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Low-Cost and Accuracy Smart Meter Prototype for Smart Grids

Abstract. *This article aims to carry out a brief bibliographical review on the main concepts related to Smart Grid, in addition to the development of a low-cost and open-source smart meter prototype. This research was carried out based on concepts involved and used in developing the CS5463 chip, an embedded Linux system, and several software libraries, which helped with the implementation of the reference algorithm and charging simplification. Furthermore, the prototype had positive results, as it was possible to implement the proposed algorithms with a cost below US $ 50.00 and achieved an accuracy above 90%. Finally, it is concluded that the concept of Smart Grid and everything that permeates it is fundamental, especially given the context of digital transformation in this area. Such a prototype is an initial entry alternative for developing technologies that are trending in this area.*

Streszczenie*.. Celem tego artykułu jest przeprowadzenie krótkiego przeglądu bibliograficznego głównych pojęć związanych ze Smart Grid, a także opracowanie taniego prototypu inteligentnego licznika o otwartym kodzie źródłowym. Badania te zostały przeprowadzone w oparciu o koncepcję wykorzystana w opracowaniu układu CS5463, wbudowanego systemu Linux oraz kilku bibliotek oprogramowania, które pomogły we wdrożeniu algorytmu referencyjnego i uproszczeniu ładowania. Co więcej, prototyp uzyskał pozytywne wyniki, ponieważ możliwe było wdrożenie proponowanych algorytmów kosztem poniżej 50 USD i osiągnął dokładność powyżej 90%. Na koniec stwierdza się, że koncepcja Smart Grid i wszystko, co się przez nią przenika, ma fundamentalne znaczenie, zwłaszcza w kontekście cyfrowej transformacji w tym obszarze. Taki prototyp jest wstępną alternatywą dla rozwoju technologii, które są trendy w tej dziedzinie. (****Tani i dokładny prototyp inteligentnego licznika dla inteligentnych sieci****)*

Keywords: Smart Meters, Smart Grids, Low-Cost Prototype.
Słowa kluczowe: Smart Grid, miernik inteligentny, pomiar mocy

Introduction

Since the invention of electrical networks, there have been no significant changes in the technology used for the generation, transmission, and distribution of electrical energy, where the technologies used to date back to the end of the 19th-century [1] [2] [3].

As the global demand for energy increases, it is neces sary to use techniques to make the network more efficient and actual, giving rise to a new concept to solve this challenge, called Smart Grids [4].

NIST (National Institute of Standards and Technology) defines Smart Grids as an electrical network that uses two-way flow information with secure communication and artificial intelligence technologies to integrate the entire spectrum of the power system, from power generation to final customer [5].

In the Brazilian context, the implementation of this concept is motivated mainly to reduce the non-technical losses of the network, which according to Aneel is around 6.6%. Also, there is a quest to increase the reliability of the system, reduce operating costs - especially those related to measurement, and increased energy efficiency [6] [7].

One of the challenges for the massive implementation of Smart Grid in Brazil is related to the large volume of investment required for its implementation. The key component, which requires most of this investment, is related to the exchange of the meter park for smart meters [8].

In this context, this work develops an initial prototype of an intelligent energy meter. The prototype will be presented as being of low cost concerning the prices of similar equipment (ranging from U$ 50 to U$ 100 for home use), with free software and code compatible with multiple embedded platforms. The decrease in cost of the meter is important, as it decreases the amount of investment needed to update the meter park [9] [10]. Besides, the prototype can be a starting point for future work in the area of Non-intrusive load monitoring (NILM).

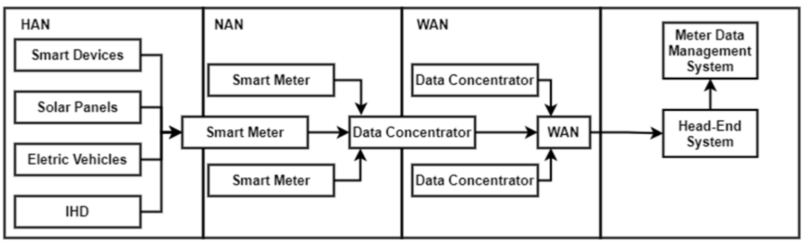

Fig. 1. Demonstration of a complete smart grid system, with its maincomponents and interconnections [12]

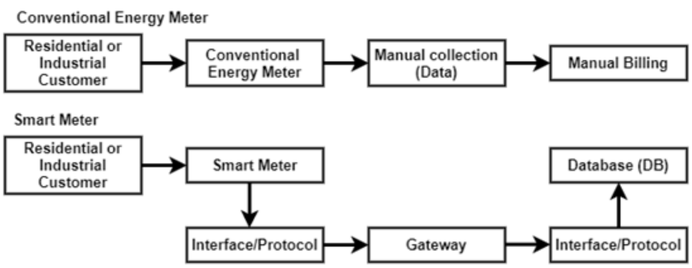

Fig. 2. Basic Conventional and Smart Meter Architectures Concept[12].

