealing with non numerical data, for instance, the input and/or outputs can be in natural language [53, 54]. As an example, it is possible with fuzzy logic to deal with a variable like temperature using natural language instead of numerical values, and it can be done using such terms as "very high", "somewhat high", "somewhat low" and "very low" [53]. The use of this type of non numerical data serves as a bridge for other concepts in fuzzy logic, that have as their main purpose data compression. One of this concepts is the fuzzy IF-THEN rule [54]. For instance, and taking into account the example given above about the temperature as a variable, a fuzzy logic model using this rule can be mapped to "assume" the following: "IF the temperature is "very high", THEN the energy consumption of the building will be "somewhat high"".

2.5.4 Artificial Neural Networks

ANNs are mathematical models that take inspiration from biological neural networks. Their composition consists on artificial neurons, which in term take inspiration from natural/biological neurons [55, 56].

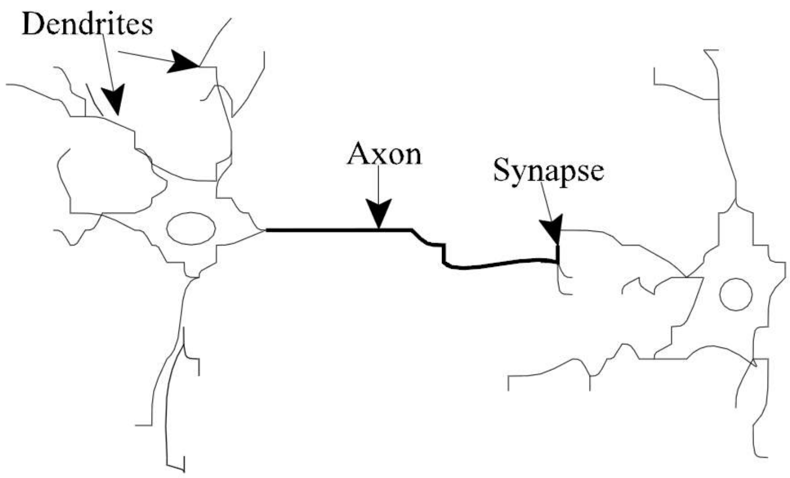


Figure 2.12: Biological neuron [55]

Figure 2.12 shows a representation of a biological neuron. These neurons receive signals through synapses located on the membranes, or dendrites of the neuron (the dendrites are the "little branches" of the neuron). When the received signals are strong enough the neuron is activated and in term emits a signal through the axon. Those signals can be sent to another synapse which then repeats this process.

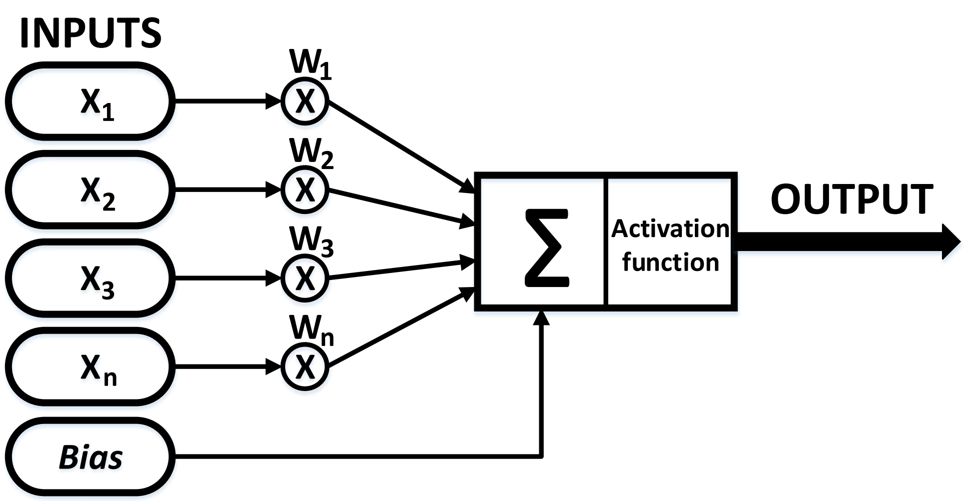


Figure 2.13: Artificial neuron, adapted from [56]

Figure 2.13 represents an artificial neuron. In this case, the information comes to the neuron in the form of inputs (X_1 to X_n). These inputs are then multiplied by weights (represented by W_1 to W_n) and are then summed along with a bias. These values are then processed by the activation function, which generates an output. A mathematical description of an artificial neuron can be viewed on Equation 2.1 [56].

$$Y(k) = F(\sum_{i=0}^{m} W_i(k) \times X_i(k) + b) \tag{2.1}$$

To breakdown Equation 2.1, $X_i(k)$ is the input value in discrete time k where i goes from 0 to m. $W_i(k)$ is the weight, also in discrete time k, where i also goes from 0 to m. The variable b is $bias$. F is the transfer (or activation) function. And finally, $Y(k)$ is the output value in discrete time k [56].

As it was mentioned before, signals processed by a neuron (biological or artificial) can be sent to another neuron. It's when two or more neurons are combined that ANNs are obtained. To better understand ANNs, the artificial neurons are displayed in layers. This type of architecture is called Perceptron and it can be singlelayer or multilayer accordingly to how many layers the ANN has. Figure 2.14 shows an example of an ANN.

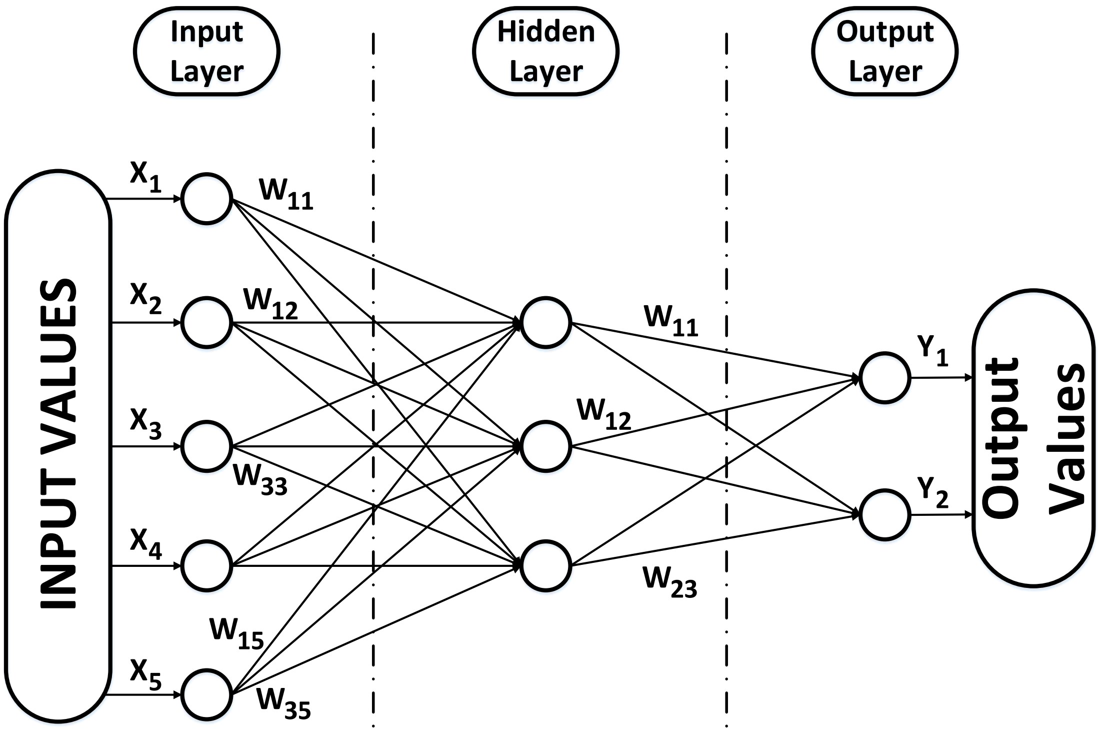


Figure 2.14: Simple representation of an Artificial Neural Network

In actuality, the example of Figure 2.14 is more specific to a feedforward ANN, but before the algorithm is briefly explained, it's important to mention that the training of an ANN can be classified as supervised and unsupervised. When an ANN uses supervised training, the learning process is a function between the difference of the output of the ANN and the wanted value, and so, the weights keep changing until that difference is considered acceptable. When the training is unsupervised the ANN "evolves" for itself until it reaches an equilibrium point. This two types of training methods are used by the feedforward algorithm, as well as the backpropagation algorithm, which will be briefly explained next.

Feedforward

This type of process, or algorithm, is the simpler one, because it has only one condition: all the information must go forward, from input to output, with no back-loops [56]. Basically, with the feedforward algorithm, the input layer passes the activation of the artificial neuron to the next layer, and so on, until the output layer is reached.

Backpropagation

The backpropagation algorithm is somewhat more complex than the feedforward algorithm, because backpropagation algorithms are used in layered feedforward ANNs [55]. Firstly this algorithm uses supervised learning, which in other words means that examples of the input and output data that is going to be processed are provided for the ANN to compute. From this "computation" an error is calculated (this error is the difference between the actual and the expected results). With this being said, initially backpropagation algorithms function in the exact same way as the feedforward algorithm, meaning that information flows forward from input to output. When the information reaches the output layer, the calculated errors of that information are propagated backwards [55].

All the CI methods presented here are valid solutions for an enormous number of problems. However, a great number of studies shows that the most commonly used method when dealing with energy consumption, energy loads, etc, is the ANN [57, 58]. In some cases, studies have shown that fuzzy logic and ANN are indeed two of the methods that have the best results when compared to other methods [59].

Besides the methods mentioned here, there are several more, like for instance statistical methods. It is important to refer that all this methods can be put together to obtain better results, but for the purpose of this thesis, only the ANN with backpropagation algorithm will be applied.

3

Proposed Solution

What is proposed in this thesis is the development of a module - hardware and software - that provides the ability to relate the Active Power of previously selected circuits from an electrical switchboard, to the total Active Power of that electrical switchboard, as Fig. 3.1 shows.

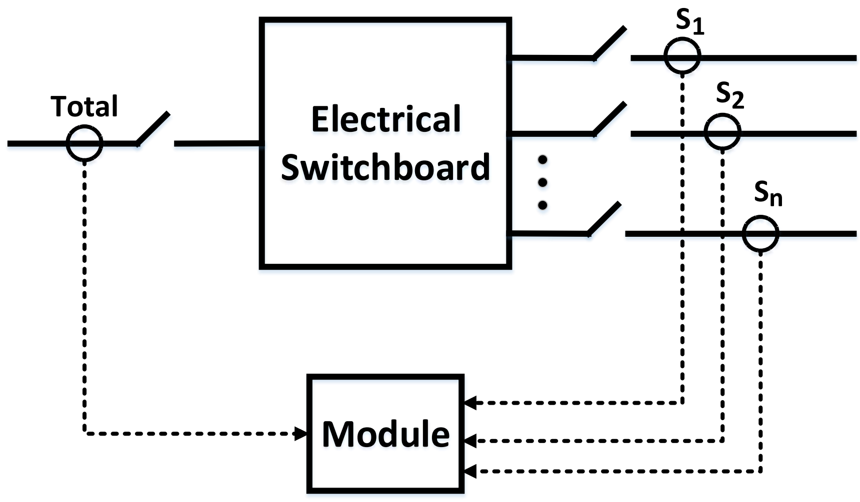


Figure 3.1: Global view of the proposed solution

In order to achieve this, it's first necessary to acquire the Active Power, among other variables, from the circuits that are going to be monitored. For this to be possible, and as it was mentioned above, a module that is capable of measuring Active Power, plus time and day of the week was developed.

The module shown in Fig. 3.1 is divided in the components shown in Fig. 3.2.

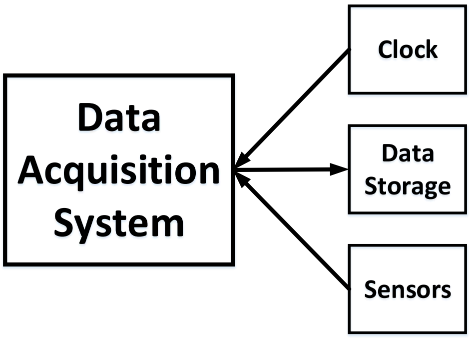
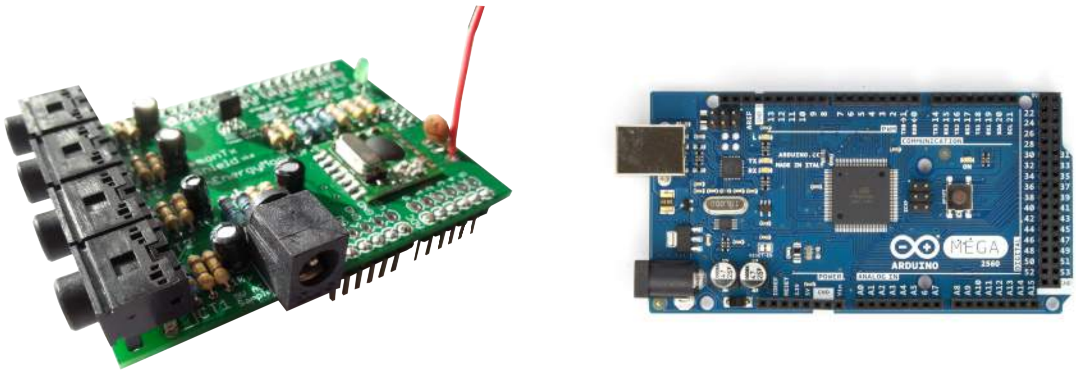


Figure 3.2: Overview of the developed module

The data acquisition system is composed by an EmonTx Shield V1 along with the Arduino Mega 2560, both shown in Fig.3.3.



(a) EmonTx Shield V1 [60]

(b) Arduino Mega 2560 [61]

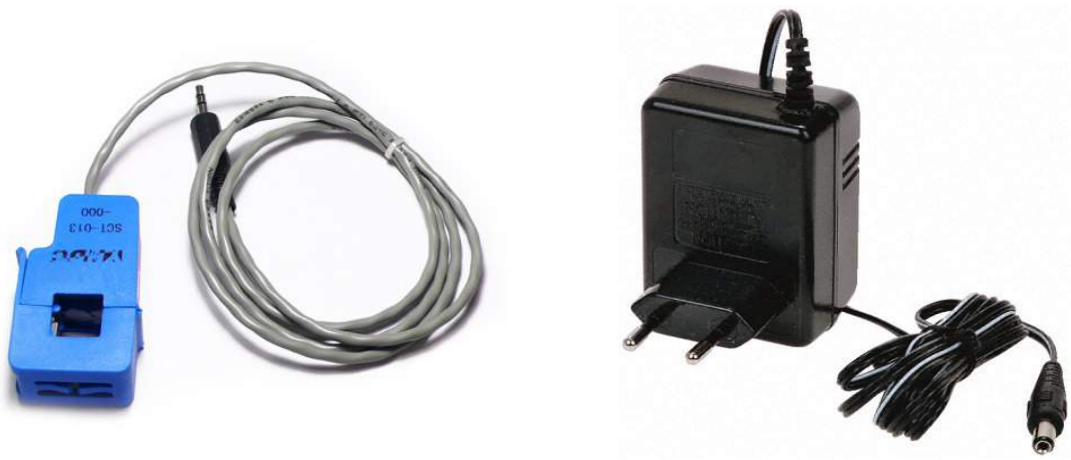
Figure 3.3: Hardware solution - EmonTx Shield V1 and Arduino Mega 2560

The reason behind the choice of this two items is because regarding the EmonTx Shield V1, this hardware provides the capability to monitor electricity, temperature, electrical current (RMS value) as well as Apparent Power, and its price is relatively low when compared to the devices shown in section 2.4, costing approximately 15 €. Because the EmonTx Shield V1 requires a "base station" to send/receive data to/from, the choice landed on the Arduino Mega 2560. This was the arduino chosen among all the others, because this arduino has all the communication pins separated, which as it will be shown further ahead, is a major concern with this setup. The price for this arduino is about 40 €.

3.1 EmonTx Shield V1

As it was mentioned above, the EmonTx Shield V1 shown on Fig. 3.3(a) is able to provide a variety of parameters. But in order to obtain those parameters the EmonTx Shield V1 requires CTs like the ones shown in subsection 2.4.2 on Fig. 2.9. The CT chosen was the one shown in Fig. 3.4(a).

All that it's left to know now is the Active Power, and in order to do that, parameters like the Power Factor and AC RMS voltage are needed. To obtain this last set of parameters, a voltage sensor (which also serves as a power plug for the system) like the one shown in Fig. 3.4(b) is required.



(a) 100A max clip-on current sensor CT [62]
(b) AC voltage sensor [63]

Figure 3.4: Hardware solution - chosen CT and AC voltage sensor

This two sensors represent the sensors shown in Fig. 3.2. It's important to refer that the price range of this two pieces is of approximately 12 € for both the CT and the AC voltage sensor.

With the setup so far, the system is capable of providing one of the parameters that is intended, which is the Active Power of a circuit to where the CT is connected. But as it was mentioned above, it is also required to know which time it is, the day of the week, and to be able to store all the data obtained. This points will be explained in the next section, for they are obtained through a few devices that need to be connected to the Arduino Mega 2560.

3.2 Arduino Mega 2560

As it was mentioned above, this was the "base station" chosen for the EmonTx Shield V1. The main reason behind this is because this arduino has its communication pins all separated. This is important because the EmonTx Shield V1 uses, among all the others, the pins 4 and 5 to send data to the "base station" (the arduino in this case). This wouldn't be a problem if it wasn't necessary to obtain parameters like the time or the day of the week, which in this case is done through a module (add-on) like the one shown on Fig. 3.5.

The module shown on Fig. 3.5 is most commonly known as a Real Time Clock (RTC),

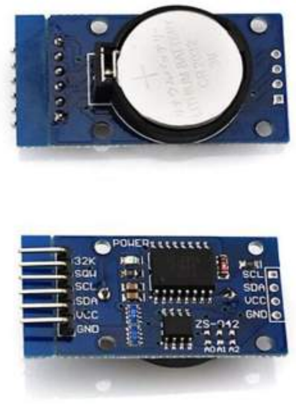


Figure 3.5: DS3231 AT24C32 Memory Module For Arduino I2C Real Time Clock

and it represents the clock as its shown on Fig. 3.2. What this module does, as the name indicates, is that it provides the time and also the date. It possesses a special feature that is a battery casing, for when the system is not powered up, the battery keeps the RTC running and so the time is always updated. The problem, or conflict between the RTC and the EmonTx Shield V1, is the fact that in most arduinos, the pins 4 and 5 are also the Serial Data (SDA) and Serial Clock (SCL) pins, which preform the Inter-Integrated Circuit (I2C) communications between the RTC and the arduino. This represents a conflict because the arduino can't receive data from the EmonTx Shield V1 and from the RTC at the same time. Plus, because the communication from the EmonTx Shield V1 to the arduino is not made using I2C, the system sometimes reads the data from the RTC, and sometimes reads the data sent from the EmonTx Shield V1. Because of this, the simpler solution for this problem was to choose the Arduino Mega 2560, which as it was already mentioned, has all the communications pins separated.

The final piece for the setup to be completed, is a module, like the one shown in Fig. 3.6, that is able to store all the data being collected, whether it's the data from the EmonTx Shield V1, or the data from the RTC. It is important to refer that this module requires an actual SD card to store the data.

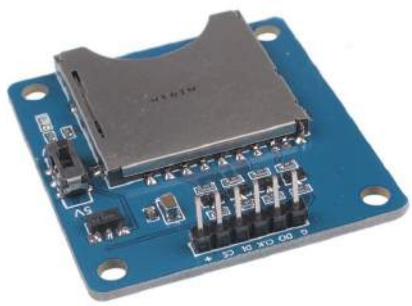


Figure 3.6: SD Card Breakout Module

Both the RTC and the SD Card Breakout Module can be acquire at relatively low prices, of about 1 € each.

3.3 Complete System Assembled

Once all the components come together, the final module - hardware wise - is obtained, as shown on Fig. 3.7.

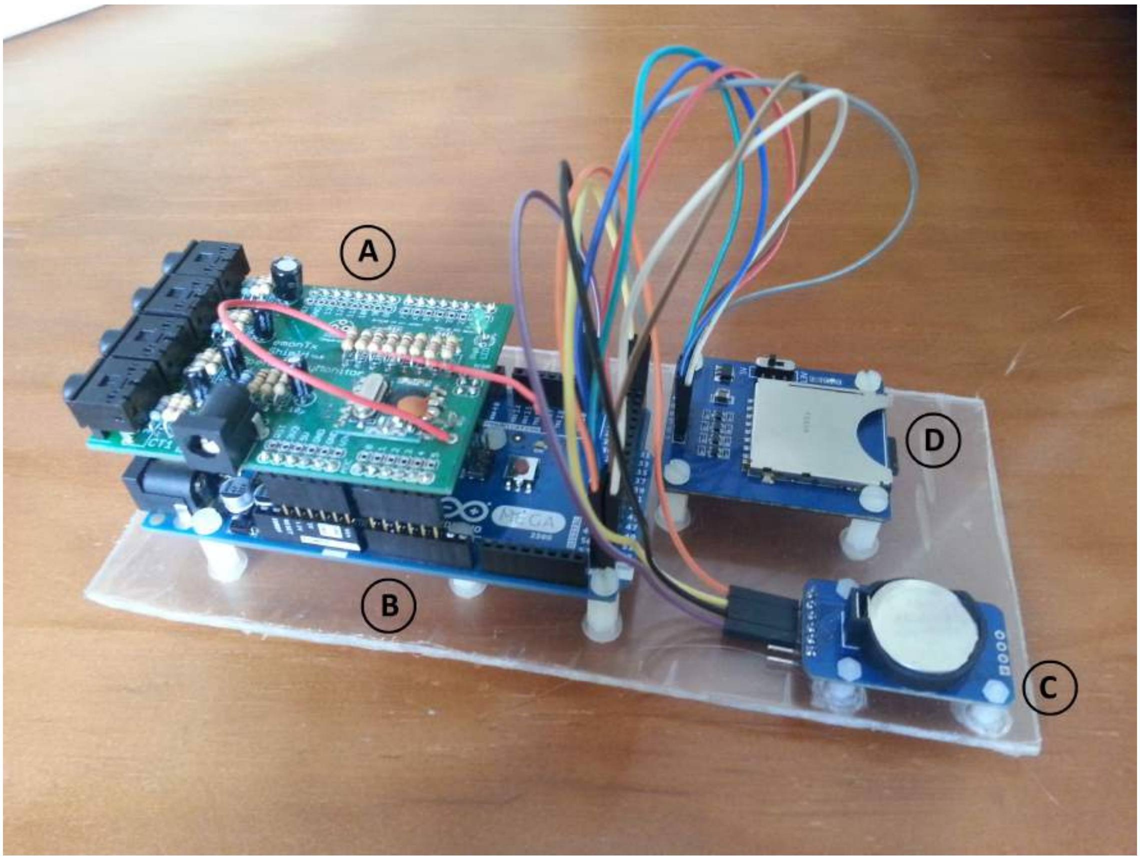


Figure 3.7: Final system

On Fig. 3.7 is possible to see:

- A - EmonTx Shield V1;
- B - Arduino Mega 2560;
- C - DS3231 AT24C32 Memory Module For Arduino I2C RTC;
- D - SD Card Breakout Module;

This system, with four CTs like the ones shown on Fig. 3.4(a), and a voltage sensor like the one on Fig. 3.4(b), is capable of reading the Active Power, along with date and time, from a minimum of four circuits from an electrical switchboard. Four is the minimum, because as it will be shown further ahead, circuits from the same nature can be grouped, if the cable's diameter allows it, and as long as the CT has the capacity to hold them, or in other words, as long as the CT is able to close itself.

