1 2 9 0

UNIVERSIDADE Ð
COIMBRA

Cláudia Alexandra Almeida Carvalho

ADVANCED MONIOTRING OF DOMESTIC APPLIANCES

Dissertação no âmbito do Mestrado Integrado de Engenharia Física, ramo de Instrumentação orientada pelo Professor Doutor Jorge Afonso Cardoso Landeck e apresentada ao Departamento de Física da Faculdade de Ciências e Tecnologia.

Outubro de 2020

Cláudia Alexandra Almeida Carvalho

Advanced Monitoring of Domestic Appliances

Thesis submitted to the
Physics Department of the
University of Coimbra for the degree of
Integrated Master in Physics Engineering,
Instrumentation

Supervisors:
Prof. Dr. Jorge Landeck, University of Coimbra

November 2020

This work was developped in collaboration with:

VPS - Virtual Power Solution, S.A.

ACKNOWLEDGMENTS

Começou por agradecer ao Professor Jorge Landeck pelo acompanhamento ao longo deste projeto. Agradecer ao Micael Santos, da VPS, pelas orientações iniciais e pela disponibilidade. À equipa da VPS que me recebeu muito bem no seu estabelecimento, que a tradição dos bolos continue.

Agradeço á minha família por todo o suporte, pois sem eles não tinha chegado onde estou hoje.

Aos meus amigos do BIF que sempre me animavam as tardes e sempre me apoiaram em todo o meu percurso em Coimbra.

Ás minhas meninas da residência da PAV, em especial à Cris e à Cláudia, que nunca me deixaram jantar sozinha e que estavam sempre cá para o que fosse preciso.

Um especial agradecimento à minha irmã, Catarina, por ser sempre a minha parceira nas lutas e o meu braço direito.

Um carinho muito grande para os meus bixinhos, Becky, Snow, Shadow, Tica, Scott, Jonny, Didinho, Tyson, Jonh e o Jimmy por me aquecerem sempre a alma nos dias mais cinzentos.

Um agradecimento à Diana e ao Pedro pela disponibilidade e ajuda durante a fase final deste projeto.

E por último, mas o mais importante de todos, um grande agradecimento ao Danny, que sempre me puxou para cima, ouviu os meus desabafos e as minhas frustrações e que sempre esteve (e está) ao meu lado.

RESUMO

Os eletrodomésticos ajudam-nos diariamente com as tarefas domésticas. Com o uso estes começam a desenvolver anomalias que se traduzem em consumos de energia mais elevados e, muita das vezes, em avarias que obrigam a reparações que representam um incómodo e um custo inesperados. Neste projeto iniciou-se o desenvolvimento de um sistema de monitorização avançada para eletrodomésticos que permite detetar falhas antecipadamente através da análise detalhada de parâmetros operacionais. Possibilitando assim um maior controlo dos gastos energéticos e das reparações do eletrodoméstico.

O sistema reutiliza uma tomada desenvolvida na VPS, a *idPlug*, que possibilita a medição de parâmetros elétricos (corrente, tensão, potência) e análise do sinal de corrente usando técnicas no domínio da frequência. A deteção de falhas baseia-se num método que compara a evolução dos máximos da transformada de Fourier da corrente. Para simplificar a operação do sistema foi desenvolvido interface web local que permite visualizar os dados e parametrizar o dispositivo.

Os requisitos especificados foram verificados através de um conjunto de testes utilizando inicialmente um motor sem carga. Posteriormente, o sistema foi testado usando um mini-frigorífico, tendo o dispositivo detetado corretamente todos os arranques do motor. Em seguida, realizaram-se testes com uma máquina de lavar onde se verificaram falhas no algoritmo implementado devido ao facto deste eletrodoméstico possuir vários elementos de carga (motores e resistência de aquecimento) e diferentes ciclos de lavagem. Assim, a evolução futura do algoritmo deverá permitir a identificação de diferentes ciclos de operação. De igual forma, a deteção de falhas poderá incluir a análise de longo termo dos dados recolhidos usando técnicas de reconhecimento de padrões e agregação.

Palavras-chave: Eletrodomésticos, Anomalias, Deteção, Monitorização, Tomada Inteligente

ABSTRACT

Home appliances help us with domestic tasks every day. With usage, they start to develop small anomalies which translate into higher energy consumptions and, most of the times, faults that require repairs that represents an unwanted extra cost. This project started the development of an advanced monitoring system for home appliances, which allows detecting anomalies through a detailed analysis of operational parameters. So, this system allows for better control of energy and appliance repair costs.

The system reuses a device developed in VPS, the idPlug. This device measures electrical parameters (current, voltage, power) and analyses the current signal using techniques in the frequency domain. The fault detection is based on a method that compared the maximums of the current Fourier transform. To simplify the system operation a local web interface was developed which allows data visualization and device parametrization.

The specified requirements were checked by a set of tests using a motor with no load. Afterwards, the system was tested using a mini-refrigerator where the number of motor starts correctly identified. Then, the system was tested using a washing machine that revealed some shortcomings in the implemented algorithm due to the existence of several load elements (motors and heating elements) and different washing cycles. So, a future algorithm evolution should allow the washing cycle identification. Likewise, fault detection may include a long-term analysis of the collected data using pattern recognition and aggregation techniques.

Keywords: Home appliances, Anomalies, Detection, Monitoring, Smart Plug

CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

AC	Alternating Current
AP	Access Point
ASIC	Application-Specific Integrated Circuit
BEMS	Building Energy Management System
DC	Direct Current
DHCP	Dynamic Host Configuration Protocol
DNS	Domain Name System
FFT	Fast Fourier Transform
HEMS	Home Energy Management System
HTTP	Hypertext Transfer Protocol
MCSA	Motor Current Signature Analyse
PCA	Principal Component Analysis
VPS	Virtual Power Solution

CHAPTER 1

INTRODUCTION

Our future is smart homes and cities, where we can manage everything using phones or computers. In this future, we will have a better health condition, more security, and more control over expenses like water and energy. With this evolution, the presence of smart devices in our lives will be more and more frequent.

How can traditional appliances be integrated into this new world? The answer is the construction of simple devices that can convert these appliances into smart ones.

1.1 Motivation

Money is most of the times a deciding factor when making choices in our daily lives. The same thinking is applied when we buy a domestic appliance. With time, the equipment starts to develop small anomalies which, in turn, can cause it to consume more energy anomalies [1]. In most cases, these faults are only noticed when it breaks down. This lack of knowledge about the appliances' malfunctions translates into unwanted extra costs. In buildings, up to 20% of energy is wasted due to faulty appliances. Detecting appliances anomalies result in more than 12% energy savings [1].

The development of an advanced monitoring system for home appliances will allow better monitoring of the appliance power energy behaviour and its electrical parameters. Analysing that behaviour and those parameters we can detect appliances anomalies. This detection allows the control of undesirable energy costs due to extra power consumption and decrease appliances maintenance costs.

This work proposes a system that, through constant monitoring, efficiently improves the user interaction with home appliances.

1.2 Objective

The main goal of the project is the development of an advanced monitoring system for domestic appliances. This device detects and predicts the appliance's malfunctions through the measurement of electrical signals (current and voltage) and other parameters (consumption, energy, number of starts).

This device will integrate the Home Energy Management System (HEMS) developed by Virtual Power Solution (VPS).

1.3 Framework - VPS Energy System

VPS is a technological company with strong knowledge and experience in developing hardware and software solution for the active energy – from a domestic, to an industrial level. The company provides services intending to reduce, optimise and monitor energy consumption.

VPS develops an energy management system both for homes (HEMS[1]), and buildings (BEMS[2]). They also develop virtual power plant platforms. The main solution of HEMS is Cloogy, and the principal product of BEMS is Kisense. The system developed in this project will be integrated the HEMS.

Cloogy allows the monitoring of energy consumption in the household, profiling the client's tariff, and controlling the equipment and microgeneration systems. Cloogy uses the cloud to store data, providing real-time information and according feedback. The proposed solution uses the Zigbee communication protocol, which allows the association between appliances that use it. Figure 1.1 presents Cloogy.

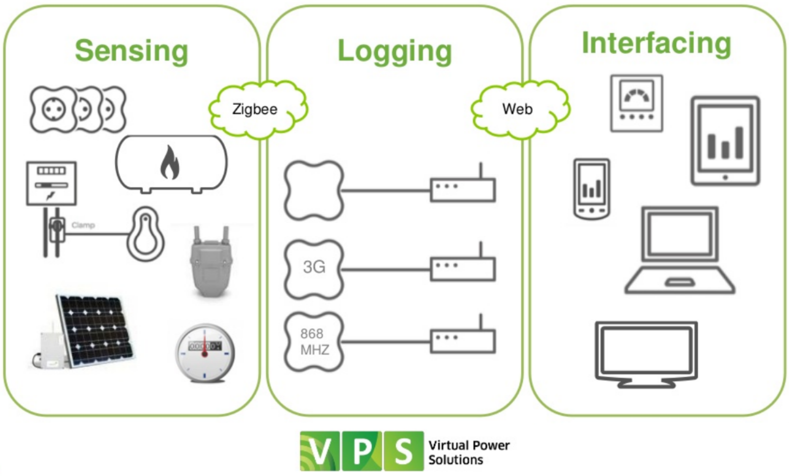


Figure 1.1: Cloogy Diagram.

The idea for this thesis project came from one of VPS's clients, a home appliances seller, who wanted to improve his customers' experiences. The seller would like to have a solution to detect and predict anomalies in home appliances because, with that, his customers would be able to repair before they stop working. This will, in theory, lead to higher satisfaction levels to the final client.

---

[1] Home Energy Management System

[2] Building Energy Management System

In this project, we reused an existing hardware platform named *IdPlug*. *IdPlug* is a power plug developed by VPS to control water heaters. This hardware will have a new propose in this project. It will be a monitoring system who possesses anomaly detection algorithms.

1.4 Structure

This thesis is divided into six chapters: *Introduction, State of the Art, Specifications, Implementation, Tests and Conclusions.*

The *State of the Art* describes the operation of electrical motors and the most common issues that they present. The chapter also dives into the causes of such issues. Furthermore, it presents techniques in the frequency domain and statistical methods to detect faults in motors. Finally, two commercial fault detection products for home appliances are presented.

In the next chapter, we have the general description of the *idPlug* operation and the general hardware specification. The device requirements are also presented in this chapter.

The *Implementation* chapter introduce the algorithm used to monitor and detect faults in home appliances. The user local interface developed to control the plug and show the data, will be also presented.

The testing methodology will be shown in the *Tests* chapter. This includes algorithm testing and functional verification. Functional verification will be further subdivided into two scenarios. Firstly, verify that all client-defined requirements are addressed. Finally, the system will be deployed on two appliances to validate its operation under real workloads.

In the *Conclusions*, we present the results and provide some insight into their meaning. Finally, we suggest possible future improvements in the plug and some methods that could produce better results in fault detection.

CHAPTER 2

STATE OF THE ART

2.1 Home Appliances

Home appliances are devices whose main objective is helping with domestic tasks, like cooking, cleaning, or doing laundry. They can also be used for entertainment, such as TV.
The devices can be classified into four distinct types [2]:

- ALWAYS ON → once they are on, they remain on 24 hours a day, 7 days a week (telephone, smoke detectors);
- ON/OFF → appliances that have only two states, on or off (toasters and lamps);
- MULTI-STATE → appliances with a finite number of operating states (washing Machines and dishwasher);
- CONTINUOUS VARIABLE → appliances that have an infinite number of states and different power levels (power tools);

These different states are represented in Figure 2.1

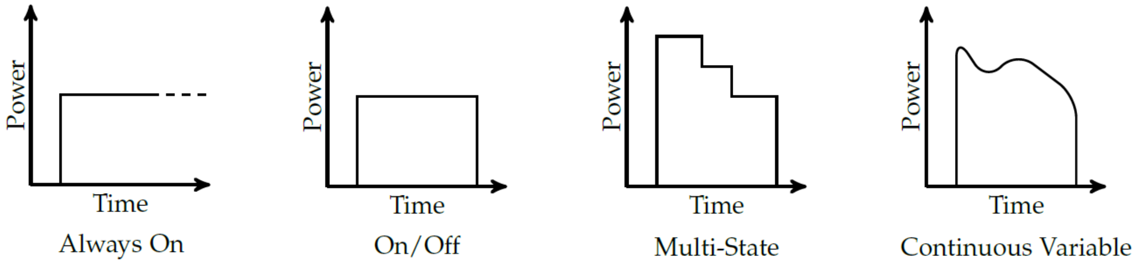


Figure 2.1: Representation of different operation behaviours. (From [2])

Another way to divide home appliances is classifying them by their basic power consumption element. So, taking this into account:

- INDUCTION COIL OR MOTOR → refrigerators, washing machines and dishwashers;
- HEATING RESISTANCE → incandescent lamps and toasters;
- ELECTRONIC CIRCUITS → TVs and computers;

For this thesis, we focused primarily on INDUCTION COIL OR MOTOR type. Therefore, the next sub-sections focus on this type of appliances.

2.1.1 Power Profile

Each type of appliance has its own behaviour and purpose. And each type has different operations and methods to achieve its goal.

2.1.1.1 Refrigerator

The refrigerator is an multi-state device, and its principal energy consumption source is the motor, more specifically the compressor. This appliance is used to regulate the temperature of a cold room.

How it works: The refrigerator has pressurized liquid or coolant. This liquid enters through the expansion valve (yellow in Figure 2.2) where it expands, cools and turns partly into gas. Afterwards that, the cold liquid will absorb and remove the heat from the food inside. Then, the fluid enters the compressor, where it is squeezed, and it becomes a heated and high-pressure gas. This gas flows through the radiator pipes on the refrigerator's back, and releases heat causing the coolant to cool down. The liquid flows to the expansion valve, and the cycle repeats itself [3].

Graph b) of Figure 2.3 has four states: normal, open door, ice-making and defrost cycle. The last two consume more energy. Looking at graph a) of Figure 1.4, we can see that the motor is turned on and off with a certain periodicity to prevent the inside from warming to room temperature. When the door is open the compressor works more time and therefore it consumes more power [4].

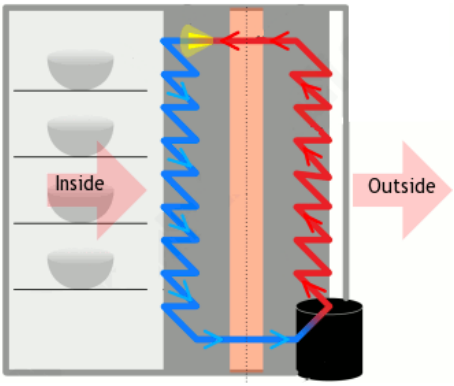


Figure 2.2: Functional diagram of a refrigerator. (From [3])

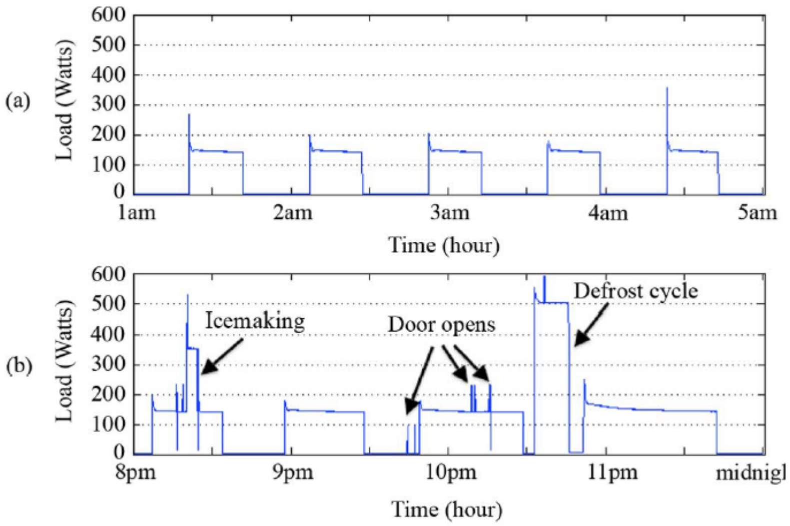


Figure 2.3: Power consumption of a refrigerator unit: (a) no activity; and (b) with door opens, an ice-making cycle and a defrost cycle. (From [5])

Another parameter that will influence the power consumption profile of home appliances is the manufacturing year. With today's continuous scientific research and technological progress, electronic devices tend to get more and more environmentally friendly. Figure 2.4 compares an 20-year-old refrigerator with a more recent mode (energy class: A). The older fridge has four cooling cycles in 24 hours, where each period lasts between 2 and 4 hours with an average consumption of 140 watts. The new fridge has approximately a cycle per hour and consumption below 60 watts. The average consumption for the old and new fridge is 1.7K W/24 h and 440 W/24 h, respectively. So, the old fridge consumes 3.86 times more than the new one [6].

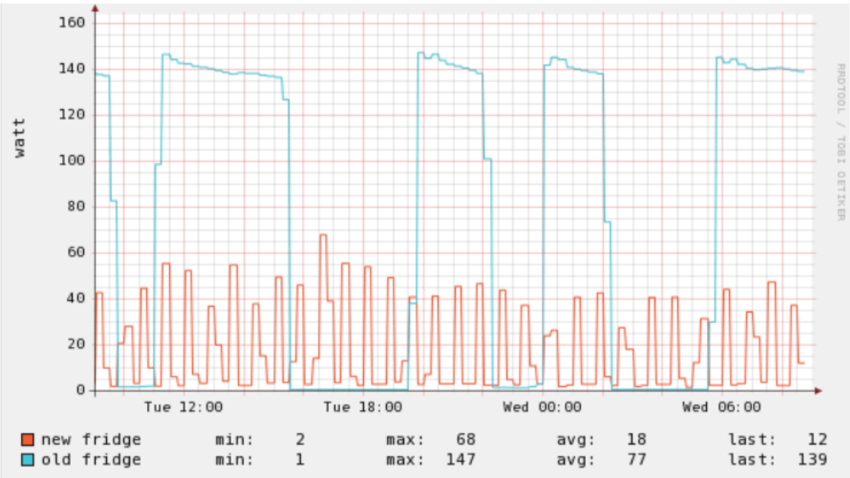


Figure 2.4: Power consumption of a new vs. old fridge.(From [6])

2.1.1.2 Washing Machine

A washing machine is a multi-state appliance whose principal energy consumption source is the heating element. The power profiles of the washing machines depend on the washing program selected by the user. Figure 2.5 shows a general diagram of a washing machine and Figure 2.6 presents the power profiles of different washing programs.

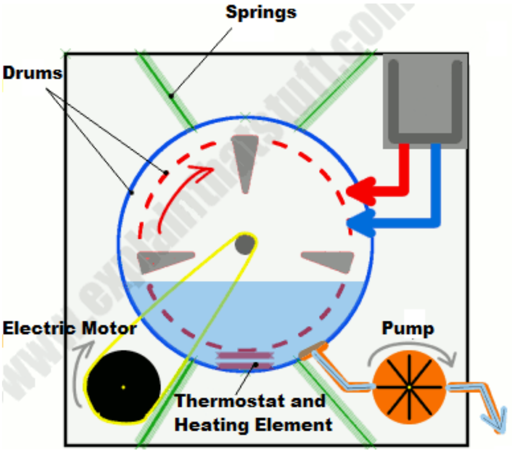


Figure 2.5: Functional diagram of a washing machine. (From [3])

How it works: When the cycle starts the hot and/or cold water valves open and the drum fill up with water and detergent. Next, the thermostat measures the temperature of the water and, if it is too cold, the heating element activates, until the water reaches the right temperature. At this stage, the inner drum rotates back and forth. After a certain amount of time, the dirty water is drained with the help of a pump. Then, clean water enters the drums again, the water temperature adjusts, the drums rotate, and the dirty water is drained again. This cycle repeats several times until all the soap is removed. After this, the drums rotate at high speed to expel water from the clothes. Finally, the pump turns on to remove any remaining water. In the end, the user can remove his clean clothes from the machine. [3].

In Figure 2.6, whenever the heating element is active there, with a maximum observed of 2000 W. About 1/4 of the washing cycle is spent heating water. During the heating stages, the pump is off. The motor is switched on in the other periods to rotate the drums back and forth and to rinse the clothes (spin cycles). Different washing programs have different durations. The total cycle time of the first plot of Figure 2.6 is about 2 hours. In the others, the cycles last around 1 hour. The number of heating and spin periods also vary with the washing program [4].

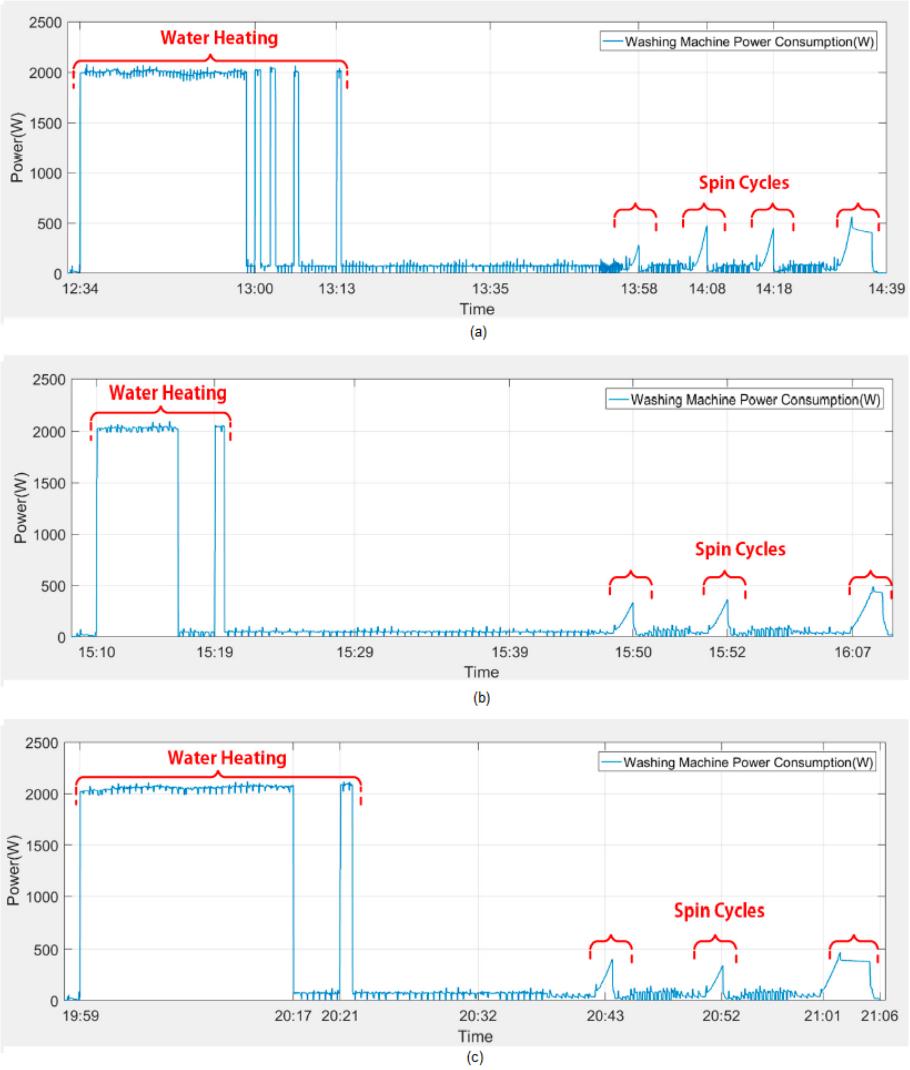


Figure 2.6: Power consumption of a washing machine for the: (a) cotton and synthetics washing programs at 40 °C; (b) mixed washing program at 30 °C; (c) mixed washing program at 40 °C. (From [4])

2.1.1.3 Dishwasher

A dishwasher is a multi-state appliance, and its principal energy consumption unit is the heating element. Similarly to what we previously observed for the washing machine, the dishwasher power profiles vary with the program selected by the user, see the Figure 2.8. Figure 2.7 we have a general flow of a dishwasher.