This article is organized as follows: Section 2 presents the concept of Smart Grid, section 3 presents the concept of Smart Meter, section 4 presents the developed prototype, and section 5 presents the results obtained. Finally, section 6 presents the conclusions.

Smart Grid Overview

In the current world scenario, the availability of electricity is essential for contemporary societies, as it is closely related to most activities. The unavailability of energy generates several negative impacts.

Unfortunately, classic networks are not resilient and agile, being susceptible to problems with generation (lack of demand) and transmission/distribution (quality problems and issues related to technical and non-technical losses) directly affecting the final consumer.

In 2005, S. Massoud Amin and Bruce F. Wollenberg coined the term Smart Grid in a publication by the IEEE (Institute of Electrical and Electronics Engineers). The authors define the term as large-scale electrical network infrastructure characterized by security, agility, and resilience/robustness facing new threats and unplanned conditions [11]. The term coined by them, meant a major paradigm shift, going beyond the simple implementation of certain technology to something bigger.

There are several motivations to justify investing in Smart Grid. Some of them are improvement in the country's energy security, reduction of greenhouse gas emissions, and the possibility of reducing operational costs and non-technical losses.

Brazil, like most developing countries, is in the initial stage of implementing the Smart Grids concept.

Looking from the distribution point of view, where there is an interconnection between the final consumer and the distribution sector, it is necessary to implement an architecture known as AMI - Advanced Metering Infrastructure, which enables bidirectional communication and several new network functionalities.

The key equipment of this architecture is Smart Meters, which collect and send data in a bidirectional way between the customer and the distributor. These devices are the target of this article. The meters can use different communication technologies, such as PLC, RF Mesh, or mobile networks, to establish the connection with the concentrators - or directly with the distributor depending on the case.

Looking at the network architecture in (Fig. 1), AMI is composed of three types of networks, they are Home area network - HAN, Neighborhood area network - NAN, and Wide area network - WAN. HAN is a network generated by smart meters and is responsible for collecting all information on consumption, micro-generation, and household occurrences.

Besides, this network can connect smart devices to the me- ter, allowing demand control by the distributor if necessary. NAN is the network responsible for concentrating data from existing meters in the neighborhood and sending it to the distributor via WAN. In this stage, concentrators are used, which concentrate data from smart meters and send them via IP network to the distributor's backbone. After sending data over the WAN, they arrive at the distributor where it will be used for the most diverse services. It is worth mentioning the module known as MDMS (meter data management sys- tem) is responsible for managing, storing, and analyzing the data received.

Smart Meter Overview

Before talking about smart energy meters, it is important to talk about the origin and evolution of the meters. Electromechanical meters were the first-meter model and are still widely used today. They are based on the principle of electromagnetic induction, having been invented by Shallenberger in 1888 [13]. This meter measures only the active energy consumption, and manual data collection is required for data collection. The flow of information is unidirectional. The useful life of this type of meter can reach 25 years [10].

With the development of digital systems and their subsequent cheapening, electronic energy meters emerged. This type of meter is based on the use of A/D converters and a microcontroller or microprocessor for sampling techniques to determine the energy consumed by the consumer.

In general, electronic meters are more accurate than electromechanical meters. This type of meter has the following disadvantages: the fact that its useful life is between 13 and 15 years; there is uncertainty about its operation under severe climatic conditions and its cost greater than the electromechanical [13]. Fig. 2 shows some aspects and characteristics of conventional energy meters in relation to Smart Meters.

Over time, electronic meters have evolved into what is now known as smart energy meters. The Edison Electric Institute (EEI) defines Smart Meters as: "electronic metering devices used by utility companies to transmit information for charging the consumer and for operating electrical systems" [14] [15]. There is still no general definition of what features define a smart meter or smart metering system. For this paper, we use the definition by Mohassel, Moahammadi, Fung, and Raahemifar [16]. They are:

- Time-based pricing;
- Providing consumption data for consumers and utility;
- Net metering;
- Failure and outage notification;
- Remote command (turn on / off) operations;
- Load limiting for Demand Response purposes;
- Power quality monitoring including phase, voltage, andcurrent, active and reactive power, power factor;
- Energy theft detection;
- Communication with other intelligent devices;
- Improving environmental conditions by reducing emis-sions through efficient power consumption.

