THD_i measurement system of home energy signal based on IoT

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***Abstract*—Monitoring information of the electrical signal is usually not available to finals users. Nowadays, consumers hardly ever actually have knowledge about how efficient is the signal which respective dealership provide because it isn't present on electrical bills or other platforms. This article presents the development of a low-cost microcontrolled system to measure and telemetry the Current Total Harmonic Distortion (THD_i) index of an electrical signal in a home environment. The purpose is to create a constant monitoring process through an IoT's architecture that uses open standards allowing an interface for real-time visualization.**

I. INTRODUCTION

Along the history of mankind, industrial revolutions act as social transformers agents, bringing more innovation and practicality to existing task's resolutions, optimizing processes and extending knowledge applicable to a certain area when built correctly. With a very similar bias, the results of new techniques coming from the fourth industrial revolution, or simply Industry 4.0[1][2] (Big Data, Data mining, Telemetry, Automation) have the power to modify routines which may be considered simple, inefficient or laborious.

At the current juncture, due to greater access to information related to technology, telemetry, and automation, it's possible to improve domestic applications and modify the way we live in habitations and others environments. Nowadays, lights, temperature, reliability, and sound, for example, can interact in a practical way with the user offering comfort and convenience[3]. Those applications, when integrated to the most diverse platforms, are clearly, playfully and consistently presented to users transforming user's experience even more fruitful and effective[4]. But, despite the benefits, products coming from industry 4.0 aren't well diffused on the social environment due to equipment, production and maintenance prices, insecurity, distance from technology used, among others[5].

In Brazil, is known that the electrical signal nationally standardized by Associação Nacional de Energia Elétrica (ANEEL) has the frequency of 60 Hz and variable voltage of 220 or 110 V depending on which region it's been analyzed. However, there is no information about the quality of the signal provided by the dealership which may be polluted due to harmonic distortions caused by non-linear loads or other noise sources. The consequences of the signal's pollution are conductors overheating, shutdowns or others unexpected actions on physical devices, and a power factor decrease[6].

Thus at the moment when electric energy benefits daily part of people's lives and becomes indispensable to business, it becomes natural a search and maintenance about the quality of that product. With consumers and industries also getting more sophisticated and informed under a point of technological view, it's important to remind that deal with energy quality isn't only about worry with service's continuity, but also to pay attention to some home appliances operation faults even when there aren't electric energy supply interruptions.

Some works already had presented with solutions and propositions at the measurement of THD_i [7][8] but they require complexes, expensive an hard to find hardwares, in addition to a tough manipulation to complete the task of monitoring signal's quality. So, due the lack of works which presents an open IoT architecture or uses the proposed hardware this paper offers an cheaper, easily handle and open system to measure THD_i.

The objective of this paper is therefore present a low-cost accessible system which remotely reports by means of a microcontroller to a central by MQTT protocol which is built with generals architecture based on open standards. Acquiring data through Current Meter Circuit (CMC), the Total Harmonic distortion index is treated and extracted by some calculation done by the microcontroller used, which has the task of sending information to a local data to render to the users and store in an external cloud. The final user will be able to access all data stored, locally or externally, by system's telemetry interface.

Is discussed the THD_i index, which is a ratio of the sum of harmonics' amplitudes to the fundamental frequency power. The low THD_i means a high signal's quality at a reduction in peak currents, heating, and emissions.

This paper is divided into five sections to a better comprehension. First, the Introduction (Section I) which gives scenarios and a context where the system is immersed. In Methodology (Section II) discusses the IoT architecture used, hardware components, the manner how information is sent and then how is mathematically calculated (Section III). Section IV shows tests' procedure, their results, system's accuracy and results' meaning. The last Section concludes the paper showing challenges, future scenarios, contexts where this application can be developed and can be necessary, his benefits and proposals for next works.

II. METHODOLOGY

This section explains the architecture and working of the system proposed. It also describes current meter setup and hardware components used. In general, the system is divided into 3 tasks: raw data acquisition, wave computation, and indexes visualization.

A. Architecture

Some IoT architectures have been researched objects by several organizations which give formal definitions and models necessary components and its interaction based on different technological integration and sundry social fields domains [9]. To project the system based on open standards, the chosen architecture better described in [10], ensures an offline continuing routine and organizes modules facilitating support and maintenance.