With all its components, this solution goes for approximately 130 €, which when compared to the systems analyzed on subsection 2.4.2, is a cheaper solution. The only one that comes close, it's the Algodue UPT210 Energy Analyzer shown on Fig. 2.8(a), but it's only the system itself, meaning that the CTs and/or Rogowski coils have to be bought, and assuming that the CTs are bought (because they're cheaper then the Rogowski coils), that system rises its price to about 250 €.

3.4 Data Acquisition, Data Storage and Data Processing

Some important factors about this solution, are the data acquisition, storage and processing parts. The data acquisition is done through the CTs and through the EmonTx Shield V1 and the Arduino Mega 2560. The data storage, as it was already mentioned, is done through the use of the SD Card Breakout Module. The data processing part in this case is the preparation of all the data collected to be trained by the ANN.

3.4.1 Data Acquisition

To acquire data, the developed module uses the CTs and the voltage sensor as it was mentioned previously. The system then needs to process that data so it can return the Active Power. This is important because every time the developed module reads the data from the CTs and the voltage sensor, a small delay occurs - normally 1 second - to read and process the data of each CT plus the voltage sensor values. Because the module has the ability to hold 4 CTs it means that to read all the values from the circuits to which the CTs are connected, it would take about 4 seconds. But, as it's obvious, to obtain decent readings, it's necessary to be constantly retrieving data and then storing it. The best solution found in order to do this, was to take several samples, during every minute, for each circuit being measured, and then perform an average of the values collected and only store that average for each circuit. Fig. 3.8 is an illustration of how this is made.

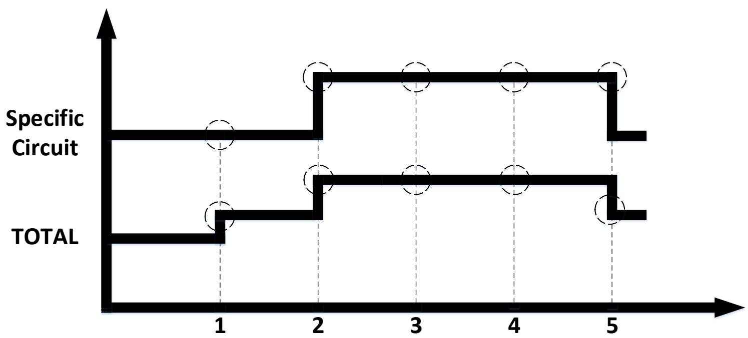


Figure 3.8: Example of data acquisition for two circuits being measured

As Fig. 3.8 shows, five samples are taken for each circuit being measured. The reason why five samples are taken is because sometimes, the delay that occurs when the values are being read and processed, can take more than 1 second, sometimes reaching 4 or 5 seconds. This presents a problem, because this could potentially mean that not all circuits were going to be fully monitored during that minute if more samples were to be taken. A representation of what was done can be seen next, in the sample of the developed code.

```
emon1.calcVI(20,2000); //Reads what the CT is reading.
potenciaActiva1=emon1.realPower+potenciaActiva1;
delay(1000);
emon2.calcVI(20,2000); //Reads what the CT is reading.
potenciaActiva2=emon2.realPower+potenciaActiva2;
delay(1000);
emon3.calcVI(20,2000); //Reads what the CT is reading.
potenciaActiva3=emon3.realPower+potenciaActiva3;
delay(1000);
emon4.calcVI(20,2000); //Reads what the CT is reading.
potenciaActiva4=emon4.realPower+potenciaActiva4;
delay(1000);
```

Listing 3.1: Sample of the arduino's code

This process is repeated five times along the minute as it was mentioned. In the example code it's possible to see that every time that a sample is taken, a manual delay of 1 second is given. This is to ensure that the developed module has enough time to read and process all the values obtained from the readings of each CT and from the voltage sensor, because, as it was mentioned, sometimes a delay - not manual - occurs and can go for up to 4 or 5 seconds. With this manual delay, those situations decreased drastically, and it was verified that, in the worst case scenario, a reading would take about 2 or 3 seconds, instead of the 4 or 5 seconds. With this, if all is read with no random delays, the system takes about 25 seconds to read and process all the values from the circuits being monitored, as well as to process other operations like retrieving the hour and day of the week, and storing all the data. In the worst case scenario, or in other words, in the case that a random delay occurs every time, it would take up to approximately 50 seconds to perform all the operations mention above. In reality, what happens most of the times, is that it takes a random reading (from a random CT plus the voltage sensor) around 2 seconds to be completed, from every cycle, and in total, it was verified that the system takes around 35 seconds to preform all the readings, on average.

Finally when the process is repeated five times, as it was mentioned previously, an average is performed and the values are stored. This values are not normalized as they should be, because at this stage of the process, it's impossible to do so. They will instead be normalized once all the data is collected, as it will be explained further ahead.

It's important to mention that one problem with the system is the fact that because the code is sequential, and because the objective is to relate the Active Power from previously selected circuits from an electrical switchboard, to the total Active Power of that electrical switchboard, sometimes the system can read one value before the other. This means for instance that sometimes the Active Power of a specific circuit being monitored is greater than the total Active Power of the electrical switchboard. Fig. 3.9 illustrates this problem.

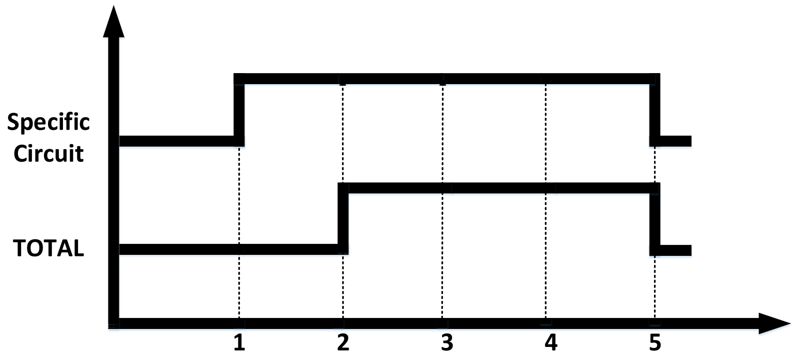


Figure 3.9: Example of one type of circuit being read before the other

As shown in Fig. 3.9, in this specific case, the circuit responsible of measuring the Active Power of the entrance of the electrical switchboard, only starts to read on the second "cycle". This means that the values from the specific circuit shown in the figure, will be greater than the total Active, which is wrong. This would represent a bigger problem if for instance the circuits were being monitored for a very short period of time, but because, at least in this work, all the circuits are monitored for more than a minute, or in other words, all the circuits being monitored are turned on for more than a minute almost every time, this means that in the worst case scenario, on average, there's going to be a difference of about 20% between those two values. Practically, this is not a serious problem, because as it was mentioned, even if a specific circuit is read before the circuit responsible for the total Active Power, it's only going to happen once. And because the values of the circuit responsible for the total Active Power are always greater than the values of the specific circuits, on average, the final value obtained for the circuit responsible for the total consumption is always going to be greater than all the other circuits. Nonetheless, one way to try to minimize this situations, was to ensure that when the arduino is programmed, the CT that will be in charge of monitoring the entrance of the electrical switchboard is the first one to perform the readings.

3.4.2 Data Storage

The way in which the data is stored, is directly linked to the data processing part of this system. An example of how the data is stored is shown next:

0.9319444656,0,0,0,0,1,0,0,8.77,4.98,4.41,4.36

At first sight it's difficult to understand what each value represents. For that, the example shown above is put on a table (table 3.1), so that it is possible to understand what each of the values signifies.

Table 3.1: Example of data stored and what each value represents

Hour Norm.	Mon	Tue	Wed	Thu	Fri	Sat	Sun	CT1	CT2	CT3	CT4
0.9430555343	0	0	0	0	1	0	0	8.77	4.98	4.41	4.36

The first column, Hour Norm. represents what hour of the day it is. These values were normalized according to equation 3.1. It's important to refer that the seconds are not taken into to account, because the samples are taken each minute, and so seconds are irrelevant to the equation.

$$Normalized\,Hour = \frac{Hour \times 60 + Minute}{1440} \tag{3.1}$$

The next seven columns represent the day of the week. The next four columns represent the Active Power obtained from the circuits to which each of the four CTs are connected to. As it was mentioned, it's possible to verify that the values obtained from the readings of each of the CTs are not normalized, but in order for the data to be processed, they need to be.

3.4.3 Data Processing

For the normalization of the values from the readings of the CTs, another equation was used.

$$Normalized\,Value = \frac{Actual\,Value - Minumun\,Value}{Maximum\,Value - Minumum\,Value} \tag{3.2}$$

As an example of how data is in its final form, table 3.2 is shown, with three samples taken.

Table 3.2: Example of three samples of data stored

Hour Norm.	Mon	Tue	Wed	Thu	Fri	Sat	Sun	CT1	CT2	CT3	CT4
0.9430555343	0	0	0	0	1	0	0	8.77	4.42	4.41	4.36
0.9437500000	0	0	0	0	1	0	0	9.88	5.56	1.99	5.21
0.9444444656	0	0	0	0	1	0	0	3.22	2.14	5.98	2.08

From table 3.2 the maximum and minimum values of each columns can be identified, being 9.88 and 3.22 for CT1, 5.56 and 2.14 for CT2, 5.98 and 1.99 for CT3 and finally, 5.21 and 2.08 for CT4. By applying equation 3.2 to each of the columns (CT1 to CT4), the values in table 3.3 are obtained.

Table 3.3: Example of final data ready to be processed

Hour Norm.	Mon	Tue	Wed	Thu	Fri	Sat	Sun	CT1	CT2	CT3	CT4
0.9430555343	0	0	0	0	1	0	0	0.83	0.66	0.67	0.72
0.9437500000	0	0	0	0	1	0	0	1	1	0	1
0.9444444656	0	0	0	0	1	0	0	0	0	1	0

Table 3.3 is a representation of what the values will be like on file when they're all processed.

Once the data is in its final form, it's necessary to apply a method that can relate the values obtained from the readings of the used CTs. The method chosen was the application of ANNs and the tool used was the Neural Network Tool™ provided by Matlab, because this tool is able to deliver reliable results and has an extremely intuitive interface, which all combined provides the user with an easy, fast and effective way of using ANNs. With that being said, this specific tool uses a feedforward ANN with two layers, using the Levenberg-Marquardt backpropagation algorithm to perform the training. In the end, this tool also provides all the data that was inserted, as well as the results of the training of the ANN, so that the data can be processed.

As it was already mentioned, the method will try to relate different types of data. On all the tests done, it will always be the same procedure, meaning that the data for which the method will try to find a correlation, is between the Active Power from the entrance of an electrical switchboard (meaning its total energy consumption) and the Active Power from specific circuits from that same electrical switchboard.

4 Implementation

In this thesis, the developed system was validated through a case study performed on a household environment. In the case study, the developed module was implemented in such way to determine the Active Power on the entrance of the electrical switchboard, as well as the Active Power of specific circuits from that electrical switchboard, that were pre-selected.

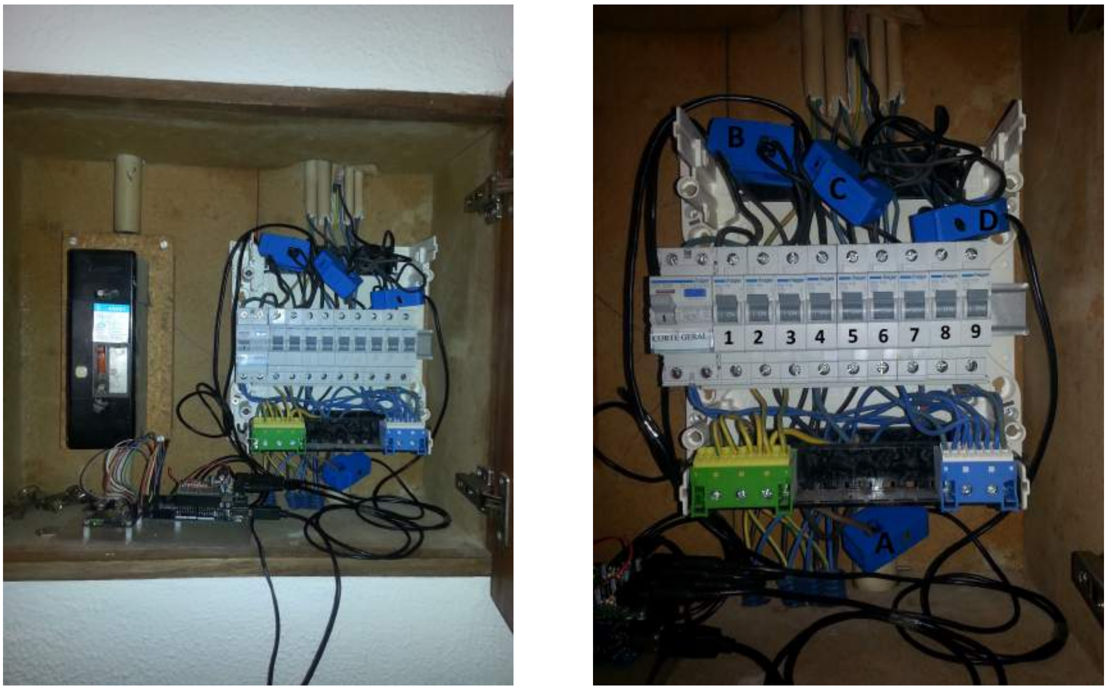
4.1 Household Environment Case Study

The reason behind the choice of this type of environment for the case study lies with the fact that a typical house has all kind of electrical devices, along side with all the electrical circuits, such as lighting systems, or power outlets with several uses. This creates the ideal test environment for the developed module, because it will be dealing not only with random systems, but also with systems that have a known and predictable behavior.

In this case, a number of circuits were tested. Primarily, and as it was mentioned previously, a CT was used at the entrance of the electrical switchboard to monitor its total Active Power. This leaves three CTs left to monitor circuits. In chapter 3 on section 3.3 it was mentioned that the chosen CT is able to hold a few number of cables as long as it can close itself. With that in mind, it was possible to group similar devices and/or circuits because as it is possible to see from Fig. 4.1, all the circuits breakers are very close to each other, and despite the fact that in that specific electrical switchboard some circuits of the same nature are not grouped together, it's relatively easy to arrange the CTs to group the devices and/or circuits that are going to be monitored.

From Fig. 4.1(b) it is possible to view where the CTs are. Although it's not completely clear in both Fig. 4.1(a) and Fig. 4.1(b), the circuit breakers are arranged, from left to right, with numbers (1 to 9). The circuits/devices connected to each of the circuit breaker are as follows:

- 1 - New outlets from the living room;
- 2 - Dishwasher;
- 3 - Electric oven;
- 4 - Washing machine;
- 5 - Outlets from the living room and from the bedrooms;
- 6 - Refrigerator;
- 7 - Kitchen outlets;
- 8 - Lighting;
- 9 - Lighting;



(a) Complete view of the proposed solution assembled

(b) Detailed view of the CTs assembled in the electrical switchboard

Figure 4.1: Electrical switchboard of the house and the assembled proposed solution

With this, the most important circuits were chosen, and a CT was used to monitor those circuits as follows:

- CT A - Feeder of the electrical switchboard;

- CT B - Circuits 2 and 4;
- CT C - Circuits 5 and 7;
- CT D - Circuits 8 and 9;

Some of the circuits were left unmonitored for the simple fact that they are almost not, if never, used. This happens because this house only holds two occupants, and so, devices like the electrical oven are rarely used. The new outlets from the living room were never used for instance. In the case of the outlet of the refrigerator, because this appliance is always on, and consumes relatively low energy, it was left unmonitored. On the other side, the circuits monitored, are the ones that "represent" the appliances/systems that are most used in that house. For instance, the circuits from the dishwasher and the washing machine were put together because they're never on at the same time, or even in the same day in this specific house, as it will be shown in the next chapter. This two appliances are typically also the appliances that consume more energy in a house. The circuits from the house lighting systems were also grouped together because they represent all the lighting systems from the house, and are completely random, which again will produce interesting results as it will be seen in the next chapter. Finally, the kitchen outlets, and the circuits that "represent" the outlets of the rest of the house were grouped, because they have connected to them the appliances that are most used in the house, ranging from the microwave, televisions, to the personal computers of the two occupants or the alarm clocks, among all the others.

4.1.1 Duration of the Case Study

This case study was divided in three parts, or in other words, the case studied was performed during three different time lengths. The first one had a duration of four weeks. The second one continued where the first one left of and went on for more four weeks. This makes a total of eight weeks of data to train the ANNs. Finally, one more week of data was collected, so simulations could be preformed with the results that were obtained from the trained ANNs.

It was important to analyze different time lengths because of two important factors. Firstly results could be find satisfactory from a short period of time point of view. But even if the results were found satisfactory from a short period of time point of view, it is important to demonstrate that the longer the system is up, or the more samples it can provide, the better the results will be, because one important factor about ANNs is that, when more data is provided, or in other words, the more samples an ANN has to be trained, the better the results will be. This will be demonstrated further on.

4.1.2 Considered Variables

In this case, all the variables mentioned in chapter 2, in section 2.1 can be applied/used in the case study to obtain better results. Nonetheless, they're all discarded (except for time of the day and which day of the week it is) because they do not influence the energy consumption of this particular house for a number of reasons. Looking at the number of occupants for instance, 95% of the time, there are only two occupants in the house as it was mentioned. Not only that but also to monitor how many occupants are in the house, another system that was capable of monitoring the entrance and exiting of people in the house was necessary, and that would mean that another module would have to be set up in the entrance of the house, which was not the purpose of this thesis. What was intended was a simple module that was set up in the electrical switchboard, and that would have minimal impact in the environment in which it was put on. Other variables like temperature and weather were also discarded simply because during the time from which the developed module was running, these variables would had little to no influence to the case study, and although the developed module has the capability of measuring temperature for instance, nothing during the case study duration justified the use of electrical devices like heaters or coolers, that would change the obtained results.

Nonetheless, it's of some interest to study how much a specific variable affects the outcome of the results. For this, once the data was all collected, the Correlation coefficient between the Active Power of the specific circuits monitored - circuits from CTs B, C and D - and the input variables was calculated with the help of Matlab. The results can be seen in table 4.1.

Table 4.1: Correlation between the Active Power from the circuits of CTs B, C and D and the different input variables

	Circuits 2 and 4 (from CT B)	Circuits 5 and 7 (from CT C)	Circuits 8 and 9 (from CT D)
Total Active Power (from CT A)	0,8791	0,4622	0,0135
Hour	0,1298	0,1357	0,0046
Monday	0,0004	-0,0148	-0,0152
Tuesday	0,0546	-0,0158	0,0457
Wednesday	-0,0367	-0,0254	-0,0168
Thursday	0,0012	-0,0124	-0,0124
Friday	0,0537	0,1012	0,0216
Saturday	-0,0367	0,0112	0,0319
Sunday	-0,0365	-0,0440	-0,0548

The correlation coefficient measures the strength of the linear relationship between two variables, and its value is always between -1 and 1, 1 indicating a perfect correlation, 0 no correlation, and -1 indicating a perfect negative correlation. With that being said table 4.1 shows some interesting results. For instance, the Correlation coefficient between the Active Power from the entrance of the electrical switchboard and the Active Power from the circuits of CT B is 0,8791 which is relatively high. This is confirmed in Fig. 4.2.

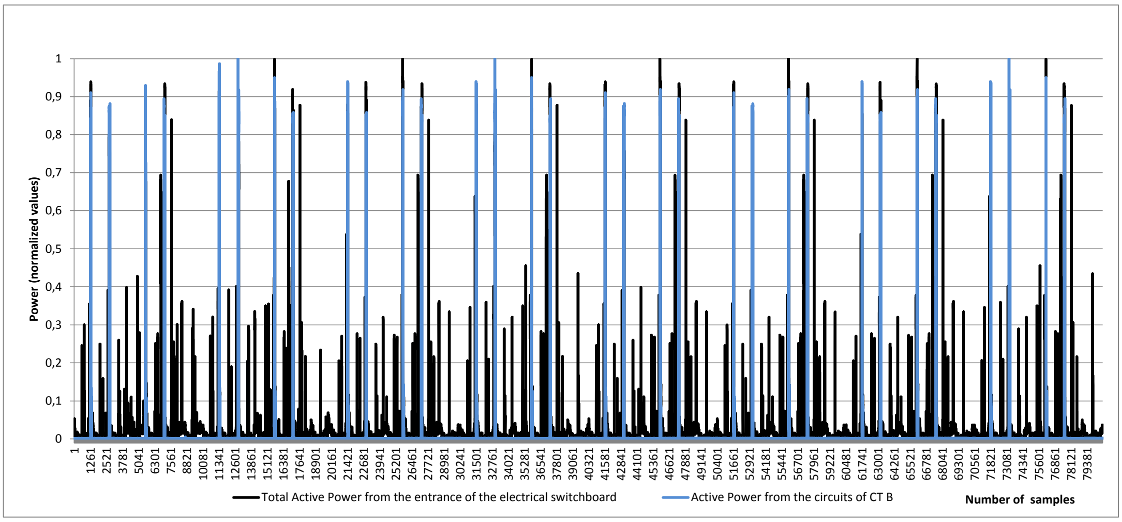


Figure 4.2: Correlation between the Active Power from the entrance of the electrical switchboard and the Active Power from the circuits of CT B - 8 weeks worth of data

By analyzing Fig. 4.2, it's possible to state that a high Correlation coefficient is expected between these two variables, mainly because the Active Power from the circuits of CT B are the ones that on average, present higher values of power, when compared to the rest of the circuits of the house.

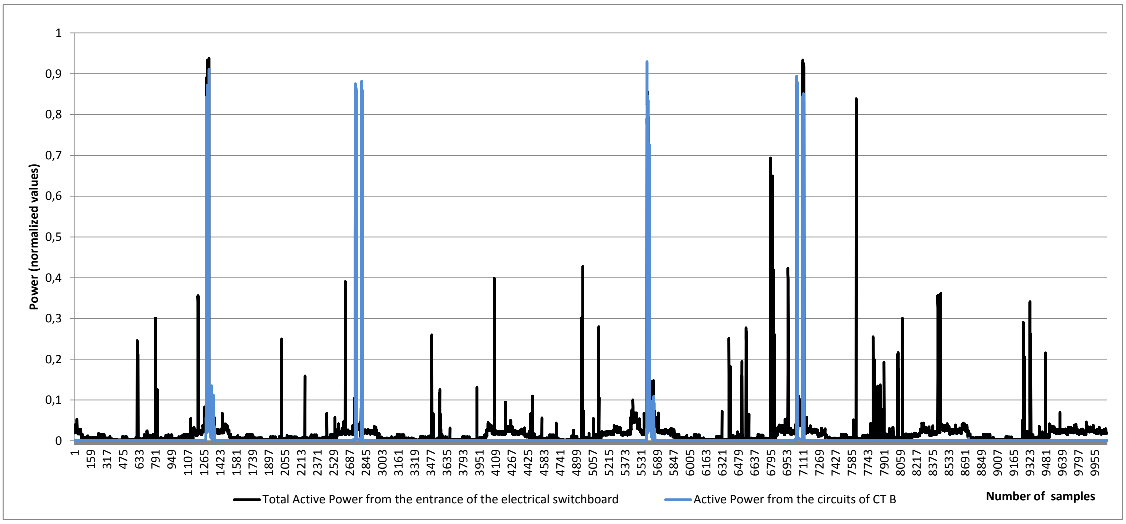


Figure 4.3: Correlation between the Active Power from the entrance of the electrical switchboard and the Active Power from the circuits of CT B - 1 week worth of data

Fig. 4.3 illustrates only one week worth of data, so it's easier to see the relation between the two variables being compared.