Looking at the market solutions, we have several meter manufacturers, where we can mention as examples: WEG, General Electric, Itron, Nansen, Siemens, Schneider Electric, among others. In general, these meters are modular, measure active and reactive energy in the four quadrants, active and reactive demand, in addition to items related to network quality. These meters are bidirectional, with the possibility of using multiple forms of communication (PLC, RF, Ethernet, Wifi, Zigbee, GSM / GPRS / CDMA). Also, these meters allow the programming of several charging models, mass memory, and the possibility of fraud detection. Optionally, some me- ters have tools for use in smart homes.

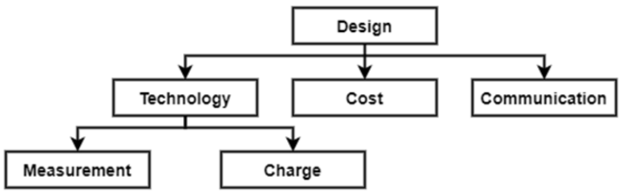

Fig. 3. Basic items utilized for the implementation of prototype Smart Meter.

Smart Meter Prototype

The implemented smart meter prototype proposed is based on non-intrusive, low cost and easy to find components. Based on the design problems presented by Depuru, Wang, and Devabhaktuni [12], we try to address issues related to the technologies used for measurement/charging, meter cost, and communication. Fig. 3 shows the diagram of the mentioned items, which during this section will be better explained.

The measurement and charging technologies involved with the proposed prototype were developed using the Cirrus Logic CS5463 IC, an integrated circuit specialized in measuring electrical parameters, together with the MRAA library - library for embedded Linux systems that easy I/O communication-, implements SPI communication, and allows code portability across multiple embedded systems. The tariff was based on a simplified version of Aneel's resolution, No. 733 of 2016, which regulates the white tariff (Brazilian seasonal tariff). It was also sought that the prototype minimally could obey the resolution of Aneel nº502, which lists the minimum requirements for energy meters, but maintaining the low-cost prerogative.

Looking at market solutions, the meter features energy measurement, active and reactive demand, bidirectional communication, mass memory, and communication with the Internet via Wi-Fi. Besides, the existing pricing is based on consumption time (Time-based pricing). The final cost of the prototype was US $ 45.00. The basic characteristics of the prototype are:

- Operation: 127 / 220V;
- Measurement of Voltage, Current, Frequency, Active, Reactive and Apparent Power and Power Factor;
- Internet connection via Wi-Fi;
- Ability to save data on the memory card;
- Display with measurement information;
- Non-intrusive, allowing easy installation of the proto type;
- Implementation of a simplified version of the White Tariff;
- Online panel with measurement information;
- Open source code: (https://bitbucket.org /Mud_Owl/ic_mud_owl_v2).

The design and construction of the hardware/software used a bottom-up approach. It started with simplified hardware and software and, after several studies and tests, it evolved to the above characteristics.

Thus, the system architecture shown in Fig. 4 was developed. The sensors gather the information from the network and the meter (IC meter and development board) is re- sponsible for allowing the visualization of the data, making the communication interfaces, and processing the electrical measurements and the tariff.

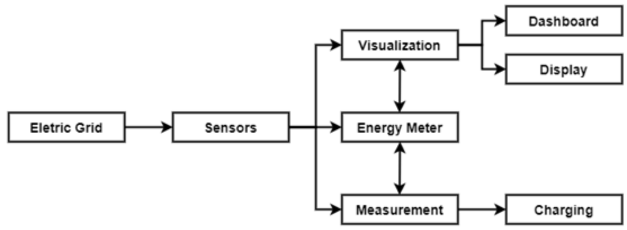

Fig. 4. Flowchart containing the architecture of prototype.