The raw data acquisition is done through the CMC (Figure 2) composed of an invasive current sensor 5A amplitude and a Wemos D1 mini board with an ESP8266 microcontroller [11]. The CMC processes data due ESP8266's ADC (analog-to-digital converter) and do some calculations (section III), at the end processing, the total harmonic distortion index is obtained. After, ESP8266 sends signal's information using a Wi-fi connection to a Raspberry Pi 3 [12] where the categorical storage, data handling, and rendering will be made. It was utilized MQTT Protocol to communicate microcontroller and Raspberry Pi. At the Figure 1, it is shown data flux from the sensor to Raspberry Pi.

It's proposed in this architecture to realize all calculations on hardware (current measurement, FFT algorithm and THD_i index information) in order to avoid network traffic overload and improve the spent time of each processes.

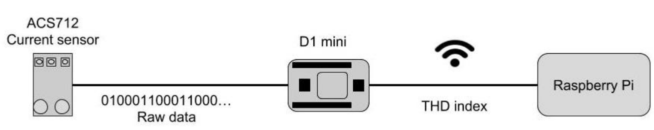

Figure 1. Data flow

The Raspberry Pi runs the server, in Figure 2, which act as a middleware intermediating the application accessed and all CMCs in the local. It counts with a local storage where data is temporarily saved before being sent to the cloud where all past information can be accessed. Also, a Web Services API (Application Programming Interface) that handles requests and updates new stored values to be rendered.

In addition to work in a local net (impossibility cloud external access), this architecture enables the system proposed to keep monitoring electric signal and access data that is locally stored. However, once the Internet connection is done, the server is able to send information to the cloud and permit the user to access persistent data.

The measurement system analysis will be divided for better understanding into Hardware, Circuit, Storage and visualization.

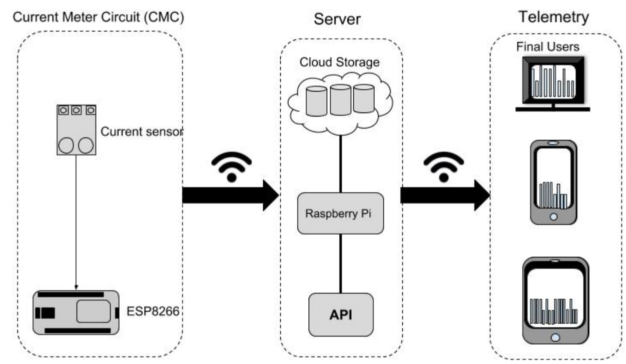

Figure 2. System's architecture

B. Hardware

The system contains a device who measures the instant electric current: The ACS712ELCTR-05B-T [13]. This electronic component is a linear sensor based on Hall effect which detects the magnetic field generated by current flow and provides at the output (OUT pin) a proportional voltage of 185 mV/A (particular sensitivity of the used sensor's version), so, the signal produced at the module output is analog. To discretize it, it's used a microcontroller that takes samples at a certain frequency through the analog port.

The chosen microcontroller for this application was the ESP8266 developed by EXPRESSIF SYSTEM. For prototyping was chosen the D1 mini board developed by WEMOS ELECTRONICS. Compared to its competitors, the ESP8266 stands out for his low cost of market, the simplicity of hardware, reduced size, a great online community and integrated Wi-fi which exempt physical wires manipulation, allows the communication with several devices with the server and the lack of works and papers which uses this microcontroller to this end. Others microcontrollers can be utilized to this application with the necessary adjustments.

The analog port of the prototype board is connected to the output (OUT pin) of the current sensor, the signal is discretized and scanned through an ADC (analog-to-digital converter) with integrated 10-bit resolution. The definition of the data range is done via software. The sampling time interval is declared and, through interruption, the data capture process is finalized by initiating the mathematical procedures for interpreting the data.

The Raspberry Pi 3 is a single-board computer with wireless LAN and Bluetooth connectivity which enables the middleware work with a local storage area and server the applications. This choice is made based on his low-cost, working low power, high availability and a big online community. To the proposed architecture it fits with requirements needed and ensure scalability depending on how data is formatted and which protocol is used [14].

C. Current Meter Circuit

The circuit counts with the electronic components mentioned above and a smaller circuit that ensures load, when connected, consumes electrical power as shown in Figure 3. The male plug was used to power the circuit at a public network voltage (in Brazil's northeast region) of 220 Volts. Male plug's first terminal is connected in series with the current sensor (since it will function as an ammeter) and soon after it is coupled to a terminal of the female plug. Also, the second 220 Volt voltage terminal is attached to the other terminal of the female plug. Thus, the load will act as a key closing or opening the circuit and allowing passage of the signal to be measured.