The Correlation coefficient decreases to 0,4622 when comparing the total Active Power from the entrance of the electrical switchboard to the Active Power from the circuits of CT C for the opposite reason given above, meaning that because on average this values are lower when compared to circuits 2 and 4 (from CT B) a lower Correlation is expected. Fig. 4.4 illustrates just that.

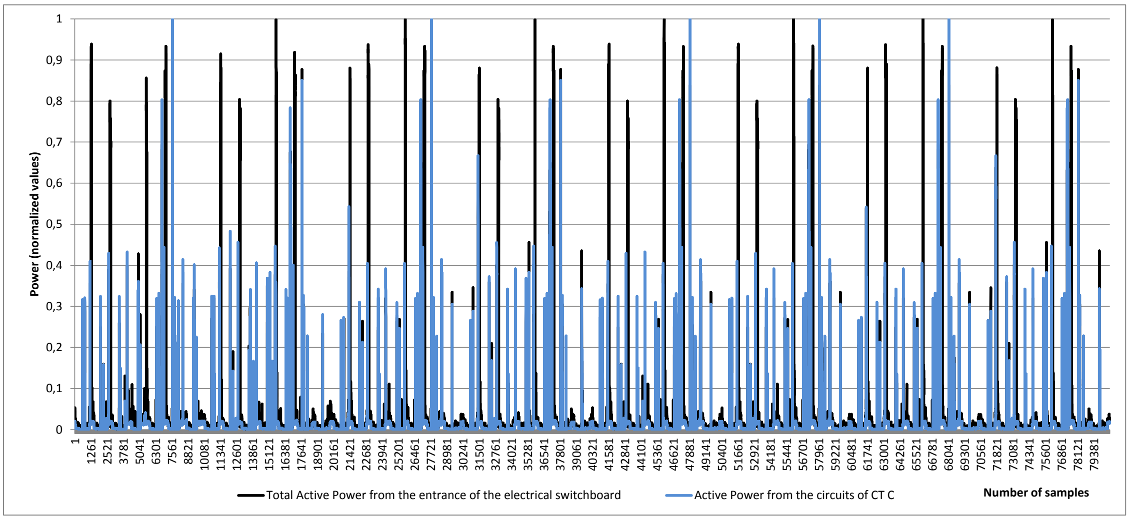


Figure 4.4: Correlation between the Active Power from the entrance of the electrical switchboard and the Active Power from the circuits of CT C - 8 weeks worth of data

On Fig. 4.5 it's easier to see the relation between the two variables, as the example it illustrates is only for a week worth of data.

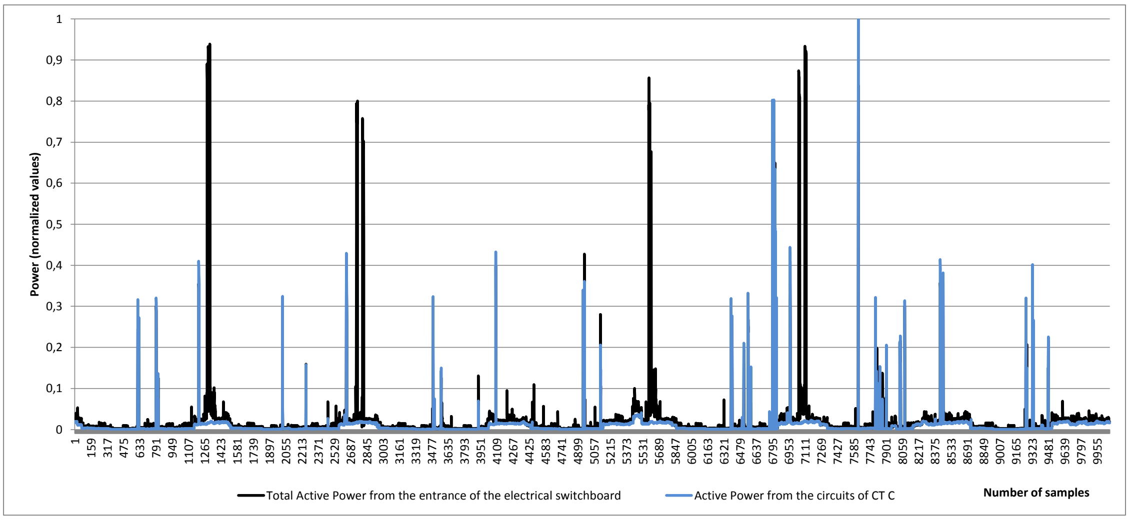


Figure 4.5: Correlation between the Active Power from the entrance of the electrical switchboard and the Active Power from the circuits of CT C - 1 week worth of data

Like it was explained, it's possible to see from Fig. 4.5 that on average, the values from circuits 5 and 7 (from CT C) are much lower when compared to values from circuits 2 and 4 (from CT B).

From table 4.1 it's possible to verify that the Correlation coefficient between the total

Active Power from the electrical switchboard entrance and the Active Power from circuits 8 and 9 (from CT D) is 0,0135 which is very close to 0. This indicates that there's almost no correlation between these two variables.

When the comparison is between the hour and the Active Power from the circuits of CTs B, C and D, it's possible to verify trough table 4.1 that the Correlation coefficients are even worse, being 0,1298, 0,1357 and 0,0046 for the circuits from CTs B, C and D respectively. Figs. 4.6 and 4.7 illustrate the relation between those two variables, for those cases.

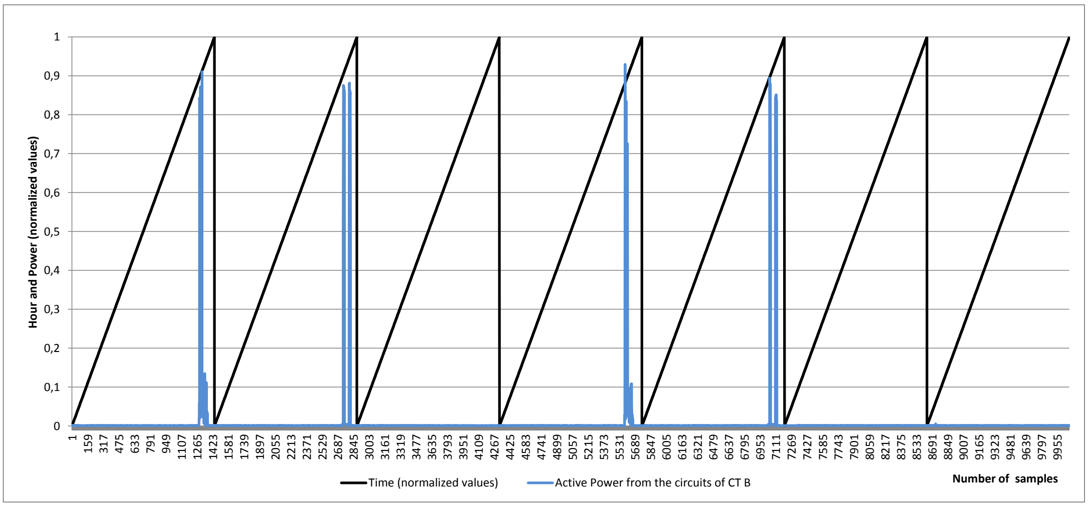


Figure 4.6: Correlation between the Hour and the Active Power from the circuits of CT B

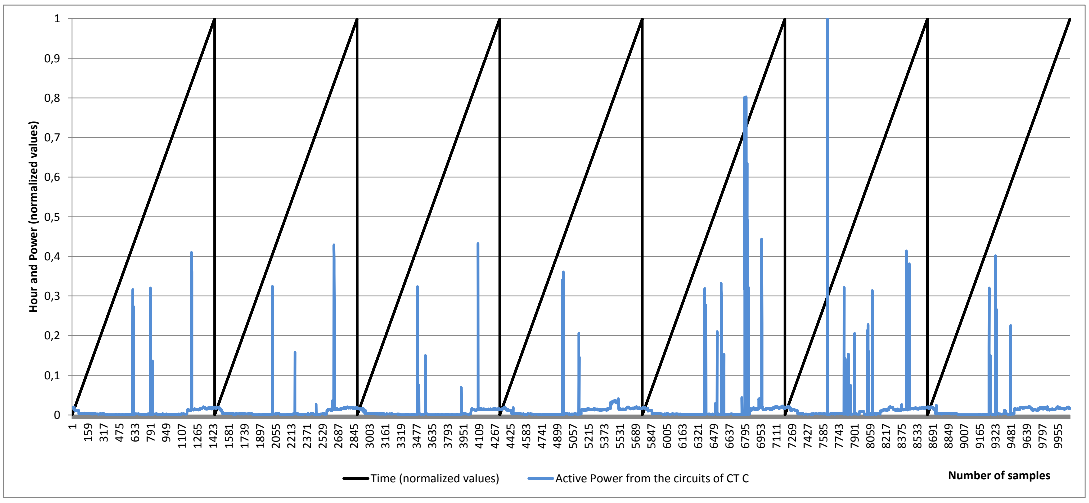


Figure 4.7: Correlation between the Hour and the Active Power from the circuits of CT C

Through Figs. 4.6 and 4.7 it's easy to understand why the results are so bad, because as it can be seen, there's almost no relation between the two variables being compared in both cases. For instance, in Fig. 4.6 it's possible to see that there are three days of the week in which those circuits are never connected, which has a great impact on the Correlation coefficient. On Fig. 4.7 it's possible to see that circuits 5 and 7 (from CT C) are connected every day, but still, their dependency on the hour of the day is somewhat low. The only logical conclusion to take from this analyses is that, the hour alone, has little influence in this case, and it only shows at which time of the day a specific circuit is connected or not. With that being said, and as it can be seen in table 4.1, the results for the Correlation coefficient between the day of the week and the Active Power from the circuits of each CT are even worse, as expected. Some even show a negative correlation, which indicates an inverse relation between the variables that are being compared.

This allows to make conclusions on how the ANNs should be trained. For instance, it doesn't make sense to train an ANN using only as an input the hour. Mainly because as it was shown, the results are bad, but also because the objective is to see if it's possible to find a relation between the electrical switchboard entrance and specific circuits from that electrical switchboard. It does however make sense to train an ANN using all the variables mentioned in table 4.1 as inputs - hour, total Active Power from the electrical switchboard entrance and day of the week. Another test that makes sense is training an ANN using only the total Active Power from the electrical switchboard entrance as an input, because from table 4.1, the Correlation coefficient in those cases can be considered relevant enough to see how that will affect the results. Finally, it's also interesting to study the affect of hour plus day of the week as inputs to train an ANN.

4.1.3 Data Processing and Extrapolations

Following all the steps leading to this point, all that is necessary to train the ANNs is obtained. In order to perform the relation between the electrical switchboard entrance and specific circuits from that electrical switchboard, an ANN with the structure shown in Fig. 4.8 was made, for each of the CTs being used, meaning that 3 ANNs were made, for each of the duration of the different time lengths that were performed, so, 6 ANNs in total for this specific case.

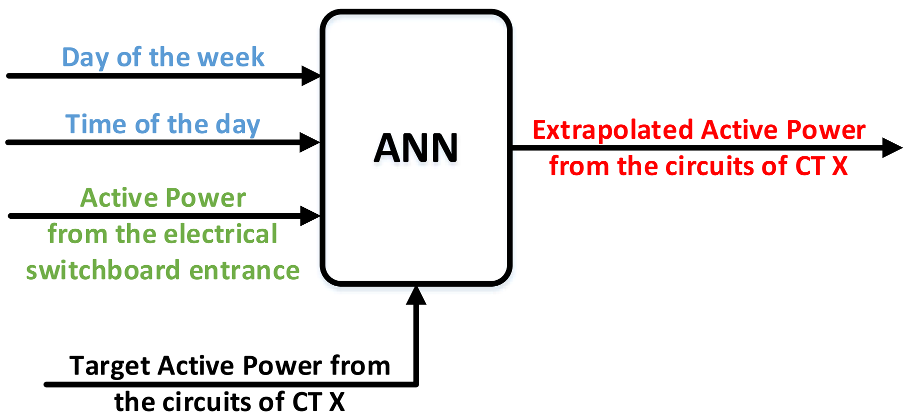


Figure 4.8: Visualization of the base ANN used for the case study

In blue, it's possible to view the standard inputs (day of the week and time of the day). This is where all the other variables that were not used would also be. Green represents the Active Power from the feeder of the electrical switchboard. In black, represented as an input, it's possible to see the target of the ANN, or in other words, these are the historical values that are supposed to be obtained as predictions or extrapolations. Lastly, red represents the output of the trained ANNs, or in other words the extrapolation between the total Active Power of the electrical switchboard and the Active Power of a specific circuit from that electrical switchboard.

Because it was interesting to analyze not only the dependency between the different inputs and outputs, but also the results that would be obtained, two more tests were done, one using only the Active Power from the electrical switchboard entrance, and another using only the day of the week and time of the day as the ANN inputs, as shown on Figs. 4.9 and 4.10 respectively. This means that in total, 18 ANNs were made.

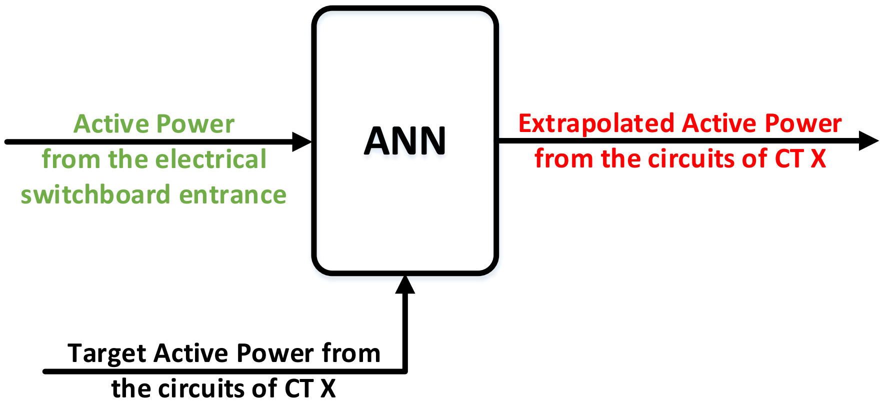


Figure 4.9: ANN with only Active Power from the electrical switchboard entrance as an input

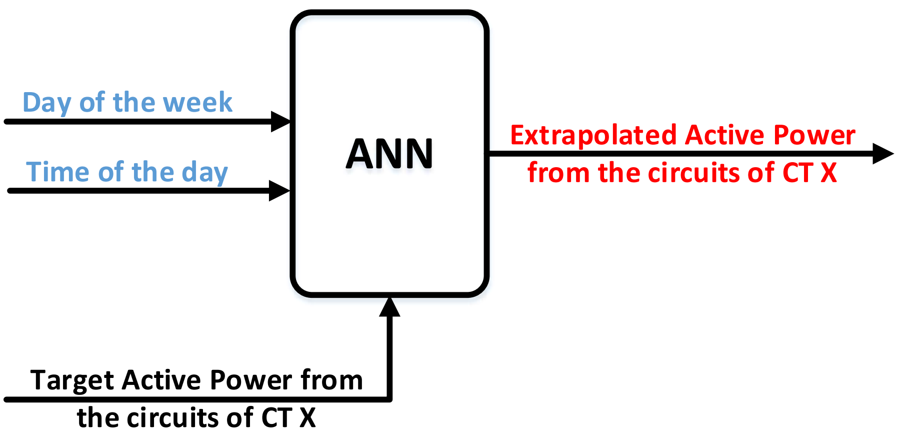


Figure 4.10: ANN with only day of the week and time of the day as inputs

With this, the method was always the same when applying the ANN from Figs. 4.8, 4.9 and 4.10. When applying the ANN from for say the first set of circuits - circuits 2 and 4 (from CT B), CT X represents exactly that, circuits 2 and 4 from CT B, and so, the extrapolated result is between the Active Power of the electrical switchboard, and the Active Power from those circuits. The other two sets of circuits follow the exact same method explained above, meaning that for one case CT X represents circuits 5 and 7 (from CT C), and for the last case CT X represents circuit 8 and 9 (from CT D).

After all the ANNs were trained, for all the cases presented above, the data that was collected apart from the eight weeks to train the ANNs was used to simulate the results obtained from their training, to determine if they're acceptable or not. What's important about this simulations is that the data collected to perform them, contains only the input variables that were considered. This means that when the simulation is performed in Matlab, what's considered is the trained ANN for each case, and the new input variables from a different week that was not used to train the ANNs. The simulation then returns the desired extrapolation between the Active Power from the entrance of the electrical switchboard and the Active Power from the specific circuits of CTs B, C and D. Those results will be shown and analyzed in the next chapter.

5

Results and Discussion

After all the data was collected, simulations using a different week of data were performed for each case of the ANNs represented in Figs. 4.8, 4.9 and 4.10. The method to perform the simulation was always the same, meaning that in a first step, the ANN would be trained - three times, one for each of the circuits of CT B, C and D - and then the trained ANN would be simulated with the week that was not used in its training, to see how well each of the ANNs was trained. Once the results of the simulation were obtained, they were compared to a week from the two different time lengths of data that were collected, and the error between the simulation results and the Active Power from the circuits of each of the CT, as well as the standard deviation of that error were performed using equations 5.1 and 5.2, respectively. The Correlation coefficient between the simulation results and the Active Power from the circuits of each CT was also calculated with the help of Matlab. It's important to refer that, while the Correlation coefficient used in section 4 on subsection 4.1.2 had the objective of determining which variables were more suited to be used as input variables to train the ANNs, in this section, the Correlation coefficient is used as a measure that indicates whether or not the ANNs were well trained.

$$\Delta e = \bar{e_i} - e_i \tag{5.1}$$

$$\sigma e = \sqrt{\frac{1}{N-1} \times \sum_{i=1}^{N} (\bar{e_i} - e_i)^2} \tag{5.2}$$

In both equations 5.1 and 5.2, $\bar{e_i}$ represents the simulation results, e_i represents the Active Power of the circuits from each CT, N represents the number of elements of the test, and i is an auxiliary variable.

Regarding the tests and results that will be shown next, it's important to refer that firstly only the results regarding the eight weeks duration will be presented. Within these results, three types of results are presented, or in other words, first, the results obtained from using all the variables as inputs to train the ANNs are presented and discussed. Next the results obtained from using only the Active Power as input to train the ANNs are presented, and finally, the results obtained from using only the date as input to train the ANNs are shown. Next, a comparison between all the results is performed, so it's possible to understand how different input variables used to train the ANNs influence the results. Finally, the comparison between the results obtained from training the ANNs with eight weeks worth of data for each variable and the results obtained from training the ANNs with only four weeks worth of data for each variable are presented, to demonstrate how having more samples to train an ANN influences its outcome.

5.1 Household Environment Case Study Results and Discussion

The results from the simulations for each of the cases mentioned previously will be presented next.

5.1.1 Eight Weeks Duration - Using all variables as inputs

Circuits 2 and 4 from CT B - all variables as inputs

As it was mentioned, the error, the standard deviation and the Correlation coefficient between the simulation results and the Active Power from circuits 2 and 4 from CT B were calculated. It's important to refer that for the error and the standard deviation, an average was performed, for all cases. With this, the obtained results can be seen in table 5.1.

Table 5.1: Results for the simulation results versus the Active Power from circuits 2 and 4 of CT B - all variables as inputs

Δe	σe	Correlation
-5,62551E-5	0,003859971	0,99833198

As it can be seen in table 5.1 the results are quite good. On average, the error between the simulation results and the Active Power from circuits 2 and 4 from CT B is approximately 0. The standard deviation is very low as well, which results in a very high Correlation coefficient, meaning that the ANN managed to establish a relation between those two sets of data, as it was intended. Graphically, the results can been seen in the figures shown next.

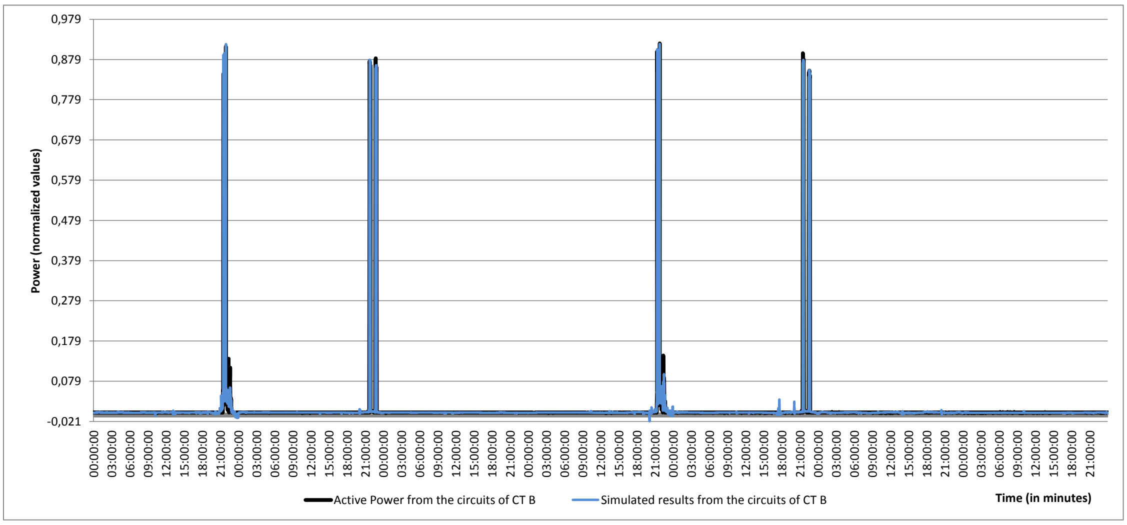


Figure 5.1: Simulation results versus the Active Power from circuits 2 and 4 from CT B - all variables as inputs

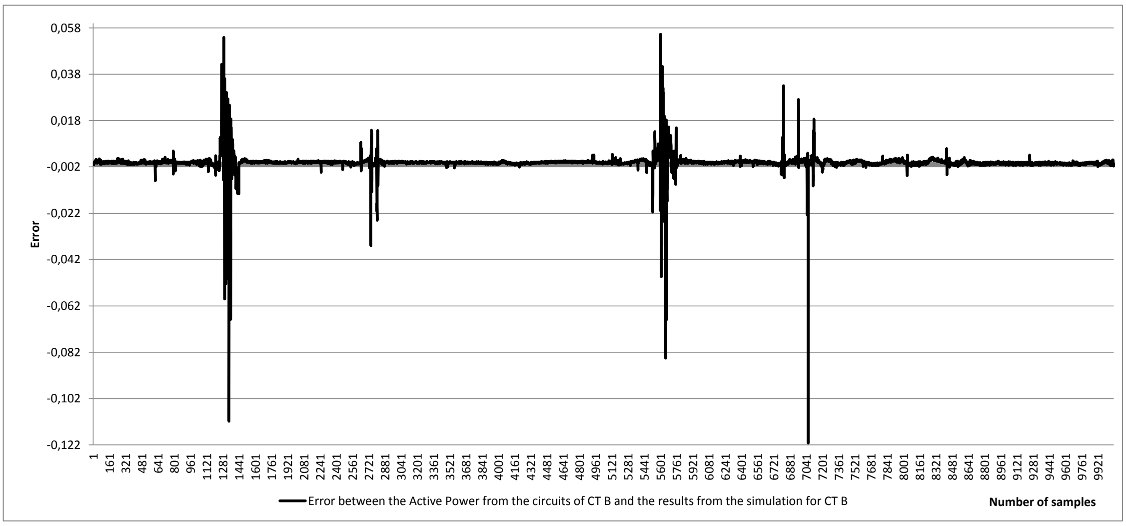


Figure 5.2: Error between the simulation results and the Active Power from circuits 2 and 4 from CT B - all variables as inputs

Fig. 5.1 shows why the correlation between the two sets of data being compared is so good. As it can be seen, blue shows the simulation results, which are very close to the actual values of the Active Power from circuits 2 and 4 from CT B.