Hardware

To easy data collection, it was decided to use an integrated circuit dedicated to energy measurement applications, CirrusLogic CS5463, responsible for obtaining the values of vari- ous electrical measurements. This made the work easier, as the measurement algorithms are in hardware. In addition to that, they were tested and had an accuracy established and guaranteed by the manufacturer. The CS5463 is an IC com- posed of two ADC converters - one for voltage and one for current, besides a calculation unit, which calculates several electrical quantities. This IC communicates with the devel- opment board using the SPI protocol. For the use of this IC (CS5463) and the modularization of the project, a printed cir- cuit board was developed following the model of the technical sheet found on the Cirrus Logic website [17]. Fig. 5 shows the diagram of the developed circuit board. The JP1 and JP2 components form a socket, which easy the connection of the IC to the board. The TC and TP components repre- sent the connections of the sensors (terminals), connected to the conditioning circuits (voltage dividers that reduce the input voltage to a maximum of 250mV RMS), passive filters, and the IC connections.

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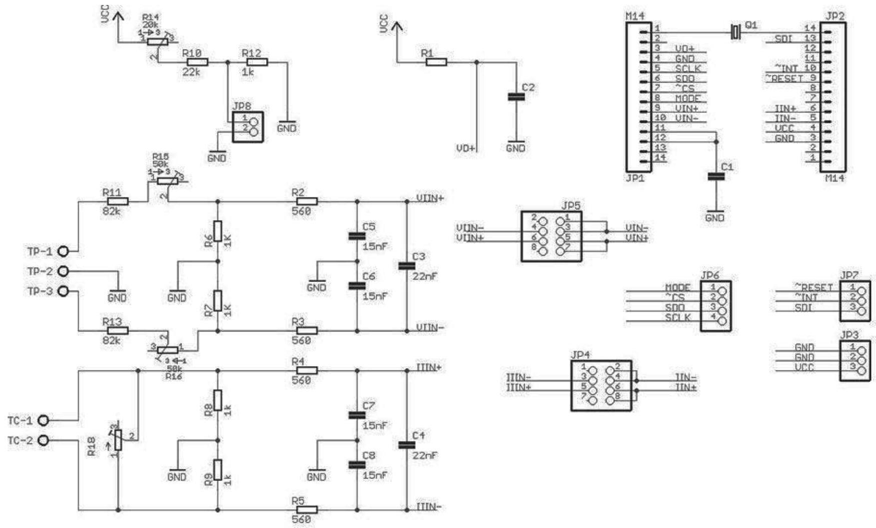

Fig. 5. Schematic diagram of the proposed prototype.

The other representations are connecting pins and pins for IC calibration. JP6 and JP7 components are connected to the pins corresponding to the SPI input of the embedded system. The hardware developed and used consists of the following items:

- Cirrus Logic CS5463 integrated circuit, two conditioning

circuits for adjusting the sensor voltage to the IC input values, and interface connectors between the sensors and the board;
• 28-pin SMD / DIP adapter;
• Intel Edison with Arduino kit;
• Base shield;
• 16x2 RGB LCD;
• Potential transformer (PT) 127 / 220V to 12 + 12V, as a voltage sensor;
• Current transformer (CT) SCT-013-000, as a current sensor;
Connection jumpers.

Software

The software developed for the prototype implements thearchitecture shown above, and it focused on two parts:

• The first part consisted of the implementation of the measurement routines, which took into account the measurement and loading functions. For this, it was needed to use the SPI protocols, for the communication between Intel Edison and CS5463, the I2C protocol, for the communication with the display, and the MQTT pro- tocol - for the WEB communication used to update the dashboard information.

• The second part consisted of implementing user views,where the dashboard was developed.

The first part used the Python language in conjunction with several libraries, mainly the MRAA library, which controls the GPIO ports of the card and allows the portability of the software to various hardware on the market and the paho.mqtt library that implements the MQTT client used to send data to the dashboard.

In the flowchart (Fig. 6) on the right, all the necessary steps to measure an electrical quantity are detailed, where it is needed to perform: IC configuration, sending initialization commands and after that, it starts to receive the chip data, which will ultimately need to convert and apply the necessaryscales.

In the flowchart (Fig. 6), on the left of the figure, the steps necessary to perform the consumption calculation are detailed according to the white tariff model - power measurement, energy consumption calculation, and application of the white tariff rules (questions related to the day of the week and times).

The second part consisted of implementing the dashboard. To facilitate the design, a free template built-in Bootstrap [https://getbootstrap.com/] and Highcharts [https://www.highcharts.com/] - used to generate the graphics were used. The functioning of the dashboard consists of receiving the information from the MQTT protocol and presenting it to the user.

Experimental Results

As an initial test, to prove that the developed firmware is functional, it was decided to measure and analyze the error in the current and voltage measurements obtained in different electrical equipment. It was decided this way because current and voltage are the fundamental quantities and the other quantities use these values in the internal calculation of the IC.