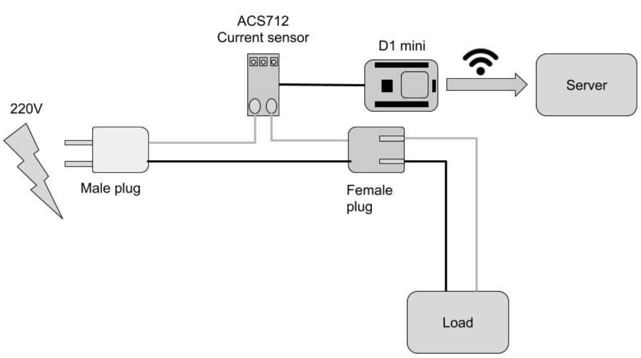

Figure 3. Circuit to detect electric currents

D. Storage and visualization

After obtaining the consumed current during the information capture interval in question and calculated the respective THD_i index, the data is grouped in the JSON (JavaScript Object Notation) format on the microcontroller, chosen due to the ease of interpretation and manipulation at server's side. Then the index is sent by MQTT (Message Queue Telemetry Transport) protocol to a web server responsible for this application, in order to treat and store them in a local database in a Raspberry Pi. This protocol was chosen due to his design for guarantee the communication of devices with limited resources of power or Internet signal [15]. Nevertheless, storage capacity is limited depending on the amount of data processed to be saved which is crescent by time, so a cloud connection to an external database is required to data persistence in cases of long pasts requirements by users. Information will be designed at the end based on specifics formats for a better visualization. After all the processes, the user has the possibility to monitor, in real time, the power consumed by a certain domestic appliance.

III. MATHEMATICAL PROCEDURES

The sensor used to measure current, ACS712ELCTR-05B-T, is able to detect currents up to $\pm$ 5A, which are responded proportionally to ranges of 0 to 5V at their analog output (OUT pin). It is inferred, therefore, that when there is no flow of electric charges in the circuit the sensor will be supplying 2.5V at its output. Because of the maximum voltage supported on the analog port of the microcontroller (limited to 3.3 Volts), a voltage divider with a 2:3 ratio is required before connecting the output.

A. Offset

In addition to the voltage divider, it is also necessary to map the read values to a range of values that is proportional to the resolution of the ADC. Therefore, knowing that such a resolution is 10 bits, the offset is set by checking the input numeric value when the system is open or when there is no electric current (theoretically this value is 512).

B. Signal analysis

The signal analysis is done on the microcontroller through the discrete data obtained from the signal. The samples are stored on the ESP8266 which also calculates the fundamental frequency and current magnitudes of each frequency are by the method Fast Fourier Transformer. It was decided to do all calculations on the microcontroller to reduce data flux before reach server. For each harmonic frequency, are added the frequency contributions of $\pm$ 5Hz for better analysis due to possible rounding errors. Then, a numerical integration is performed through the statistical method Root Mean Square (RMS) which considering a sequence of samples of the input signal x[n], where n is a sampling frequency, have to:

$$Irms = \sqrt{\frac{\sum_{i=0}^{n} x_i^2}{n}} \tag{1}$$

C. THD_i

With the contribution value of each harmonic obtained, it is possible to calculate the THD_i. The harmonic distortion rate is a used and well-accepted notation that defines the contribution percentage of the harmonic content of an alternating signal in comparison to its fundamental frequency [16]. Where, I_h is the effective current value, and I is the value of the current at the fundamental frequency.

$$THD_i = \frac{\sqrt{\sum_{i=2}^{n} I_h^2}}{I} \tag{2}$$

The end of the process, after all calculations, THD_i value is grouped, as previewed mentioned, in a JSON format with the respective measurement date, time and value, and is sent to server where after been store in a local database, becomes viewable by users.

IV. RESULTS

Initially, alternating signals were simulated in the analogical port of the microcontroller to prove all the mathematical procedures and the operating capacity of the chosen hardware. Then, the current sensor has been isolated since it is necessary to prove its correct operation. Through a verification experiment based on Ohm's law, given a known ohmic resistance and a known potential difference, it is possible to know approximately the electric current flowing in that system. Thus, it was used in the WEG test stand along with a kit of electrical measurements, with a fixed voltage at 220V, and several circuits to measure it.

The table I shows values which validate the current sensor isolated in those conditions mentioned above. Currents values detected by sensor (I_{sensor}) are compared with practical values ($I_{ammeter}$) measured with an ammeter during such a test. The last column shows the difference between the current measured by the ammeter and the current calculated by the sensor that ensures correct measurement of the values with the hardware used. Thus, a significant increase of the error by the hardware is realized as the current values decrease and also is important to quote the noise generated by the sensor (to the 5A version is 21mV about 0.42% of output error). Thus, for the sensor in question, it was tried to avoid test conditions for small currents.