Fig. 5.2 is the representation of the error between the two sets of data being compared, and as the figure shows, the error is very low. The spikes that are visible occur on a small number of occasions, and are easily explained, because most of the times those spikes are between sets of values that are supposed to be 0, but are not. Of course oscillations on other cases still occur. To better understand this, Figs. 5.3 and 5.4 are shown next.

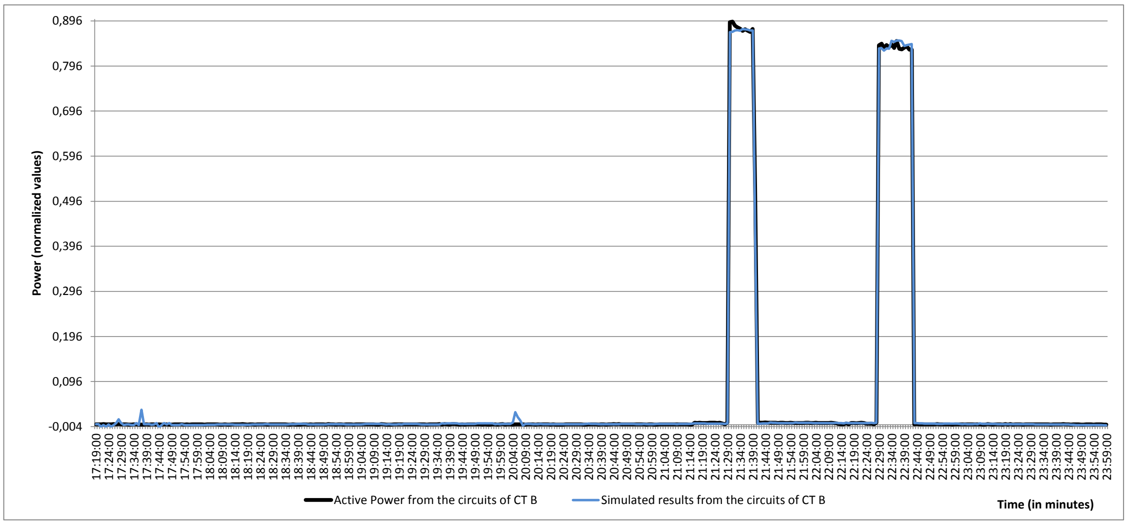


Figure 5.3: Simulation results versus the Active Power from circuits 2 and 4 from CT B - all variables as inputs (for 400 samples)

Fig. 5.3 is an example for only 400 samples, and shows a period of time where the circuits are not connected at all, and the period of time at which they're connected. Fig. 5.4 is representation of the error from Fig. 5.3. As it can be seen, it shows two initial spikes that represent those smaller spikes seen in Fig. 5.3 at around 17:30PM and 20:00PM. The bigger (negative) spike is now the difference for when the circuits are actually connected and the simulation results.

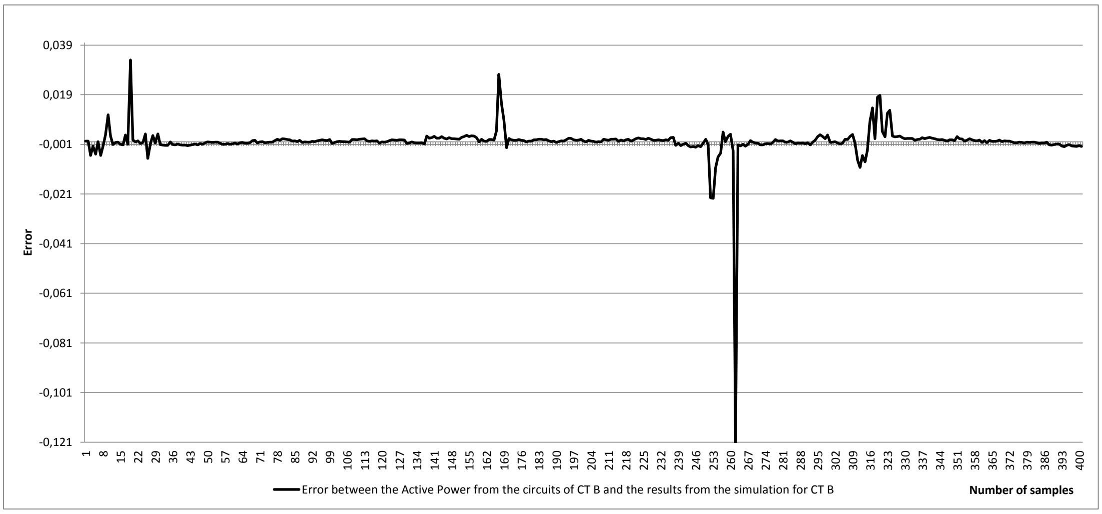


Figure 5.4: Error between the simulation results and the Active Power from circuits 2 and 4 from CT B - all variables as inputs (for 400 samples)

Circuits 5 and 7 from CT C - all variables as inputs

As table 5.2 shows, the results in this case are also very good, even if a bit lower when compared with the previous results. Fig. 5.5 demonstrates again why the Correlation coefficient is so good.

Table 5.2: Results for the simulation results versus the Active Power from circuits 5 and 7 of CT C - all variables as inputs

Δe	σe	Correlation
4,85697E-05	0,007090717	0,979287549

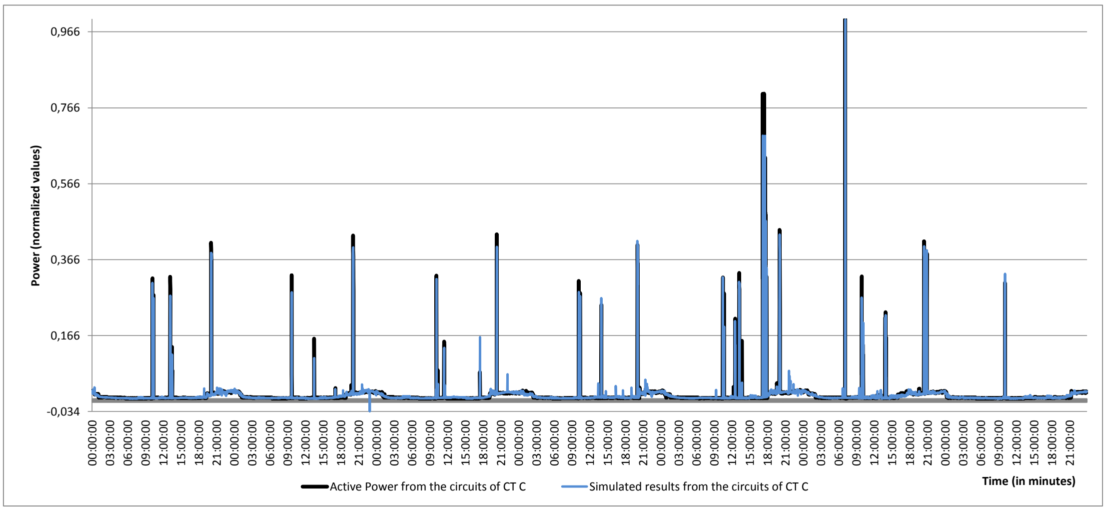


Figure 5.5: Simulation results versus the Active Power from circuits 5 and 7 from CT C - all variables as inputs

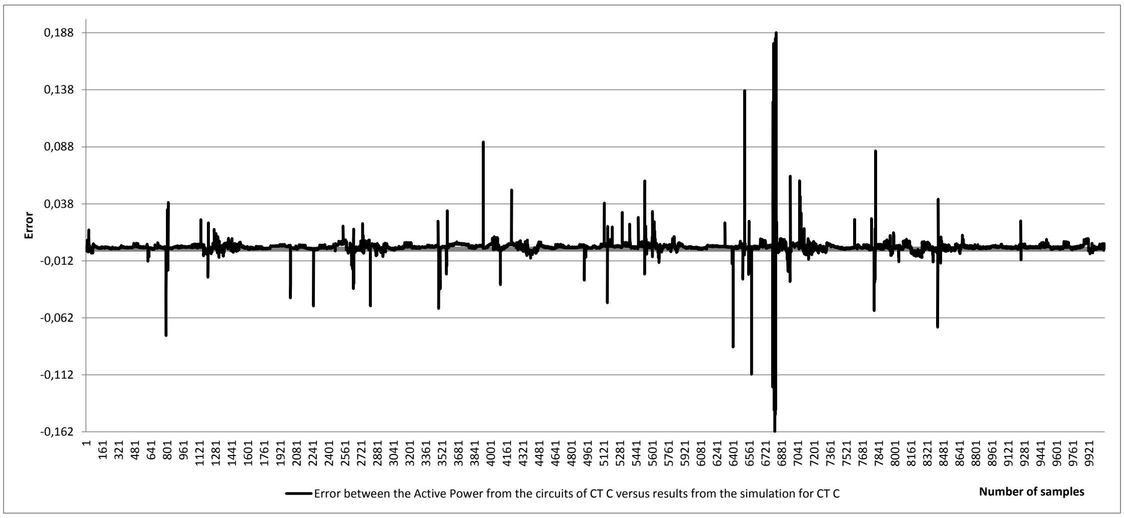


Figure 5.6: Error between the simulation results and the Active Power from circuits 5 and 7 from CT C - all variables as inputs

Overall the error is very good, and the spikes and variations that happen here have the same explanation given previously. To better understand the differences between the two sets of data being compared, Figs. 5.7 and 5.8 are shown next.

Fig. 5.7 shows different time periods of the circuits being used, at different power rates. One interesting aspect about Fig. 5.7 is the fact that a few patters can be identified. For instance, at around 19:00PM a rise in Active Power is visible and it shows when the

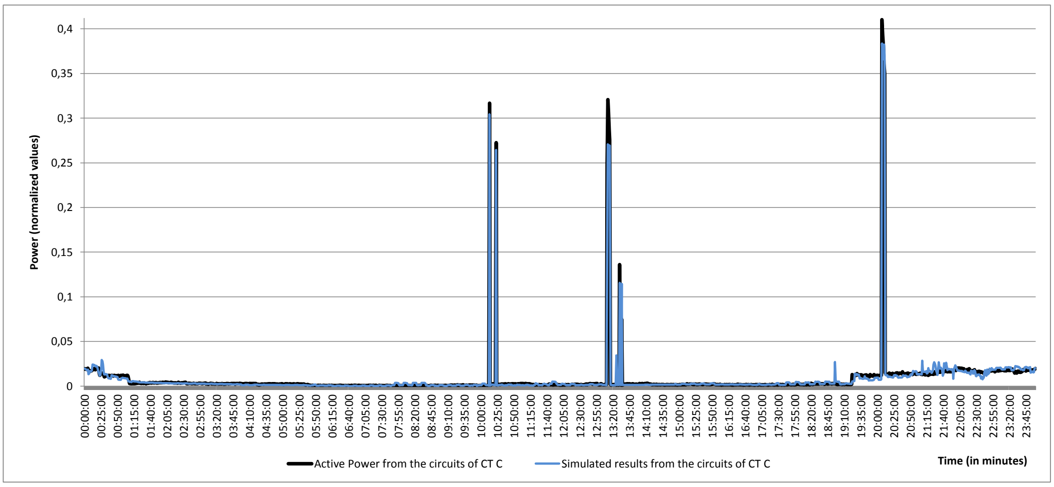


Figure 5.7: Simulation results versus the Active Power from circuits 5 and 7 from CT C - all variables as inputs (for 1440 samples)

lights of a floor standing light are turned on. Another pattern can be seen at around 20:00PM. This pattern occurs almost every single day, at around the same hour, and it represents the microwave. Similar, but smaller spikes can be seen earlier in the day at around 10:00PM. Those spikes represent the coffee machine. At around 13:00PM, a mix between the two previous patterns occurs. Fig. 5.8 shown next, is the error from Fig. 5.7.

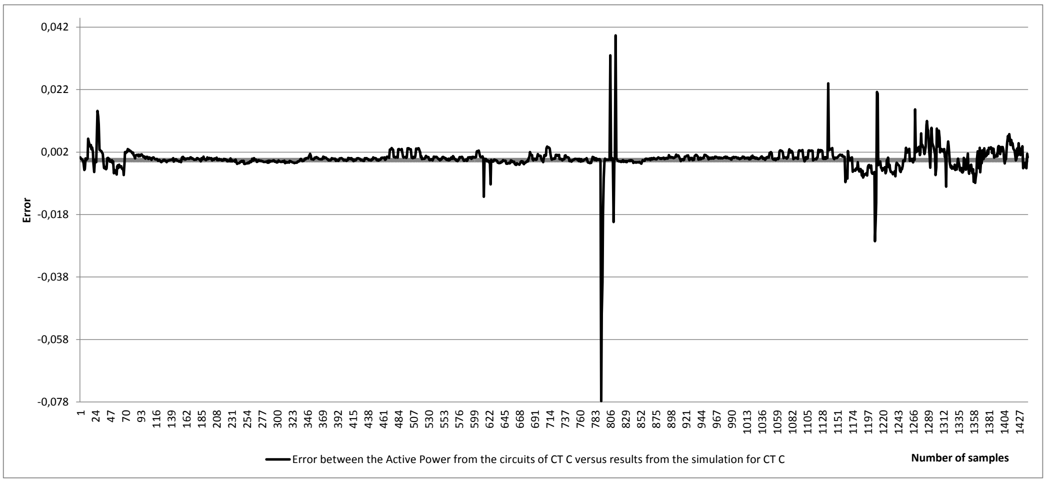


Figure 5.8: Error between the simulation results and the Active Power from circuits 5 and 7 from CT C - all variables as inputs

Circuits 8 and 9 from CT D - all variables as inputs

Table 5.3: Results for the simulation results versus the Active Power from circuits 8 and 9 of CT D - all variables as inputs

Δe	σe	Correlation
-0,002365118	0,041901147	0,424904765

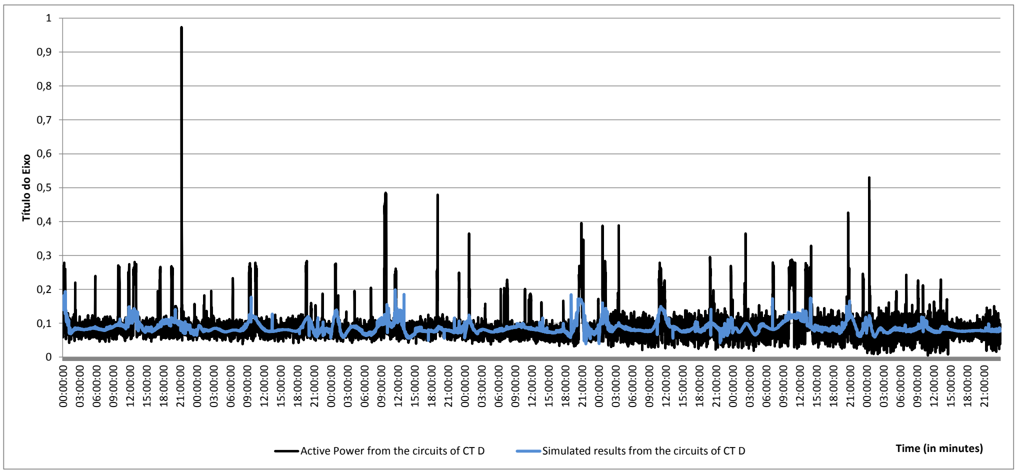


Figure 5.9: Simulation results versus the Active Power from circuits 8 and 9 from CT D - all variables as inputs

The results from table 5.3 are the worse in comparison with the previous two. These results were expected to be bad, because the lighting systems, when compared to any other systems in a house, are completely random. Aside from maybe the morning routines, patterns are very difficult to detect - note that every bigger spike here represents a moment where the lights were turned on. Not only that, but also the time usage of this type of systems is random. It can be seconds, or minutes. Of course that other systems in the house can present this kind of behavior, but as it's shown by Fig. 5.9, when compared to the other figures shown (Figs. 5.1 and 5.5) this example presents the most random behavior. Aside from that, lighting systems also have very low power consumption nowadays, which makes it even harder to track this types of systems. With this, what was desired was that the blue line - the simulation results - would be as close to the black line - Active Power from circuits 8 and 9 from CT D. That it's clearly not the case.

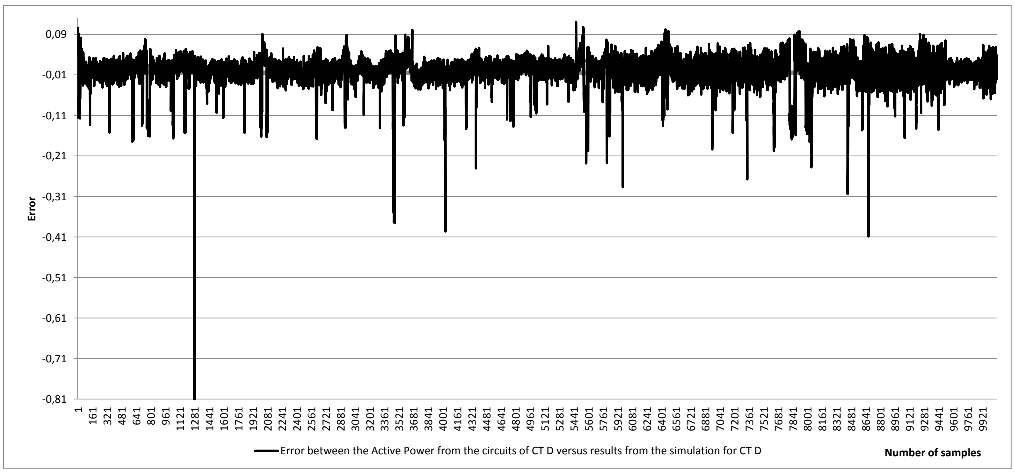


Figure 5.10: Error between the simulation results and the Active Power from circuits 8 and 9 from CT D - all variables as inputs

The error, although it can be considered low, it's actually bad in this case. This is due to the fact that the lights are very rarely turned on. And so the Active Power is almost always very close to 0, and although the error, on average, and its standard deviation can be considered low, the Correlation coefficient is also low which indicates a somewhat random relation between these two sets of data. This means that the developed system is not indicated to be used in these types of systems. At least as it currently stands.

5.1.2 Eight Weeks Duration - Using only the total Active Power from the electrical switchboard entrance as input

Another set of ANNs were trained using only the Active Power from the electrical switchboard entrance as their input. After the results were obtained, the simulations using the week stored for tests were made.

Circuits 2 and 4 from CT B - using the Active Power from the electrical switchboard as the only input

Table 5.4: Results for the simulation results versus the Active Power from circuits 2 and 4 of CT B - using the Active Power from the electrical switchboard as input

Δe	σe	Correlation
6,04304E-05	0,015380888	0,973122658

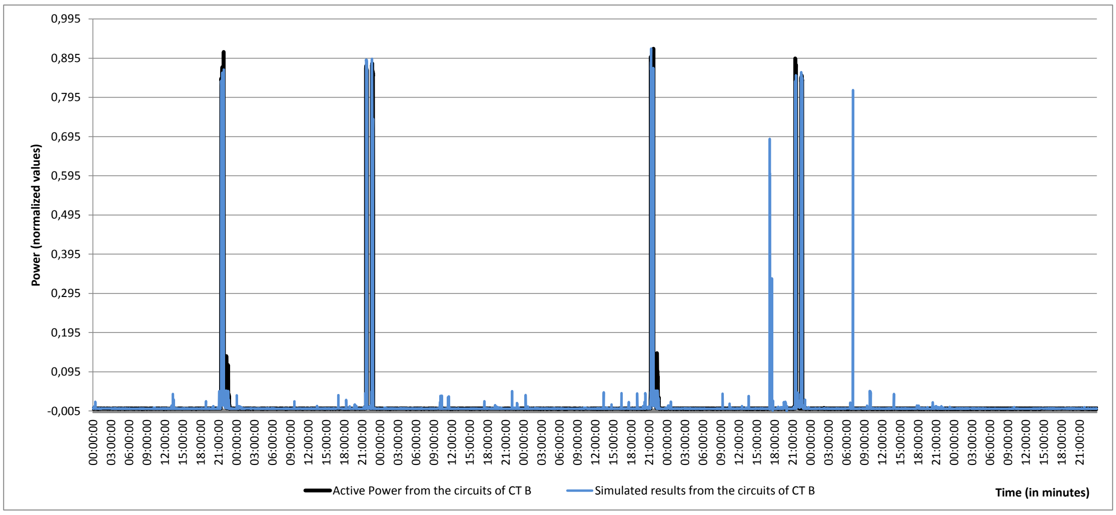


Figure 5.11: Simulation results versus the Active Power from circuits 2 and 4 from CT B - using the Active Power from the electrical switchboard as the only input

Fig. 5.11 shows why this results are slightly worse when compared to the results from section 5.1.1. Overall, Fig. 5.11 shows more differences between the two sets of data.

Not only do more differences exist between the sets of data being analyzed, but also this simulation presented more cases where it shows Active Power, when there shouldn't

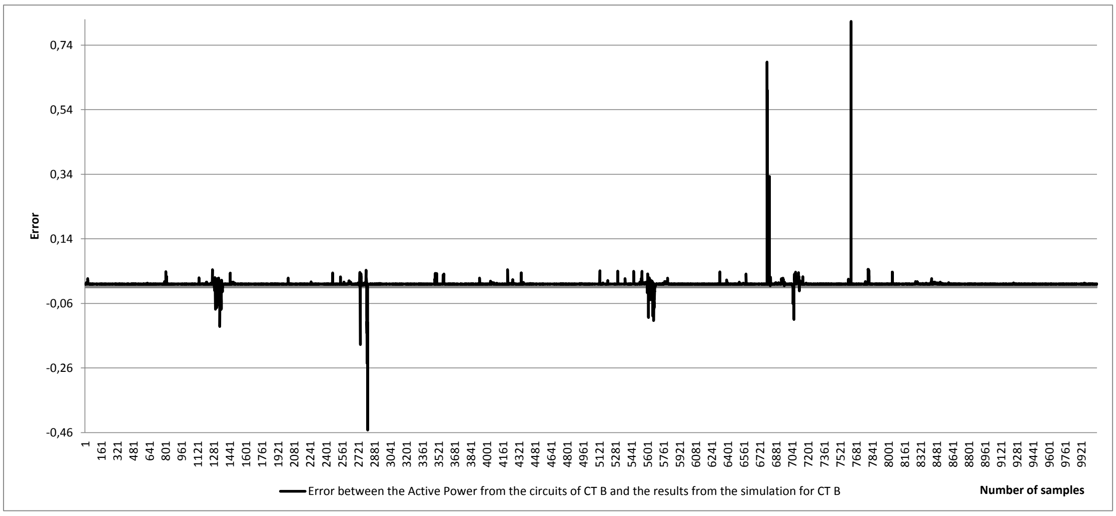


Figure 5.12: Error between the simulation results and the Active Power from circuits 2 and 4 from CT B - using the Active Power from the electrical switchboard as the only input

be any. To better understand this, Figs. 5.13 and 5.14 are shown next.