How it works: The cold water enters in the machine. The thermostat measures the water temperature and turns on the heating element if the water is not hot enough. An electric pump sends the hot water to different parts of the machine, and it squirts up to clean the dishes. The waterfalls turn to the bottom of the machine, where it is heated and pumped again. In the end, the dirty water is pumped out of the machine. [3]

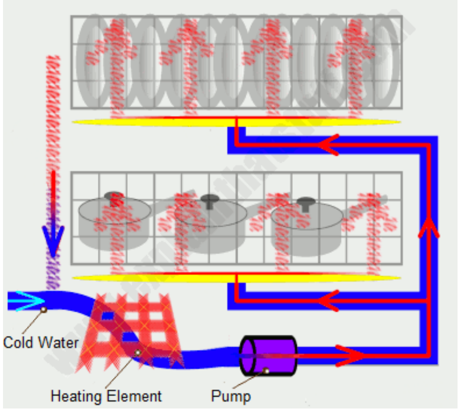


Figure 2.7: Functional flow of a dishwasher. (From [3])

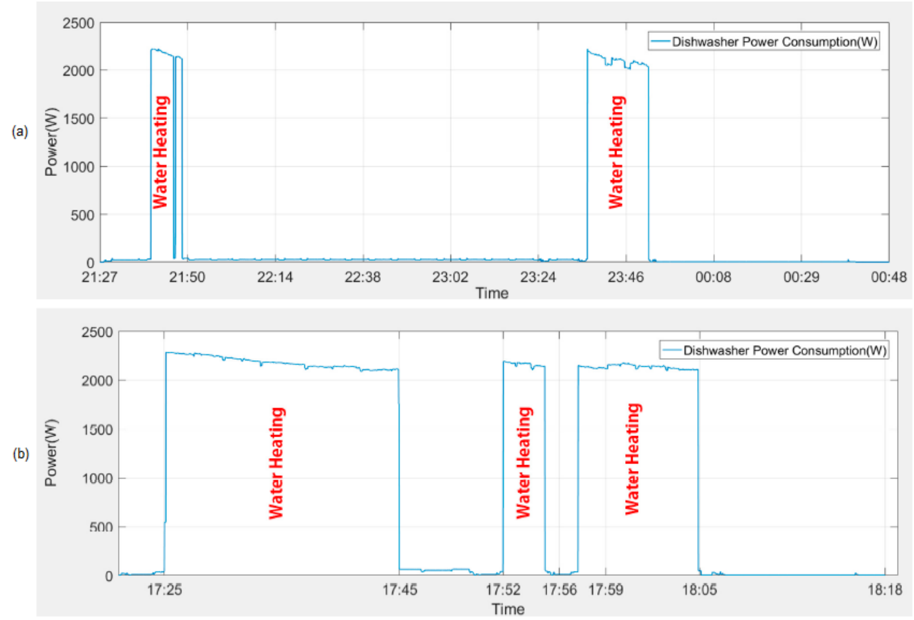


Figure 2.8: Power consumption of a dishwasher for the: (a) 55 °C economy program; (b) 65 °C power program. (From [4])

Similar to washing machines, in the dishwasher the higher power consumption is caused by the heating element, as seen in Figure 2.8. When this element is off the motor is switched between on and off to move the water throughout the machine. In Figure 2.8, it is possible to see the cycle on/off of the electric pump between the two water heating periods.

2.2 Motors

The majority of domestic appliances use single-phase motors. These motors generally run at a constant speed and have a low rate-power – less than 2 kW [7]. Such types of motors have a permanent magnet and a coil arrangement, known as rotor and stator, where the former is the rotating part and the latter is the stationary part (Figure 2.9) :

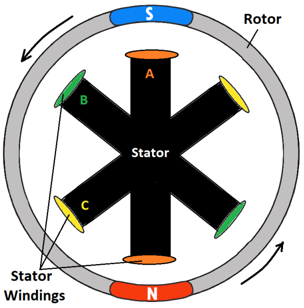


Figure 2.9: Diagram of a DC motor with 6 poles.

2.2.1 Single-Phase Motors

Single-phase motors have the stator which is a coil winding with an AC [1] power input. The winding passes through the stator slot. When current passes through the winding, according to Faraday's law, a rotating magnetic field is produced, which causes the rotation of the rotor. This happens because the alternating current variation causes a variation in the field's orientation. The combination of uniform strength rotation, which interacts with the squirrel cage rotor - a conductor (Figure 2.10)-, producing an electromagnetic force (EMF) as per Lorentz's Law. Consequently, the squirrel cage will rotate [8].

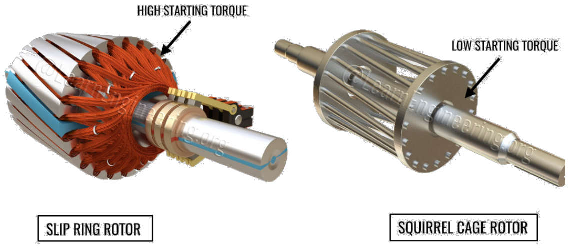


Figure 2.10: Diagram of a slip ring rotor and a squirrel cage rotor. (From [9])

---

[1] Alternating Current

The squirrel cage produces a very low starting torque, which can lead to problems in motors. Therefore, when needed, a slip ring induction is used (Figure 2.10) due to the high starting torque they produce. In a slip ring rotor, three windings are used instead of bars – as was the case in the squirrel cage [9].

Induction motors are robust, reliable, durable, and easier to design than DC [2] motors. This type of motor allows adjusting the rotation speed by controlling the input power frequency. Furthermore, these motors don't have a permanent magnet, brush commuter rings, position sensors [10, 8]. The following list highlight some technical features of the single-phase induction motor.

- Uses a single-phase supply;
- Low starting torque, so is not self-starting;
- Easy to maintain and repair;
- Simple and cheap;
- Low efficiency;
- Low power factor;

2.2.2 Problems in Single-phase motors

Induction motors can be affected by both external and internal stress, resulting in anomalies that decrease its efficiency. This stress can be observed in different components, as shown in Figure 2.11 [10].

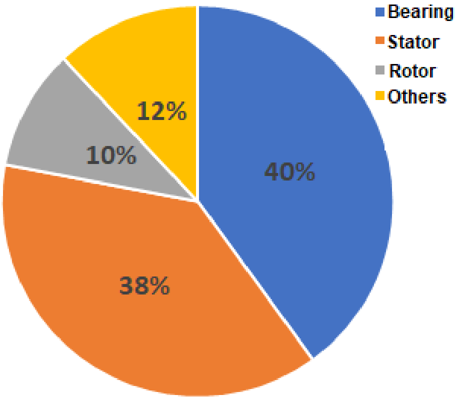


Figure 2.11: Percentage of motor components failures. (From [10])

---

[2] DC: Direct Current

Anomalies present in induction motors can happen due to a defective design, short circuits, or excessive loads. The main faults are usually [10]:

- Bearing wear: wear causes the gap eccentricity to increase which, in turn, can result in serious stator core damage and destruction of the stator's winding.
- Stator Faults: faults are due to opening or shorting stator phase winding.
- Irregularities in air-gap, which will reduce the electromagnetic field, the current and consequently the torque.
- Increased centrifugal force due to high mechanical imbalance in the rotor.
- Broken rotor bars.
- Critical speed shaft resonance, resulting in increased rotor core vibrations and forces.

The motor's breakdown translates into a loss of trust in the product from the users, affecting the brand's reputation and potentially leading to financial losses [10]. For the consumer, an appliance malfunction represents extra costs if the warranty period has ended. Therefore, it is important to use methods that can either detect or predict motor malfunctions as a preventive way to reduce unnecessary expenses.

2.2.3 Signals to Detect Motors Faults

Signals like vibration, current, reactive power, and energy consumption are commonly used to detect failures in motors. Collecting and processing data on such parameters is important to correctly detect faults.

Vibration

The vibration sensors have to be installed near the vibration source. This is quite limiting because the vibration source is very difficult to access (once the motor is fully assembled). Another disadvantage of using these sensors is that its analysis is too general, and every machine has a specific vibration standard. So it can't be used in a general way because every machine has its specific vibration standard. Despite this, this type of sensors can detect incipient mechanical anomalies in machines [11].

Current

The current is one of the best parameters to identify anomalies. The electric current sensors are non-invasive, meaning that the sensor doesn't need to be put inside the device. To obtain electrical current data, a sensor must be installed on the supply cable of the appliances. Furthermore, the current signal is not subject to as much interference as the vibration signal. Data collected can be analysed with simple analytical methods like the Fast Fourier Transform (FFT) [12].

Reactive Power

As seen in section 2.1, household appliances can be separated according to their basic power consumption element: induction coil or motor (e.g. washing machines), heating resistance (e.g. incandescent lamps) and electric circuits (e.g.Tv). Reactive power, as the name indicates, is power dissipated by reactive loads, such as inductors and capacitors. This parameter is a powerful tool as it allows detecting faults before they happen [13]. This parameter is given by:

$$Q = V \times I \times PF \tag{2.1}$$

Where V is the voltage, I the current and PF is the power factor.

Consumption

Consumption is commonly used to check the healthy behaviour of machines. When an appliance is new, it consumes a specific amount of energy. However, with time, this consumption tends to increase due to wear and tear of the equipment. This parameter is, therefore, a good indicator for long term anomalies.

2.3 Fault Detection Methods

There is a large array of methods to detect malfunctions in induction motors. The two main types are: pattern recognition techniques, and advanced signal processing. The former mostly relies on neuro-fuzzy and artificial intelligence applications, while the latter spans time, frequency, and time-frequency domain approaches.

The signal processing methods in the time domain are very effective in detecting faults on electrical power systems. On the other hand, the techniques in the frequency and time-frequency domain are more commonly used in malfunction detection in motors. These techniques allow getting spectra with high resolution, like the Fast Fourier Transform (FFT). Other spectra that can be used are the higher-order spectra (HOS), such as the bispectrum and the trispectrum. The HOS are powerful but require more computational resources [14].

2.3.1 Motor Current Signature Analysis (MCSA)

The Motor Current Signature Analysis (MCSA) uses the current spectrum to detect motor faults.

The FFT is applied to construct the spectrum of the current's signal. An advantage of this transform is the computational speed. However, it has spectral leakage due to the limited time window and light loads don't allow for an exact distinction between healthy and faulty rotors [15].

The stator current analysis is done during normal operation of the motor or at start-up [13]. MCSA can diagnose faults in real-time without interrupting or stopping the motor [16].

In a healthy motor, the stator current spectrum has a single frequency supply component, but more components will appear if any fault is present. [17]. When a motor has a broken rotor bar, no magnetic field is generated on it, hence creating an asymmetry in the rotor's magnetic field that will lead to new harmonics in the stator current - used as broken rotor bar signatures. Consequently, new sideband components will appear, following the expression [10]:

$$f_b = (1 \pm 2ks)f_s \tag{2.2}$$

k=1,2,3,..., s: motor slip, f_s*: main frequency*

The lower sideband ($f_l = (1 - 2ks)f_s$) is due to the broken bar. The upper sideband ($f_u = (1 + 2ks)f_s$) is due to the speed oscillation and saturation phenomena. However, other factors like motor load inertia can affect the sidebands and need to be taken into account. Resulting in:

$$f_b = \left[\frac{k}{p}(s-1) \pm s\right] f_s \quad , \quad \frac{k}{p} = 1,3,5,... \tag{2.3}$$

The fundamental and the lower sideband components are used to differentiate a healthy motor from a motor with broken bars.

In short, MSCA has limited accuracy in diagnosing broken rotor bars as it is influenced by saturation, inter bar currents and magnetic asymmetry. MCSA works only with steady-state signals, which are hard to achieve in real life situations. [13].

In [12], MSCA was used to detect different types of faults in motors. The first depicted case, with compressor drives A and B, is the most relevant to our project. The authors used MCSA to diagnose beating noises and pulsating vibrations produced by compressor A, obtaining the spectrum shown in Figure 2.12 with the motor at reduced load.

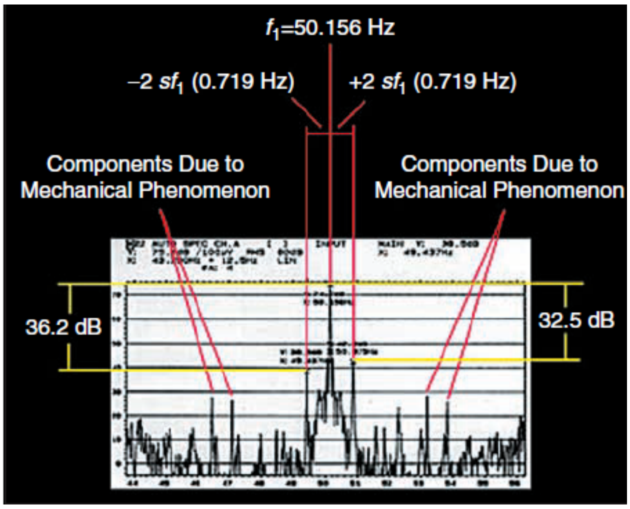


Figure 2.12: Current spectrum of faulty motor A. (From [12])

In the spectrum, sidebands can be observed at ±0.72 Hz, this means the motor has broken rotor bars. The authors concluded that the compressor had at least five or six broken bars. Figure 2.13 depicts compressor B's spectrum. This motor didn't have broken rotor bars as the compressor A. Both spectra have sidebands from normal mechanical phenomena.

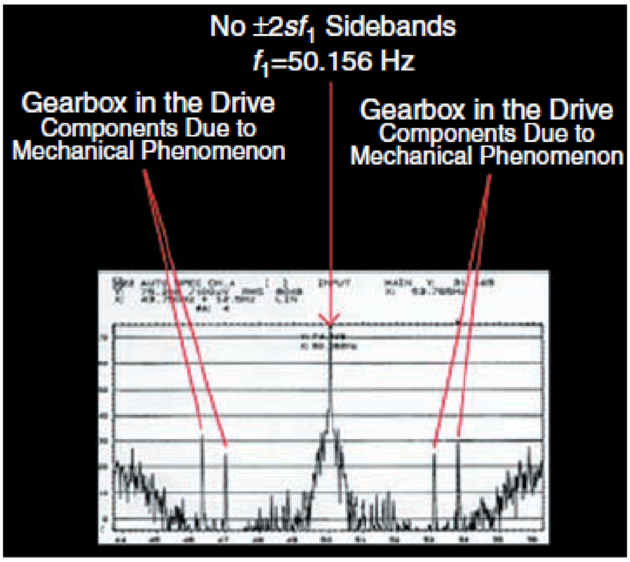


Figure 2.13: Current spectrum of motor B which didn't have broken rotor bars. (From [12])

Another example of using MCSA to study motors failures was presented in [18]. In this study, LabVIEW 8.2 was used to construct a virtual instrument to obtain the spectrum of current. The authors used a three-phase induction motor (0.5 hp, 415 V, 1.05 A, and 1380 r/min) where rotor faults were replicated. In this experiment, the spectrum of a single current was obtained, and tested with different numbers of rotor bars (Figure 2.14).

Observing the plots of Figure 2.14, we can conclude that increases in the number of broken bars results in higher side-band peaks (notice the peaks at 42 Hz and 59 Hz). The authors concluded that MCSA was capable to detect faulty conditions.

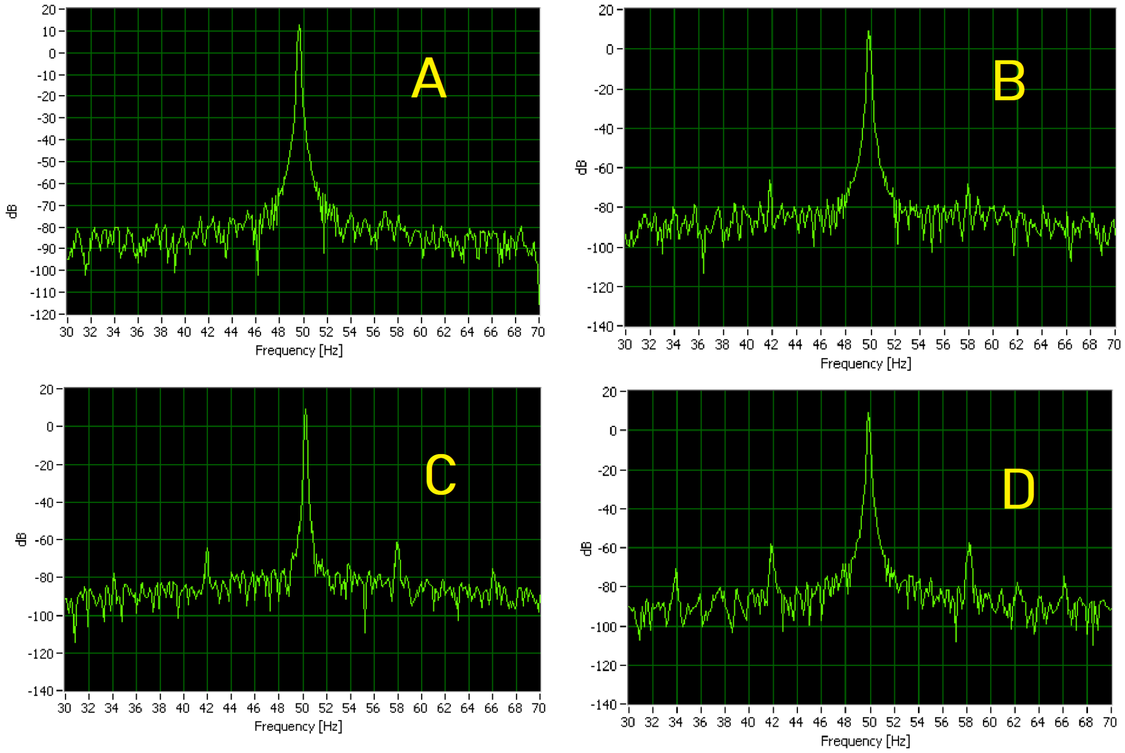


Figure 2.14: Current spectrum of the three phase induction motor (0.5 hp, 415 V, 1.05 A and 1380 r/min) with A) no broken bar (healthy) B) 1 broken bar under full load, C) 5 broken bar under full load and D) 12 broken bars under full load. (From [18])

Sometimes, however, it is difficult to detect faulty frequencies in the current spectrum. To mitigate this issue, an approach to combine the frequency domain analysis with a method of pattern recognition called Principal Component Analysis (PCA) has been suggested [19]. Initially, PCA is applied to different current spectrum samples, and he calculated the key index, more specifically, the Hotelling's T^2 distribution and the squared prediction error (SPE). The results are presented in Figures 2.15 and 2.16 [19].

Figure 2.15 shows that the samples of faulty motors diverge from the healthy motor circle. Furthermore, Figure 2.16, demonstrates that the T^2 is a good indicator of whether a motor is faulty, as the values are higher when there is a motor anomaly.

This method allows determining faults in motors with more accuracy. To use PCA, samples need to be collected for a long period of time, requiring in a greater computational capacity.

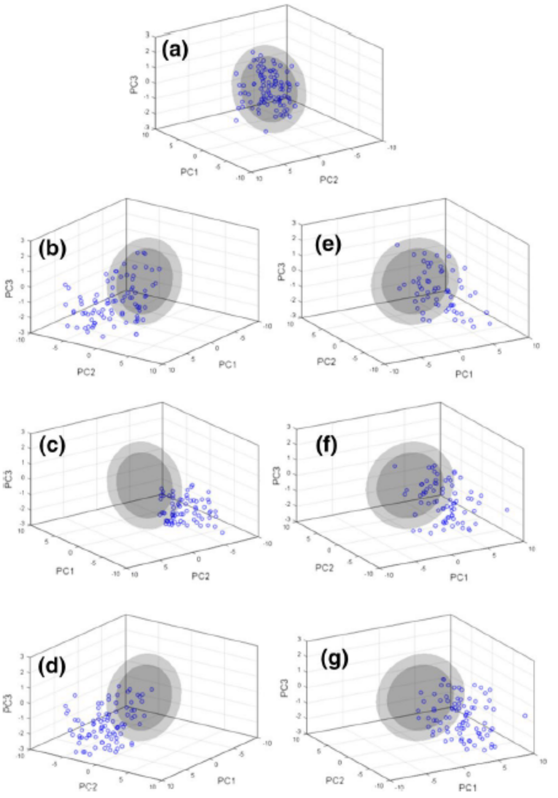


Figure 2.15: PCA Loads of the feature selection of FFT frequency and amplitude: a) healthy condition, b) one broken bar condition, c) two broken bar condition, d) three broken bar condition, e) one broken end-ring condition, f) two broken end-ring condition, g) three broken end-ring condition. (From [10])

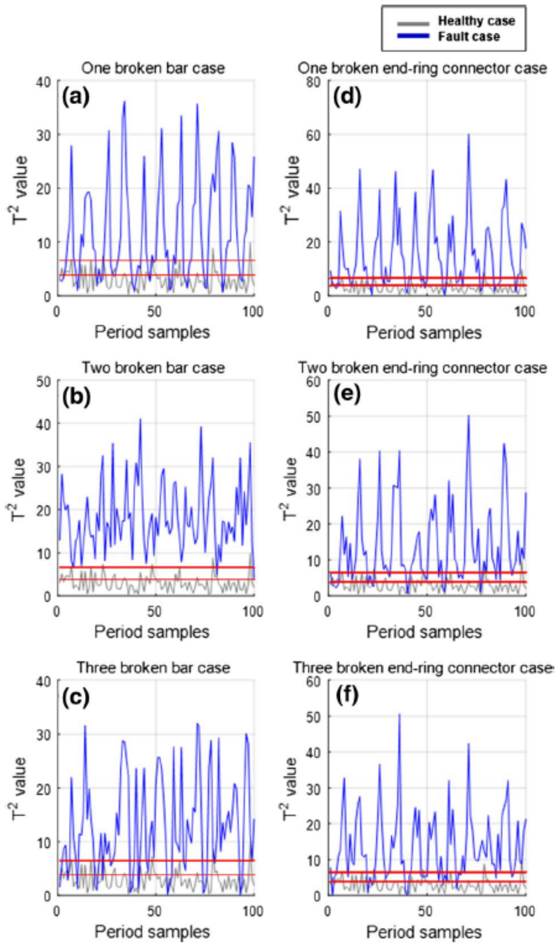


Figure 2.16: Hotelling's T^2 value of the feature selection of FFT frequency and amplitude: Healthy condition (gray line), Fault condition (blue). a) One broken bar condition, b) two broken bar condition, c) three broken bar condition (blue), d) one broken end ring condition, e) two broken end-ring condition, f) three broken end-ring condition. Cases and confidence limit of healthy at the loading plot of the PCA and Hotelling's T^2 value (From [10])

2.3.2 Bispectrum

Signal statistics can be used to calculate different moments: the first moment - the average; the second – the signal's power or variance; the third – the skewness. Skewness is the degree of distortion from a symmetrical normal distribution. The bispectrum result from the decomposition of the third moment of the signal (skewness) over frequency. This type of spectrum is used to analyse asymmetric non-linearities in systems, providing information about non-linear coupling between frequencies of a signal [20, 21].