Table I
TABLE WITH SENSOR'S TESTS VALUES

$R_{eq}(\Omega)$	$I_{ammeter}$(A)	I_{sensor}(A)	Error(%)
66	3,20	3,18	0.63 %
100	2,10	2,13	1.42 %
133,3	1,59	1,61	1.26 %
150	1,42	1,44	1.39 %
200	1,06	1,07	0.94 %
250	0,84	0,81	3.57 %
400	0,41	0,43	4.65 %
600	0,33	0,36	8.33 %

After this verification, the tests of all the processes presented for the system were started. By employing an example device that consumes electrical current as a load, the circuit was placed under a constant regime of capture, calculation, sending, storage and expression of the data.

The routine of data capture process is limited by the number of samples required to perform the FFT (Fast Fourier Transformer) algorithm configured in the firmware. For the tests, it was defined that the number of such processes would be 1024 samples, as it was shown a suitable value for the accumulation of data without compromising the computational capacity of the microcontroller and without compromising the processing of the system.

In tests performed with the microcontroller, used for such application, produced sampling frequency of 1024 Hz, defined and controlled on firmware, range enough to get the influence of several harmonics without giving any loss to the routine established. However, some works in the signal analysis showed that the contribution of high-frequency harmonics is low when compared to low-frequency harmonics [17]. Then, this application will deal only until the 8th harmonic once it fits on Nyquist–Shannon sampling theorem. After obtaining the influence data of each harmonic signal through the FFT algorithm, the THD_i calculation is performed.

In the example below, was used a simple home appliance (Sandwich Maker) for tests. It can consume maximum an average of 3.4A depending on the operations processes. Two comparative tests were performed in order to understand the influence of other loads on the quality of the network signal. All connected in the same grid, the first one analyze the behavior of the signal, first, in a quiet scenario with only a few electrical appliances connected (a tv, a microwave, and a fan), and after with some computers working at the same time. The test wants to prove sensor's capacity to detect harmonic distortion once the computer, being a system electronically commanded, are intrinsically non-linear (Switch Mode Power Supply) requiring electrical current peaks when it is necessary [18].

Table II
TABLE PRESENTING HARMONIC CONTRIBUTIONS WITH A FEW HOME APPLIANCES INFLUENCE

$N_{harmonic}$	$I_{harmonic}$ (A)
1 (fundamental)	1.55
2	0.01
3	0.00
4	0.01
5	0.00
6	0.00
7	0.00
8	0.00
TOTAL	1.57

Table III
TABLE PRESENTING HARMONIC CONTRIBUTIONS WITH COMPUTERS ON THE GRID

$N_{harmonic}$	$I_{harmonic}$ (A)
1 (fundamental)	1.64
2	0.02
3	0.02
4	0.01
5	0.00
6	0.00
7	0.00
8	0.00
TOTAL	1.69

After acquiring data, the firmware, using the method RMS to calculate the electric current explained in the session III (Equation 1) and using the THD_i formula (Equation 2) through the frequency spectrum resulted by FFT algorithm, came up at the result of a total harmonic distortion based on the current wave approximately of 1.05% in the first test, while in the second we reach the result of 1.83%. The variation on signal's quality as we can see have an affect on load's consumptions of 0.12 A.

In spite of a small THD_i index difference, owing to the low load's current consumption used at the tests, a scenario where appliances are connected to a high harmonic distorted electric grid and are demanding high current values are going to receive more overcurrents as pollution's effect and increase the risk of cause damage to an equipment.

Tests realized in the firmware proved that the algorithm keeps a routine that takes 330 ms to acquire new raw data, calculate them and send THD_i information, adding the time on the server's side until be rendered, the total time to the information go through the proposed architecture is approximately 1 second as presented at the following images where it's seen the THD_i index measurement over the current time.

The first image (Figure 4) is the result of the first test done. During the plot at 11:10:56 it's possible to verify the THD_i index measured in the first test of approximately 1.05% (Table II. Also at the second image (Figure 5) verify the results obtained at the second test which shows at the moment 11:35:04 an elevation of THD_i to 1.8% before the load be turned off (Table III).