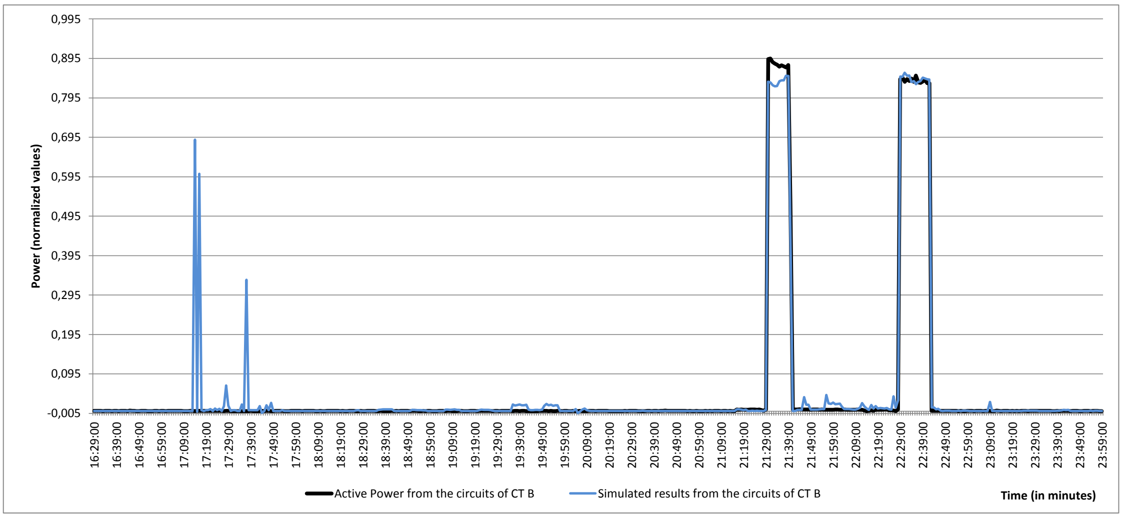


Figure 5.13: Simulation results versus the Active Power from circuits 2 and 4 from CT B - using the Active Power from the electrical switchboard as the only input (for 450 samples)

It's clear in Fig. 5.13 what was mentioned previously. Overall there are more oscillations between the two sets of data, and that's why the results are slightly worse. This is an indicator that with less input data for the ANNs to be trained with, the worse the results will be, at least when the data is relevant as a whole.

Fig. 5.14 shows all the variations between the two sets of data that were mentioned.

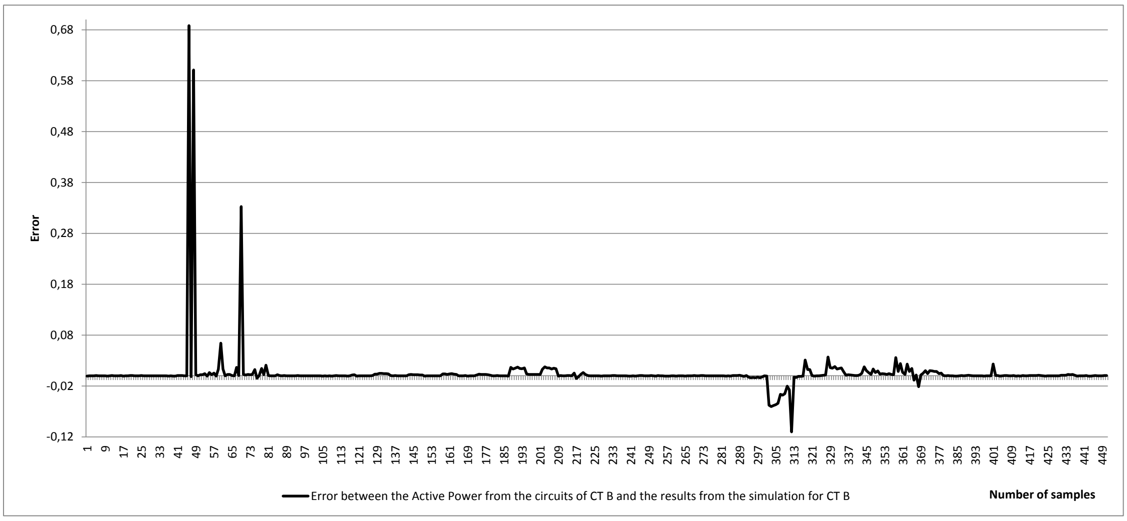


Figure 5.14: Error between the simulation results and the Active Power from circuits 2 and 4 from CT D - using the Active Power from the electrical switchboard as the only input (for 450 samples)

Circuits 5 and 7 from CT C - using the Active Power from the electrical switchboard as the only input

Table 5.5: Results for the simulation results versus the Active Power from circuits 5 and 7 of CT C - using the Active Power from the electrical switchboard as the only input

Δe	σe	Correlation
-4,86446E-06	0,015942309	0,890223806

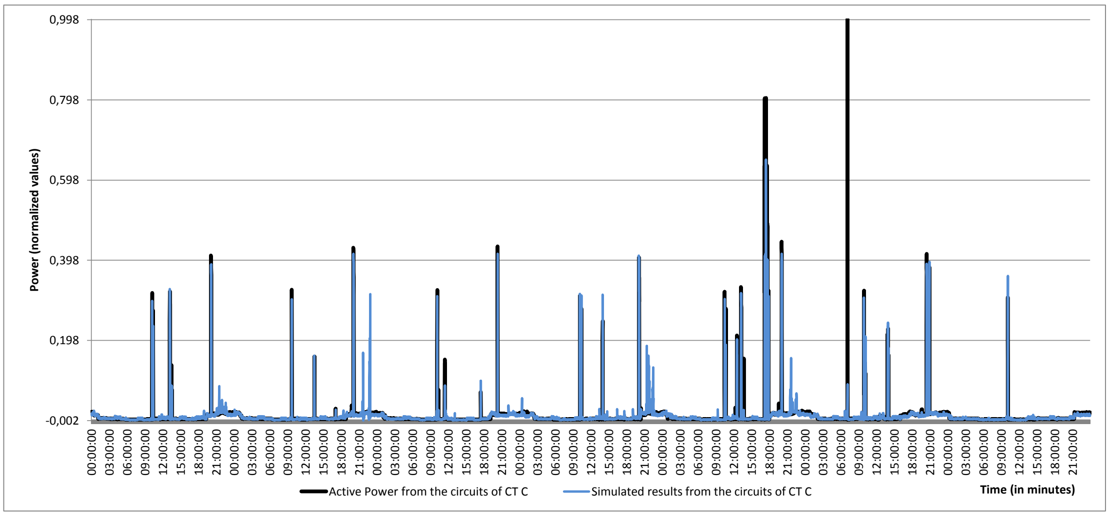


Figure 5.15: Simulation results versus the Active Power from circuits 5 and 7 from CT C - using the Active Power from the electrical switchboard as the only input

Figs. 5.15 and 5.16 show the same problems mentioned previously, which are more oscillations when compared to the results from section 5.1.1.

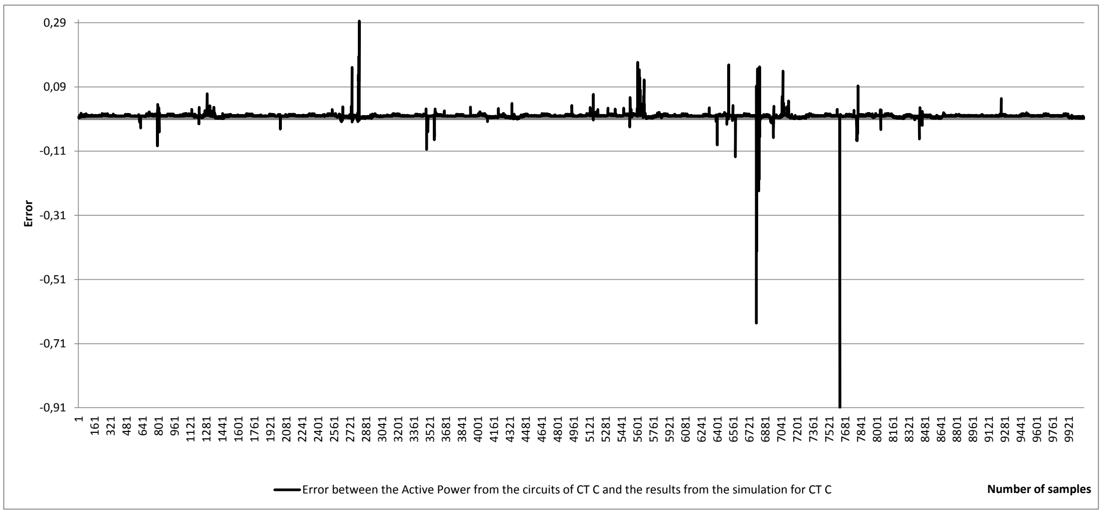


Figure 5.16: Error between the simulation results and the Active Power from circuits 5 and 7 from CT C - using the Active Power from the electrical switchboard as the only input

To better understand all the differences mentioned previously, Figs. 5.17 and 5.18 are shown next.

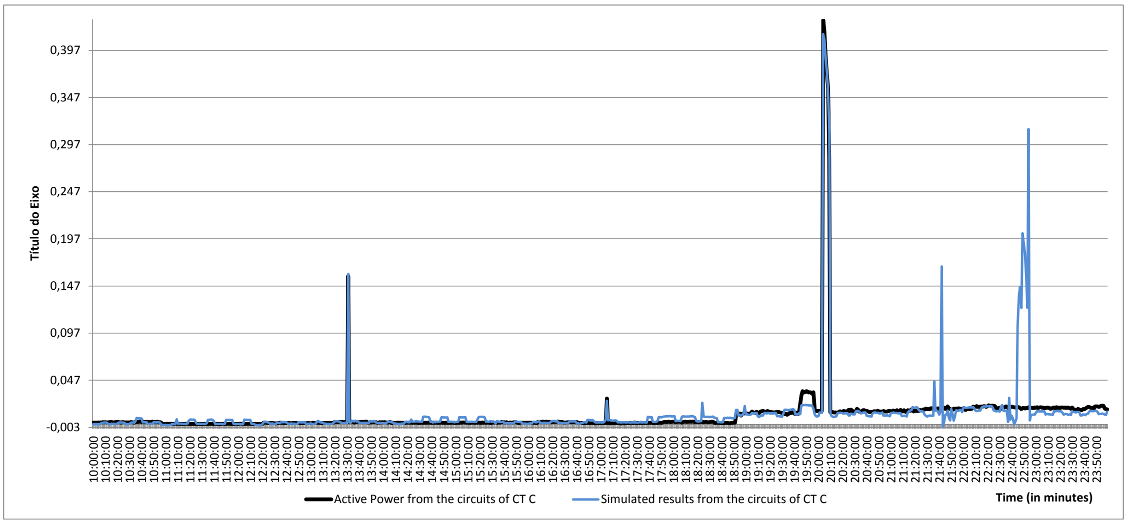


Figure 5.17: Simulation results versus the Active Power from circuits 5 and 7 from CT C - using the Active Power from the electrical switchboard as the only input (for 850 samples)

It's clear from Figs. 5.17 and 5.18 that this results present more oscillations when compared to the results from Figs. 5.7 and 5.8 from subsection 5.1.1.

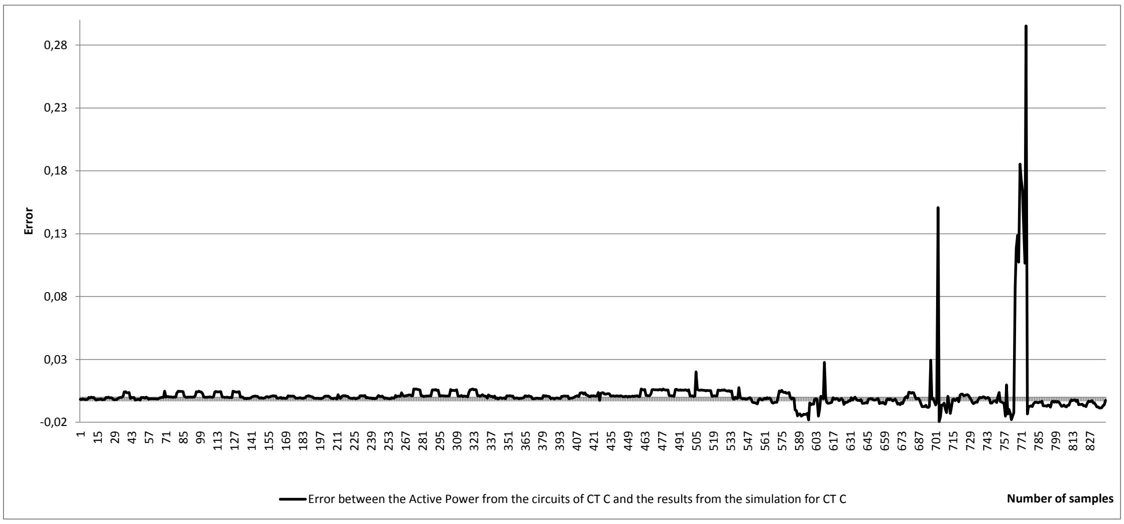


Figure 5.18: Error between the simulation results and the Active Power from circuits 5 and 7 from CT C - using the Active Power from the electrical switchboard as the only input (for 850 samples)

Circuits 8 and 9 from CT D - using the Active Power from the electrical switchboard as the only input

The results from this test were expected to be bad again, because if with more input variables, the results are already bad, with less input variables it was not expected for the results to be better.

Table 5.6: Results for the simulation results versus the Active Power from circuits 8 and 9 of CT D - using the Active Power from the electrical switchboard as the only input

Δe	σe	Correlation
-0,002002733	0,045872418	0,117108457

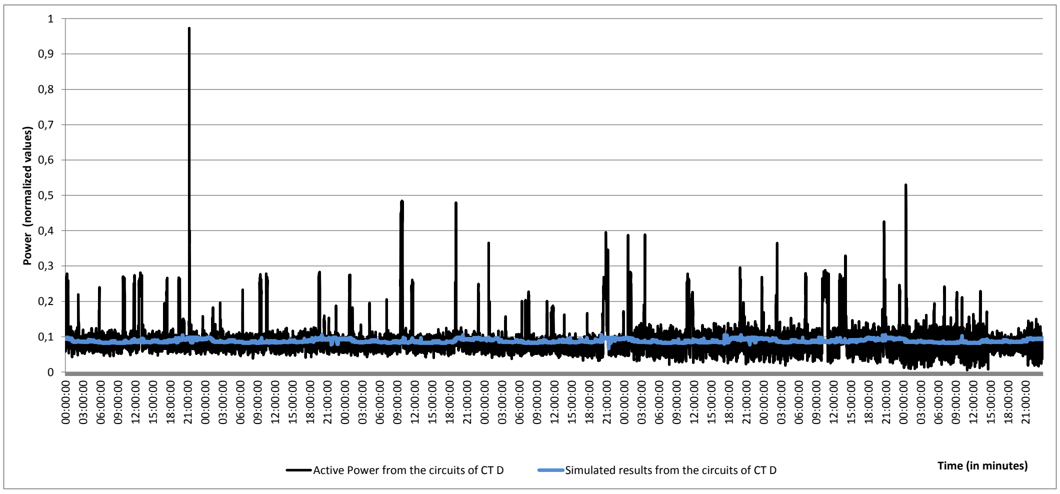


Figure 5.19: Simulation results versus the Active Power from circuits 8 and 9 from CT D - using the Active Power from the electrical switchboard as the only input

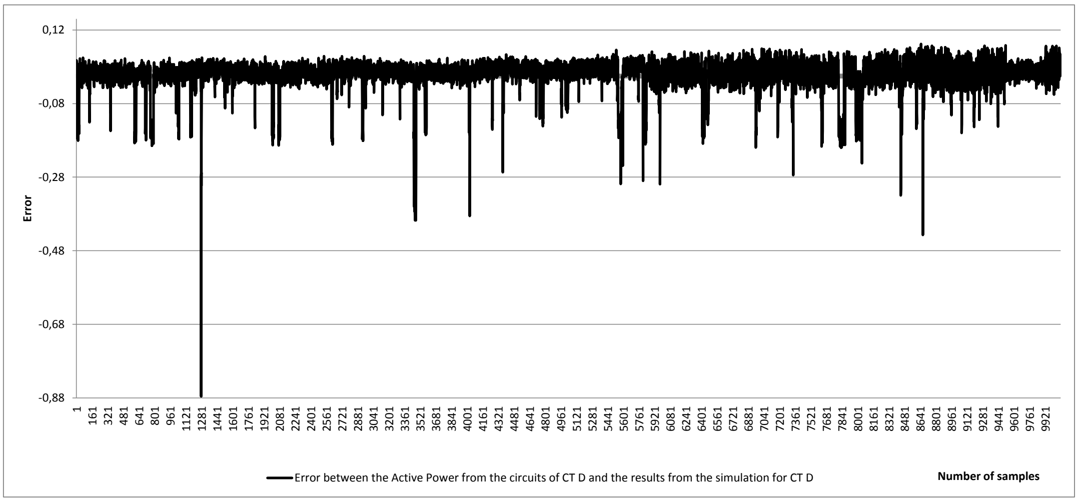


Figure 5.20: Error between the simulation results and the Active Power from circuits 8 and 9 from CT D - using the Active Power from the electrical switchboard as the only input

As it was mentioned, Figs. 5.19 and 5.20 show just how bad this results are. If in Fig. 5.11 it was possible to see some slight relation between the two sets of data being analyzed, in this case, it's possible too see that, overall that relation is non-existing.

5.1.3 Eight Weeks Duration - Using only the time of the day and day of the week as inputs

Because of the examples given in section 4.1.2 from the previous chapter, this results were expected to be very bad overall. This is because the objective it to relate the Active Power from the entrance of the electrical switchboard and specific circuits from that electrical switchboard, and if the Active Power from the electrical switchboard is not provided the results will be bad. This was confirmed as the results presented next will show.

Circuits 2 and 4 from CT B - using the date as the only input

Table 5.7: Results for the simulation results versus the Active Power from circuits 2 and 4 of CT B - using the date as the only input

Δe	σe	Correlation
-7,21136E-05	0,060782069	0,414259095

Table 5.7 shows a very low error on average and also a low standard deviation. This is normal because for this case, the circuits are not turned on every day as it was shown, and when they are, it's for a relatively short period of time of the day and so, it's normal for the error to be this low because most of the time the values of both data sets are approximately 0. The Correlation coefficient on the other hand gives the indication that the results are indeed bad, at least when compared to the results obtained from subsections 5.1.1 and 5.1.2.

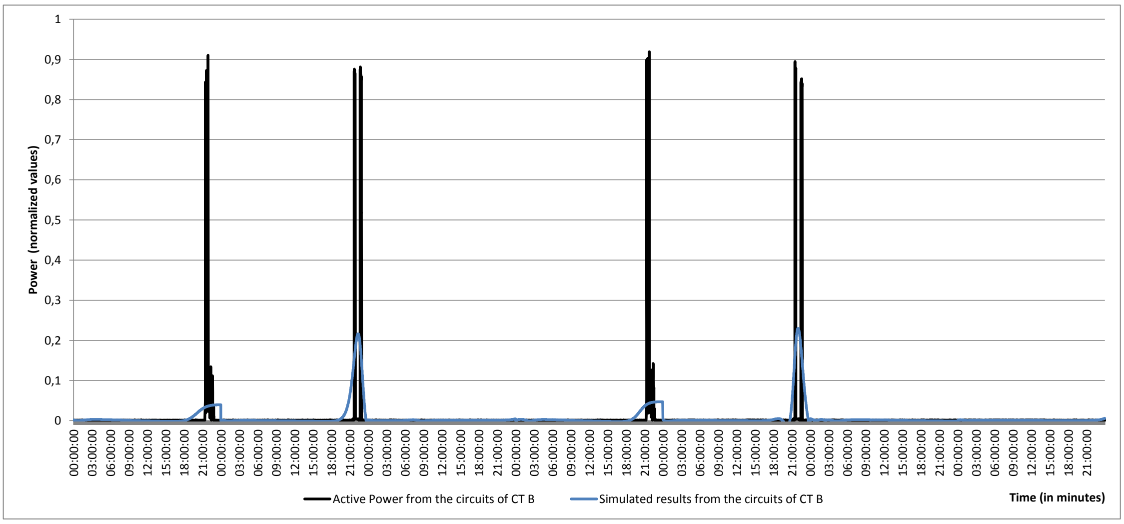


Figure 5.21: Simulation results versus the Active Power from circuits 2 and 4 from CT B - using the date as the only input

Fig. 5.21 shows why this results are bad. Some spikes can be seen where the Active Power is high, but they are nowhere near what the results should be. This is also the reason for why the error on average is so low. Because the simulations results are bad and not close to the Active Power from circuits 2 and 4 from CT B when those circuits are turned on, the error is going to be even lower when compared with the results obtained previously. Fig. 5.22 shows exactly what was explained in the previous page. Overall, there are less oscillations, except for when the circuits are turned on.

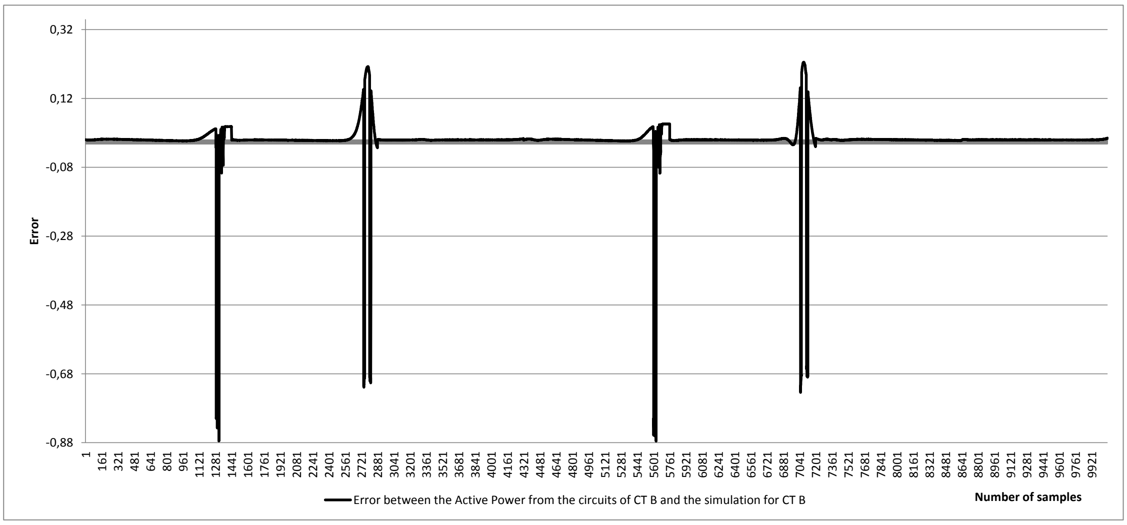


Figure 5.22: Error between the simulation results and the Active Power from circuits 2 and 4 from CT B - using the date as the only input

Circuits 5 and 7 from CT C - using the date as the only input

Table 5.8: Results for the simulation results versus the Active Power from circuits 5 and 7 of CT C - using the date as the only input

Δe	σe	Correlation
0,000450262	0,030270813	0,501959391

Again, table 5.8 shows a low error on average, as well as a low standard deviation, but also a low Correlation coefficient. It's possible to see less oscillations between the two sets of data being analyzed, except for when the circuits are turned on. This is shown in Fig. 5.23, where there's clearly a low relation between the sets of data being analyzed. Fig. 5.24 is the error between the two sets of data being analyzed.