The bispectrum is calculated using a double Fourier transform of the skewness of a time signal. As seen in equation 2.4, there are two frequency components (both amplitudes and phases) of the signal together with a frequency component summation, this is [21, 22]:

$$B(f_1,f_2) = F(f_1)F(f_2)F^*(f_1+f_2) \tag{2.4}$$

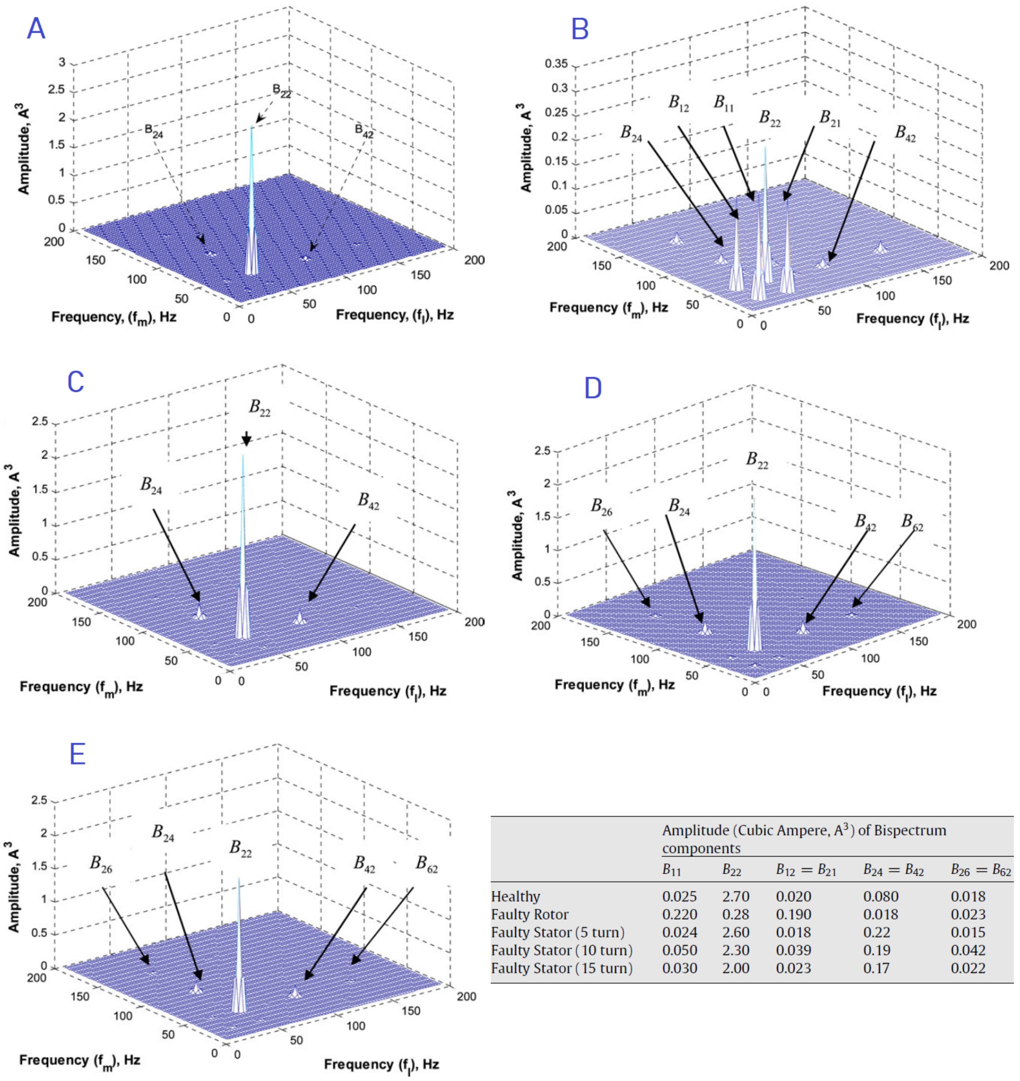
Where F is the Fourier transform and f_1 and f_2 are frequencies.

The bispectral estimates may vary due to dependencies on power spectral properties. The bicoherence results from a normalisation of the bispectrum, and allows to obtain more accurate information. It also allows the detection of phase coupling. The range of bicoherence values is $[0, 1]$ corresponds uncoupled to complete coupling, respectively. The bicoherence is given by [22]:

$$b(f_1,f_2) = \frac{|B(f_1,f_2)|}{\sum_{f_1,f_2} |F(f_1)F(f_2)F^*(f_1+f_2)|} \tag{2.5}$$

The bispectrum is a very powerful tool as it allows the analysis of components that can't be seen in the power spectrum.

J. Treetrong and Ball ([21]) conducted a study using bispectrum of stator current to detect faulty motor conditions. In these experiments, they used three-phase induction motors (4 kW, 1400 RPM) with a load cell, and analysed different conditions: healthy motor, motors with a short circuit (5, 10 and 15 turns short), and with broken bars. The data was collected at a sample rate of 1280 samples/s and obtained the graph. Figure 2.17 shows the results obtained.



	Amplitude (Cubic Ampere, A^3) of Bispectrum components				
	B_{11}	B_{22}	$B_{12} = B_{21}$	$B_{24} = B_{42}$	$B_{26} = B_{62}$
Healthy	0.025	2.70	0.020	0.080	0.018
Faulty Rotor	0.220	0.28	0.190	0.018	0.023
Faulty Stator (5 turn)	0.024	2.60	0.018	0.22	0.015
Faulty Stator (10 turn)	0.050	2.30	0.039	0.19	0.042
Faulty Stator (15 turn)	0.030	2.00	0.023	0.17	0.022

Figure 2.17: The bispectrum of the stator phase current for a A) healthy motor, B) a motor with broken rotor bars, C) 5 turns short circuit, D) 10 turns short circuit, E) 15 turns short circuit. The Table contains the information of the peaks graphs amplitude.(From [21])

For a healthy motor, the only relevant peak is B_{22}, however for faulty motors, this component decreases while other peaks increase. For instance, motors with short circuits the peaks $B_{24}(= B_{42})$ and $B_{26}(= B_{62})$ increase Furthermore, motors with broken rotor bars the peaks with highest gain are B_{11} and $B_{12}(= B_{21})$. The amplitude of spectral peaks can be observed in the table contained in Figure 2.17.

In short, different motor conditions result in different predominant peaks, enabling the distinction between healthy and faulty motors, and the identification of the fault's type. Thus, it can be concluded that this method successfully identifies different types of faults at an early stage.

2.4 Commercial Fault Detection Systems for Home Appliances

2.4.1 Renesas Failure Detection e-AI Solution

Renesas Electronics Corporation launched an Artificial Intelligence (AI) solution to detect faults in home appliances motors.

This solution uses the Renesas Motor Control Evaluation System as well as the Renesas RX66T 32-bit, which acts as a single micro controller that regulates the motor and detects anomalies. This AI solution also possesses a Graphical User Interface (GUI) Tool that is responsible for collecting data and analysing it, providing information about the motor's state. To detect faults, the AI algorithm must, initially, learn the characteristics of a healthy motor. The GUI tool allows training the algorithm to such effect. Furthermore, there is the possibility of algorithmic optimisation to improve fault detection [23]. The abnormal motor state is detected using an acceleration sensor,as well as measurements of current, torque, and rotation speed. [24].

The Renesas' solution can trigger an alarm whenever a fault is found, identifying its location and estimating the maintenance schedule. It is important to note that Renesas' product can control up to 4 motors, which is quite useful since some home appliances have more than one motor – washing machines, for example, have 3 [23].

In 2019, Renesas presented this solution at *electronica* [3] by using a small DC motor with a minimal load (Figure 2.18). To show a conditioning failure, some additional load was added to the system, leading to a fault percentage indication on the board's display.

---

[3] World's leading trade fair and conference for electronics

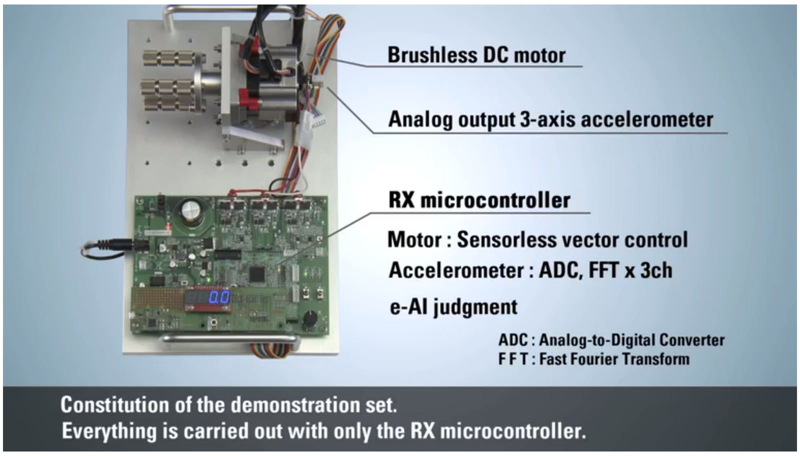


Figure 2.18: Demonstration set used.(From [24])

Figures 2.19 and 2.20 show Renesas' interface. These Figures show the vibration data, the corresponding FFT, and the percentage of faulty condition for a motor with 75% (Figure 2.19) and more than 100% of abnormal behaviour (Figure 2.20).

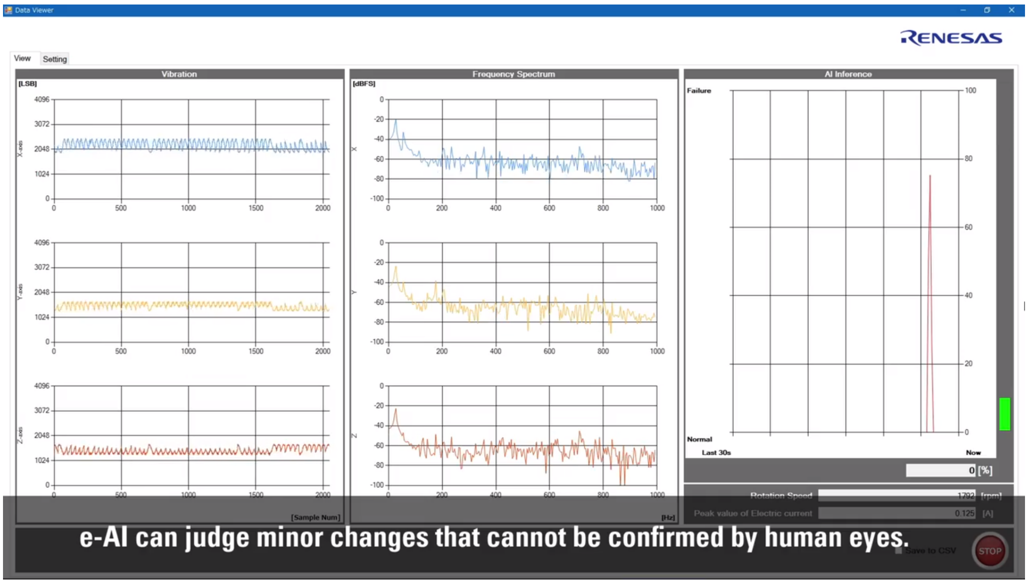
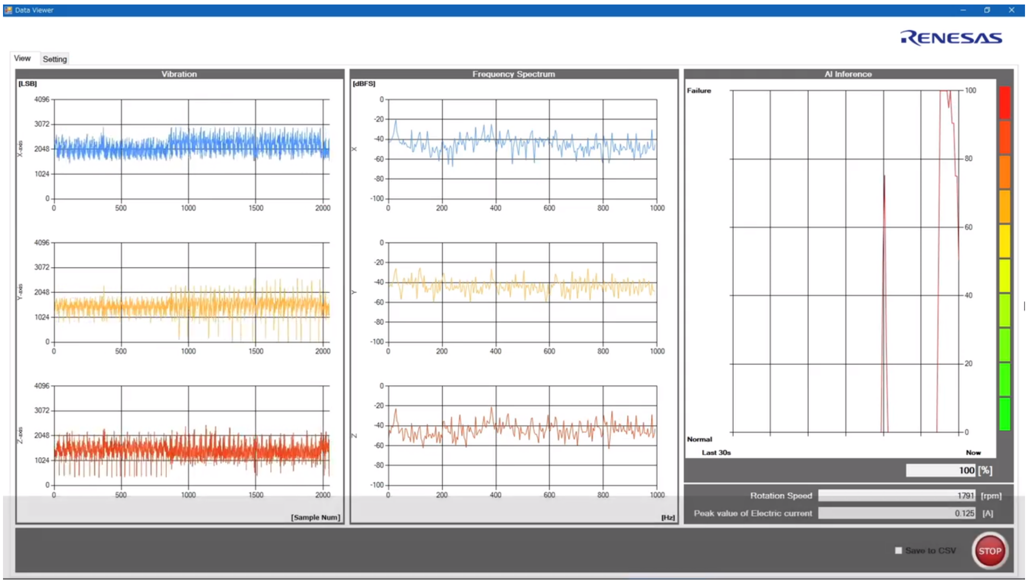


Figure 2.19: The Renesas interface for vibration data when there is about 75% of abnormal behaviour.(From [24])

Renesas' solution allows home appliance manufacturers to improve the efficiency of maintenance and the safety of their products [23].



100 [%]

Rotation Speed 1791 [rpm]

Peak value of Electric current 0.125 [A]

Figure 2.20: The Renesas interface for vibration data when there is more than 100% of abnormal behaviour.(From [24])

2.4.2 Verv

Verv was founded in 2017, with a proposition to reduce the number of appliances that are thrown away every year and, as a consequence, reducing the overall environmental impact of disposing and replacing them.

The company focuses on monitoring commercial and domestic appliances' health *in quasi-real-time*, detecting anomalies by analysing their energy signatures, as seen in Figure 2.21. With those signatures, Verv can locate where the fault is, or will be, and identify incipient component fatigue.

The proposed solution resorts to artificial intelligence as a mean to train the algorithms to detect faults. Using high-speed data acquisition – about 10 000 samples per second – , a high resolution image is generated, and anomalies that cannot be detected by traditional sensors are found.

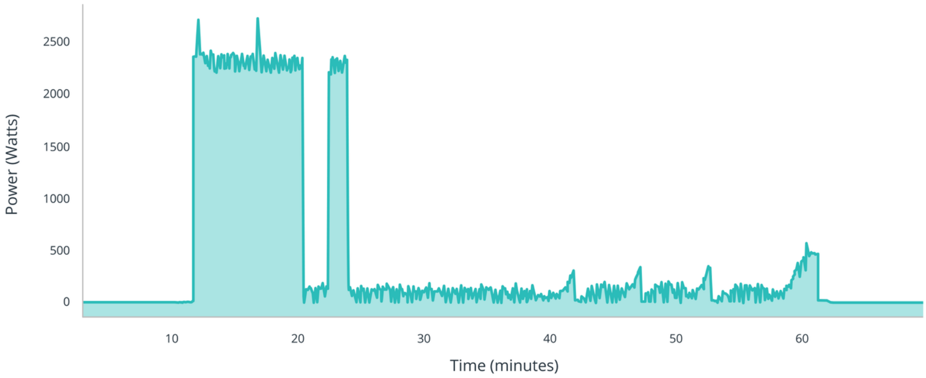


Figure 2.21: A normal energy signature of a washing machine cycle using the Verv technology. (From [25])

Furthermore, the solution can be commercialized in two different ways (Figure 2.22): either as an embedded microchip that integrates the appliance's circuit board; or as an in-line adapter called *Verv Connect*, which is an in-line adapter that works as an extension. The latter option does not change the manufacturing process, making it useful to use in an existing install base.

Figure 2.22: Verv solution: embedded microchip (right) and *Verv Connect* (left). (From [25])

CHAPTER 3

SPECIFICATIONS

3.1 General Description

The system, herein proposed, is based on the idPlug – developed by VPS – , whose original purpose was monitoring electric boilers. For this project, the plug measures the current, voltage, power (active, reactive, and apparent), power factor, frequency, active energy, and the network's current signal. All the data is collected and processed in the plug and can be further analysed as a way to monitor household appliances and detect faults. The FFT is the principal mean to detect anomalies, as we will see in section 4.1.3.1. Each FFT has 1024 samples and its sampling frequency is 512Hz, this values will be discussed in section 5.1.1.

The processed data can be accessed through a local user interface that allows better data visualization and facilitates the user's interaction with the product.

In Figure 3.1, we can observe how the system developed in this project works.

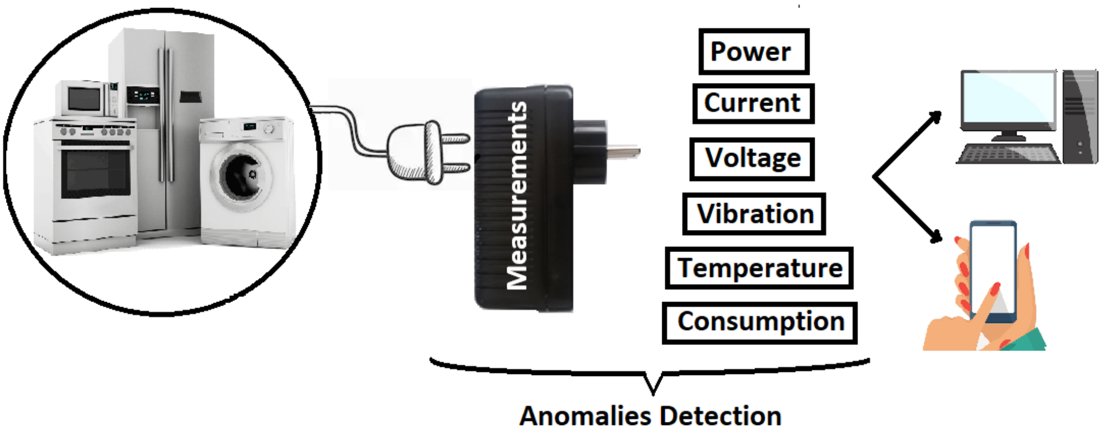


Figure 3.1: Explanatory diagram of the system to be developed in this project.

3.2 Plug - Hardware

The hardware used for this work is the *idPlug*, see Figure 3.2. This device encompasses a low-power micro controller with integrated Wi-Fi and dual-mode Bluetooth, called ESP32-WROOM-32D [1]. An user interface (button and bicolor LED [2]), mechanical relay, as well as temperature and vibrations sensors - that were not used in our experiments – can also be found in the *idPlug*. A high-performance energy metering device, called ATMEL-M90E26 [3], is present as well. This ASIC

---

[1] The ESP32 general specifications are in section A.2

[2] LED: Light Emitting Diode

[3] The ATMEL-M90E26 general specifications are in section A.3

(Application-Specific Integrated Circuit) measure voltage, current, power (real and reactive) and other parameters. The ATMEL-M90E26 is cheap, and it doesn't need too many external components. The energy is measured using this ASIC instead of using the microcontroller, which allows us to do short time measurements.

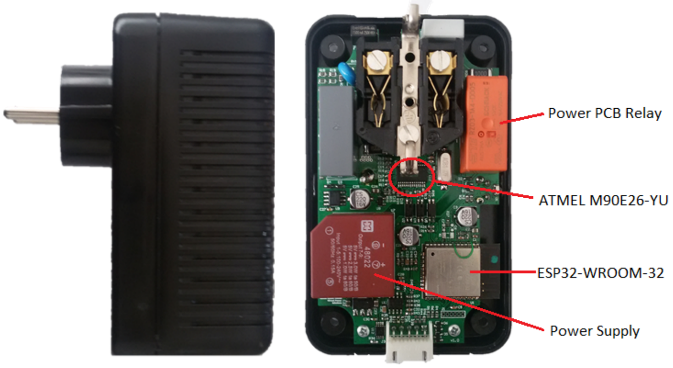


Figure 3.2: *IdPlug* developed in VPS.

To achieved the system goal a current transformer was added to the *IdPlug*. The sensor transform the voltage into current using a resistor (180 Ω) , and has a gain of 1/3000. The maximum current supported by the sensor is 75A, which means that, at the transformer output, the current is 25 mA. A diagram of the hardware can be accessed in section A.1.

3.3 Requirements

This section describes the system requirements classified into four main groups: Hardware, Software, Local User Interface, and General. The requirements can be functional or non-functional, and optional (OP) or mandatory(M).

3.3.1 Hardware

All the hardware's requirements can be considered non-functional because they have been previously defined and therefore, are just being reused. This requirements are divided into four groups: Electrical, Aspect, Measurement, and Communication requirements.

3.3.1.1 Electrical

The Electrical requirements are related to the hardware limitations.

Req. nº 1: **Home Network** (M) → The device must works on a standard domestic installation (220 V-240 V and 50/60 Hz).

Req. nº 2: **Power Consumption** (M) → The device power consumption must be less than 3 W.

Req. nº 3: **Maximum Current** (M) → The maximum current is 16 A.

Req. nº 4: **Socket and plug type** (M) → Type C and F.

3.3.1.2 Interface

The interface requirements define what the user can see and interact with.

Req. nº 5: **Indicators** (M) → The device should have at least one bi-colour LED as an indicator.

Req. nº 6: **Button** (M) → The device should have a button for the interaction user-device.

3.3.1.3 Measurement

These requirements are related to the type of data that the hardware is capable of measuring.

Req. nº 7: **Electrical Measurement** (M) → The device should measure the current, voltage, and power of the load connected to it.

Req. nº 8: **Additional Measurement** (OP) → The device should measure the energy, consumption, vibration, and temperature.

Req. nº 9: **Meter** (M) → The measurement of energy and electrical parameters must have a precision of about 3%.

3.3.1.4 Communication

This requirement specifies the type of communication interface used.

Req. nº 10: **Communication** (M) → To communicate the device uses Wi-Fi (IEEE 802.11n).

3.3.2 Software

The software requirements are all functional and are related to code implemented on the device to monitor the appliance and detected faults. They are divided into 2 groups: Operation (from ten to fourteen) and Data (from fifteen to seventeen).

3.3.2.1 Operation

In Operation requirements the software behaviour and its aims are defined.

Req. nº 11: **Fault Detection** (M) → The device must be able to detect anomalies in the monitored appliance.

The fault detection can be done in real-time, analysing data directly on the device, but can also be done with long term data, offloading the computation to the cloud and using machine learning algorithms for the processing, for example.

Req. nº 12: **Standby mode** (OP) → The fault detection frequency should decrease when the appliance is not operating for a long time (at least 3 minutes).

When an appliance is not being used for some time, it is not necessary to measure and process data with the same frequency as when the appliance is under active used because there is less variation in the data collected.

Req. nº 13: **Turned On/Off the load** (OP) → The device must be able to control whether the load (appliance) is connected.

This requirement enables the client to turn on/off an appliance remotely.

Req. nº 14: **Real time Clock** (M) → The device must have an internal clock synchronized with a web service.