To perform the tests, it was needed to perform the calibration steps described in the IC datasheet [17]. This is necessary to obtain the precision described by the manufacturer. Also, there was a need to adjust the conversion scales of the software, once the IC did not present the values directly, but in scale. The test performed was in accordance with the following methodology:

• The prototype smart meter and a set of multimeters configured as ammeter and voltmeter were connected;
• A set of electrical equipment was chosen, in this case:
– Amazon Alexa (15 W);
– Cellphone Charger (10 W);
– Incandescent Lamp (25 W);
– Electric Citrus Juicer (250 W);
– Led Lamp (9 W);
– Computer Monitor (15 W);
– Notebook Power Adapter (45 W);
– TV (120 W);
– Fan (80 W).
• One device was turned on at a time and the data obtained from the prototype meter was collected, 5000 samples of each equipment were used (Voltage, Current, Active Power, Apparent Power, Reactive Power, Frequency and Power Factor) and the average was calculated to obtain the values presented in Table 2;
• The data obtained by the prototype were compared with the data obtained by the multimeters and a subsequent calculation of the agreement between the types of data was performed in Table 1.

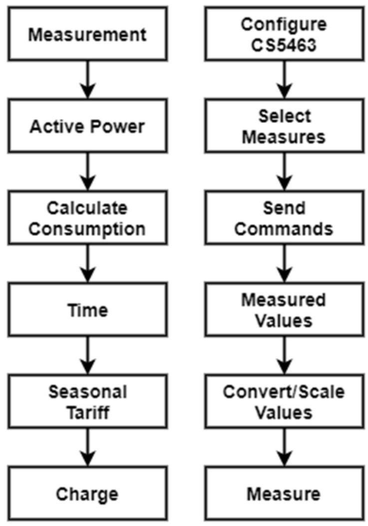

Fig. 6. Diagram of the Developed Software.

Table 1. Comparison between multimeter and proposed smart meter.

		Proposal (Smart Meter)		Multimeter		Concordance	
		Voltage	Current	Voltage	Current	V-V(%)	A-A(%)
Amazon Alexa	Mean	121,914	0,010	121,480	0,010	99,64	96,96
	SD	0,271	0,000	0,084	0,000		
Cellphone Charger	Mean	122,541	0,061	122,240	0,060	99,75	98,00
	SD	0,290	0,001	0,055	0,000		
Incandescent Lamp	Mean	121,552	0,190	122,420	0,200	99,29	95,23
	SD	0,258	0,000	0,084	0,000		
Eletric Juicer	Mean	119,084	1,515	119,240	1,512	99,87	99,79
	SD	0,164	0,012	0,182	0,004		
Led Lamp	Mean	120,371	0,132	119,440	0,136	99,22	97,28
	SD	1,735	0,002	1,974	0,005		
Computer Monitor	Mean	122,732	0,150	122,620	0,138	99,91	91,32
	SD	0,110	0,001	0,084	0,004		
Notebook Power Adapter	Mean	120,986	0,203	120,760	0,188	99,81	92,13
	SD	0,143	0,025	0,055	0,015		
TV	Mean	121,626	0,585	121,660	0,588	99,97	99,46
	SD	0,172	0,026	0,089	0,004		
Fan	Mean	120,436	0,529	119,600	0,544	99,30	97,23
	SD	0,523	0,001	0,158	0,005		