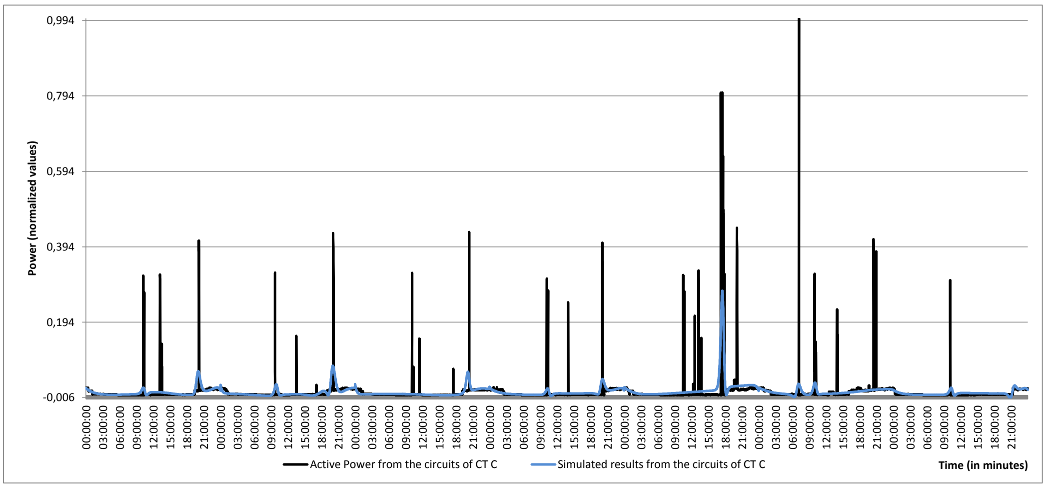


Figure 5.23: Simulation results versus the Active Power from circuits 5 and 7 from CT C - using the date as the only input

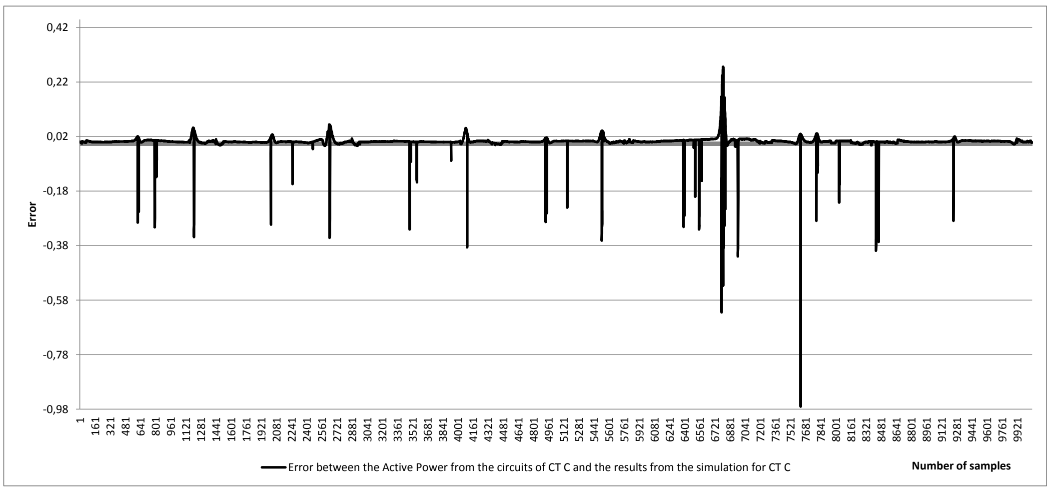


Figure 5.24: Error between the simulation results and the Active Power from circuits 5 and 7 from CT C - using the date as the only input

Circuits 8 and 9 from CT D - using the date as the only input

Table 5.9: Results for the simulation results versus the Active Power from circuits 8 and 9 of CT D - using the date as the only input

Δe	σe	Correlation
-0,00196529	0,042423427	0,403675271

Table 5.9 again shows a relatively low error on average, as well as a low standard deviation of that error. Nonetheless, the Correlation coefficient is low, which as it was already mentioned, indicates a somewhat random relation between the data being analyzed.

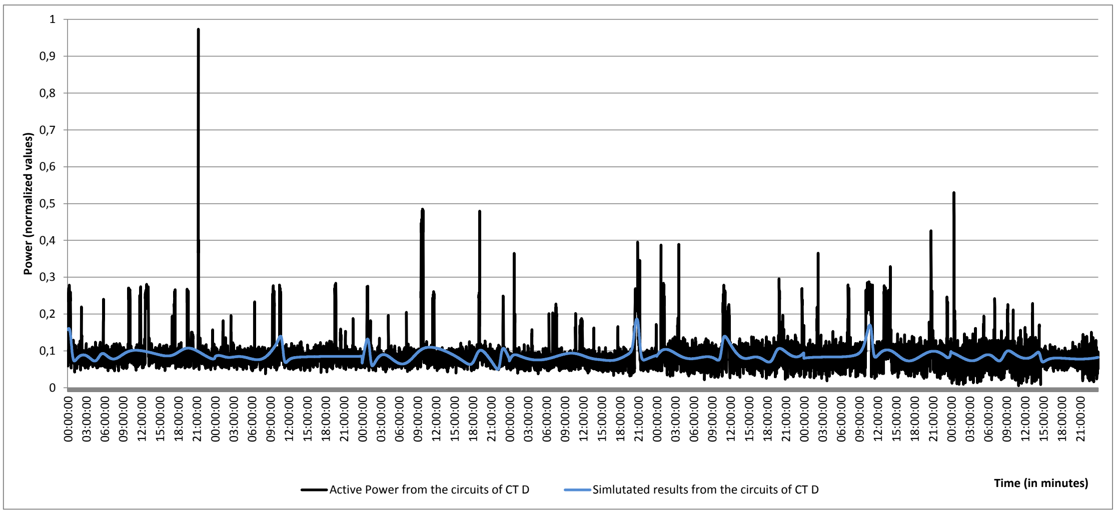


Figure 5.25: Simulation results versus the Active Power from circuits 8 and 9 from CT D

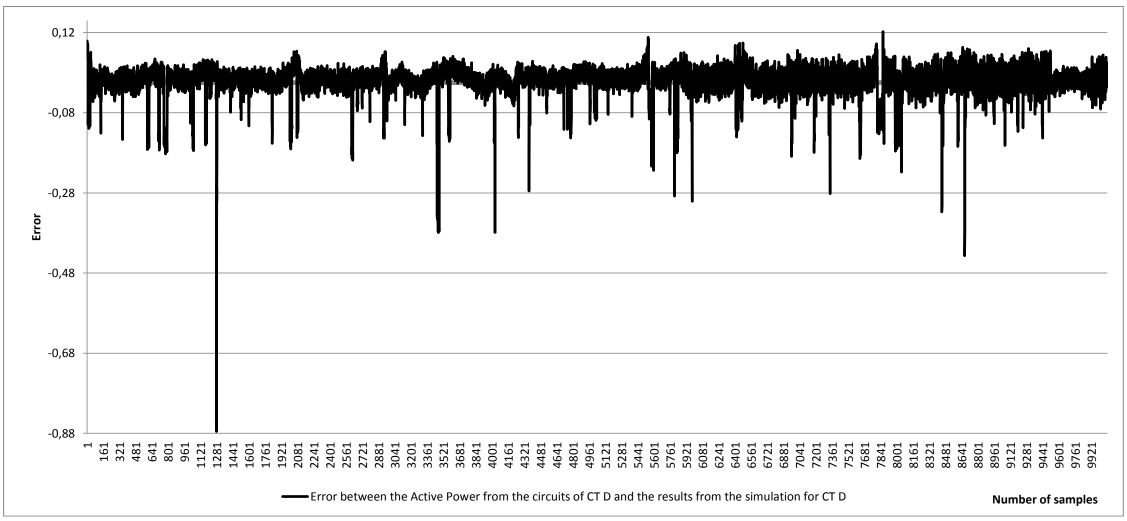


Figure 5.26: Error between the simulation results and the Active Power from circuits 8 and 9 from CT D

In this case, there's an improvement when comparing these results with the results from table 5.6. Nonetheless, they are equally bad in the sense that a relation between the two sets of data is not achieved.

5.2 Comparison between results

In this section, two types of results will be compared. First, a comparison between the results obtained from the previously subsection will be made. Secondly, a comparison between the results obtained for the 4 weeks test will be compared to the results obtained in the previous subsection - 8 weeks test. This comparison is important because it will show that, with more data available to train the ANNs, better results will be obtained.

5.2.1 Comparison between the results obtained in section 5.1

Circuits 2 and 4 from CT B

Table 5.10 shown next, shows all the results obtained for circuits 2 and 4 from CT B.

Table 5.10: Comparison between the results obtained in section 5.1 for circuits 2 and 4 from CT B

Circuits 2 and 4 from CT B	Δe	σe	Correlation
all variables as input	-5,62551E-05	0,003859971	0,99833198
Active Power from the electrical switchboard entrance as the only input	6,04304E-05	0,015380888	0,973122658
using the date as the only input	-7,21136E-05	0,060782069	0,414259095

As it's possible to see from table 5.10, the best results are obtained when all the variables - Active Power from the electrical switchboard entrance, day of the week and time - are used as inputs to train the ANNs and also to simulate them. As expected, the quality of the results decreases when some of those variables are not considered as inputs. Nonetheless, when using only the Active Power from the electrical switchboard entrance, the results are still very good. This indicates a somewhat low dependency of the time and day of the week. It's important to note that, although that dependency is low, it's not completely null, because the results are indeed better when those variables are considered. Finally, the worst results are obtained when using only the date - time and day of the week - as the inputs used to train and simulate the ANNs. This results were expected to be bad, because as it was shown in chapter 4, on subsection 4.1.2, the Active Power from the circuits of CTs B, C and D show little relation with the time and day of the week, which was confirmed with these results.

Circuits 5 and 7 from CT C

Overall, table 5.12 also shows a decrease in the quality of the results as different variables are used to train the ANNs.

Table 5.11: Comparison between the results obtained in section 5.1 for circuits 5 and 7 from CT B

Circuits 5 and 7 from CT C	Δe	σe	Correlation
all variables as input	4,85697E-05	0,007090717	0,979287549
Active Power from the electrical switchboard entrance as the only input	-4,86446E-06	0,015942309	0,890223806
using the date as the only input	0,000450262	0,030270813	0,501959391

Once again, the decrease in the quality of the results was expected, for the same reasons explained in the previous page.

Circuits 8 and 9 from CT D

Table 5.12: Comparison between the results obtained in section 5.1 for circuits 8 and 9 from CT D

Circuits 8 and 9 from CT D	Δe	σe	Correlation
all variables as input	-0,002365118	0,041901147	0,424904765
Active Power from the electrical switchboard entrance as the only input	-0,002002733	0,045872418	0,117108457
using the date as the only input	-0,00196529	0,042423427	0,403675271

The results from the simulation results versus circuits 8 and 9 from CT D were already expected to be bad, because of the random nature of this circuits, as it was explained previously, and so, despite the fact that in this case the results from the tests that used only the date - time and day of the week - are better than the results that used the Active Power from the entrance of the electrical switchboard as the only input to train and simulate the ANNs, it's possible to say that, overall, the results continue bad.

5.2.2 Comparison between results obtained from different time lengths

As it was mentioned, a comparison between tests that were performed during different time lengths is important because it will show that as more samples are provided to train the ANN, better results will be obtained. In this particular case, two different time lengths

- 4 weeks and 8 weeks worth of data - were considered. As it was mentioned in chapter 3 in subsection 3.4.1 samples are taken every minute, which means that for 4 weeks worth of data, there will be 40320 samples for each and every variable being stored. On the other hand, for 8 weeks worth of data, there will be double the samples for every stored variable, meaning 80640 samples for every variable stored. With that being said, tables 5.13 was created so the results could be analyzed.

Table 5.13: Comparison between results from 4 weeks worth of data and 8 weeks worth of data - using all variables as inputs

	Time length	Δe	σe	Correlation
Circuits 2 and 4 from CT B	4 weeks	3,43081E-05	0,027860567	0,912464212
	8 weeks	-5,62551E-05	0,003859971	0,99833198
Circuits 5 and 7 from CT C	4 weeks	-0,001346707	0,017485568	0,873628213
	8 weeks	4,85697E-05	0,007090717	0,979287549
Circuits 8 and 9 from CT D	4 weeks	-0,003442323	0,04340033	0,30287116
	8 weeks	-0,002365118	0,041901147	0,424904765

It's clear through the analyzes of table 5.13 that the results are better when more samples are provided for the training of the ANNs, for every single case presented. Nonetheless one important conclusion can be made, which is that, even with half the samples, the results can be considered good. This is also true for the cases where different variables were used as inputs to train the ANNs as tables 5.14 and 5.15 presented next will show.

Table 5.14: Comparison between results from 4 weeks worth of data and 8 weeks worth of data - using the Active Power from the electrical switchboard entrance as the only input

	Time length	Δe	σe	Correlation
Circuits 2 and 4 from CT B	4 weeks	-0,000132167	0,032883004	0,876248466
	8 weeks	6,04304E-05	0,015380888	0,973122658
Circuits 5 and 7 from CT C	4 weeks	-0,001320076	0,023998412	0,74525823
	8 weeks	-4,86446E-06	0,015942309	0,890223806
Circuits 8 and 9 from CT D	4 weeks	-0,003356537	0,045389018	0,083625786
	8 weeks	-0,002002733	0,045872418	0,117108457

Table 5.15: Comparison between results from 4 weeks worth of data and 8 weeks worth of data - using the date as the only input

	Time length	Δe	σe	Correlation
Circuits 2 and 4 from CT B	4 weeks	1,1572E-05	0,060158202	0,43383745
	8 weeks	-7,21136E-05	0,060782069	0,414259095
Circuits 5 and 7 from CT C	4 weeks	-0,000968968	0,031153004	0,473966394
	8 weeks	0,000450262	0,030270813	0,501959391
Circuits 8 and 9 from CT D	4 weeks	-0,00344733	0,041980084	0,389322477
	8 weeks	-0,00196529	0,042423427	0,403675271

As both table 5.14 and 5.15 confirm, as more data is provided to train the ANNs, the better the results will be. Graphically, the results are very similar to the graphics presented in the figures of the previous subsection, and so they will not be presented here. They can be seen in the appendixes, chapter A, from sections A.1, A.2 and A.3, from Figs. A.1 to A.18.

6

Conclusions and Future Work

6.1 Conclusions

In this thesis, the objective was to see if a correlation between the Active Power of an electrical switchboard and the Active Power of a few predetermined circuits from that same electrical switchboard was possible, to see if, for instance, the prediction of energy consumption of certain circuits instead of just a prediction of energy consumption of the electrical switchboard as a whole is possible. In other words, it was intended to determine the influence that some circuits have on the total energy consumption of an electrical switchboard.

With that in mind, a module was developed that, with the help of current and voltage sensors, is capable of reading the Active Power of the circuits being monitored by it, and then store those values so they can be processed later. It's important to refer that the developed method is also capable of providing the day of the week, and time of the day - both important variables for this work as it was shown.

After its development, the module was implemented in a household environment, because this environment provides a wide range of electrical devices that are interesting to be monitored, from microwaves, to lighting systems, or in other words, this type of environment has electrical devices that present complete random behaviors, and other circuits that have a somewhat predictable behavior. The module monitored three different sets of systems. First it monitored a washing machine plus a dishwasher, which are relevant electrical devices because on a typical house, these are responsible for the highest power consumption. Secondly the circuits responsible for most of the power outlets of the house were monitored, which again are relevant because they have connected to them electrical devices that range from microwaves, to televisions. Finally, the last circuits that were monitored, were the lighting systems of the house, which are relevant for the sole purpose that in a house, these systems are very random. It's important to mention that the developed module was used to collect relevant data during three different time lengths, the first being for 4 weeks, the second being for 8 weeks, and finally, the module collected one more week worth of data, so simulations could be made.

Once all the data was collected, it was necessary to process it, so it could be trained by the different ANNs, and after the ANNs were trained, simulations were made to determine if the correlation between between the Active Power of the electrical switchboard entrance and the Active Power of specific circuits from that electrical switchboard is indeed possible.

As the results showed, a successful correlation between the Active Power of the entrance of the electrical switchboard and the Active Power of specific circuits from that electrical switchboard was presented, except for when the systems being analyzed are completely random. Apart from the systems with a complete random behavior, on average the error and its standard deviation between the simulation results and the real values for the Active Power of the circuits being analyzed were extremely low. Also, the Correlation coefficient for those cases is very high (almost 1 in the best cases) which indicates that the simulation results and the Active Power from the circuits that were monitored have an extremely close relation.

An important aspect of this work was also to verify if different variables used as inputs to train the ANNs would influence the results. As it was shown, using all the variables considered - Active Power from the electrical switchboard entrance, time of the day and day of the week - the results obtained were the best ones. When using only the Active Power of the electrical switchboard entrance as the input to train the ANN, the results were very good (apart from the random systems that were monitored), coming very close to the results obtained using all the variables as inputs to train the ANN. On average, the error and its standard deviation were also very low, and the Correlation coefficient was also high. This indicates a low dependency of the other two variables - time of the day and day of the week. Finally, when using only the time of the day and day of the week as inputs to train the ANN, the results were very bad, which was expected, because as it was mentioned, the dependency between this two variables and the Active Power from the circuits is very low.

Another important aspect of this work was to show that, with more samples provided to train the ANNs, the better the results obtained would be. Again, this was demonstrated, as the results obtained for the tests and simulations made using only 4 weeks worth of data, were worse when compared to the results from the tests and simulations made using 8 weeks worth of data.

Summing up, it was proven that this module, along with the use of CI methods -

in this case ANNs - can indeed establish a correlation between the Active Power of certain circuits of an electrical switchboard, to the total Active Power of that same electrical switchboard. This can be very useful because this type of information can help enterprises, industrial commerce, etc, in for instance energy audits by being able to predict the behavior/energy consumption of certain circuits, which allows the taking of preventing measures before those audits happen. It's also helpful by simply allowing to see the load output of certain circuits, and thus being able to see if something is wrong with that circuit or not. One advantage of the developed module is its price, because when compared to other tools that are able to do the same, this module comes at a much lower price, and with an important advantage which is the fact that this module is non-intrusive.

6.2 Future Work

This work has introduced some interesting topics that can be further improved.

- Further tests could be made in different kinds of environments, and with a longer duration, so more situations could be analyzed, providing also a more solid base for comparison between results.
- The design of the module could be further optimized so it can be made smaller, although when compared to similar solutions on the market, it's already smaller then those. Nonetheless, it could be made even smaller, and thus even more practical.
- The data collection part of this module, can be optimized, in the sense that the EmonTx Shield V1 supports Wi-Fi communications. With that being said, this ability could be integrated with this solution, so the SD Card Breakout Module can be discarded, because in this case, data could be sent and processed in a specific Web-site.

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A

Appendix

On this chapter, some graphics regarding chapter 5 will be presented, most specifically graphics that represent the tests performed for 4 weeks. The developed Arduino code will also be presented. Finally, a published scientific article is also presented.

A.1 Four Weeks Duration - Using all variables as inputs

Circuits 2 and 4 from CT B - all variables as inputs

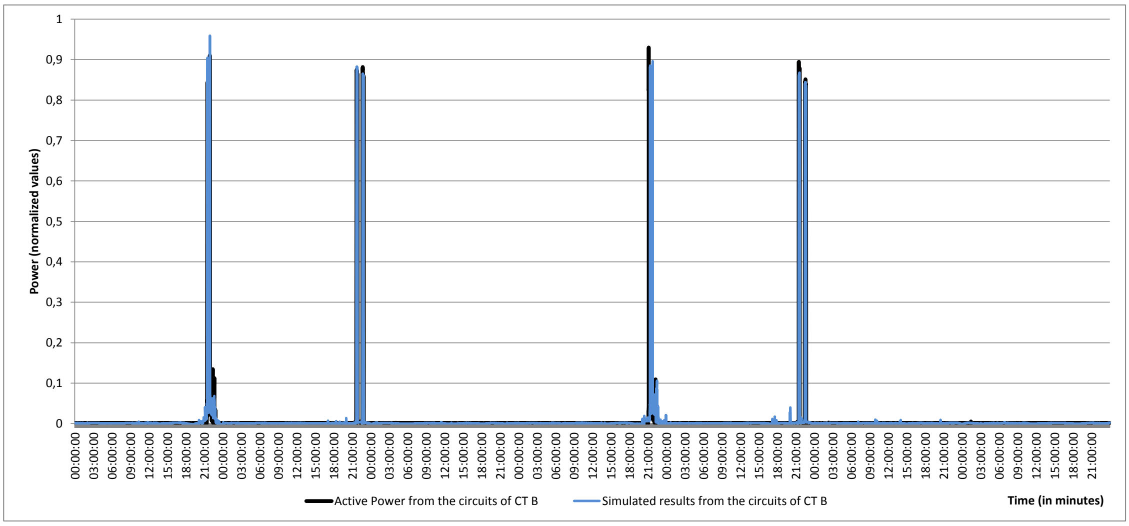

Figure A.1: Simulation results versus the Active Power from circuits 2 and 4 from CT B - all variables as inputs

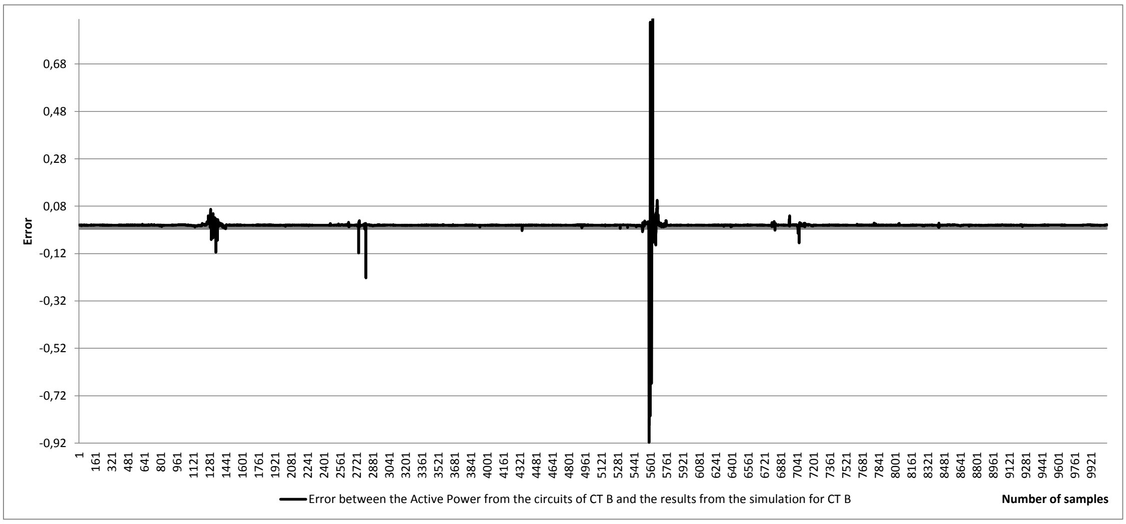

Figure A.2: Error between the simulation results and the Active Power from circuits 2 and 4 from CT B - all variables as inputs