Req. nº 15: **AP Mode** (M) → The device must possess a mode that allows settings Wi-Fi parameters and access to all collected data when there is no Wi-Fi network available.

3.3.2.2 Data

These requirements are related to the data specification and its acquisition and analysis frequency.

Req. nº 16: **Detection** (OP) → The fault analysis must occur at least once every two minutes.

The appliance work cycle can have a duration of minutes or hours. High frequency fault analysis is not required due to the low variance in the appliance's state.

Req. nº 17: **Data Measurement** (OP) → Data measurement should be done at most every minute for a minimum of one day.

Req. nº 18: **Data storage** (OP) → Data must be stored at most every minute.

As stated in requirement 15, the appliance's behaviour doesn't change very often. Hence, data can be stored infrequently.

3.3.3 Local User Interface

A local user interface, in this case a graphical user interface (GUI) [4] exists to facilitate the data visualization and the interaction between the device and the user. The specifications for this interface are as follows.

Req. nº 19: **Power Behaviour** (OP) → Consult the appliance's power behaviour over a long period (minimum 3 hours).

Power behaviour is essential to recognise the type of appliance and identify irregularities in its consumption. The specified three hours are is a good minimum time to observe two to three consecutive work cycles , providing a good overview of consuming patterns.

Req. nº 20: **Measurements** (M) → Consult the appliance's electrical information such as current, voltage, power, frequency, and consumption.

---

[4] GUI: Graphical User Interface

Req. n^o 21: **Fault information** (M) → Consult the number of faults, the data used to detect the fault, and a list of failures.

Req. n^o 22: **Wi-Fi** (M) → Consult Wi-Fi information and change the connectivity, i.e. alternate between networks.

Req. n^o 23: **Settings** (M) → Consult and change parameters in device's software, like electrical appliance information and parameters of the metering device.

Req. n^o 24: **Web message** (M) → Provide notifications and warnings via a web page.

3.3.4 General

There are two general requirements:

Req. n^o 25: **Price** (M) → Lower than 30 €.

Single unit price is 30€. However, the bulk price (1000+) is 17.02 €per unit. Both values are excluding the assembly cost.

Req. n^o 26: **Installation** (M) → The system installation must be easy for non-technical people.

This requirement is essential as this product must be accessible to everybody, from electrical-savvy to the clueless.

CHAPTER 4

IMPLEMENTATION

The previous chapter provided insight into the proposed solution for fault detection in home appliances. Furthermore, a description (and enumeration) of specific customer requirements for the developed system were provided. This chapter focuses on the technical details of the implementation.

4.1 System Operation

As specified in Chapter 3 the system's main goal is to monitor appliances and detect faults. Hence, it is required to collect and process data–mostly on-chip. The main parts of the developed system are, thus, the ATMEL90E26 current meter – to collect data – , and the ESP32 micro-controller – to process it. The focus of this section is to explain system operation. In that regard, descriptive flowcharts of critical algorithms will be presented. These will allow a deep understanding over the data processing that occurs on the device. Five such flowcharts will be presented, namely: main, machine status, peaks calculation, fault detection, reference data, and meter.

4.1.1 Main

The Main flowchart describes the user interaction with the device. As illustrated in Figure 4.1, upon initialization, the system will immediately move to the 'Machine Status' stage to determine whether the appliance is on or off. This will also perform some initialization procedure – to be described below. Upon return the "Meter" stage will be launched as a parallel process. The main thread will then wait for user input (button press). The user might, at this point, enable the device's network (with a long press of the available button), or set the value of "Reference variable" to the boolean value True.

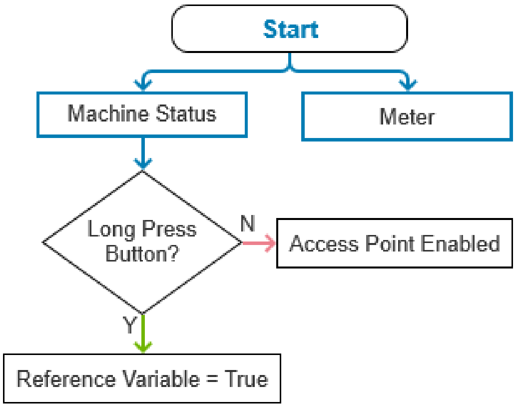


Figure 4.1: Flowchart of the "Main".

4.1.2 Machine Status

The main goal of "Machine Status" (see Figure 4.2) is to initialize the monitoring systems once the appliance (machine) is determined to be turned on. To do so, the system analyses the current going through it and compares its amplitude against 2 mA. This value – determined experimentally to avoid any small oscillations – is the cut-off point used, anything above this is associated with "on" state. Once the machine is determined to be operating, a thread is launched with the "Fault detection" algorithm–to be explained in section 4.1.3.

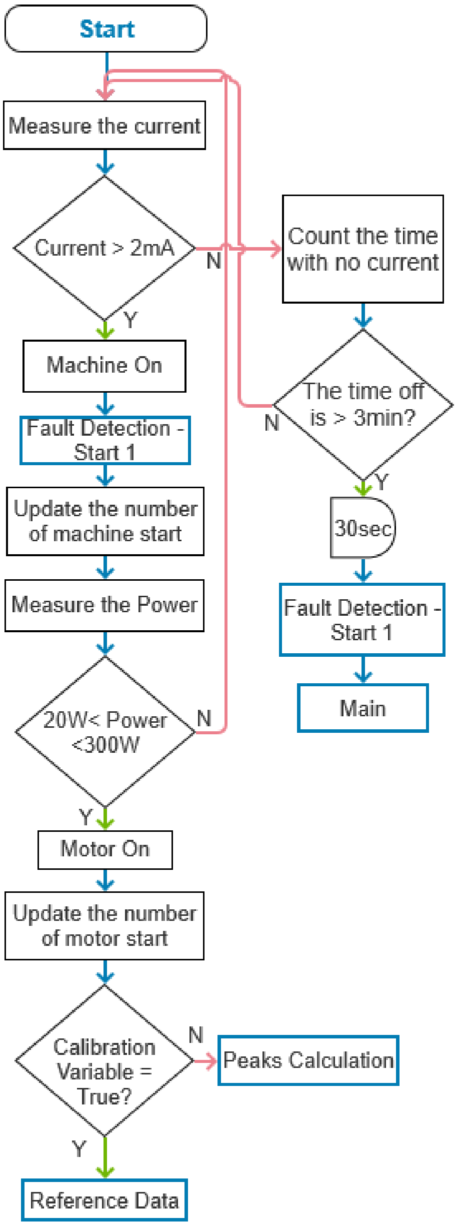


Figure 4.2: Flowchart of the "Machine Status".

After launching the ”Fault detection” thread the system proceeds to analyse the power being drawn – this will determine whether the appliance’s motor has been enabled. The motor is determined to be on if the appliance is drawing more than 20 W and less than 300 W – which correspond to the power range of the majority of motors in home appliances, such as dishwashers or washing machines. They have a heating element, it is assumed than when this element is on the motor is off. The distinction of motor and heating element is easily done at the power level, an heating element will draw close to 2000 W, which corresponds to 6.7 more than the maximum for an average appliance motor. Finally, once the motor is considered to be working the program will either enter ”Reference data” mode (if selected by the user), or ”Peaks calculation” mode (by default). The system keeps track of how many times a given appliance is started. If the appliance is determined to be in stand-by mode (due to a drop in current to below 2mA) for more than three consecutive minutes, the fault detection algorithm will run only every 30 seconds.

4.1.3 Fault Detection

4.1.3.1 Fault Detection Methods

Chapter 2 identified two possible methods for detecting faults: MCSA and using a combination of Hottelling’s T-squared distribution on the current spectrum with PCA. Both of these methods proved challenging to implement and, therefore, were discarded. To work, MCSA requires knowing, at every moment, the rotor’s speed. This requires a sensor to be placed inside the motor. Hence, it is infeasible to use as a non-intrusive method. However, it could be employed with direct manufacturer support. Furthermore, the second method, requires comparing the measurements taken in the developed system against a baseline taken from a known-to-be-healthy motor. This would require some assistance from appliance manufacturers which, at the time of writing, was not possible due to global social-economical conditions.

To tackle the lack of algorithmic support, a method was devised. Careful evaluation of both approaches described above indicate that, in normal conditions, the current’s FFT value will peak near 50 Hz. Hence, by knowing the peak frequency of a new device (assuming such an appliance to have a healthy motor), a baseline can be established. However, this approach has two drawbacks: assuming that a new appliance has a healthy motor and relying on the user to perform the initial calibration. The former can be tackled by considering the manufacturer’s datasheet for the appliance. The latter, however, is easily achieved by using the user interface present on the device.

Once a baseline is established, by means of the initial data collection, the newly acquired data can be viewed as an offset to this. A bigger deviation from the baseline will, likely, mean a fault. The following sections will focus on data acquisition and processing.

4.1.3.2 Peaks Calculation

The main goal of "Peaks Calculation" is the FFT computation and peak detection algorithm.

First, we calculate the FFT of the current signal and, after that, we identify its peaks. In section 5.1.1, we conclude, that to have a better identification of the spikes, it is essential to do the average of some FFTs. Therefore, in the flowchart of Figure 4.3, we collect one FFT each second until we have ten FFTs. Afterwards, the average is computed and the seven highest maximums are estimated. The current procedure takes, roughly, one minute to complete. Increasing the number of FFT samples could delay the start of the next sampling period, hence, a trade-off has to be made, measurement stability for processing time. Between FFT computations there is a three minute interval where the motor state is monitored, any change would trigger the process to restart. After computing the spikes, the "Fault Detection - Start 2" can start.

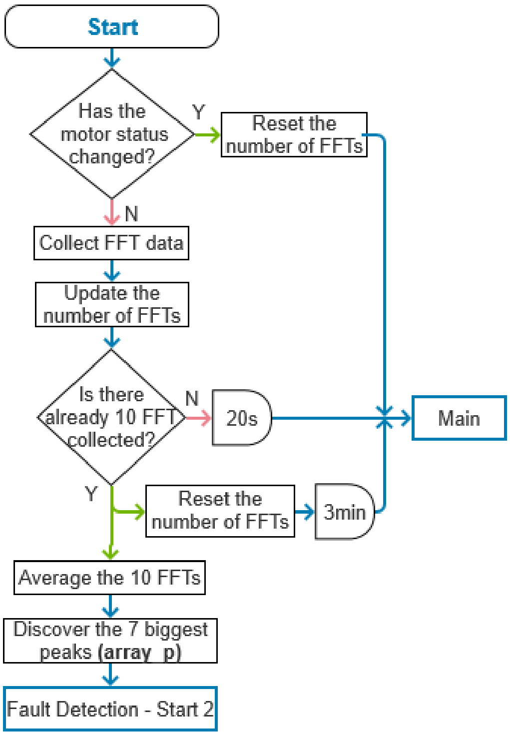


Figure 4.3: Flowchart of the "Peaks Calculation".

In the Table 4.1, we have some general time information about the fault detection method used.

Table 4.1: General time information about the fault detection code.

Information		Value
FFT sampling frequency		512 Hz
FFT samples		1024
FFT number (FFT block)		10
Delay between FFT		20 seconds
Delay between FFT block		3 minutes
Delay between each detection (start1)		3 minutes
Delay between each detection (start2)		5 seconds
After the fault detection (start2)	Time to collect FFTs again	3 minutes
	Time to go back to check the machine status	1 minute

4.1.3.3 Fault Detection

The "Fault Detection" flowchart illustrates the fault detection methods. This algorithm can be reached via two distinct paths, which shall be identified as "Start 1" and "Start 2".

Similarly to the FFT values, an average is used for the power value to avoid noise, hence, a measurement of instantaneous power is made periodically and averaged. For refrigerators or freezers, the average value is calculated with the power values obtained during five minutes. However, for washing machines and dishwashers, due to their multitude of states, the values are considered for only one minute at a time.

"Start 1" can be reached via the "Machine Status" flow. This path is focused on detecting discrepancies in energy consumption, power, current, and standby power, whose acceptable ranges have been defined by the user through the GUI – as shall be seen in 4.2.2) of the user interface. If the measured value is outside the range limits, a failure is detected and signalled to the user. Otherwise, no anomaly is detected.

Differently, "Start 2" is reached directly from the "Peaks Calculation" flow. This branch is used to detect failures in a working motor. This method is based on the analysis of the FFT spikes. Initially, it is verified if the highest spike happens near to network frequency. Then, the average of the frequencies at which the spikes occur is compared with reference value. Finally, a similar comparison is performed on the average amplitude of the peaks.

If, at any point in the described algorithms, a fault is found then a corresponding "Fault Code" [1] will be added to a list of failures that can be consulted by the user. Similarly, a counter keeps track of the total number of faults detected.

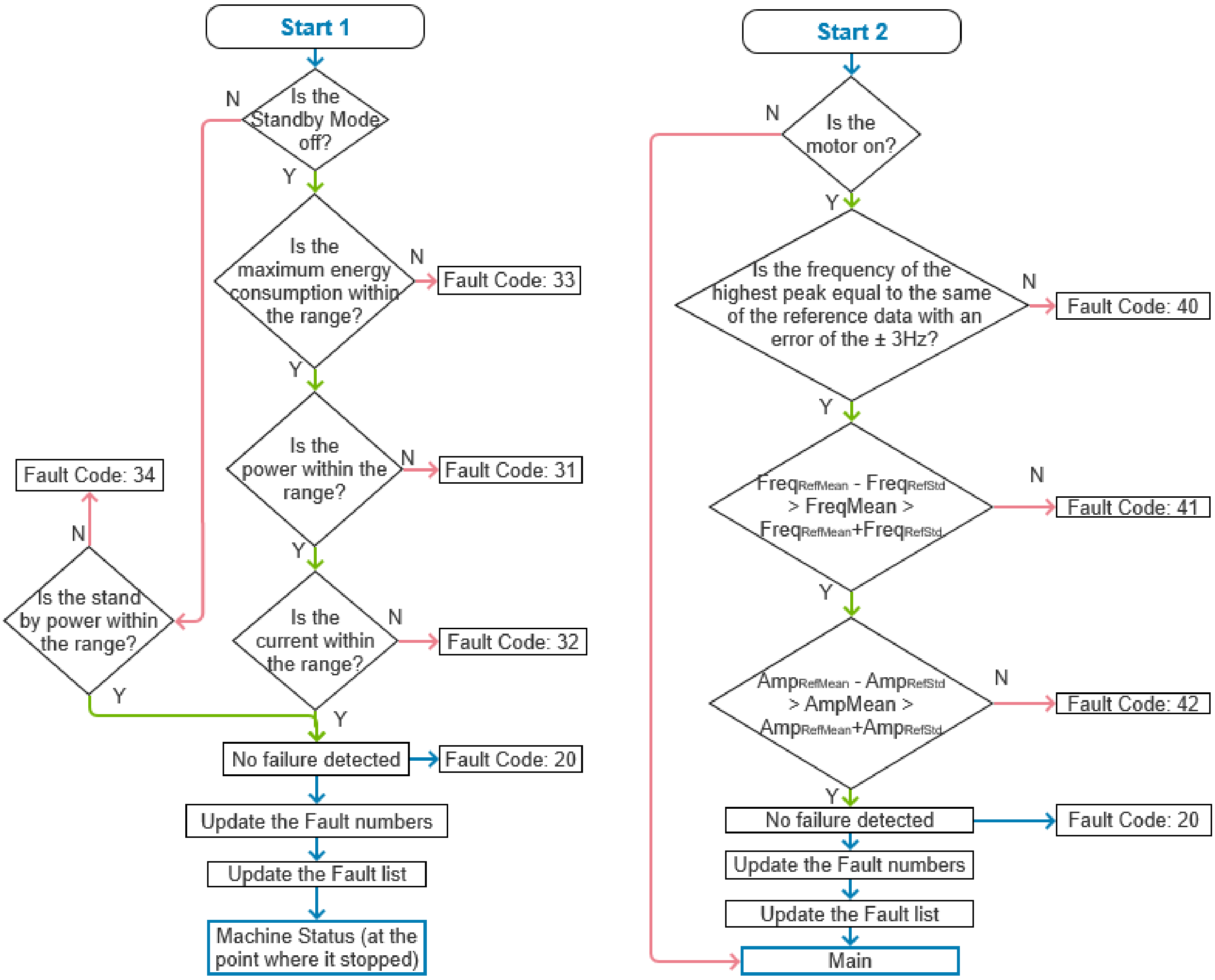


Figure 4.4: Flowchart of the "Fault Detection Mode".

4.1.4 Meter

"Meter" is the main data collection algorithm. Using the ATMEL-M90E26 module data such as current, voltage, energy consumption, frequency, and power (reactive and active) is acquired. Measurements occur every second and are used in the previously described "Fault detection", "Peaks Calculation", and "Machine Status" algorithms

---

[1] See the "Fault Code" list in Figure 4.8

4.1.5 Reference Data

The ”Reference data” flowchart is the reference data generation algorithm, where the baseline used on the fault detection algorithm is defined. The reference data generation algorithm is similar to the ”Peaks Calculation” flow, as can be seen in Figure 4.5. In this flow, data is collected to perform ten FFTs and find the seven highest values of the average FFT. Then, the average and the standard deviation of the frequency and amplitude of the spikes is calculated. This data will be used as reference values to detect anomalies, and will be saved it will be saved in the device memory.

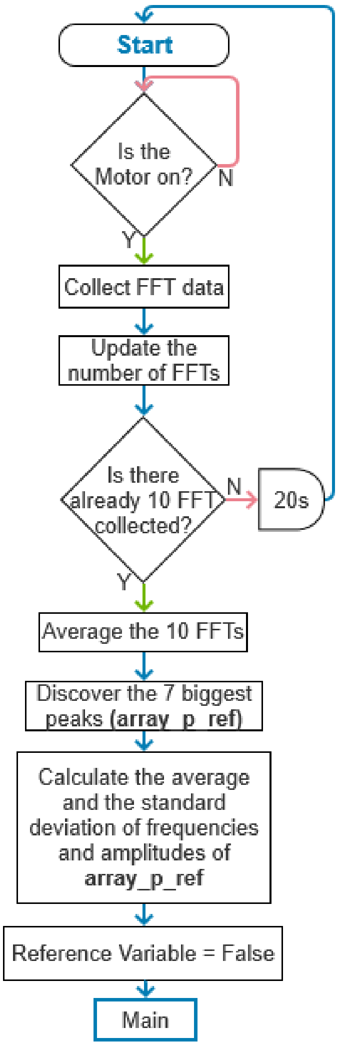


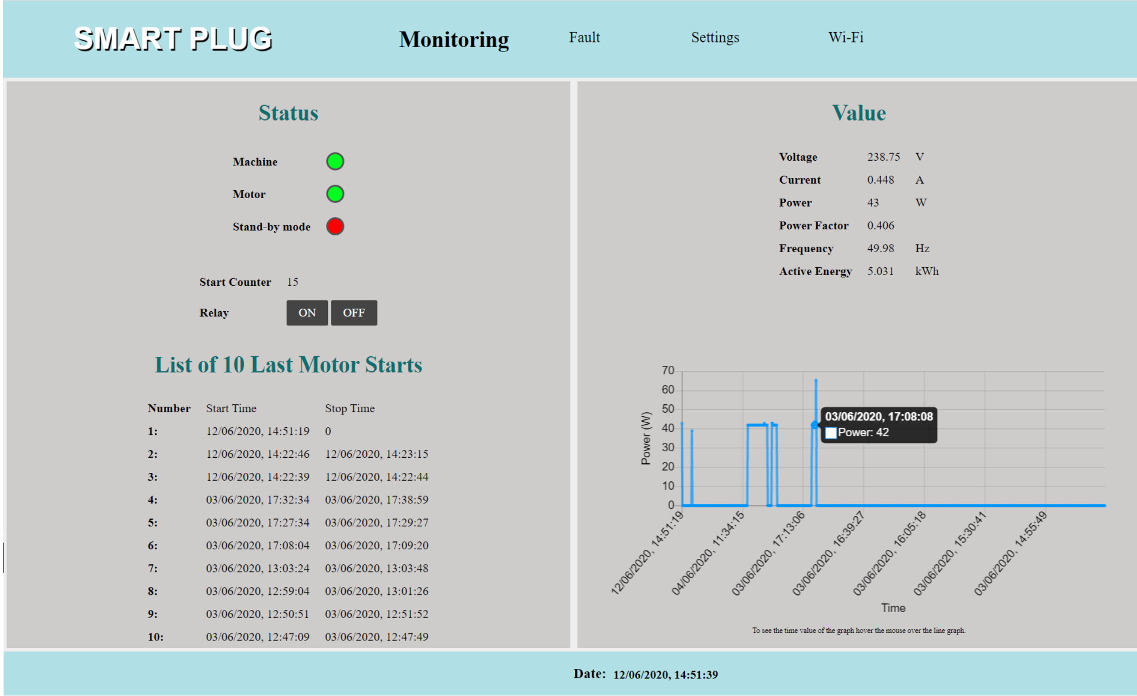
Figure 4.5: Flowchart of the ”Calibration Mode”.

4.2 User Interface

A local user interface was developed to assist in testing and visualizing the data gathered by the device, as it allows easy access to the network functionalities in the host. This interface is composed by four tabs: **"Monitoring"**, **"Fault"**, **"Settings"**, and **"Wi-Fi"**.

4.2.1 Monitoring page

The **"Monitoring"** page (as seen in Figure 4.6) is directed towards general data of machine operation. In this page, information such as machine operating status, the list of operating cycles, some electrical information, and the machine power behaviour can be seen.



Start Counter 15

List of 10 Last Motor Starts

Number	Start Time	Stop Time
1:	12/06/2020, 14:51:19	0
2:	12/06/2020, 14:22:46	12/06/2020, 14:23:15
3:	12/06/2020, 14:22:39	12/06/2020, 14:22:44
4:	03/06/2020, 17:32:34	03/06/2020, 17:38:59
5:	03/06/2020, 17:27:34	03/06/2020, 17:29:27
6:	03/06/2020, 17:08:04	03/06/2020, 17:09:20
7:	03/06/2020, 13:03:24	03/06/2020, 13:03:48
8:	03/06/2020, 12:59:04	03/06/2020, 13:01:26
9:	03/06/2020, 12:50:51	03/06/2020, 12:51:52
10:	03/06/2020, 12:47:09	03/06/2020, 12:47:49

Voltage	238.75	V
Current	0.448	A
Power	43	W
Power Factor	0.406	
Frequency	49.98	Hz
Active Energy	5.031	kWh

To see the time value of the graph hover the mouse over the line graph.

Date: 12/06/2020, 14:51:39

Figure 4.6: Webpage "Monitoring" of the localhost interface.

On the right there are three indicators. The first one informs if the machine is currently operating or not. The second one indicates if the motor or pump is currently working by turning green (state on), something that can only occur if the previous indicator is also on. The **"Stand by mode"** turns on if the machine has been inactive for at least three minutes.