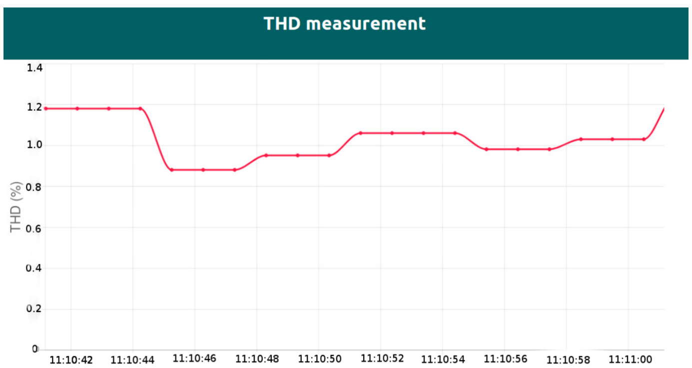

Figure 4. THD_i graphics with the respective time resulted from the first test: Few appliances connected at the same grid.

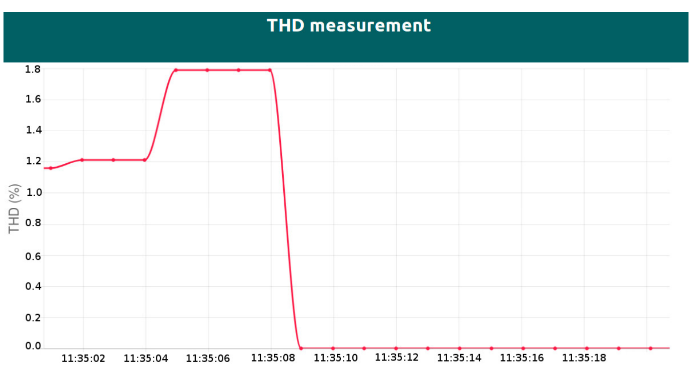

Figure 5. THD_i graphics with the respective time resulted from the second test: Some computers connected at the same grid

The tests proved that the presented system has the capacity to measure and telemetry small differences at the quality of the signal while a load is been used and also measure the electrical current consumption at acquiring data interval. It's important to quote that the system is able to detect small currents consumptions due to small circuits operations in the loads in situations where the load is connected to the electric network but it isn't been used.

According to ANEEL, Total Harmonic Distortion corresponding to values over 10% to a nominal voltage under 10kV already characterizes a consistent harmonic pollution in the network, but, the value measured at the tests are low meaning that despite small differences at THD_i, the signal's quality levels still were maintained elevated. If the THD_i value exceeds 10%, the pollution is quite considerable, with a risk of malfunction in the network.

For the ideal operation of the system in real situations, it was considered some details that prevent its ideal operation [19]. Power failure, hardware malfunction, magnetic interference (taking into account the Hall effect of the current sensor), problems in the web services responsible for storing data, numerical rounding, poor wire contact, hardware noise, among other faults that should be analyzed in isolation, since all information obtained by the system will be sent to the server.

It is important to emphasize that the whole system was developed so that when it is open or without any activity, the current level is zero, even if small fluctuations are pointed by the hardware, it is important that software ensure that they are minimized during the process.

V. CONCLUSIONS

It is concluded that in fact there are already technologies that allow the instantaneous monitoring of the energy quality signal and this solution can be used to indicate electrical faults of a load or the network and, therefore, avoid unintentional consumptions, equipment failures, installation damages, and thus generate savings through better management in them.

There are still problems that influence the results and have not been treated. Problems which their origins vary according to the device, and therefore is very hard to circumvent or minimize them, because they are linked to internal aspects of the components. An example of such errors is the measurement non-linearity with the approximation of the measurement limits of the current sensor (OV or 5V). Moreover, despite the fact that the harmonic distortion level has already been developed in this paper, there is still much to be researched in the area of energy quality in homes and industries. How household appliances can influence the home network, overcurrent and overvoltage detection [20], among others, are examples of research fields in this scope.

It was testified benefits on adopting the proposed architecture on performance by doing all mathematical calculation in the microcontroller to prevent a great amount of information at the communications between the physical system and the server. This lets the communication between the server and final user faster and also guarantee a better behavior in server's processes of store in an external cloud.

Although this paper introduces an IoT system tested in a home environment it's relevant mention the proper functioning at others ambiances as industries, public services and buildings. For exemplification, a factory that works with a good quantity of electrical motors (a great non-linear signal's polluter), or a public department which has several computers working, is going to have pollution in their electric signal due to the abundance of non-linear equipment, but once the action of monitoring electrical quality be implemented, this type of information can guide people giving base to take measures to avoid high levels of pollution and consequently increase the equipment and installation materials lifetime. Consequently, business' owners, public administrators and residents minimize the costs of the loss and maintenance of electrical appliances. Future researches will be done focusing on large-scale, automation and high social impact applications of IoT systems.

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