Circuits 5 and 7 from CT C - all variables as inputs

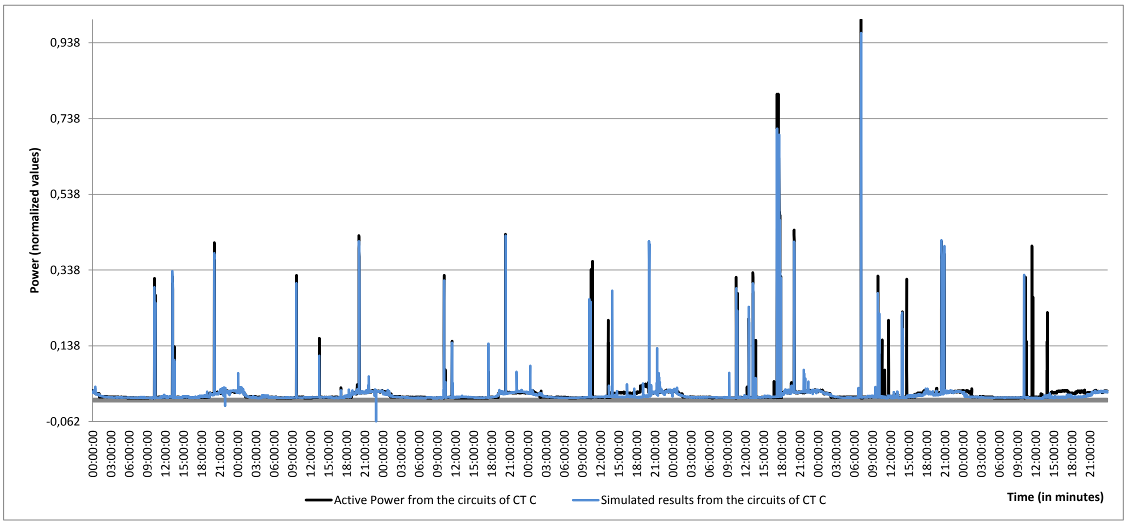

Figure A.3: Simulation results versus the Active Power from circuits 5 and 7 from CT C - all variables as inputs

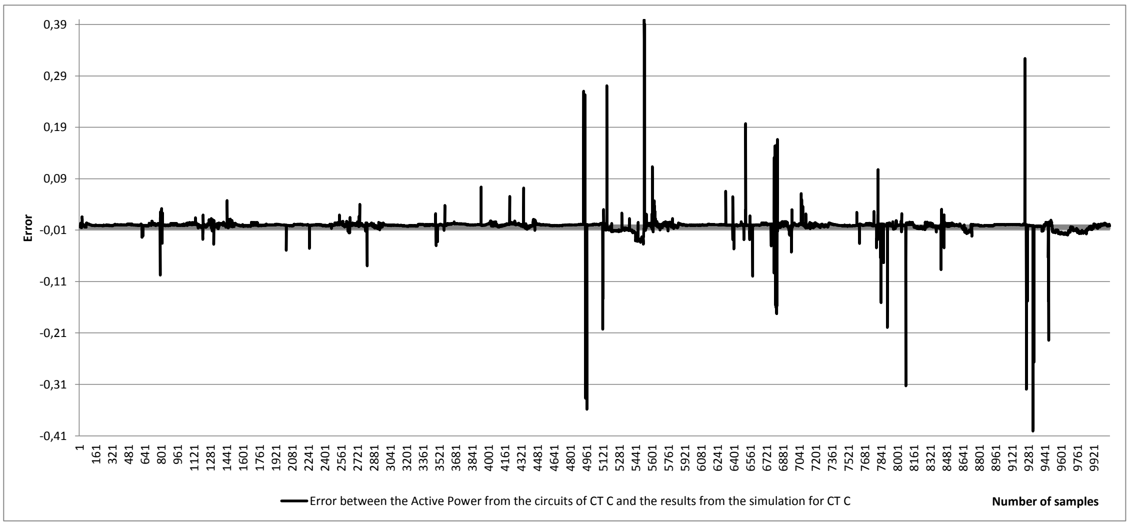

Figure A.4: Error between the simulation results and the Active Power from circuits 5 and 7 from CT C - all variables as inputs

Circuits 8 and 9 from CT D - all variables as inputs

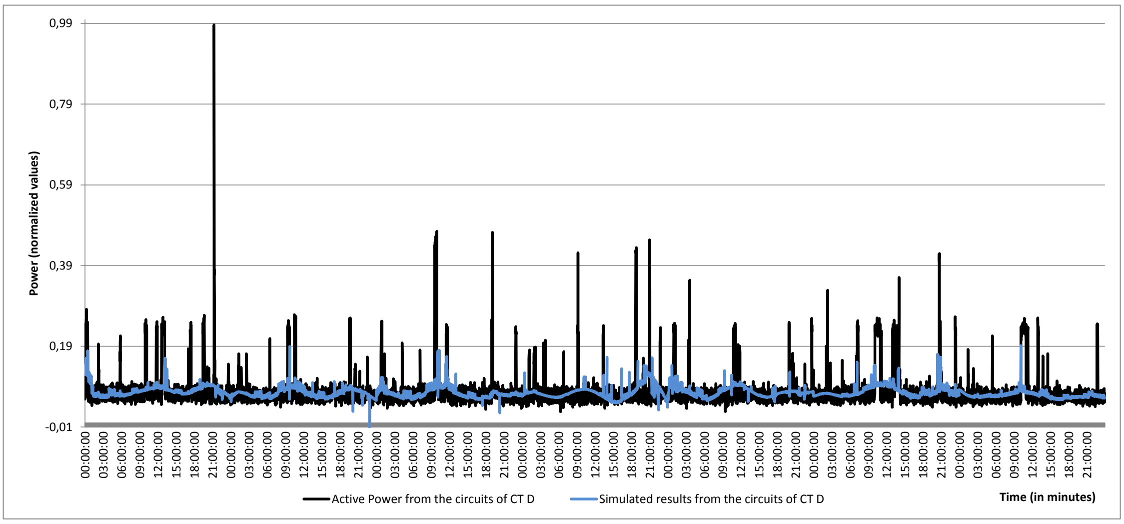

Figure A.5: Simulation results versus the Active Power from circuits 8 and 9 from CT D - all variables as inputs

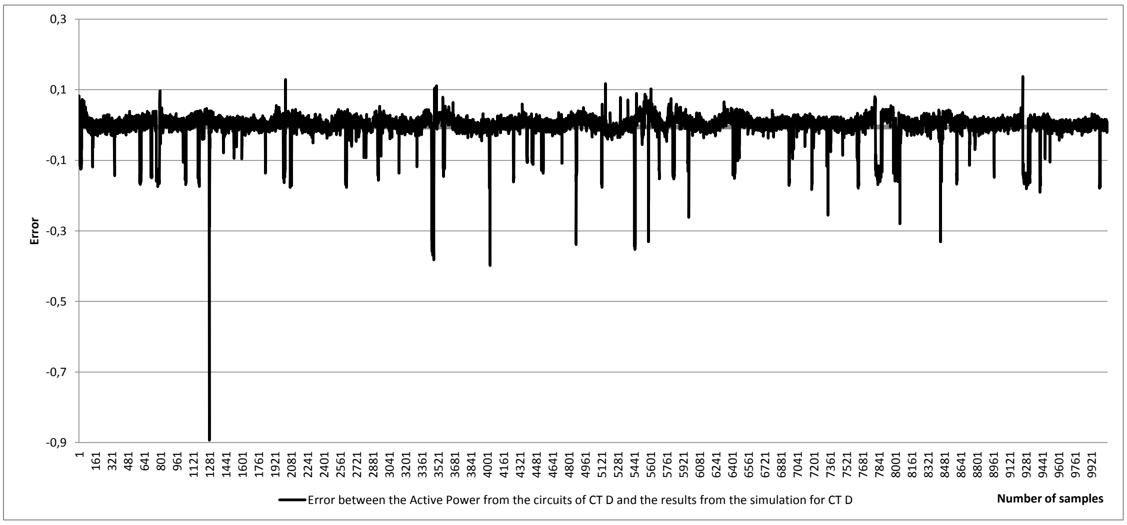

Figure A.6: Error between the simulation results and the Active Power from circuits 8 and 9 from CT D - all variables as inputs

A.2 Four Weeks Duration - Using only the total Active Power from the electrical switchboard entrance as input

Circuits 2 and 4 from CT B - using the Active Power from the electrical switchboard as the only input

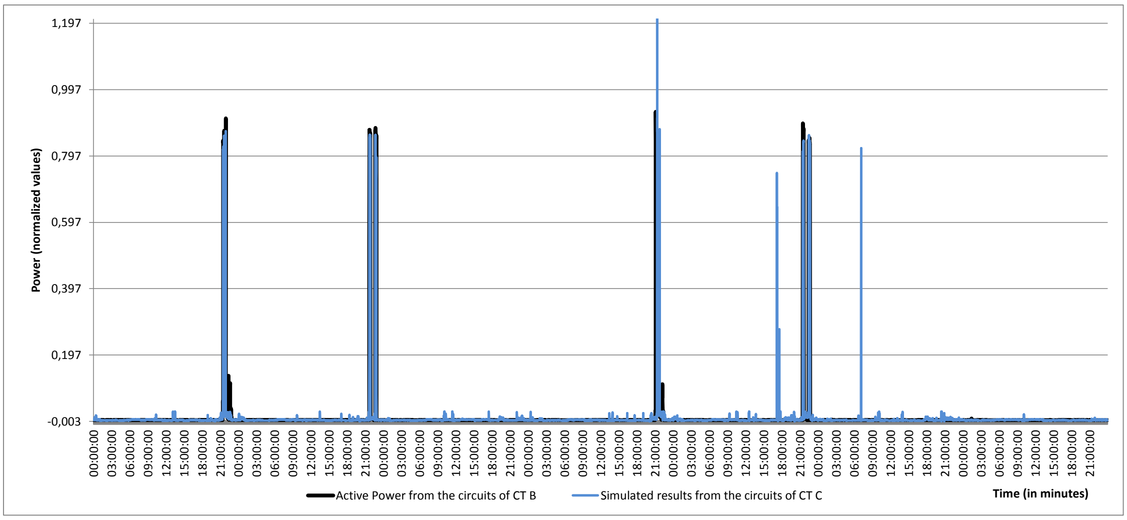

Figure A.7: Simulation results versus the Active Power from circuits 2 and 4 from CT B - using the Active Power from the electrical switchboard as the only input

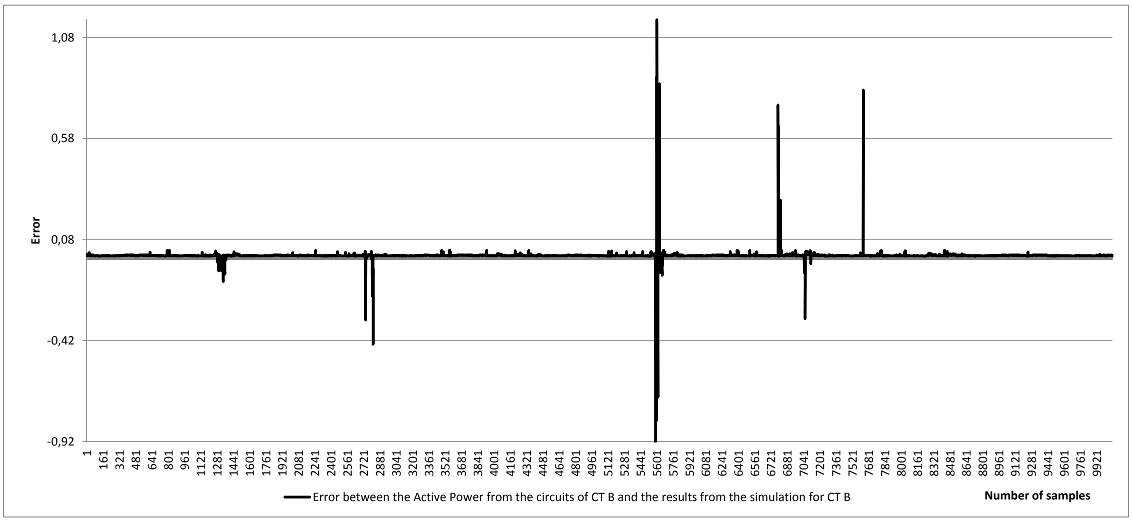

Figure A.8: Error between the simulation results and the Active Power from circuits 2 and 4 from CT B - using the Active Power from the electrical switchboard as the only input

Circuits 5 and 7 from CT C - using the Active Power from the electrical switchboard as the only input

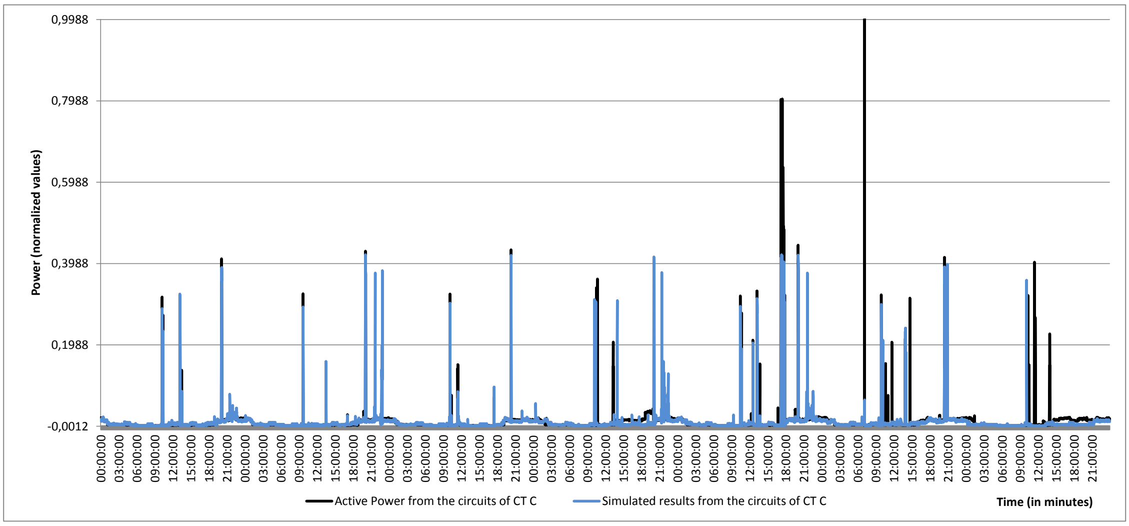

Figure A.9: Simulation results versus the Active Power from circuits 5 and 7 from CT C - using the Active Power from the electrical switchboard as the only input

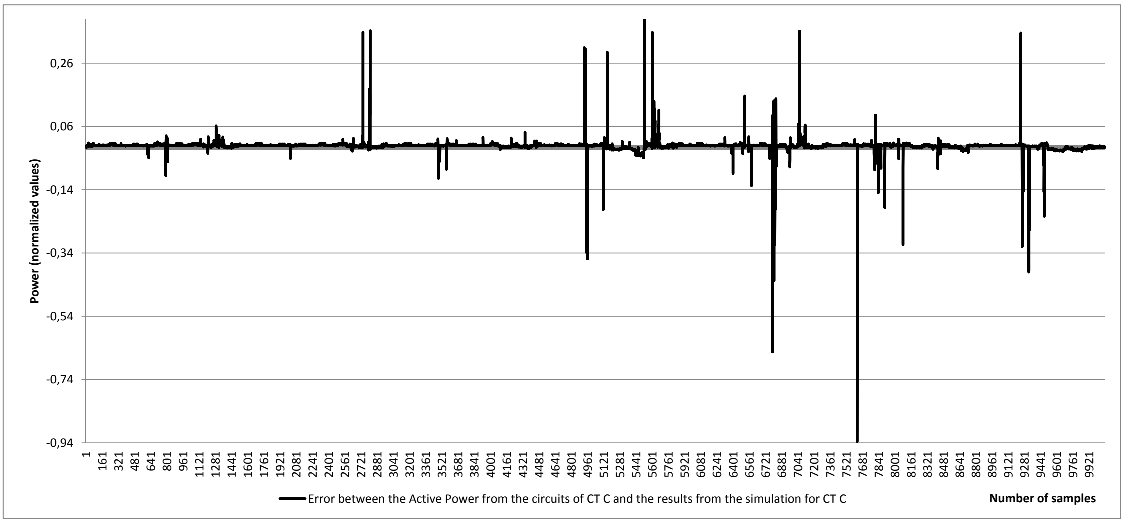

Figure A.10: Error between the simulation results and the Active Power from circuits 5 and 7 from CT C - using the Active Power from the electrical switchboard as the only input

Circuits 8 and 9 from CT D - using the Active Power from the electrical switchboard as the only input

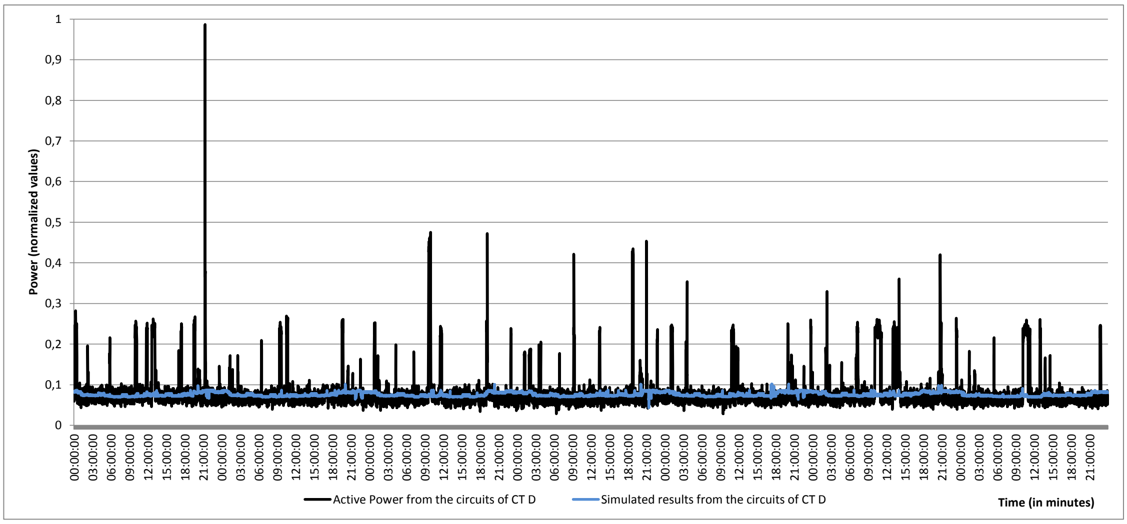

Figure A.11: Simulation results versus the Active Power from circuits 8 and 9 from CT D - using the Active Power from the electrical switchboard as the only input

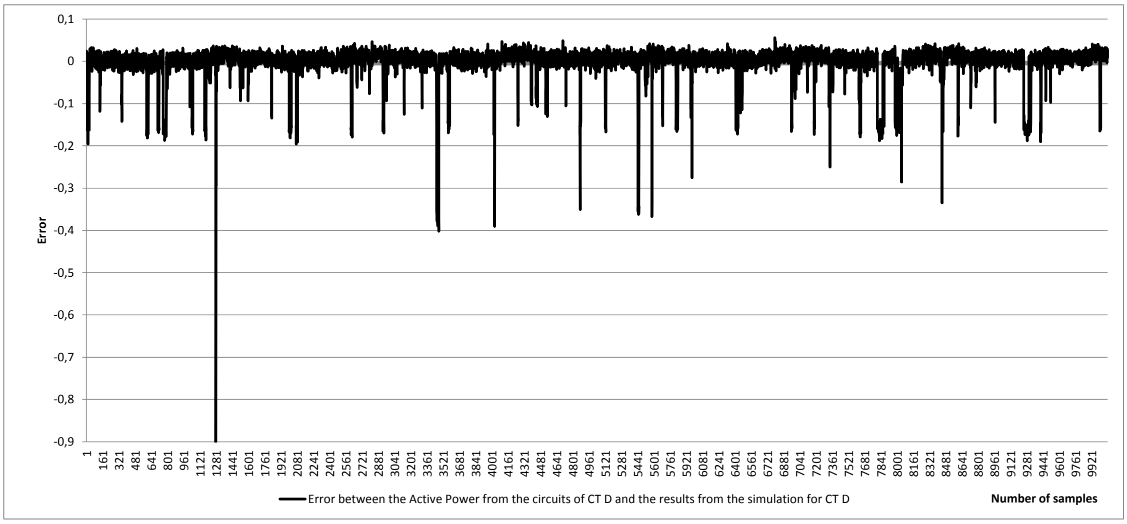

Figure A.12: Error between the simulation results and the Active Power from circuits 8 and 9 from CT D - using the Active Power from the electrical switchboard as the only input

A.3 Four Weeks Duration - Using only the time of the day and day of the week as inputs

Circuits 2 and 4 from CT B - using the date as the only input

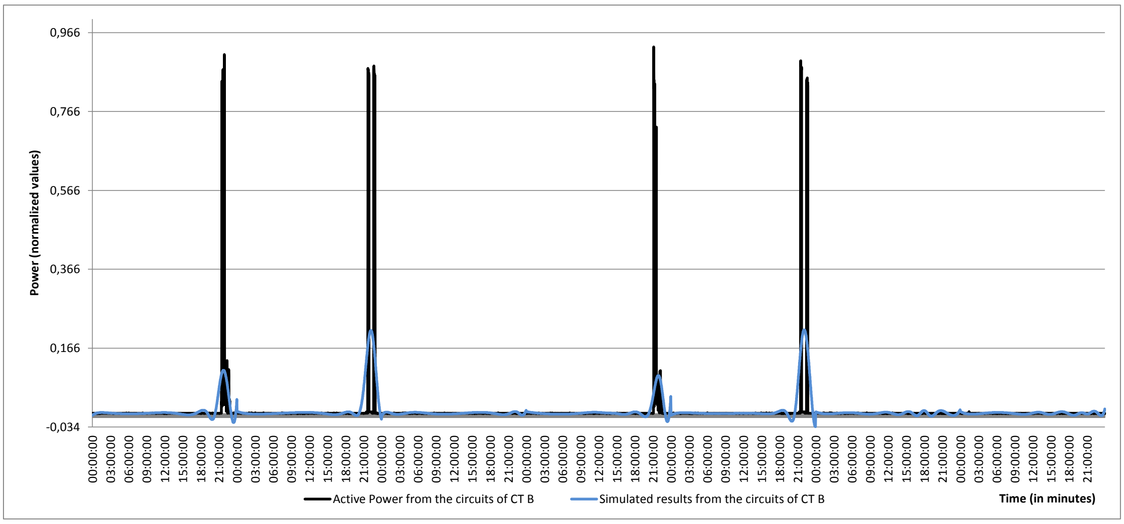

Figure A.13: Simulation results versus the Active Power from circuits 2 and 4 from CT B - using the date as the only input

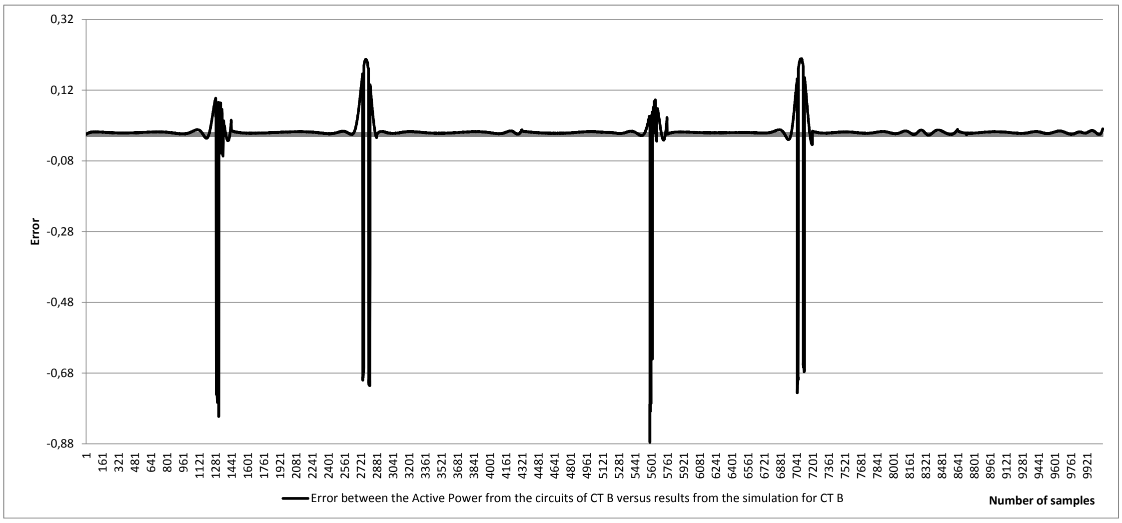

Figure A.14: Error between the simulation results and the Active Power from circuits 2 and 4 from CT B - using the date as the only input