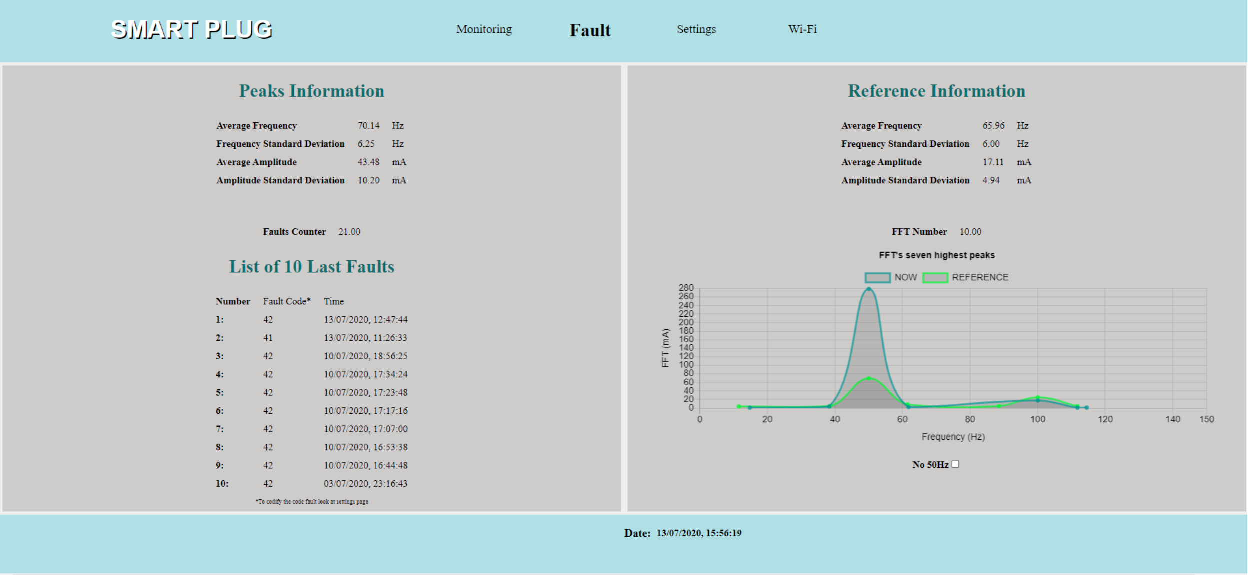
The "**Start Counter**" shows the number of times that the machine's motor has been started. This information can be useful for future fault estimations since it allows to correlate the number of motor starts with likelihood of fault (and failure) occurrence. The "**Relay**" buttons allow us to switch the device's load on and off.

Also present is a "**List of 10 Last Motor Starts**", where information about time operation cycles can be found.

The Value table presents ongoing voltage, current, power factor, frequency, and active energy data for that appliance. The power graph grants details about the machine's energy signature, an useful indicator of the kind of appliance presently linked to the device (see section 2.1). By knowing which type of appliance is currently connected, the graph can be analysed to infer if any anomalies are present in the machine. The graph will show the power data of the last three to six hours since the device is on, three hours being for washing machines and dishwashers, and six hours for refrigerators and freezers.

4.2.2 Fault page

In the **"Fault"** page (Figure 4.7) presents a list of the last ten faults occurred, among other details.



Peaks Information

Average Frequency	70.14	Hz
Frequency Standard Deviation	6.25	Hz
Average Amplitude	43.48	mA
Amplitude Standard Deviation	10.20	mA

Faults Counter 21.00

List of 10 Last Faults

Number	Fault Code*	Time
1:	42	13/07/2020, 12:47:44
2:	41	13/07/2020, 11:26:33
3:	42	10/07/2020, 18:56:25
4:	42	10/07/2020, 17:34:24
5:	42	10/07/2020, 17:23:48
6:	42	10/07/2020, 17:17:16
7:	42	10/07/2020, 17:07:00
8:	42	10/07/2020, 16:53:38
9:	42	10/07/2020, 16:44:48
10:	42	03/07/2020, 23:16:43

*To codify the code fault look at settings page

Reference Information

Average Frequency	65.96	Hz
Frequency Standard Deviation	6.00	Hz
Average Amplitude	17.11	mA
Amplitude Standard Deviation	4.94	mA

FFT Number 10.00

Date: 13/07/2020, 15:56:19

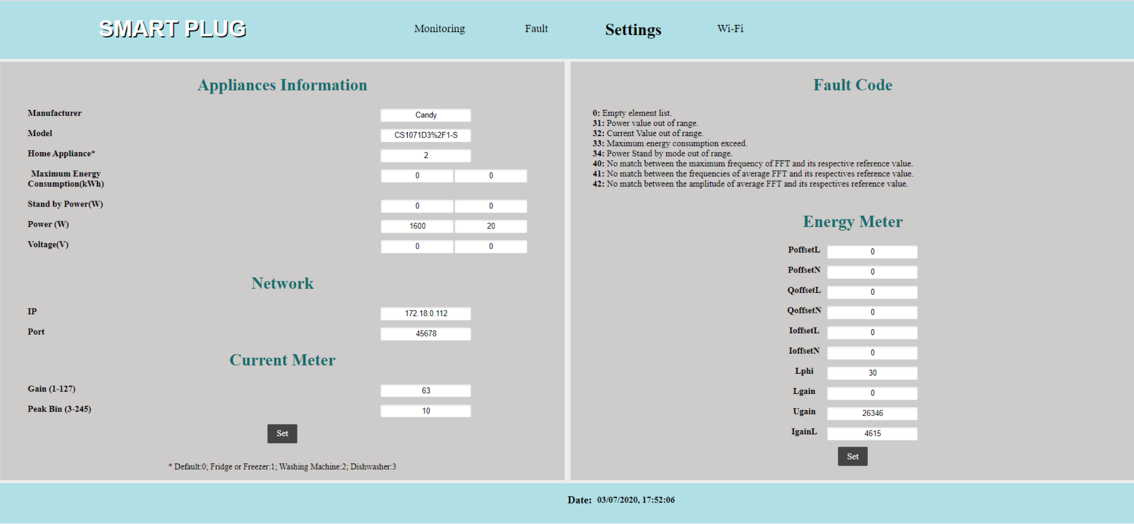
Figure 4.7: Webpage "Fault" of the localhost interface.

The current signal's FFT is an important tool to detect faults, as we see in section 4.1.3.1. The graph is a representation of the reference and current spikes. The check box "No 50 Hz" removes the spike at 50 Hz, which allows for a better visualizations of other spikes.

The Faults page indicates the number of anomalies encountered, and presents a **"List of 10 Last Faults"**, which has the fault code and information on when it occurred. The fault code can be decoded using the information in the **"Settings"** page.

4.2.3 Settings page

The **"Settings"** page (see Figure 4.8) allows consulting and modifying the information used in the code.



Appliances Information

Manufacturer	Candy	
Model	CS1071D3%2F1-S	
Home Appliance*	2	
Maximum Energy Consumption(kWh)	0	0
Stand by Power(W)	0	0
Power (W)	1600	20
Voltage(V)	0	0

Network

IP	172.18.0.112
Port	45678

Current Meter

Gain (1-127)	63
Peak Bin (3-245)	10

* Default:0; Fridge or Freezer:1; Washing Machine:2; Dishwasher:3

Fault Code

0: Empty element list.
31: Power value out of range.
32: Current Value out of range.
33: Maximum energy consumption exceed.
34: Power Stand by mode out of range.
40: No match between the maximum frequency of FFT and its respective reference value.
41: No match between the frequencies of average FFT and its respectives reference value.
42: No match between the amplitude of average FFT and its respectives reference value.

Energy Meter

PoffsetL	0
PoffsetN	0
QoffsetL	0
QoffsetN	0
IoffsetL	0
IoffsetN	0
Lphi	30
Lgain	0
Ugain	26346
IgainL	4615

Date: 03/07/2020, 17:52:06

Figure 4.8: Webpage "Settings" of the localhost interface

The **"Appliances Information"** table has information regarding the machine's model and characteristics, information that is not used in the code but can be useful for eventual future upgrades. The next element is the home appliance's type, which is used to change some of the timing variables in the code. As previously explained, modifications are necessary since the operating cycle of the of a refrigerator, for example, is more stable and regular than the cycle of a washing machine or a dishwasher. The next elements have two inputs, the first one is the data-sheet value (Maximum energy consumption, Stand by power, Power and Voltage), and the second is the maximum acceptable error associate to the value. If the value is not know, a zero has to be inserted in the respective input box.

The **"Network"** table provides network information, such as the Internet Protocol (IP) address, and the "Port", that we can be modified.

The **"Current Meter"** table displays the "Gain" element that allows changing the gain of the digital device potentiometer. The "Peak Bin" gives frequency interval between two consecutive points.

In the left, on this tab a glossary of the fault codes can be found. The "energy meter" table is also present, showing the energy metering device's (ATMEL-M90E26) parameters. And the **"Energy Meter"** table which has some parameters of the energy metering device, the ATMEL-M90E26. The elements of this table are described below.

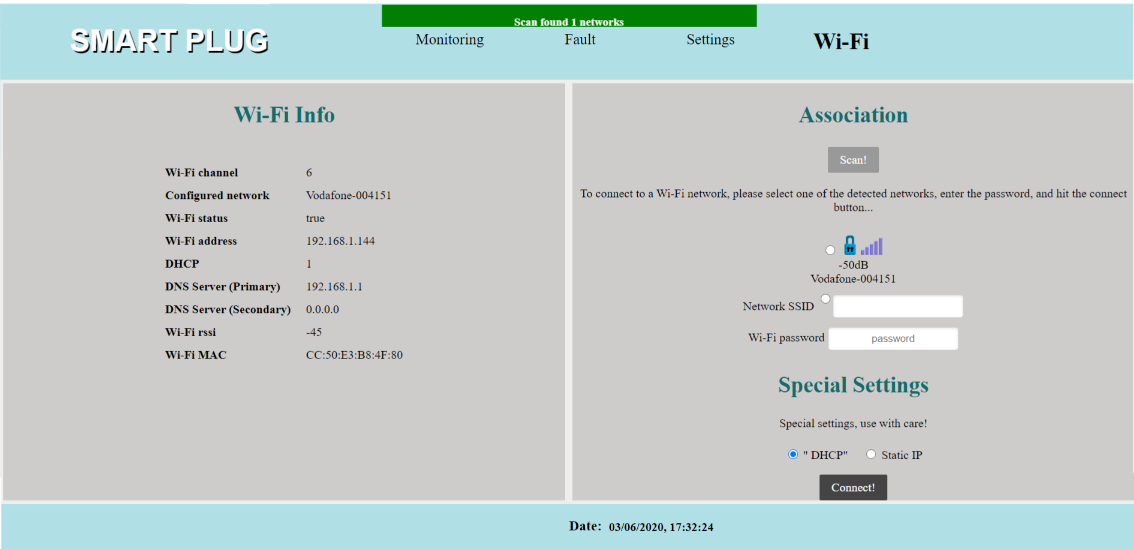
→ "PoffsetL/N" - Active power offset of the "N" or "L" line;
→ "QoffsetL/N" - Reactive power offset of the "N" or "L" line;
→ "IoffsetL/N" - Current offset of the "N" or "L" line;
→ "Lphi" - "L" line calibration angle;
→ "Lgain" - "L" line calibration gain;
→ "Ugain" - Voltage RMS gain;
→ "IgainL" - "L" line current RMS gain.

The button "Set" allows sending data from this page to the device, updating it.

4.2.4 Wi-Fi page

The **"Wi-Fi"** page (Figure 4.9) allows visualizing information regarding the Wi-Fi network that the device is connected to, and change the Wi-Fi network.

In order to do so, we need to connect the computer to the device's Wi-Fi network, named "ESP32". After making the connection, the localhost can be accessed, directing us to the Wi-Fi page – to do so the address 192.168.5.1 is utilized. The button scan initializes a search for all available networks. Upon finishing, a network must be selected, the password must be introduced, and the connect button must be clicked. If the connection is successful, a notification will appear. If not, an error message will be shown. After connecting successfully, a new the Wi-Fi address is generated.



Scan found 1 networks

Wi-Fi Info

Wi-Fi channel	6
Configured network	Vodafone-004151
Wi-Fi status	true
Wi-Fi address	192.168.1.144
DHCP	1
DNS Server (Primary)	192.168.1.1
DNS Server (Secondary)	0.0.0.0
Wi-Fi rssi	-45
Wi-Fi MAC	CC:50:E3:B8:4F:80

Association

To connect to a Wi-Fi network, please select one of the detected networks, enter the password, and hit the connect button...

-50dB
Vodafone-004151

Special Settings

Special settings, use with care!

● " DHCP" ○ Static IP

Date: 03/06/2020, 17:32:24

Figure 4.9: Webpage "Wi-Fi" of the localhost interface.

Additionally, the page displays the **"Wi-Fi Info"** table. Table (see Figure 4.9) exhibits the following information about the connected network.

- "Wi-Fi channel": medium through which the Wi-Fi networks can send and receive data.
- "Configured network": name of the network.
- "Wi-Fi status": indicates if the Wi-Fi network is connected or not.
- "Wi-Fi address": IP address of the device.
- "DHCP":[1] indicates if the "Dynamic Host Configuration Protocol" is activated.
- "DNS Server (Primary)": "Domain Name System" does the connection between the domain and the IP number.
- "DNS Server (Secondary)": serves the same purpose of the primary DNS server but, since in this application it won't be used, it is set to "0.0.0.0".
- "Wi-Fi RSSI": "Received Signal Strength Indicator", it indicates how well the device can receive the signal from the router. The lower the number, the better the signal reception.
- "Wi-Fi MAC": unique identifier assigned to a network interface controller to use as a network address in communications.

---

[1] DHCP is a protocol that provides quick, automatic, and central management for the distribution of IP addresses within a network.

4.3 API

An API (Application Programming Interface) is a connector between different systems, facilitating the data exchange between them. Moreover, APIs provide data protection and security. A Web API is a set of HTTP [2] request and response methods expressed in a given format, this work shall use the JavaScript Object Notation (JSON) format.

JSON is a simple and easy data-interchange format between systems. As such, it shall be used to exchange data between the device and local user interface.

HTTP is a communication protocol used in information systems, such as the World Wide Web (WWW). The protocol defines various request methods such as "GET", "POST", "PUT", and "DELETE". The following section will give a detailed overview of the methods used within the context of this project.

4.3.1 HTTP Requests

In the next Tables (4.2 e 4.3), the HTTP request methods used in the webpages of the user interface are described. All the time data sent to local user interface has a timestamp based on the UNIX timestamp – the number of seconds that have passed since 00:00:00 on the 1st January 1970, UTC.

Table 4.2: HTTP request used between the device and the user interface.

Page	**HTTP Request**	**URI**	**Description**
Monitoring	GET	/moni/info	Get all the information on the tables "Status" and "Value".
		/moni/startlist	Give the information of the table "List of 10 Last Motor Starts". This request returns an array, where the first 10 elements are the "Start Time" values and the last 10 elements are the "Stop Time" values.
		/graph/power	Give the power array of the graph.
		/graph/timep	Give the time array of the graph.
	POST	/relay/state	Turn on or off the load of the device

---

[2] HTTP: *Hypertext Transfer Protocol*

Table 4.3: HTTP request used between the device and the user interface. (Continuation)

Page	**HTTP Request**	**URI**	**Description**
Fault	GET	/fault/info	Get all the information on the tables ”General Information” and ”Reference Information”.
		/fault/flist	Give the information of the table ”List of 10 Last Faults”. This request returns an array, where the first 10 elements are the ”Fault Code” values and the last 10 elements are the ”Time” values.
		/graph/ref	Give the REFERENCE array of the graph. Where the first 7 elements are the FFT values and the last ones are the frequency values.
		/graph/now	Give the NOW array of the graph. Where the first 7 elements are the FFT values and the last ones are the frequency values.
Settings	GET	/set	Get all the information on the tables ”Appliances Information”, ”Network”, ”Current Meter” and ”Energy Meter”.
	POST	/set1	Send the information insert in the input cells of the right page side to the device and make the update of that information.
		/set2	Send the information insert in the input cells of the left page side to the device and make the update of that information.
Wi-Fi	GET	/wifi/info	Get all the information of the table ”Wi-Fi Info”.
		/wifi/scan	Research for available networks and give the list of them.
	POST	/wifi/conf	Send the data inserted to the device, which allows the connection of the device to the desired network.

CHAPTER 5

TESTS

This chapter presents the tests made to validate the device functionality. In section 5.1, we have the validation tests of the fault detection method describe in section 4.1.3. In section 5.2, the results of the test to validate the implementation of the functional requirements are presented. Furthermore, the results of the tests using home appliances are discussed.

5.1 Experimental setup

5.1.1 FFT Acquisition

This work heavily relies on the FFT of the appliance's electrical current, hence, it is critical to compute a high-resolution FFT with enough detail to determine any possible malfunctions. The first step towards a good quality FFT is defining the correct sampling rate. With this regard, there are two main constraints: Nyquist theorem or sampling theorem (see Equation 5.1), and satisfying the coherent sampling condition (see Equation 5.2).

$$f_s \geq 2f_0 \tag{5.1}$$

f_s: sampling frequency, f_0: fundamental frequency.

$$N = f_s \delta T \tag{5.2}$$

N: sampling number, δT: signal period.

The fundamental frequency considered in this work is $f_0 = 50\ Hz$, which yields $\delta T = \frac{1}{f_0} = \frac{1}{50Hz} = 20\ ms$. To decrease distortion, multiple cycles of the signal are sampled. Therefore, assuming that samples are taken over five cycles, the total sampling period is $5\delta T = 100\ ms$. Furthermore, if 1024 samples are taken in total, the sampling frequency is, thus, $f_s = \frac{1024}{0.1s} = 10240\ Hz$.

The *idPlug* has a potentiometer than allow to regulate the gain of the current signal. This potentiometer is digital and has 7bits, so there are 128 (2^7) steps. The maximum resistance provided by the potentiometer is 100kΩ, thus each step (p) corresponds to 781.25 Ω (1000k Ω/128). Thus, the resistance for a given step (p) of the potentiometer is given by $R_p = 781.25p$. The plug features a non-inverting assembly (as shown in Figure A.2), ergo the devices input voltage can be calculated by $V_{IN} = V_0 \frac{1000}{1000+R_p}$, furthermore, the current can be determined as $I = V_{IN} \frac{3000}{180}$, using the current transformer information.

5.1.2 Set-up Validation

The proposed set-up was validated using three different loads: an incandescent lamp, a fluorescent lamp, and a motor.

Initially, the system was validated using lamps due to their low-noise current signal (consumption is mostly constant). Hence, using both, an incandescent and a fluorescent lamp, the resistance of the potentiometer is varied while taking 1024 samples of the signal with a sampling rate of 10240 Hz. Figures 5.1 and 5.2 show the results obtained. The Figures plot frequency (horizontal axis) versus current (vertical axis), where the current is presented as decibels of Ampere (dBI) to clearly present the amplitude peaks. As previously explained, the fundamental frequency is 50 Hz, furthermore, as shown in Section 2.3.1, the frequency harmonics for a given appliance will be present in the range of up to 200 Hz. For these two reasons, the frequency range presented is of $[0, 200]\ Hz$. The FFT is constructed using the Hanning Window, a method that reduces the leakage effect – this effect results in increased error in the amplitude's value due to discontinuities in the sampled data preventing a perfect reconstruction of the periodic signal.

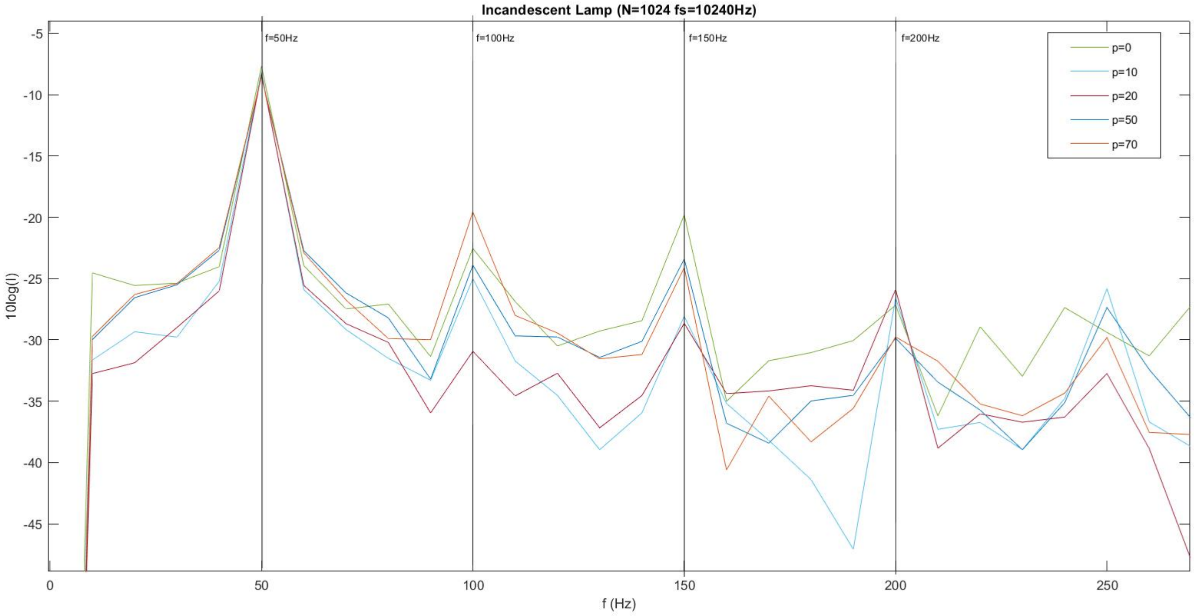


Figure 5.1: The FFT of the current signal of an incandescent lamp for different gains.

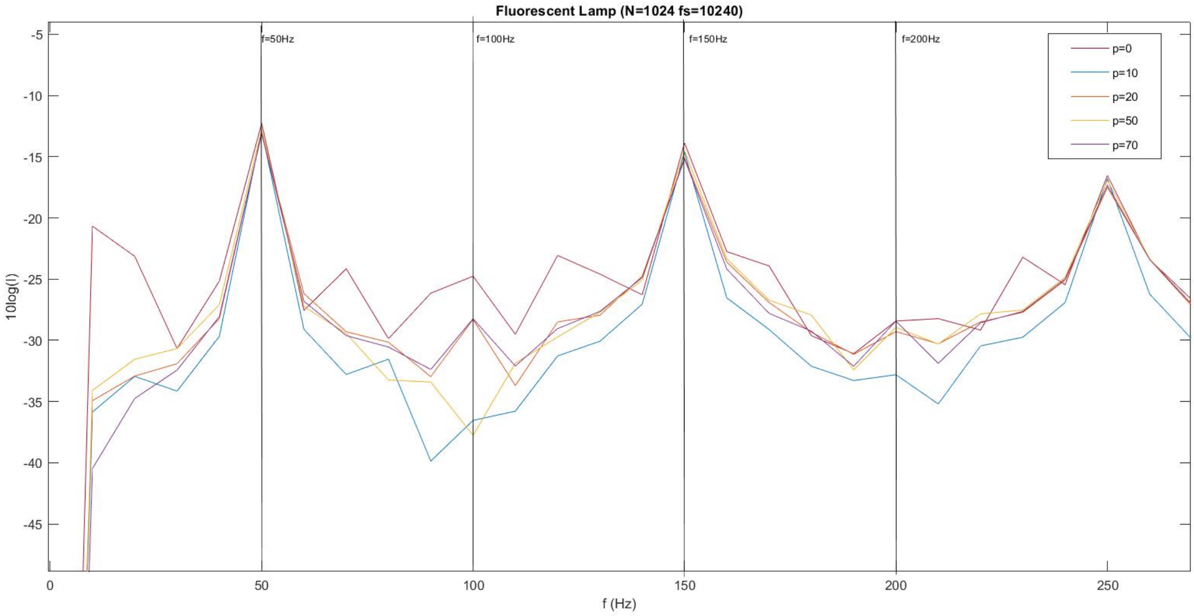


Figure 5.2: The FFT of the current signal of a fluorescent lamp for different gains.