Table 2. Proposed smart meter collected data

		Voltage (Vrms	Current (Arms)	Active Power (W)	Apparent power (VA)	Reactive power (VAR)	Frequency (Hz)	Power factor
Amazon Alexa	Mean	121,9136	0,0103	0,5686	1,2560	1,1199	59,9738	0,4527
	SD	0,2707	0,0003	0,0159	0,0359	0,0323	0,0292	0,0026
	Min	121,2762	0,0099	0,5543	1,2123	1,0752	59,9442	0,4441
	Max	122,4807	0,0132	0,7326	1,6099	1,4336	60,0553	0,4620
Cellphone Charge	Mean	122,5413	0,0612	4,2387	7,4990	6,1858	59,9978	0,5653
	SD	0,2897	0,0007	0,0066	0,0880	0,1060	0,0299	0,0066
	Min	120,0093	0,0576	4,2204	7,0458	5,6250	59,9442	0,5532
	Max	123,1502	0,0634	4,2583	7,6620	6,3827	60,0553	0,6022
Incandescent lamp	Mean	122,5413	0,0612	4,2387	7,4990	6,1858	59,9978	0,5653
	SD	0,2583	0,0002	0,0739	0,0751	0,0146	0,0312	0,0000
	Min	121,0958	0,1901	22,6728	23,0250	4,0061	59,8888	0,9846
	Max	122,1595	0,1910	22,9711	23,3288	4,1299	60,0553	0,9848
Electri Citrus Juice	Mean	119,0836	1,5152	137,1450	180,4393	117,2165	59,9704	0,7602
	SD	0,1641	0,0116	1,0749	1,5748	3,3536	0,0279	0,0114
	Min	118,7380	1,4982	135,1277	177,8900	112,7201	59,9442	0,7327
	Max	119,6226	1,5468	139,2276	184,7137	125,6563	59,9999	0,7751
Led Lamp	Mean	120,3712	0,1323	9,1561	15,9244	13,0286	59,9787	0,5750
	SD	1,7348	0,0023	0,1672	0,3499	0,3227	0,0311	0,0051
	Min	117,2652	0,1284	8,7761	15,0713	12,2499	59,9442	0,5699
	Max	121,9560	0,1386	9,6104	16,8224	13,8069	60,0553	0,5857
Computer Monitor	Mean	122,7316	0,1500	10,3710	18,4060	15,2060	59,9964	0,5635
	SD	0,1101	0,0005	0,0187	0,0661	0,0868	0,0323	0,0027
	Min	122,4592	0,1430	10,3222	17,5326	14,1157	59,9442	0,5568
	Max	122,9873	0,1514	10,4523	18,6025	15,4521	60,0553	0,5931
Notebook Power Adapter	Mean	120,9859	0,2028	11,6568	24,5348	21,5827	59,9773	0,4730
	SD	0,1431	0,0255	1,9435	3,0861	2,4519	0,0381	0,0170
	Min	120,6833	0,1627	8,8366	19,6714	17,5750	59,8888	0,4430
	Max	121,6044	0,3183	20,8521	38,6131	32,4986	60,0553	0,5400
TV	Mean	121,6257	0,5848	43,3950	71,1333	56,3527	59,9808	0,6101
	SD	0,1715	0,0262	1,9955	3,1975	2,7263	0,0306	0,0126
	Min	121,0282	0,3122	21,2797	38,0544	31,5486	59,8888	0,5532
	Max	122,0131	0,6010	44,2831	73,0167	58,2399	60,0553	0,6734
Fan	Mean	120,4358	0,5289	61,6698	63,7042	15,9705	59,9774	0,9681
	SD	0,5230	0,0014	0,4109	0,4278	0,1206	0,0274	0,0001
	Min	119,6133	0,5261	60,9577	62,9641	15,5521	59,9442	0,9678
	Max	121,9857	0,5334	62,9432	65,0278	16,4348	59,9999	0,9683

Discussion

By analyzing the table above, it is possible to infer an accuracy above 90% in all the test cases, demonstrating that the data are within an acceptable range. As it is an initial prototype and as there is no need to use test methodologies that are used in commercial products, standardized by INMETRO (Brazilian Metrology Institute), these values are acceptable for this research. The voltage data reached an accuracy close to that described in the datasheet (+/-0.1%), indicating a good fit. Current data achieved an accuracy above 90%, but there is room for improvement during the calibration step aiming at reaching a value close to that indicated in the datasheet. The main objective of this experiment was achieved, as it indicates a good working of the measurement algorithm. In future work, two interesting paths to be followed are: to improve the calibration step - especially in the current part - and carry out measurements at the site's energy input to have a general value for the installation.

Conclusion

This article presented the scenario of smart grids in Brazil and in the World, contextualizing the importance of the development of the open source smart meter proposed prototype. Concerning the prototype, it was possible to implement several concepts of Smart Meters.

The goal of creating a low-cost prototype was achieved, as equipment costs were below US $ 50. Another interesting point is that through the implementation of AMI, and consequently the massification of smart meters, a new market will emerge that will be based on the information obtained by smart meters, where there will be many opportunities for the creation of innovative services.

Finally, smart meters can bring new economic and technological opportunities and, mainly, bring investments to modernize electrical systems, bringing more sustainability and awareness about the use of electric energy.

For future work, we will extend the research with: first, collect more data about many electrical devices using a low- cost smart meter; second, training a CNN to identify con- nected electrical devices; third, create a recommendation system for smart home environments.

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