Circuits 5 and 7 from CT C - using the date as the only input

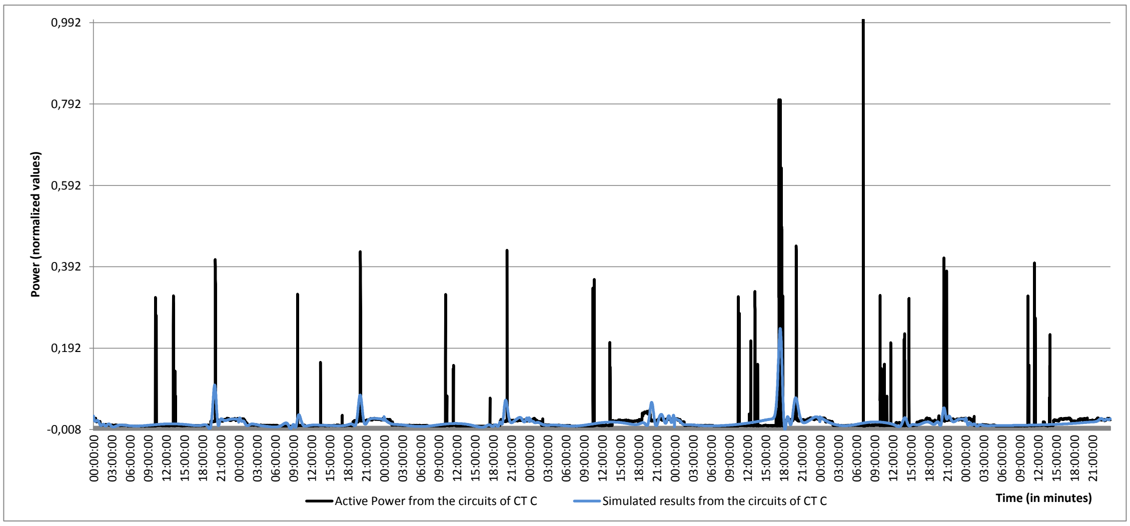

Figure A.15: Simulation results versus the Active Power from circuits 5 and 7 from CT C - using the date as the only input

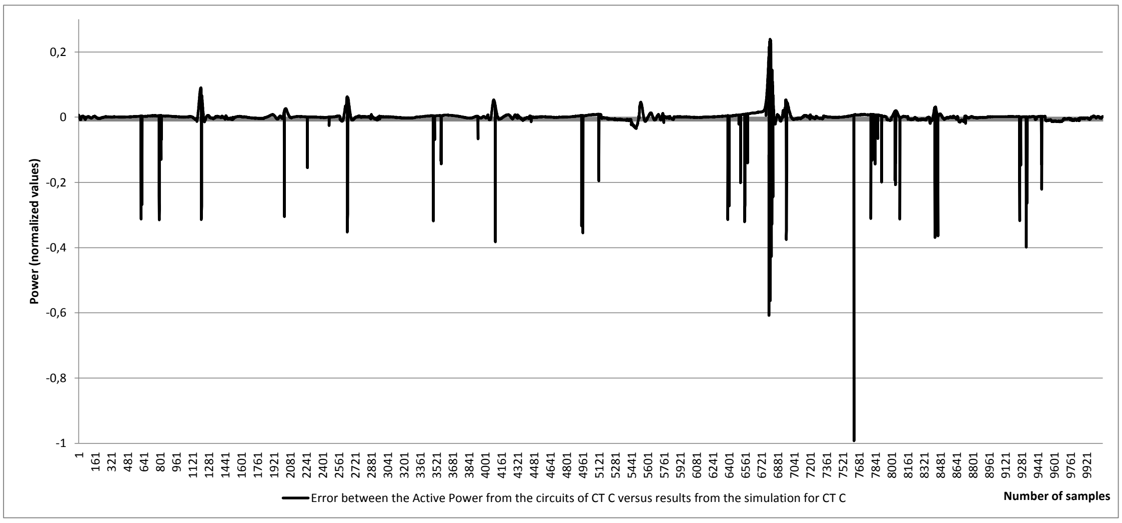

Figure A.16: Error between the simulation results and the Active Power from circuits 5 and 7 from CT C - using the date as the only input

Circuits 8 and 9 from CT D - using the date as the only input

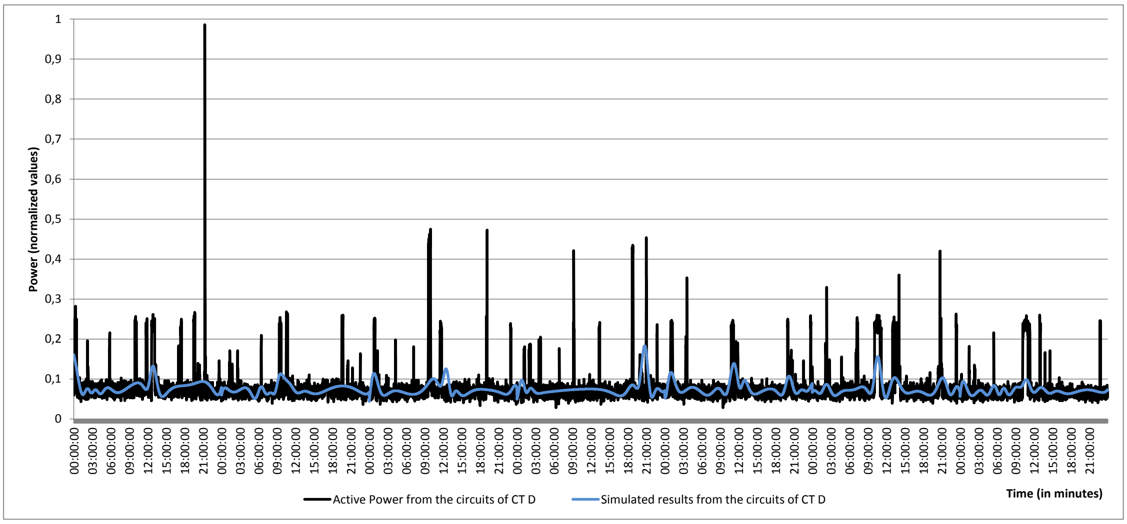

Figure A.17: Simulation results versus the Active Power from circuits 8 and 9 from CT D - using the date as the only input

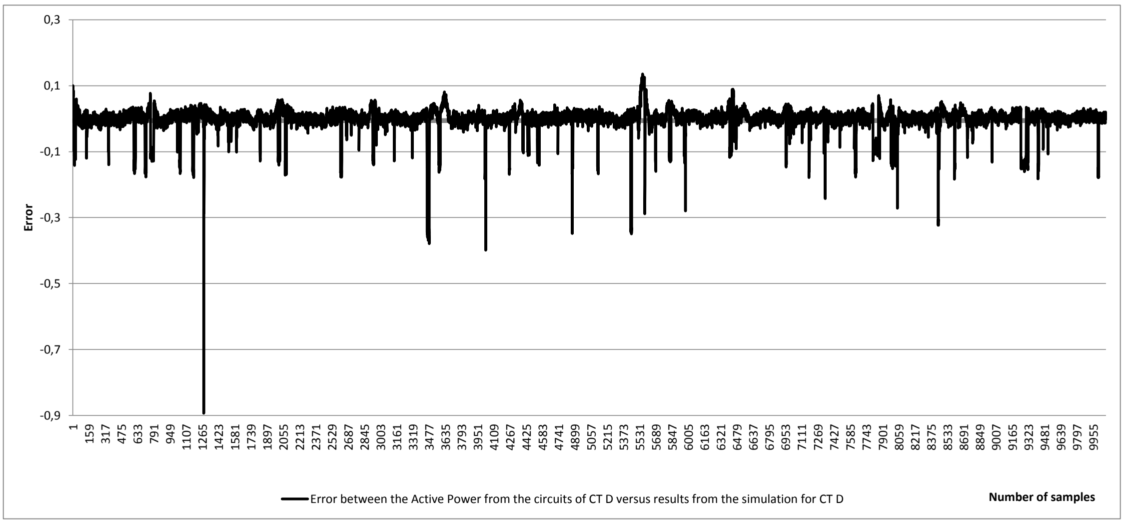

Figure A.18: Error between the simulation results and the Active Power from circuits 8 and 9 from CT D - using the date as the only input

A.4 Developed Arduino Code

,

```

/*
Developed By Joao Almeida
*/

#include <SD.h>
#include <Time.h>
#include <Wire.h>
#include <DS1307RTC.h>  // a basic DS1307 library that returns time as a time_t
#include "EmonLib.h"

//*********************************************************************
//Global Variables
//*********************************************************************
EnergyMonitor emon1, emon2, emon3, emon4;

File myFile;

float normalizedHour = 0.0;
int minutesInDay = 1440;
int minuteComp = 0;
float conversionVariable = (float)1 / (float)minutesInDay;
//*********************************************************************


void setup()
{
  // Open serial communications and wait for port to open:
  Serial.begin(9600);
  // If the system breaks for some reason, this sentence helps to know
  // Comment when proceding for final tests.
  Serial.println("###################################################################");
  Serial.println("SYSTEM RESETED! START NEW MEASURE ROM HERE!");
  Serial.println("###################################################################");

//*********************************************************************
//Initialization of the sensors
//*********************************************************************

  emon1.current(1, 111.1);             // Current: input pin, calibration.
  emon1.voltage(1, 233.3, 1.7);          // Voltage: input pin, calibration, phase_shift
    emon2.current(2, 111.1);           // Current: input pin, calibration.
    emon2.voltage(2, 233.3, 1.7);        // Voltage: input pin, calibration, phase_shift
```

```
      emon3.current(3, 111.1);           // Current: input pin, calibration.
      emon3.voltage(3, 233.3, 1.7);       // Voltage: input pin, calibration,
    phase_shift
        emon4.current(4, 111.1);         // Current: input pin, calibration.
        emon4.voltage(4, 233.3, 1.7);     // Voltage: input pin, calibration,
    phase_shift


//*****************************************************************************

//*****************************************************************************
//RTC verification
//*****************************************************************************

  setSyncProvider(RTC.get);   // the function to get the time from the RTC
  if(timeStatus()!= timeSet)
     Serial.println("Unable to sync with the RTC");
  else
     Serial.println("RTC has set the system time");

//*****************************************************************************

//*****************************************************************************
//Code already done for the inicialization of the SD card
//*****************************************************************************
  Serial.print("Initializing SD card...");
//  // On the Ethernet Shield, CS is pin 4. It's set as an output by default.
//  // Note that even if it's not used as the CS pin, the hardware SS pin
//  // (10 on most Arduino boards, 53 on the Mega) must be left as an output
//  // or the SD library functions will not work.
  pinMode(53, OUTPUT); //53 because it's te CS pin on teh MEGA
//
  if (!SD.begin(53)) { //53 because it's te CS pin on teh MEGA
    Serial.println("initialization failed!");
  return;
  }
  Serial.println("initialization done.");

//*****************************************************************************
//Variavel para controlo de leituras.
//*****************************************************************************
minuteComp = minute(); //Insert the current minute to a variable for
    comparisson of time.
//*****************************************************************************
//*****************************************************************************
}

void loop(){ //MAIN//

  myFile = SD.open("test.txt", FILE_WRITE); //Opens the file for reading.
```

```

  if(myFile){
                                        //minute()==0) && (second()==0)
        if( (minuteComp<minute()) || ((minute()==0) && (minuteComp>0)) ){ //Guarantees that the measures are done every other minute.

              printRealHour();          //At the beggining of the line, prints the real our, for tracking purposes.
              Serial.print(",");
              myFile.print(";");
              printNormalizedHour();  //Prints the hour and minutes converted to a value between 0 and 1.
              Serial.print(",");
              myFile.print(";");
              printWeekday();       //sets 1 to the correspondent weekday. Example, it's monday: 1, 0, 0, 0, 0, 0, 0, 0
              Serial.print(",");
              myFile.print(";");
              getSensorValues();              //Gets all the values from the sensors.
              Serial.println();
              myFile.println();               //When we get to the end of the line, prints out a new line.

              minuteComp=minute();            //When in this cycle, it's necessary to update the variable to the new actual minute.
        }
    myFile.close(); //Closes the file.
  }
}


//*************************************************************************
//Function that prints the hours in the correct format
//*************************************************************************
void printRealHour(){

    Serial.print("Hora: ");
    myFile.print("Hora: ");
    Serial.print(hour());
    myFile.print(hour());
    Serial.print(":");
    myFile.print(":");
    printDigits(minute());
    Serial.print(":");
    myFile.print(":");
    printDigits(second());

}
//*************************************************************************
```

```
//*************************************************************************

//*************************************************************************
//Function that prints 0 in case "digits" is < 10
//*************************************************************************
void printDigits(int digits){

  if(digits <10)
    Serial.print('0');
      Serial.print(digits);

  if(digits <10)
    myFile.print('0');
      myFile.print(digits);
}
//*************************************************************************
//*************************************************************************

//*************************************************************************
//Function that prints the normalized hour
//*************************************************************************
//This function guarantees that the normalized hour is in the range [0,1[
void printNormalizedHour(){

  normalizedHour = (float)60*(float)hour();
  normalizedHour = normalizedHour + (float)minute();
  normalizedHour = normalizedHour*conversionVariable;
  Serial.print(normalizedHour,10);
  myFile.print(normalizedHour,10);

}
//*************************************************************************
//*************************************************************************

//*************************************************************************
//Function that prints out the weekday (Sunday -> weekday = 1)
//*************************************************************************
void printWeekday () {

int monday = 0;
int tuesday = 0;
int wednesday = 0;
int thursday = 0;
int friday = 0;
int saturday = 0;
int sunday = 0;

  if(weekday() == 1)
    sunday = 1;
    if(weekday() == 2)
```

```
      monday = 1;
      if(weekday() == 3)
        tuesday = 1;
        if(weekday() == 4)
          wednesday = 1;
            if(weekday() == 5)
              thursday = 1;
              if(weekday() == 6)
                friday = 1;
                if(weekday() == 7)
                  saturday = 1;

Serial.print(monday);
Serial.print(",");
Serial.print(tuesday);
Serial.print(",");
Serial.print(wednesday);
Serial.print(",");
Serial.print(thursday);
Serial.print(",");
Serial.print(friday);
Serial.print(",");
Serial.print(saturday);
Serial.print(",");
Serial.print(sunday);

myFile.print(monday);
myFile.print(";");
myFile.print(tuesday);
myFile.print(";");
myFile.print(wednesday);
myFile.print(";");
myFile.print(thursday);
myFile.print(";");
myFile.print(friday);
myFile.print(";");
myFile.print(saturday);
myFile.print(";");
myFile.print(sunday);
}
//***************************************************************************
//***************************************************************************

//***************************************************************************
//Fucntion to get the values of the sensors
//***************************************************************************
void getSensorValues (){

//int test=1;
float potenciaActiva1=0;
```

```
float potenciaActiva2=0;
float potenciaActiva3=0;
float potenciaActiva4=0;
float potenciaActiva11=0;

 emon1.calcVI(20,2000);
 potenciaActiva1=emon1.realPower+potenciaActiva1;
 Serial.print(potenciaActiva1);
 Serial.print(",");
 delay(1000);
 emon2.calcVI(20,2000);
 potenciaActiva2=emon2.realPower+potenciaActiva2;
 Serial.print(potenciaActiva2);
 Serial.print(",");
 delay(1000);
 emon3.calcVI(20,2000);
 potenciaActiva3=emon3.realPower+potenciaActiva3;
 Serial.print(potenciaActiva3);
 Serial.print(",");
 delay(1000);
 emon4.calcVI(20,2000);
 potenciaActiva4=emon4.realPower+potenciaActiva4;
 Serial.print(potenciaActiva4);
 Serial.println(",");
 delay(1000);
 //######################################################################
     emon1.calcVI(20,2000);
     potenciaActiva1=emon1.realPower+potenciaActiva1;
     Serial.print(potenciaActiva1);
     Serial.print(",");
     delay(1000);
     emon2.calcVI(20,2000);
     potenciaActiva2=emon2.realPower+potenciaActiva2;
     Serial.print(potenciaActiva2);
     Serial.print(",");
     delay(1000);
     emon3.calcVI(20,2000);
     potenciaActiva3=emon3.realPower+potenciaActiva3;
     Serial.print(potenciaActiva3);
     Serial.print(",");
     delay(1000);
     emon4.calcVI(20,2000);
     potenciaActiva4=emon4.realPower+potenciaActiva4;
     Serial.print(potenciaActiva4);
     Serial.println(",");
     delay(1000);
 //######################################################################
         emon1.calcVI(20,2000);
         potenciaActiva1=emon1.realPower+potenciaActiva1;
         Serial.print(potenciaActiva1);
```

```
        Serial.print(",");
        delay(1000);
        emon2.calcVI(20,2000);
        potenciaActiva2=emon2.realPower+potenciaActiva2;
        Serial.print(potenciaActiva2);
        Serial.print(",");
        delay(1000);
        emon3.calcVI(20,2000);
        potenciaActiva3=emon3.realPower+potenciaActiva3;
        Serial.print(potenciaActiva3);
        Serial.print(",");
        delay(1000);
        emon4.calcVI(20,2000);
        potenciaActiva4=emon4.realPower+potenciaActiva4;
        Serial.print(potenciaActiva4);
        Serial.println(",");
        delay(1000);
//######################################################################
            emon1.calcVI(20,2000);
            potenciaActiva1=emon1.realPower+potenciaActiva1;
            Serial.print(potenciaActiva1);
            Serial.print(",");
            delay(1000);
            emon2.calcVI(20,2000);
            potenciaActiva2=emon2.realPower+potenciaActiva2;
            Serial.print(potenciaActiva2);
            Serial.print(",");
            delay(1000);
            emon3.calcVI(20,2000);
            potenciaActiva3=emon3.realPower+potenciaActiva3;
            Serial.print(potenciaActiva3);
            Serial.print(",");
            delay(1000);
            emon4.calcVI(20,2000);
            potenciaActiva4=emon4.realPower+potenciaActiva4;
            Serial.print(potenciaActiva4);
            Serial.println(",");
            delay(1000);
//######################################################################
                emon1.calcVI(20,2000);
                potenciaActiva1=emon1.realPower+potenciaActiva1;
                Serial.print(potenciaActiva1);
                Serial.print(",");
                delay(1000);
                emon2.calcVI(20,2000);
                potenciaActiva2=emon2.realPower+potenciaActiva2;
                Serial.print(potenciaActiva2);
                Serial.print(",");
                delay(1000);
                emon3.calcVI(20,2000);
```

```
                    potenciaActiva3=emon3.realPower+potenciaActiva3;
                    Serial.print(potenciaActiva3);
                    Serial.print(",");
                    delay(1000);
                    emon4.calcVI(20,2000);
                    potenciaActiva4=emon4.realPower+potenciaActiva4;
                    Serial.print(potenciaActiva4);
                    Serial.println(",");
                    delay(1000);
  //####################################################################
  potenciaActiva1=potenciaActiva1/5;    //An average of the values stored is
    performed.
  Serial.print(potenciaActiva1);
  Serial.print(",");
  myFile.print(potenciaActiva1);
  myFile.print(";");
    potenciaActiva2=potenciaActiva2/5;    //An average of the values stored is
    performed.
    Serial.print(potenciaActiva2);
    Serial.print(",");
    myFile.print(potenciaActiva2);
    myFile.print(";");
      potenciaActiva3=potenciaActiva3/5;    //An average of the values stored
    is performed.
      Serial.print(potenciaActiva3);
      Serial.print(",");
      myFile.print(potenciaActiva3);
      myFile.print(";");
        potenciaActiva4=potenciaActiva4/5;    //An average of the values stored
     is performed.
        Serial.print(potenciaActiva4);
        Serial.print(",");
        myFile.print(potenciaActiva4);

}

//**************************************************************************
//**************************************************************************
```

A.5 Published Paper

"Towards a web-based energy consumption forecasting platform"

Towards a web-based energy consumption forecasting platform

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***Abstract*—Nowadays, energy efficiency is a major issue in modern day societies, due to increasing worldwide energy demands. Having this in mind several different solutions are emerging with the purpose of helping the control of energy in all possible ways, whether at its starting pipeline, i.e. where the energy is produced, at the middle pipeline, i.e. where and how the energy is transported, or finally, at the end of the pipeline, where the energy is consumed. At the moment, most solutions are addressing the problem at the end of the pipeline, because it is easier to control the consumption, than it is to alter all of the parts that compose an energy system.**

Thus, the solution proposed in this paper refers to the development of a platform capable of providing energy prediction on buildings, whether the building is commercial, industrial or residential. The platform will be composed of prediction algorithms, supported by the use of computational intelligence methods such as Artificial Neural Networks (ANN). The main objective of this platform is to use datasets previously recorded of the building energy consumption, along with a number of other parameters, to accurately predict the energy consumption of a given day, so that future, and pondered actions can be taken in order to provide a suitable response for that given day. Technically, the platform itself will be based on standard online remote communication protocols, and this platform is to be integrated with, amongst other equipment, energy meters.

Keywords: Energy efficiency, environmental impact, energy prediction, computational intelligence methods, artificial neural network, energy consumption, online remote communication protocols, energy meter.

I. Introduction

Predictions state that there will be a rise in energy demand of about 53% by the year 2030 [1]. This obviously means that the increase of available energy is a necessity. On the other hand, energy sectors world wide face serious problems, with the most commonly appointed solution being a sustainable energy development, because this solution takes into account some of the most important factors, like the fight against climate changes, and also the increasingly scarce nature of fossil fuels. All the factors mentioned are major issues when it is taken into account that regions like the EU is the largest energy importer in the world [2]. It's mainly because of the on growing scarce nature of this said resources, and the impact of their applications on the environment, that governments worldwide are implementing this kind of measures, and so the need to implement new sources of energy increases [3].

A. Sustainable Energy Development - Energy Efficiency

It is important to tackle the sustainable energy development theme, because its foundations are based on energy efficiency. On the other hand, it's widely agreed that energy efficiency is the most effective, and better way, to impact today's environmental issues, at least when the subject is energy [4]. Aside from the energy sources already known, e.g. fossil fuels, renewable energies, nuclear power, in this context, energy efficiency can be considered a new energy source, in the sense that energy efficiency is all about harnessing, the best possible way, all the energy that is produced, and consequently consumed. With this, it can be said that energy efficiency takes into account energy flow and its losses. Those losses can occur in a variety of processes, ranging from the energy transformation process, transmission and distribution, to the point where the energy is actually used, i.e. end-use. What's important regarding the present work, is the end-use process, arguably because reducing the losses in those processes is more of a technological problem (e.g. switching from fossil fuels to renewable energies, or improving the existing renewable energy sources to better outputs). The end-use process is more complex, because it has to take into account all the end-uses of energy, and to change all of those end-usages, it will ultimately require changes in consumers behavior, whether industrial, commercial or domestic. Of course changes in management and organization are also necessary. Thus, to ensure the best energy efficient improvements, energy consumption has to be introduced, and consequently managed as any other activity [5].

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