Figures 5.1 and 5.2 show peaks at the fundamental frequency and in its harmonics as expected. However, in both plots, the bin is $F_{bin} = \frac{f_s}{N} = 10$, meaning that between two consecutive points there is a difference of 10Hz. This value is too large to obtain meaningful data showing small changes in the current's signal, hence, the precision needs to be increased. So, we need to decrease this value changing the value of N and f_s, respecting the rules mentioned previous.

The frequency range being studied is $[0, 200]$ Hz, requiring a sampling rate of at least 400 Hz. Combining the need to decrease F_{bin} and to keep the frequency above 400Hz, the final product shall have a sampling frequency of 512 Hz with 2048 samples per FFT. The increase in resolution for the FFT will be accompanied with a corresponding increase in sample acquisition time, however, for the proposed application is a reasonable time (see Table 5.1).

As explain before, to increase the bin value changes need to be made to the values of N (number of samples) and fs (sampling frequency) – considering equations 5.1 and 5.2. Table 5.1 shows possible combinations of Fs and N that respect all the required constraints.

Table 5.1: Value of sampling rate (Fs), number of samples (N), the FFT bin (F_{bin}), period number and time needed to acquisition the signal.

Fs (Hz)	N	F_{bin}	Number of periods	Acquisition Time (s)
10240	1024	10.00	5.00	0.20
5120	1024	5.00	10.00	0.40
2048	1024	2.00	25.00	1.00
1024	1024	1.00	50.00	2.00
512	1024	0.50	100.00	4.00
301	1024	0.29	170.10	6.80
200	512	0.39	128.00	5.12
512	2048	0.25	200.00	8.00

Figure 5.3: TL5A Danfoss Compressor from a freezer.

Table 5.2: General information about the freezer motor used during the tests.

Manufacture	Model	Voltage (V)	Frequency (Hz)	Power (W)
Danfoss	TL5A - 2010	220∼240	50	—
Note: This motor is not commercialized any more. The new service type is TFS5ST-102U2130.				

The third test validates the sampling frequency selected above. Using a old Danfoss TL5A motor (see Figure 5.3 and it information is in Table 5.2) with an unknown health condition (expected to be poor) the number of samples and sampling frequency for the FFT of the motor's current was varied. Figure 5.4 demonstrates that with the original set-up there was not enough signal detail and some peaks were overlooked. Similarly, if the sampling frequency is low (200 Hz) any peak occurring after 100 Hz can not be detected. Both these issues are non-existent in the selected frequency, however, some noise is present and many local maximums are detected. To address this situation, as alluded to in Section 4.1.3.2, the average of multiple (ten or twenty) FFTs is considered, as shown in Figure 5.5. This solution keeps all the detail on the higher peaks, while smoothing the curve for the small lower ones. Peak identification is, thus, greatly simplified.

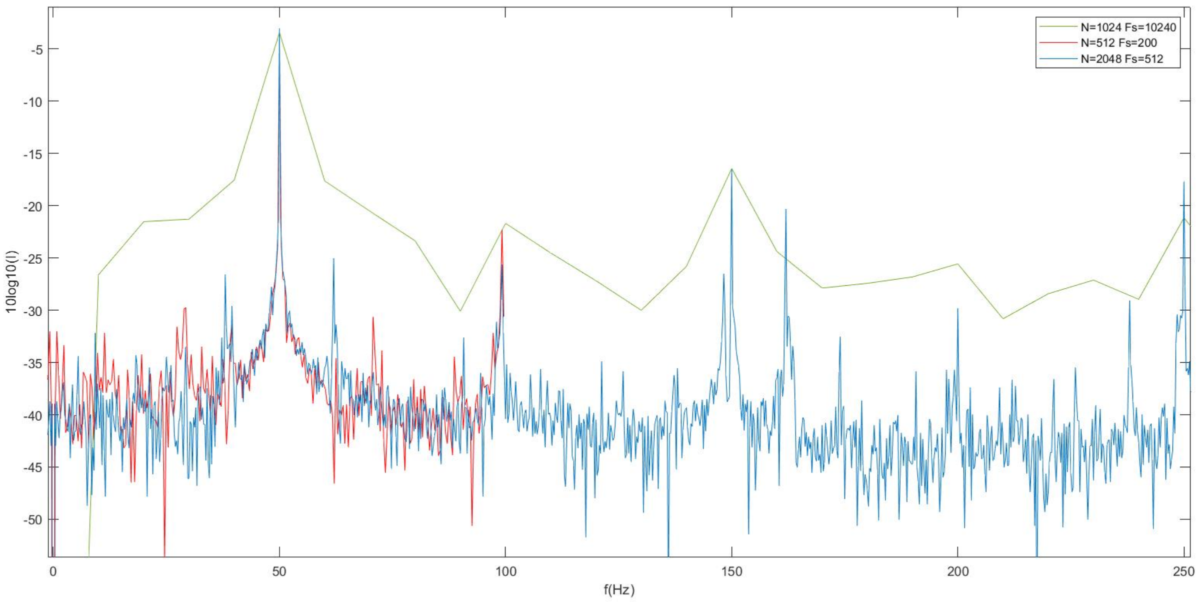


Figure 5.4: The FFT of the current signal of a motor from a old freezer with different number of sampling and sampling rates.

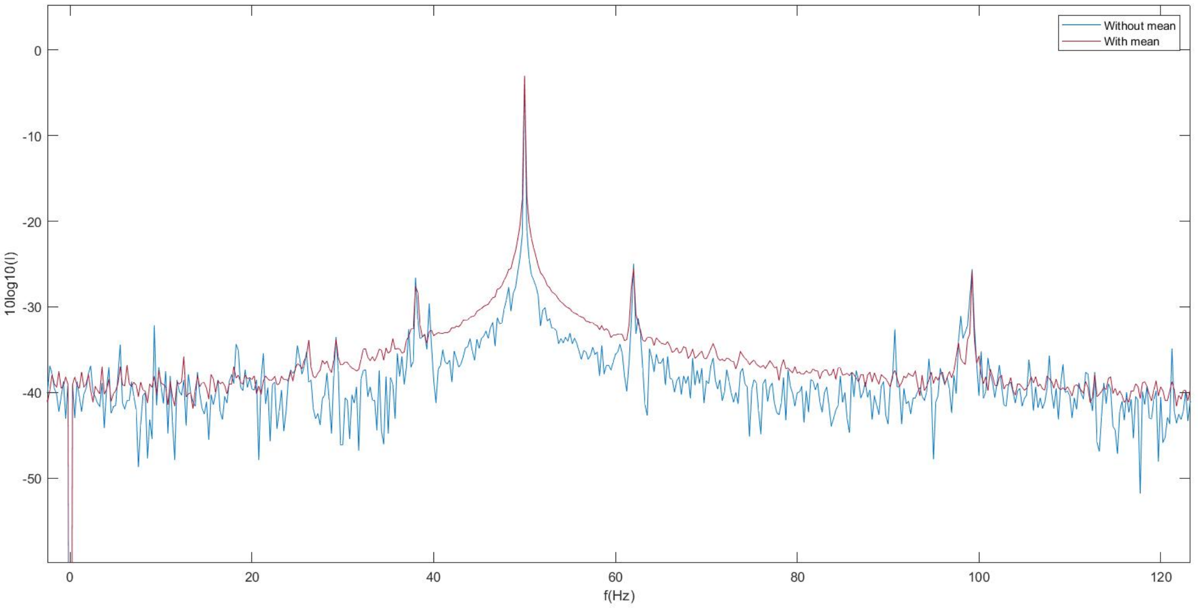


Figure 5.5: Comparison between one FFT and the mean of ten FFTs.

5.1.3 Operation time

Home appliances operate in cycles that can range from minutes to hours. Thus, a system to monitor said appliances must react to any change in operation within a reasonable time frame. To detect all possible condition changes in the monitored appliance, the proposed solution executes its algorithms in the range of seconds and minutes, as summarized in Table 5.3.

Table 5.3: Comparison table between the intended time in a method step and the real-time obtained.

Information		**Expected Value**	**Actual Value**	**Error (%)**
Interval between FFT		20 seconds	22 seconds	10
Interval between FFT block		3 minutes	3.67 minutes	22.33
Interval between each detection (start1)		3 minutes	3minutes	0
Interval between each detection (start2)		5 seconds	5 seconds	0
After the fault detection (start2)	Time to collect FFTs again	3 minutes	3 minutes	0
	Time to go back to check the machine status	1 minute	1 minute	0

The discrepancies between ”actual” and ”expected” values involving the FFT algorithms are not significant when considering the operating cycles of the appliances, not resulting in any drop in accuracy for fault detection.

5.2 Functional Tests

This section highlights the testing methodology used to validate whether the functional requirements were satisfied. Validation was separated into three stages, with one test per stage, of increasing monitoring difficulty . Initially, the device is tested by monitoring a single motor with no load. The second scenario uses a domestic appliance with a constant load. Finally, the device is tested using an appliance with a variable load. Figure 5.6 summarizes the testing approach.

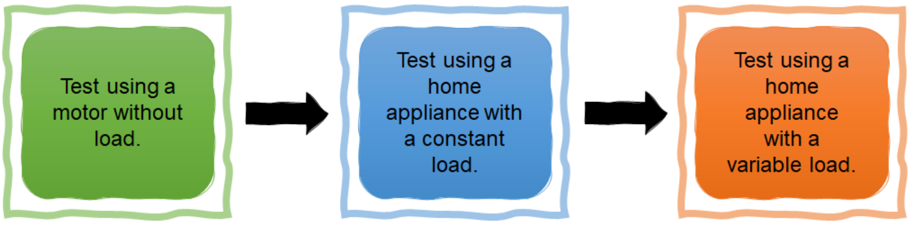


Figure 5.6: Diagram of the different scenarios used during the tests.

5.2.1 Test scenario 1: Load-free motor

A motor was selected as the first testing stage due to its simplicity and ease of control (compared to a standard domestic appliance), and also due to its similarity to constant load appliances, such as refrigerators.

The motor used in the experiment, seen in Figure 5.7, was extracted from a dishwasher, where it acted has a pump. The motor characteristics are in table 5.4. The testing occurred in a closed environment and, as previously mentioned, without any load attached to the motor. Given the nature of the devised tests (see Table 5.5) all requirements, expect requirement number 17, could be quickly verified. The tests were divided in nine scenarios.

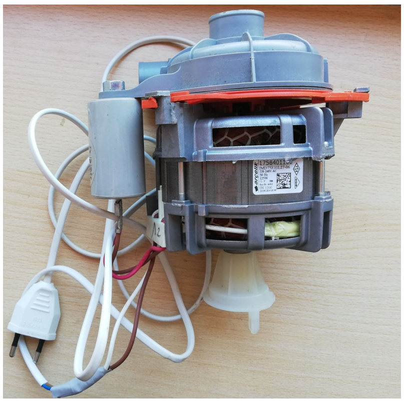


Figure 5.7: Dishwasher pump used in the scenario 1.

Table 5.4: General information about the dishwasher motor used during the tests.

Manufacture	Model	Voltage (V)	Frequency (Hz)	Power (W)
arcelik	1758401100 IMD75E31L27-06	220∼240	50	125

The tests and its corresponding results are exposed in the tables of the appendix B. The table 5.5 has the description of appendix B tables.

Test 1: the AP [1] mode of the device, which is enabled or disabled with a short press of the device's button was tested. When this mode is enabled the device has its own network, named "ESP32". This network allows the user to change the local home network connected to the device. Moreover, it also provides access to all the information pages when there is no local home network available. The device passed all but two tests regarding AP mode. Both failing scenarios derive from starting fault detection simultaneously to the test, since fault detection takes three minutes to complete and can not be interrupted. However, these two negative results can

---

[1] AP: *Access Point*

Table 5.5: Description of the appendix B tests.

Test Number	Table	Description	Passed Steps
1	B.1	Test the activation and deactivation of AP mode	3/5
2	B.2	Test the information of the Wi-Fi web pages and the device connection to new networks.	7/7
3	B.3	Test the internal clock synchronization with a web service.	8/8
4	B.4	Test the data of the ”Settings” page and its update in the software.	7/7
5	B.5	Test the data updating of the ”Monitoring” page.	7/7
6	B.6	Test the device load switching	6/6
7	B.7	Test the data updating of the ”Fault” page.	6/6
8	B.8	Test the fault detection action.	9/9
9	B.9	Test the calculation of the reference FFT. And test if it is correctly stored in the device's memory.	5/5

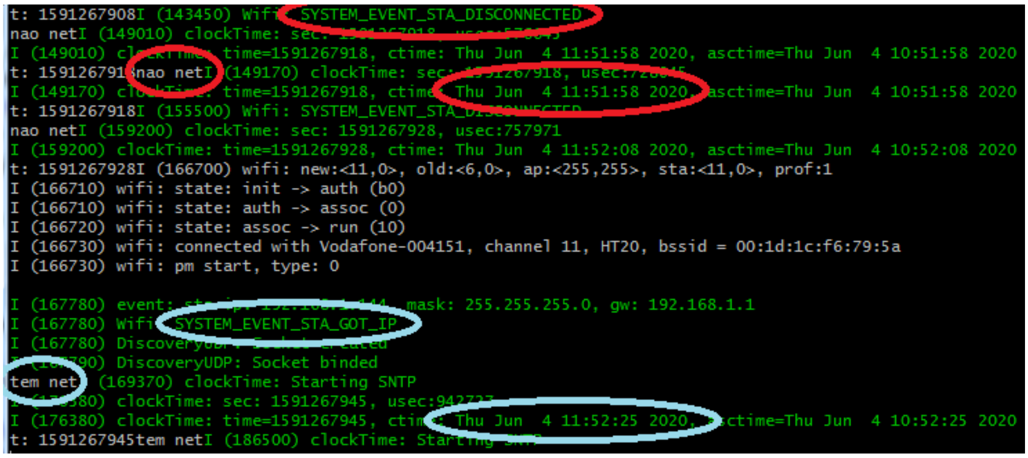
be neglected considering that, under normal utilization, AP Mode would be set upon the initial installation and not while loading the device. For all other AP related tests the results were successful, meaning that the user can easily access the connectivity settings of the device, meeting all the requirements.

Test 2: is related to the connection to the local home network. As explained before, to connected the device to a local home network, the AP mode must be enabled. Once in AP mode, the user must navigate to the ”Wi-Fi” page, scan for available networks, and connect to the desired one. Upon connecting, the device will be attributed a local IP address that can then be used to access all available information. During testing the device successfully connected to a given Wi-Fi network, hence this requirement was met.

Test 3: verifies the synchronization between the system's clock with a web-service, Figure 5.8 illustrates this process where the device is connected to a network and the clock synchronizes successfully. Then, the system is disconnected (”`SYSTEM_EVENT_STA_DISCONNECTED`”) and keeps the synchronized clock.

Test 4: focuses on adjusting variables from the ”Settings” page. The test comprises changes to the values of variables and storing the updated values on the device.

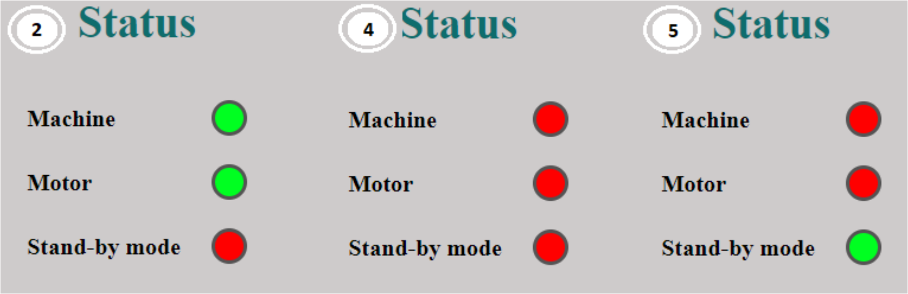
Test 5: checks the measurement and the analysis of the data according to the behaviour of the motor (turn on/off). All the test steps had the expect results. In the image 5.9, we have status indicators in step 2, 4 and 5 of the Table B.5.



```
t: 1591267908I (143450) Wifi: SYSTEM_EVENT_STA_DISCONNECTED
nao netI (149010) clockTime: sec: [illegible]
I (149010) clockTime: time=1591267918, ctime: Thu Jun  4 11:51:58 2020, asctime=Thu Jun  4 10:51:58 2020
t: 1591267918nao netI (149170) clockTime: sec: 1591267918, usec:7[illegible]
I (149170) clockTime: time=1591267918, ctime: Thu Jun  4 11:51:58 2020, asctime=Thu Jun  4 10:51:58 2020
t: 1591267918I (155500) Wifi: SYSTEM_EVENT_STA_DISCONNECTED
nao netI (159200) clockTime: sec: 1591267928, usec:757971
I (159200) clockTime: time=1591267928, ctime: Thu Jun  4 11:52:08 2020, asctime=Thu Jun  4 10:52:08 2020
t: 1591267928I (166700) wifi: new:<11,0>, old:<6,0>, ap:<255,255>, sta:<11,0>, prof:1
I (166710) wifi: state: init -> auth (b0)
I (166710) wifi: state: auth -> assoc (0)
I (166720) wifi: state: assoc -> run (10)
I (166730) wifi: connected with Vodafone-004151, channel 11, HT20, bssid = 00:1d:1c:f6:79:5a
I (166730) wifi: pm start, type: 0

I (167780) event: sta ip: 192.168.1.144, mask: 255.255.255.0, gw: 192.168.1.1
I (167780) Wifi: SYSTEM_EVENT_STA_GOT_IP
I (167780) DiscoveryUDP: Socket created
I (167790) DiscoveryUDP: Socket binded
tem netI (169370) clockTime: Starting SNTP
I (176380) clockTime: sec: 1591267945, usec:9427[illegible]
I (176380) clockTime: time=1591267945, ctime: Thu Jun  4 11:52:25 2020, asctime=Thu Jun  4 10:52:25 2020
t: 1591267945tem netI (186500) clockTime: Starting SNTP
```

Figure 5.8: The clock time test in the terminal.



② Status		④ Status		⑤ Status	
Machine	🟢	Machine	🔴	Machine	🔴
Motor	🟢	Motor	🔴	Motor	🔴
Stand-by mode	🔴	Stand-by mode	🔴	Stand-by mode	🟢

Figure 5.9: The status indicators in step 2, 4 and 5.

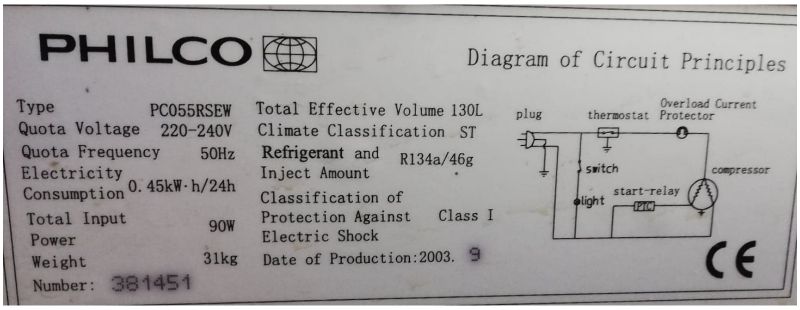
Test 6: verifies the remote turning on/of. of the motor using the buttons "Relay ON" and "Relay OFF".

Test 7 and 8: both tests are related to the "Fault" page. Test number seven examined how the data used in fault detection was updated. Moreover, test eight (B.8) an intentional fault is caused by changing a parameter in the "Settings" page, then it is verified if the fault has been detected. In the two tests, the results were positive.

Test 9: also related to "Fault" page. The "Reference FFT" is used in fault detection as the expected values for a healthy machine. Anomalies are detected by comparing these values with the values obtained during runtime. The "Reference FFT" is calculated when the user does a long press in the device button. Test 9 verifies that the "Reference FFT" calculation occurs when requested via the interface.

5.2.2 Test scenario 2: Mini-refrigerator

The second scenario revolves around a small refrigerator (commonly named 'mini-refrigerator' (see Figure 5.11), whose characteristics are in Table 5.6 and its compliance plate (see Figure 5.10). The testing chamber–a standard household kitchen–contains a window which is exposed to the sun in the late afternoon. The appliance was placed against a wall near the window.



PHILCO

Diagram of Circuit Principles

Type PC055RSEW
Quota Voltage 220-240V
Quota Frequency 50Hz
Electricity Consumption 0. 45kW·h/24h
Total Input Power 90W
Weight 31kg
Number: 381451

Total Effective Volume 130L
Climate Classification ST
Refrigerant and Inject Amount R134a/46g
Classification of Protection Against Electric Shock Class I
Date of Production:2003. 9

Figure 5.10: Mini refrigerator compliance plate.

Table 5.6: General information about the refrigerator used during the tests.

Manufacture	Model	Voltage (V)	Frequency (Hz)	Electricity Consumption (kW.h/24h)	Power (W)
Philco	PC055RSEW	220∼240	50	0.45	90

Figure 5.11: Photo of the mini-fridge used in the tests.

Figure 5.12: Calibrated power device.

Initially, the system's correct measurement was verified by measuring the power being drained by the appliance. A first test revealed that, when the pump is on, the power level jumps to 135 W, subsequently decreasing to 112 W. These values are above the values defined on the compliance plate (90 W). The discrepancy can be due to three causes: device measurement, the machine can have a small factory anomaly, or the home appliance developed a fault over time. Hence, to ensure the proper functioning of the proposed system, the values were compared against those of a calibrated power meter (Figure 5.12). Table 5.7 summarizes the results obtained by the calibration device and the proposed device.

Table 5.7: Comparison between Chacon's values and the ones obtained with our device, in different situations.

Day	**29/06/2020**	
Event	**Start of measurements**	
Start Counter	91	
Fault Counter	2	
Device	Chacon	Our device
Hours	4:53pm	
Voltage (V)	234.60	234.58
Current (A)	0.06	0.062
Power (W)	14.80	14.00
Power Factor	0.97	0.97
Frequency (Hz)	50.00	50.05

Event:	**Motor ON**							
Device	Chacon	Our device	Chacon	Our device	Chacon	Our device	Chacon	Our device
Hours	4:55pm		4:57pm		4:59pm		5:01pm	
Voltage (V)	233.70	233.77	233.70	333.87	233.60	233.37	234.40	234.42
Current (A)	0.80	0.78	0.78	0.77	0.78	0.76	0.78	0.76
Power (W)	127.00	125.00	118.00	116.00	115.00	113.00	113.00	111.00
Power Factor	0.64	0.65	0.65	0.66	0.64	0.65	0.64	0.65
Frequency (Hz)	50.00	50.02	50.00	50.04	50.00	50.05	50.00	50.02

Event:	**Motor OFF**					
Device	Chacon	Our device	Chacon	Our device	Chacon	Our device
Hours	5:02pm		5:07pm		5:12pm	
Voltage (V)	234.70	234.59	235.00	235.09	234.40	234.64
Current (A)	0.06	0.06	0.06	0.062	0.06	0.06
Power (W)	14.80	14.00	14.00	14.80	14.00	14.80
Power Factor	0.97	0.97	0.97	0.96	1.00	0.97
Frequency (Hz)	50.00	50.06	50.00	50.05	50.00	50.01

The values measured, as shown, for voltage and current have a discrepancy of less than 0.01%. Similarly, the power measurements differ by, roughly, 2 W – corresponding to an error of approximately 2%. All three types of measurements fall within the imposed limit of 3%, ruling out any defect in the measuring system. Thus, it can be concluded that the appliance operates outside of the stated nominal power.

Subsequently, the mini-fridge was monitored for two days. The upper limits of 90 W and 120 W were established for issuing a warning and an error, respectively. Then, considering that the door has not been opened in the last 4 hours, the effect on power of having the appliance's door open is studied, the results are shown in Table 5.8.

Table 5.8: Mini refrigerator power behaviour depending on the door opening.

Door Open			**After closing the door**	
Initial Time	**Duration**	**State**	**Time with motor ON (minutes)**	**Time with motor OFF (minutes)**
5:29pm	3seg	Motor OFF	8	15
6:55pm	30seg	Motor OFF	14	7
7:28pm	30seg	Motor ON (118.6W)	21	9

During the night the door has not been opened, so at the morning the "List of 10 Last Motor Starts" is analysed. And it can be concluded that, during this time, the pump is ON for 8 minutes and OFF for 15 (see Figure 5.13).

List of 10 Last Motor Starts

Number	Start Time	Stop Time
1:	30/06/2020, 09:36:25	30/06/2020, 09:44:38
2:	30/06/2020, 09:12:58	30/06/2020, 09:21:04
3:	30/06/2020, 08:50:38	30/06/2020, 08:58:09
4:	30/06/2020, 08:28:00	30/06/2020, 08:35:40
5:	30/06/2020, 08:05:34	30/06/2020, 08:13:09
6:	30/06/2020, 07:43:06	30/06/2020, 07:50:42
7:	30/06/2020, 07:20:25	30/06/2020, 07:28:07
8:	30/06/2020, 06:57:31	30/06/2020, 07:05:28
9:	30/06/2020, 06:35:01	30/06/2020, 06:42:52
10:	30/06/2020, 06:13:15	30/06/2020, 06:20:38

Figure 5.13: "List of 10 Last Motor Starts" during a long period without open the mini-refrigerator door.

As expected, Table 5.8 and Figure 5.13 shows that the time the door remains open influences the motor's behaviour. If the door is kept open for 3 seconds, when the motor is off, there is no change in the pump cycle time. However, if the door is open for 30 seconds the time with the pump ON increases to 14 minutes and the time with the motor OFF decreases to 9 minutes. Furthermore, if the same is repeated when the pump is ON, the discrepancies are higher. The time with the motor ON is 21 minutes and the time with motor OFF is 7 minutes. These results are expected since the longer the door remains open, the longer heat is exchanged with the exterior – commonly referred to as "loss of heat".The appliance then has to compensate this loss with more refrigeration time (pump ON).

At the end of one day, there was a total of 66 pump cycles and, at the end of two days, there were 127 cycles.

Figure 5.14 shows the power behaviour and the seven peaks charts at 14:34 on the 30th of July 2020. Previously (Figure 2.3 - plot b), the power behaviour of a refrigerator was shown, as expected, the observations closely resemble the previous plots. The second plot of Figure 5.14 shows that the chart "NOW" is very similar to the chart "REFERENCE". This similarity happens because the graphs have been obtained with a difference of two days, which is a relatively short amount of time to see discrepancies between them.

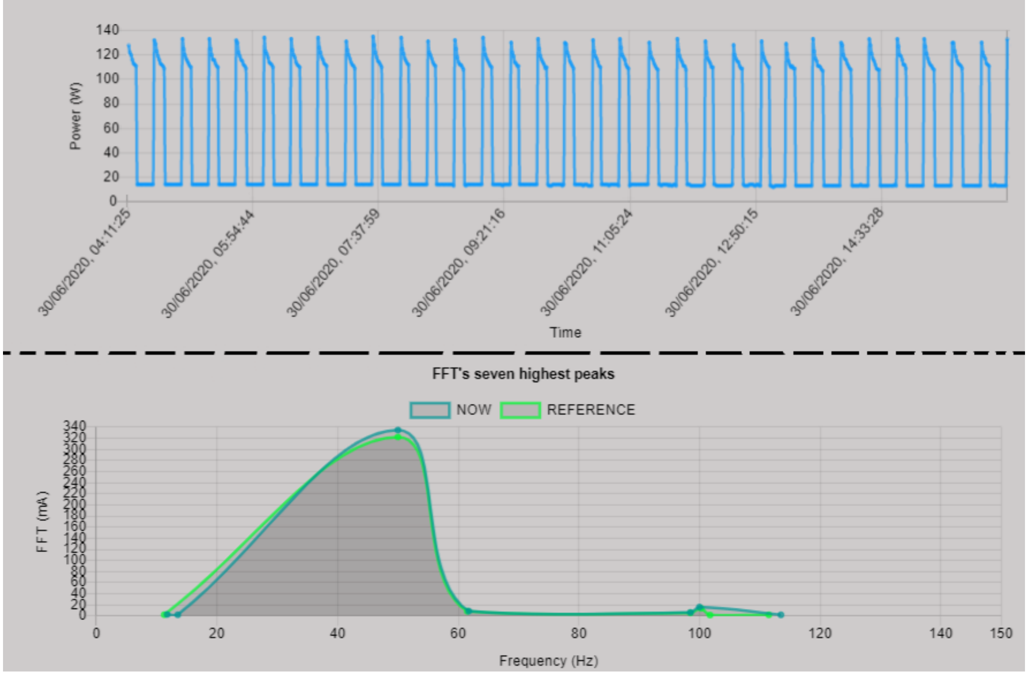


Figure 5.14: Power behaviour and the seven peaks charts at 14:34 on the 30th of July 2020.

5.2.3 Test scenario 3: Washing Machine

The third, and final, test features ”Candy” washing machine, whose characteristics are in Table 5.6 and compliance plate is in Figure 5.15. As previously stated, this type of appliance has a variable amount of states, furthering the device’s testing.

Figure 5.15: *Candy* washing machine and its compliance plate.

Table 5.9: General information about the washing machine used during the tests.

Manufacture	Model	Voltage (V)	Frequency (Hz)	Current (A)	Power (W)
Candy	CS 1071D3/1-S	220-240	50	10	1600

The appliance’s manufacturer provides its users with an application (app) named ”Candy simply-Fi App”. This application monitors the total load cycles and overall operation time, allowing the user to adjust the washing mode that better suits the utilization. Hence, before starting the test, the app’s information is checked (Figure 5.16). Initially, there was a total of 428 cycles and 423 hours and 8 minutes of operating time.

Últ. sinc:
02/07/2020 - 22:46
Ciclo Smart Touch atual
Autolimpeza

428 Ciclos	423H08M
Atividade Total Lavagem	Tempo Total Funcionamento

Ciclos mais Usados

CICLOS	NOME DO CICLO		
123	Sintéticos	40°	🟡
106	Rápido 30 min.	30°	🟢
88	Descarga + Centrifugação	0°	🟢
68	Diária 59 min.	60°	🔴
21	Algodões	40°	🟡

59 min	100%
Tempo Médio Funcionamento	Nível de Saúde

Figure 5.16: Screenshot from the app *Candy simply-Fi*

Initially, the machine was set to the light colours' laundry program (60 ^oC and 59 minutes). Table 5.10 shows the electrical values for different states of the washing machine program, while Figure 5.17 plots the power behaviour for this program.

Table 5.10: Electrical values during different states of the light colours' laundry program.

Washing program status	Resistor	Motor	Power (W)	Voltage (V)	Current (A)	Power Factor (%)
No Operating	OFF	OFF	0	229.7-230.5	0.072	-
Washing	ON	OFF	1325-1480		6-7	99
	ON	ON	1420-1560		7-8	90
Washing	OFF	ON	64-83		3	88
	OFF	OFF	3-4		0.05	-

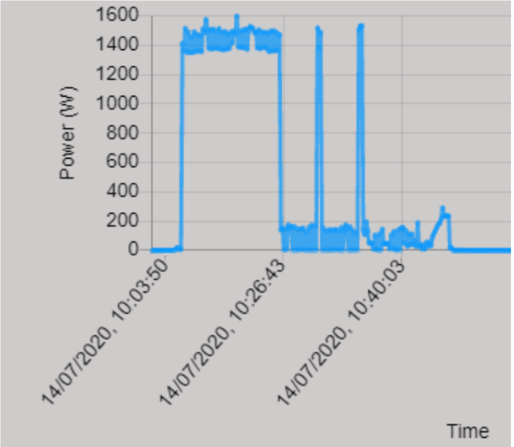


Figure 5.17: Power behaviour of light colours' laundry program.

The measured values (Table 5.10) are within the bounds specified in the appliance's compliance plate (Figure 5.15). The power behaviour resembles, very closely, the one exposed in Chapter 2 (Figure 2.6) for multi-state appliances, with the exception of when the motor is on (resistance is off), which is more noticeable in the appliance used. Furthermore, the spin mode (”centrifuge” mode to expel water from the clothes) can be clearly seen at the right end of the graph in the shape of a ramp in power.

The machine was further tested with the dark colours' laundry program (40 ^oC). The same parameters and graph obtained in the previous test were collected and compiled.

Table 5.11: Electrical values during different states of the dark colours' laundry program.

Washing program status	**Resistor**	**Motor**	**Power (W)**	**Voltage (V)**	**Current (A)**	**Power Factor (%)**
No Operating	OFF	OFF	0	229.7-229.5	0.071	-
Washing	ON	OFF	1375-1410		6-6.5	88
	ON	ON	1480-1530		7-7.5	91
	OFF	ON	120-160		3	90
	OFF	OFF	3-4		0.05	-
Spining	OFF	ON	366-90		7	-

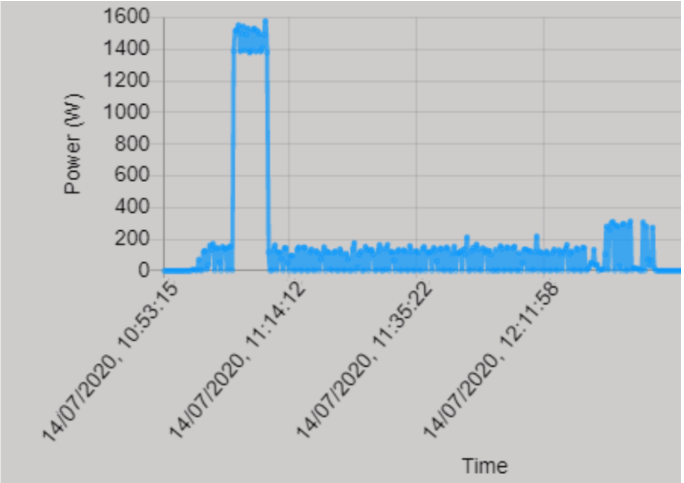
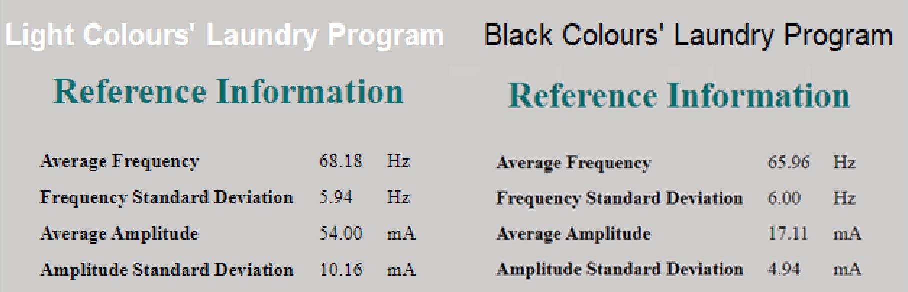


Figure 5.18: Power behaviour of dark colours' laundry program.

The voltage, current and power factor values are similar to the previous test. However, when the resistor is ON, the power values are slightly lower than before. This difference is due to the lower temperature the water must be heated to (40 ^{o}C vs 60 ^{o}C).

To detect faults, we use the reference values of the first test, and we obtained new elements in the fault list of the page "Fault". So, we decide to calibrate the device again with this laundry program. The reference information for both cycles is presented in Figure 5.19. In both tests, the reference information related with frequency is similar, on the contrary the values corresponding to the current's amplitude are very different. This discrepancy can have different causes, such as the parametrization of the chosen washing program or the weight of the clothes in the machine, which modify the motor load. Using the light laundry program's data as reference the device wrongly identified a fault due to the difference in peak amplitude of the generated FFT (see Figure 5.20).

Furthermore, analysis of the spinning state reveals that the device detects a fault which turned out to be a false positive. Both false positives were detected due to the algorithm condition related to the spikes amplitude. Hence, it can be concluded that either the peaks amplitude is not a good parameter to use in fault detection, or the condition related to the peaks amplitude it is not correctly defined, or the fact that the washing machine has, at minimum, two motors, one to rotate the drum and other to remove the water. When there are more than one motor working, each motors have different reference values.



Light Colours' Laundry Program

Reference Information

Average Frequency	68.18	Hz
Frequency Standard Deviation	5.94	Hz
Average Amplitude	54.00	mA
Amplitude Standard Deviation	10.16	mA

Black Colours' Laundry Program

Reference Information

Average Frequency	65.96	Hz
Frequency Standard Deviation	6.00	Hz
Average Amplitude	17.11	mA
Amplitude Standard Deviation	4.94	mA

Figure 5.19: Reference information of light and dark colours' laundry programs.

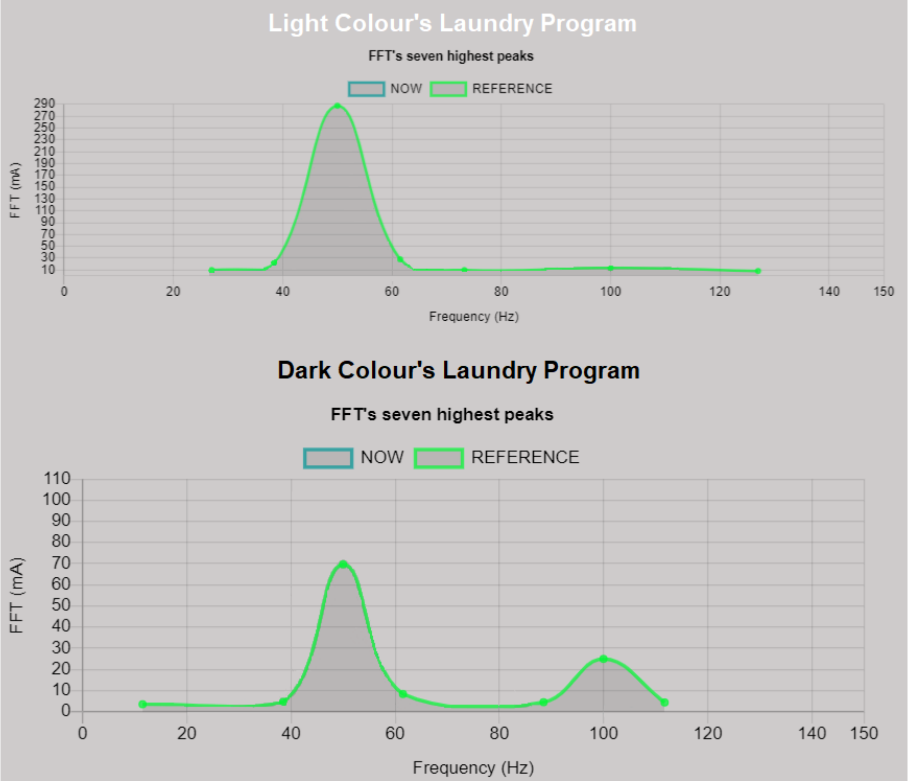
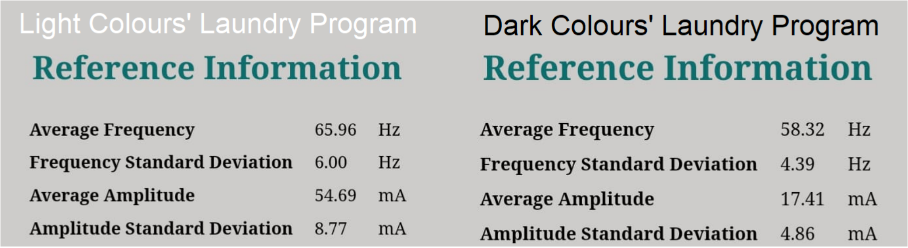


Figure 5.20: Reference peak amplitude of light and dark colours' laundry programs

For accuracy checking, the previous tests were repeated, as shown in Figure 5.21. The power plots were identical to Figures 5.17 and 5.18, however, comparing Figure 5.21 with Figure 5.19 shows that there are differences in the reference values.



Light Colours' Laundry Program

Reference Information

Average Frequency	65.96	Hz
Frequency Standard Deviation	6.00	Hz
Average Amplitude	54.69	mA
Amplitude Standard Deviation	8.77	mA

Dark Colours' Laundry Program

Reference Information

Average Frequency	58.32	Hz
Frequency Standard Deviation	4.39	Hz
Average Amplitude	17.41	mA
Amplitude Standard Deviation	4.86	mA

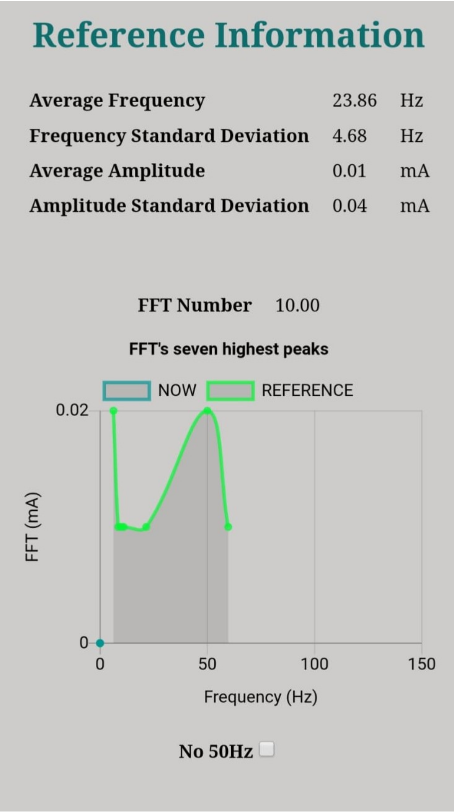
Figure 5.21: Reference information of light and dark colours' laundry programs for the repeated tests.

Comparing the light and dark colours' laundry programs values of Figures 5.19 and 5.21. Only the frequency values of the ”Dark Colours' Laundry Program” and the amplitude standard deviation of the ”Light Colours' Laundry Program” have a greater discrepancy. The percentage discrepancy of these values is presented in Table 5.12. These discrepancies can be attributed to timing differences in the data acquisition, since the acquisition moment is not precise due to lack of control over the machine's operation. All reference data measurements are taken immediately after the heating period.

Table 5.12: Percentage error of the reference information values for both laundry programs in the two tests performed.

	Program	Light Colours	Dark Colours
error (%)	**Average Frequency**	3.26	11.58
	Frequency Standard Deviation	1.01	26.83
	Average Amplitude	1.28	1.75
	Amplitude Standard Deviation	13.68	1.62

Furthermore, reference and peaks acquisition is influenced by the amount of time the motor is turned on. Due to the algorithms formulation – taking the average of 10 FFTs with the same time interval – the motor should be working, uninterrupted, for 3.7 minutes. However, after the heating period, the motor is turned ON and OFF during small periods (20 or 40 seconds). Hence, sometimes the device can't detect changes in the motor's state, leading to wrong FFT peak computations, as shown in Figure 5.22.



Reference Information

Average Frequency	23.86	Hz
Frequency Standard Deviation	4.68	Hz
Average Amplitude	0.01	mA
Amplitude Standard Deviation	0.04	mA

FFT Number 10.00

No 50Hz ☐

Figure 5.22: Wrong acquisition of the reference information during a dark colours' laundry program.

CHAPTER 6

CONCLUSION

The aim of this project consisted in the development of an advanced home appliance monitoring system, as a way to predict and detect faults through the analysis of electrical signals.

Initially, there were some setbacks in the fault detection method development. Due to current global socio-economic circumstances it became impossible to obtain multiple motors with different known health states, which was crucial to apply known fault detection methods. Hence, this work focused a comparative method, taking the initial appliance state as the "golden" reference and detecting faults as a deviation from this behaviour.

The developed device had to follow a set of pre-established requirements (see Section 3.3.), whose verification required the development of nine tests with a simple induction motor. Overall, our system met all requirements – although with minor setbacks – hence, it is considered to be successful.

Upon meeting all basic requirements, the device was tested for its main functionality, namely, monitoring home appliances. First, the device was tested using a mini refrigerator. Some discrepancies were encountered between measured values and reference values, something that was probably due to poor insulation or the age of the appliance. Nonetheless, the device operated as expected, correctly detecting when the appliance's pump was turned on or off. Furthermore, the device was able to detect faults related with the discrepancies mentioned before. Lastly, a newer washing machine was used to test the device. The power behaviour graphs generated by the device were as expected. All the motor start and stop events were detected, except when the motor's state changed with high frequency – faster than the total sampling time. For home appliances with variable load, the fault detection method failed – the device detected false positives.

Concluding, the device works very well for home appliances with a constant load. However, for other types of home appliances, the fault detection algorithm proposed presents some limitations. Nonetheless, the device works correctly for monitoring the power behaviour.

6.1 Future works

First of all, it is necessary to acquire home appliances with different types of anomalies and known health conditions to do more precise tests.

The system developed during this project was the first monitoring system to be created to detect and predicts faults in home appliances, at VPS. Notwithstanding, this work did not focus on fault prediction, leaving this as a future work development.

Fault detection in washing machines was proved to be quite problematic. A possible mitigation strategy for this problem could be using power measurements to know, with certainty, at which stage in its cycle the washing machine is during testing. This information would then be useful to create reference data for each stage, hence, facilitating the fault detection.

Furthermore, a similar approach to the one used in this project for current could be applied to the power signal (as the product of Verv 2.4.2) is another interesting parameter that could be used to detect and predict anomalies. Since appliances have a fingerprint that varies with usage, using this information could add another dimension to the solution developed and tested.

Moreover, tools such as machine learning and data science methods are possible ways to expand this work and improve results. Finally, regarding the user's interface, some form of authentication could be added to protect personal and appliance's data.

BIBLIOGRAPHY

[1] Pushpendra Singh Haroon Rashid MuratKuzlu. "Poster: Energy Disaggregation for Identifying Anomalous Appliance". In: (2017). URL: `https://doi.org/10.1145/3137133.3141438`.

[2] M. B. Figueiredo. "Contributions to Electrical Energy Disaggregation in a Smart Home". PhD thesis. Faculty of Science and Technology of University of Coimbra, 2013.

[3] Explain that Stuff! Mar. 2020. URL: `https://www.explainthatstuff.com/refrigerator.html`.

[4] Fih Issi and Orhan Kaplan. "The Determination of Load Profiles and Power Consumptions of Home Appliances". In: *Energies* 11 (2018). URL: `http://dx.doi.org/10.3390/en11030607`.

[5] SaifurRahman Manisa Pipattanasomporn MuratKuzlu and Yonael Teklu. "Load Profiles of Selected Major Household Appliances and Their Demand Response Opportunities". In: *IEEE TRANSACTIONS ON SMART GRID* 5.2 (2014). URL: `http://dx.doi.org/10.1109/TSG.2013.2268664`.

[6] ICARUS75. *Old vs new fridge.* Mar. 2020. URL: `https://www.flukso.net/content/old-vs-new-fridge`.

[7] F. Marignetti D. D'Aguanno and F. Faginoli. *Single-Phase Motors for Household Applications.* Ed. by Adel El-Shahat. Electric Machines for Smart Grids Applications - Design, Simulation and Control. 2018. Chap. 8.

[8] Mayuri Baradkar. *How does an Induction Motor work ?* URL: `https://www.learnengineering.org/how-does-an-induction-motor-work.html`.

[9] Mayuri Baradkar. *Slip ring Induction Motor, How it works ?* URL: `https://www.learnengineering.org/slip-ring-induction-motor-how-it-works.html`.

[10] M. Iorgulescu and R. Beloiu. “Faults diagnosis for electrical machines based on analysis of motor current”. In: *International Conference on Optimization of Electrical and Electronic Equipment (OPTIM)* (2014), pp. 291–297. URL: `https://doi.org/10.1109/OPTIM.2014.6850944`.

[11] M. E. Zervakis S. K. Goumas and G.S. Stavrakakis. “Classification of washing machines vibration signals using discrete wavelet analysis for feature extration”. In: *IEEE Transactions on Instrumentation and Measurement* 51.3 (2002), pp. 497–508. URL: `https://doi.org/10.1109/TIM.2002.1017721`.

[12] W. Thomson and M. Fenger. “Current signature analysis to detect induction motor faults”. In: *IEE Industry Application Magazine* 7.4 (2001), pp. 26–34. URL: `https://doi.org/10.1109/2943.930988`.

[13] M. H. Marhaban M. R. Mehrjou N. Mariun and N. Misron. “Rotor fault condition monitoring techniques for squirrel-cage induction machine — A review”. In: *Mechanical Systems and Signal Processing* 25 (2011), pp. 2827–2848. URL: `http://dx.doi.org/10.1016/j.ymssp.2011.05.007`.

[14] M. Gonçalves. “Técnicas avançadas de processamento de sinal no diagnóstico de avarias em rolamentos de motores de indução trifásicos”. MA thesis. Faculty of Science and Technology of University of Coimbra, 2015. URL: `https://estudogeral.sib.uc.pt/handle/10316/40468`.

[15] O. E. Hassan M. Abd-el-Malek A. K. Abdelsalam. “Induction motor broken rotor bar fault location detection through envelope analysis of start-up current using Hilbert transform”. In: *Mechanical Systems and Signal Processing* 93 (2017), pp. 332–350. URL: `http://dx.doi.org/10.1016/j.ymssp.2017.02.014`.

[16] M. Dubravko and Z. HEP. “Brief Review of Motor Current Signature Analysis.” In: (2015).

[17] M. Iorgulescu and R. Beloiu. “Study of DC motor diagnosis based on the vibration spectrum and current analysis”. In: *International Conference on Applied and Theoretical Electricity (ICATE)* (2012), pp. 1–4. URL: `https://doi.org/10.1109/ICATE.2012.6403430`.

[18] N. Turk. “Fault Diagnosis of Induction Motor using MCSA”. In: *International Journal of Electrical and Computer Engineering* 8.1 (2016), pp. 13–18. URL: `https://doi.org/10.1007/s12541-019-00176-z`.

[19] Y. Yoo. "Fault Detection of Induction Motor Using Fast Fourier Transform with Feature Selection via Principal Component Analysis." In: *International Journal of Precision Engineering and Manufacturing* (2019). URL: `https://doi.org/10.1007/s12541-019-00176-z`.

[20] P. R. White W. B. Collis and J. K. Hammond. "Higher-order spectra: bispectrum and trispectrum". In: *Mechanical Systems and Signal Processing* (1998), pp. 375–394.

[21] F. Gu J. Treetrong J. K. Sinha and A. Ball. "Bispectrum of stator phase current for fault detection of induction motor". In: *ISA Transactions* 48 (2009), pp. 378–382. URL: `https://doi.org/10.1016/j.isatra.2009.03.002`.

[22] turbustat. *Bispectrum*. URL: `https://turbustat.readthedocs.io/en/latest/tutorials/statistics/bispectrum_example.html`.

[23] Renesas. *Renesas Electronics Simplifies Home Appliance Maintenance with Failure Detection e-AI Solution for Motor-Equipped Home Appliances*. URL: `https://www.renesas.com/us/en/about/press-center/news/2019/news20190121.html`.

[24] Renesas. *e-AI Failure Prediction Becomes Standard Operation*. URL: `https://www.renesas.com/eu/en/solutions/key-technology/e-ai/e-ai-motor-failure-detection.html`.

[25] *Verv*. URL: `https://verv.energy/`.

[26] *Single-Phase High-Performance Wide-Span Energy Metering IC - DATASHEET*. Atmel M90E26. Microchip.

Appendices

APPENDIX A

CIRCUIT TECHNICAL DATA

A.1 IdPlug

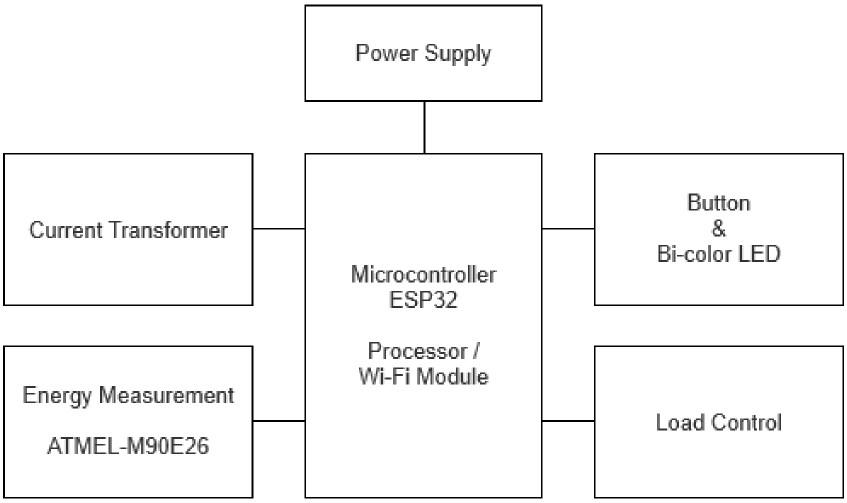


Figure A.1: General scheme of the system.

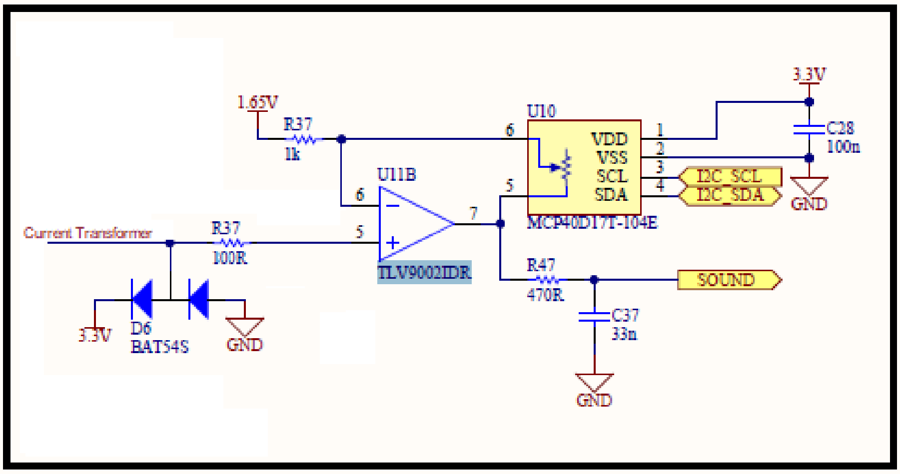
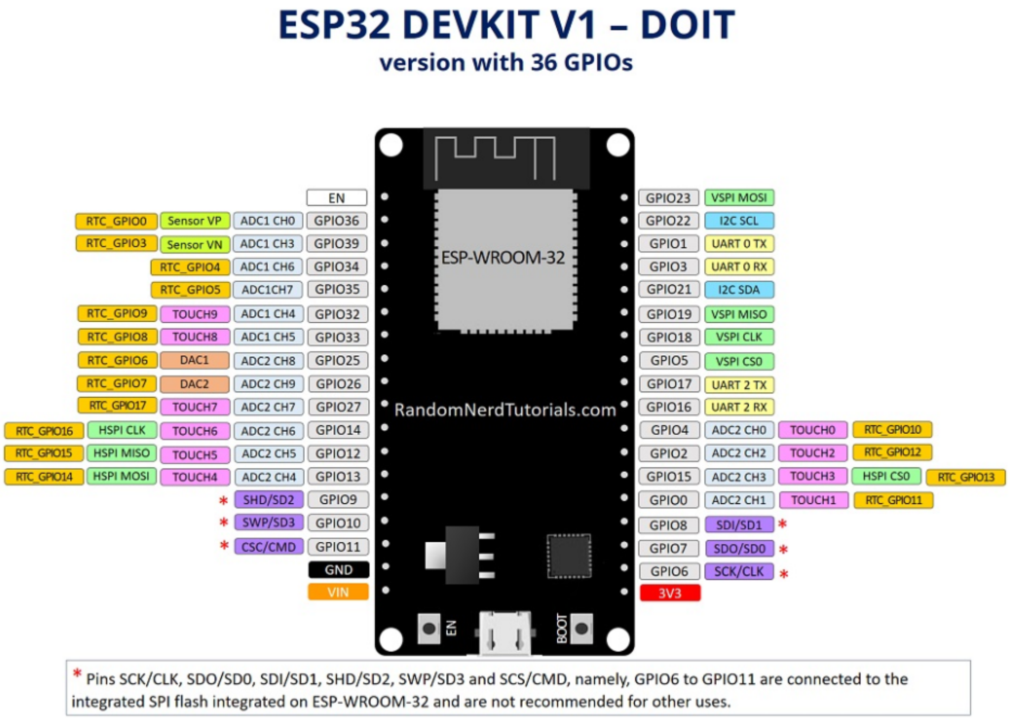


Figure A.2: Current signal conditioning.

A.2 ESP32

The Figure A.3 is a representation of ESP32 board and its pin location.



* Pins SCK/CLK, SDO/SD0, SDI/SD1, SHD/SD2, SWP/SD3 and SCS/CMD, namely, GPIO6 to GPIO11 are connected to the integrated SPI flash integrated on ESP-WROOM-32 and are not recommended for other uses.

Figure A.3: ESP32 pin representation . (From [])

The next tables (A.1 and A.2) have the general specification of ESP32.

Table A.1: ESP32 general specification.

Processors	CPU	Xtensa dual-core 32-bit LX6 microprocessor with 600 DMIPS (160 or 240 MHz)
	Ultra low power (ULP) co-processor	
Memory	520 KiB SRAM	
Wireless	Wi-Fi	802.11 b/g/n (HT40)
	Bluetooth	v4.2 BR/EDR
Connectivity	SAR ADC	12-bit and up to 18 channels
	2 DACs	8-bits
	10 touch sensors	
	4 SPI	
	2 I2S	
	2 I2C	
	3 UART	
Peripheral Interfaces	SD/SDIO/CE-ATA/ MMC/eMMC host controller	
	SDIO/SPI slave controller	
	Ethernet MAC	With Dedicated DMA and IEEE 1588 Precision Time Protocol suport
	CAN bus 2.0	
	Infared remote controller (Tx/RX)	up to 8 channels
	Motor PWM	
	LED PWM	
	Temperature Sensor	
	Hall effect sensor	
	Ultra low power analog pre-amplifier	

Table A.2: ESP32 general specification. (continuation)

Security	IEEE 802.11 standard security	WFA, WPA/WPA2 and WAPI
	Secure boot	
	Flash encryption	
	OTP	1024-bit and up to 768-bit for customers
	Cryptographic hardware acceleration	AES, SHA-2, RSA, elliptic curve cryptograpgy (ECC), random number generator (RNG)
Power Management	Internal low dropout regulator	
	Individual power domain for RTC	
	5uA deep sleep current	
	Wake up from GPIO interrupt, timer, ADC measurements, capacitive touch sensor interrupt	

A.3 ATMEL-M90E26

The Figure A.4 is the pin assignment of the ATMEL-M90E26. The Table A.3 has the general specification and the measurement range of ATMEL-M90E26.

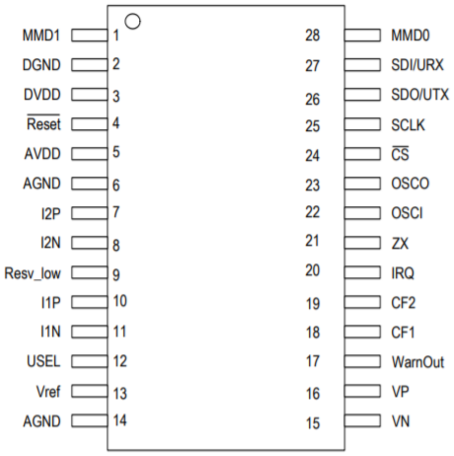


Figure A.4: ATMEL-M90E26 pin assignment (Top View). (From [26])

Table A.3: ATM90E26 general specification and measurement range. (From [26])

Parameter	**Value**
Dynamic Range	5000:1
Operating Voltage(Vcc)	3-3.6
SPI	1
Energy Metering Analog Front-End	3 channels
Reactive Energy Accuracy (%)	0.2
Active Energy Accuracy (%)	0.1
ADC Channels	3
ADC Resolution (bits)	16
UART	1
Meter Type	Single-Phase

Measurement	**Range**
Voltage RMS	0 ∼655.35 V
Current RMS	0 ∼65.535 A
Apparent Power	0 ∼+32.767 kVA
Active/ Reactive Power	-32.768 ∼+32.767 kW/kvar
Frequency	45.00 ∼65.00 Hz
Power Factor	-1.000 ∼+1.000
Phase Angle	-180^o ∼+180^o

APPENDIX B

TEST TABLES - SCENARIO 1

Table B.1: Test nº 1: Web Pages (AP Mode).

nº: Title	1: Web Pages (AP Mode)	
Description	Test the activation and deactivation of AP mode.	
Functional Requirements	15	
Precondition	The device and the computer are connected to the local home network.	
	The user needs to know the Webpages IP associate to the local home network.	
Test (Steps)	**Results**	**Verdict**
1. Short press in device button and wait 1min.	A new network is available in the computer	Passed
2. Short press in device button and wait 1min.	The new network disappeared from the available network in the computer.	Passed
3. Connected the motor to the device.	Nothing changes.	Passed
4. Short press in device button and wait 1min.	Nothing changes.	Didn't Passed
5. Short press in the device button.	Nothing changes.	Didn't Pass

Table B.2: Test nº 2: Connect the device to the local home network.

nº: Title	2: Connect the device to the local home network.	
Description	Test the information of the Wi-Fi web pages and the device connection to new networks.	
Functional Requirements	15, 22, 24	
Precondition	The device is not connected to any network.	
	The user needs to know the predefine IP of the device network.	
Test (Steps)	**Results**	**Verdict**
1. Turn on the device and short press in the button.	The led turned green during the click.	Passed
2. Connected the computer to the device network and insert the predefine IP in the navigator to acess to the web pages.	Home page displayed.	Passed
3. Select ”Wi-Fi”.	The page ”Wi-Fi” displayed with the ”Wi-Fi Information”, the ”Scan” option and the ”Special Settings”.	Passed
4. Make the scan of networks.	After pressing in the button ”Scan”, a text ”Scanning...” appeared. After that, a detected network and the notification ”Scan found 1 network” appeared.	Passed
5. Select the wanted network, introduce the wrong password and click in bottun ”connect.”	A notification appeared ”Waiting for network change...”.The ”Wi-fi” information didn’t change and the IP address has not been assigned.	Passed
6. Select the wanted network, introduce the correct password and connect.	A notification appeared ”Waiting for network change...”. The ”Wi-fi” information changed and a new IP address has been assigned.	Passed
7. Connect the computer to the network that the device is connectedto and insert the new IP in the navigator.	Home page displayed.	Passed

Table B.3: Test n° 3: Internal Clock synchronization.

n°: Title	3: Internal Clock synchronization	
Description	Test the internal clock synchronization with a web service.	
Functional Requirements	14	
Precondition	Test made in the terminal.	
	The device is not connected to any network.	
Test (Steps)	**Results**	**Verdict**
1. Turn on the device.	The device restarted.	Passed
2. Wait at most 1 minutes.	The first data to appear was "Mon Jan 1 00:00:00 1970"	Passed
3. Turn on the local home network to which the device is associated.	The device connected to the network.	Passed
4. Wait at most 1 minute.	The appeared data was the current date.	Passed
5. Turn off the local home network to which the device is associated.	In the terminal, appeared a message warning about the network disconnection.	Passed
6. Wait at most 1 minute.	The appeared data was the current date.	Passed
7. Turn on the network to which the device is associated.	The device connected to the local home network.	Passed
8. Wait at most 1 minute.	The appeared data was the current date.	Passed

Table B.4: Test n° 4: Settings Update.

n°: Title	4: Settings Update	
Description	Test the data of the Settings page and its update in the software.	
Functional Requirements	18, 23, 24	
Precondition	The device and the computer are connected to the local home network.	
	The user needs to know the Webpages IP associate to the local home network.	
Test (Steps)	**Results**	**Verdict**
1. Acess to the home page.	Home page displayed.	Passed
2. Select "Settings".	The "Settings" page appeared. In the page, there were 5 tables: "Appliances Information", "Network", "Current Meter", "Fault Code" and "Energy Meter".	Passed
3. Change a parameter of table "Appliances Information" and select the button "Set".	A notification "Posting advanced settings..." appeared.	Passed
4. Reload the page.	The changed value appeared in the respective box.	Passed
5. Turn off the device.	Loss of access to the web pages.	Passed
6. Turn on the device and access to the "Settings" page.	The changes remained.	Passed
7. Repeat this process to other parameters.	Same result.	Passed

Table B.5: Test n^o 5: Monitoring - page data update.

n^o: Title	5: Monitoring - page data update	
Description	Test the data updating.	
Functional Requirements	12, 18, 19, 20	
Precondition	The device and the computer are connected to the local home network.	
	The user needs to know the Webpages IP associate to the local home network.	
Test (Steps)	**Results**	**Verdict**
1. Acess to the home page.	Home page displayed.	Passed
2. Connected the motor to the device and reload the page.	The colour of the indicator ”Machine” and ”Motor” changed to green. The ”Start Time” of the list, table ”Value” and the ”Start Counter” updated.	Passed
3. Wait 3 or 5 minutes and reload the page.	The chart updated with new data.	Passed
4. Disconnected the motor and reload the page.	The colour of the indicator ”Machine” and ”Motor” changed to red. The ”Stop Time” of list updated.	Passed
5. Wait at least 5 minutes and reload the page.	The colour of the indicator ”Stand by mode” changed to green. The chart updated with new data.	Passed
6. Connected the motor to the device and reload the page.	The page didn’t change.	Passed
7. Wait 30 seconds and reload the page.	The colour of the indicator ”Machine” and ”Motor” changed to green. The ”Start Time” of the list and the ”Start Counter” updated.	Passed

Table B.6: Test nº 6: Turn on/off load.

nº: Title	6: Turn on/off load	
Description	Test the device load switching	
Functional Requirements	13	
Precondition	The device and the computer are connected to the local home network.	
	The user needs to know the Webpages IP associate to the local home network.	
Test (Steps)	**Results**	**Verdict**
1. Access to the home page.	Home page displayed.	Passed
2. Do click in the Relay ”ON” button.	The notification ”Relay State changed” appeared.	Passed
3. Do click in the Relay ”OFF” button.	The notification ”Relay State changed” appeared.	Passed
4. Connected the motor to the device.	The motor didn’t turn on.	Passed
5. Do click in the Relay ”ON” button.	The notification ”Relay State changed” appeared and the motor turned on.	Passed
6. Do click in the Relay ”OFF” button.	The notification ”Relay State changed” appeared and the motor turned off.	Passed

Table B.7: Test nº 7: Fault Page.

nº: Title	7: Fault Page	
Description	Test the data updating.	
Functional Requirements	18, 21	
Precondition	The device and the computer are connected to the local home network.	
	The user needs to know the Webpages IP associate to the local home network.	
Test (Steps)	**Results**	**Verdict**
1. Access to the home page.	Home page displayed.	Passed
2. Select the ”Fault”.	The ”Fault” page displayed. In the page, we have the ”Peak Information”, ”Reference Information”, ”List of the Last Faults” and graph.	Passed
3. Connected the motor to the device and reload the page.	Nothing change.	Passed
4. Wait 4 minutes and reload the page.	The ”Peaks Information” changed and the line ”NOW” appeared in the graph.	Passed
5. Disconnected the motor and reload the page.	Nothing change.	Passed
6. Wait 30 seconds and reload the page.	All the parameters in ”Peaks Information” reset and the line ”NOW” disappeared.	Passed

Table B.8: Test nº 8: Fault Detection.

nº: Title	8: Fault Detection	
Description	Test the fault detection action	
Functional Requirements	11, 16, 18, 21	
Precondition	The device and the computer are connected to the local home network.	
	The user needs to know the Webpages IP associate to the local home network.	
Test (Steps)	**Results**	**Verdict**
1. Access to the ”Fault” page.	The ”Fault” page displayed.	Passed
2. Connected the motor to the device and reload the page.	Nothing change.	Passed
3. Wait 4 minutes and reload the page.	The ”Peaks Information” changed and the line ”NOW” appeared in the graph.	Passed
4. Select ”Settings”.	The ”Settings page” appeared.	Passed
5. Change the power value of ”Appliances Information” table to 500W and in the button ”Set”.	A notification ”Posting advanced settings. . . ” appeared.	Passed
6. Select the ”Fault”.	Nothing change.	Passed
7. Wait 4 minutes and reload the page.	The list and the ”Faults Counter” updated with new data.	Passed
8. Go to ”Settings” and change the power value of ”Appliances Information” table to 0W and click in the button ”Set”.	A notification ”Posting advanced settings. . . ” appeared.	Passed
9. Wait 10 minutes and go to ”Fault”.	Nothing change.	Passed

Table B.9: Test nº 9: Reference FFT.

nº: Title	9: Reference FFT	
Description	Test of the calculation of the reference FFT. And test if it is correctly stored in the device's memory.	
Functional Requirements	11, 21	
Precondition	The device and the computer are connected to the local home network.	
	The user needs to know the Webpages IP associate to the local home network.	
Test (Steps)	**Results**	**Verdict**
1. Access to the ”Fault” page.	The ”Fault” page appeared.	Passed
2. Long press in the device button.	Nothing happened.	Passed
3. Connected the motor to the device.	The led turned red and after 2 seconds it Turn green.	Passed
4. When the led if off, disconnected the motor from the device. Reload the ”Fault” page.	The ”Reference Information” and the line ”REFERENCE” changed.	Passed
5. Turn off manually the device. After 10 seconds turn on the device and load the ”Fault” page.	The reference data remain on the page.	Passed