Advanced Metering Infrastructure System and Massive Data Simulation, Based on the Smart Grid Concept

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***Abstract*— Nowadays accelerated population growth has increased electric energy demand, which sometimes affects the quality, availability, and providers' distribution capacity. Developed technologies for improving electrical parameters are mainly focused on the three-phase power factor (PF) correction and the reduction of total harmonic distortion. An advanced metering infrastructure (AMI) system has been designed to measure electrical parameters and transmit them to a database (DB) on the smart grid (SG) concept. The present system allows remote monitoring of electrical parameters for a single-phase residential service, being able to correct the PF and automatically upload information to a DB. The system's performance has been tested by calculating the non-homogeneous parameters of ten thousand residential users to simulate its massive operation. The geographical coverage of more than two thousand users clustered as a private wireless network can be ensured in line-of-sight. It has been estimated the reduction of average current consumption around 29%. Collected data in the DB can be used for modeling and optimization purposes in electricity generation and distribution according to demand-side management techniques.**

***Index Terms*— Advanced metering infrastructure, power factor correction, data simulation.**

I. INTRODUCTION

Electricity is a fundamental part of the development of countries, it allows activities in different economic sectors such as health, agriculture, education, transportation, among others. However, accelerated population growth has increased energy demand; therefore, guaranteeing electricity supply has become a permanent challenge, while the consumer will soon be forced to reduce consumption or maximize efficiency [1]-[4]. In the face of these challenges, Smart Grids (SG) arise, whose purpose is the decentralization and restructuring of traditional electric grids for energy efficiency [5], [6], applying advanced metering infrastructure (AMI), information and communication technologies (ICT), intelligent sensors, wired or wireless communication, databases (DB), electronic instrumentation, etc. [5], [7].

This interoperability of elements allows SG to provide benefits such as the characterization of consumption habits, introduction of clean energy, information backup, bidirectional communication between the customer and the energy supplier and improvement of energy quality and efficiency [2], [5]. These benefits allow the customer to manage their consumption through incentives offered by the electricity supplier, to keep a balance between produced energy and consumed one, this set of actions is called demand-side management (DSM) [4], [8], [9].

Residential services represent a significant percentage of energy consumption [4], and the residential sector in Mexico is the second largest consumer [10]. Currently, the energy distributor provides a bimonthly bill for their accumulated consumption [11], this being one of the different variables that allow estimates and planning for energy generation in the short, medium and long term [12], [13].

Therefore, it is relevant to know, back and characterize the consumption habits of residential customers to achieve a transition to the SG and contribute to energy efficiency. Although the power factor (PF) is not measured or penalized for residential single-phase services, it is a factor that causes inefficient consumption that affects both the user, who must pay for the energy, and the supplier, who must distribute it with sufficiency and quality.

The aim of this research is to test an electronic system that can obtain electrical consumption parameters of a residential service, correct the power factor, and collect data for characterization, modeling, and analysis. The data can be used for informed decision-making regarding economic energy dispatch.

This paper is divided in six sections. Section II analyzes published research of smart metering technology, communication techniques, users data access and implementation results. Section III describes the electronic system, communication details, information processing and storage in the cloud. In section IV presents the mathematical support for simulating data variability distributions of one instantaneous scenario, and the experimental trials. Section V presents the results and section VI presents the conclusion.

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II. RELATED WORK

Several researchers propose implementation for the intelligent monitoring of electrical parameters to the improvement in energy efficiency and quality, for example, the authors of [13] propose a demand response (DR) management system, allowing the participation of the residential customer to reduce or change their electricity consumption at peak hours through economic incentives. For real-time total harmonic distortion (THD) percentage measurement, they consider four loads as typical in the real world: compact fluorescent lamps (CFL), LED, exhaust fan and Switched Mode Power Supplies (SMPS), so activating switches they perform combinations of these four loads, acquiring the current signal from a NI-Crio 9082 controller, processing the signal in a personal computer in LabView software and calculates the percentage of THD with a Fast Fourier Transform (FFT) algorithm interpolated dual spectrum line enhanced with a minimum sidelobe window of four terms, having as a result that minimizing this percentage. In [14] the authors propose the implementation of Internet of Things (IoT) technology for a long-term lithium battery performance monitoring system in SGs. Implementing a battery management unit (BMU) measured voltage, current, temperature and state of charge (SOC) then interpreted the collected data with a Python script, to be stored in a relational database, performing this process on a Raspberry Pi. This device allows a remote online access with internet to the Grafana software for graphical visualization of the data stored in the DB. The authors of [15] propose a demand-side management system by acquiring the voltage and current from a microcontroller, calculating other electrical parameters: active, reactive, apparent power and power factor (PF), then, data were transmitted to a Raspberry Pi, to calculate the consumption based on rates stored in a DB through IoT platforms. Their tests were executed in a commercial building, when exceeding the kWh limit, the electrical equipment was turned off in series until the consumption was minimized. With this data they were able to compare consumption with and without the implementation of an AMI. In [16] the authors propose a DSM system using IoT technology, starting with the acquisition of voltage and current from individual loads corresponding to a CFL and a filament bulb with a microcontroller. These acquired data are sent through a Wi-Fi connection to a DB in the cloud, suggesting that they can be accessed from a web page or a mobile application. It is worth mentioning, that these tests were performed for a single user. In the research work [3], the authors acquire voltage and current from a microcontroller, which has a wireless communication module with ZigBee protocols, to send the information to a desktop computer as a server, to debug and then transmit to a local DB, to be displayed from a Graphical User Interface (GUI). To run their trials, they established two scenarios, the first one was the simulation of a microgrid and the second one was the emulation of different loads in a house. The execution of their processes was satisfactory; however, it is not directed to real-time data management. Other authors [17] executed a simulation in Matlab where they set a time of 5 minutes for the acquisition of the electrical data simulating smart sensors. Subsequently, some electrical parameters such as active, apparent and reactive power are calculated and transmitted every 30 minutes to an open source IoT platform in the cloud. The 5G communication used for transmission to DB was successful and was focused for a single user. On the other hand, the authors of [18] performed a cellular-assisted Device-to-Device (D2D) communication simulation for the connection of multiple smart meters (SM) integrated as an AMI, with the purpose of studying that the distribution of these has an impact on a good performance of operations. This research focused on the comparison of algorithms for the good distribution of smart meters. The authors of [6] provide an aggregator model to deal with short-term DR programs. They used an OP5600 real-time simulation computer connected to a personal computer to emulate a village of twenty-seven commercial and residential consumers using a bank of resistive loads through Simulink-Matlab. The aggregator contains information from different DR plans to incentivize the user through economic discounts and could turn on/off electronic devices. The information is not stored in any database and does not incorporate any communications technology in its system. A smart energy management system is proposed by the authors in [9], which uses a microcontroller to acquire voltage and current signals, sending the data through a link with a universal asynchronous receiver/transmitter (UART) to another microcontroller, where it calculates other parameters such as active, reactive, apparent power and PF, to be sent later through IoT protocols for storage in the cloud and be available on the Web. The smart meters were implemented in four facilities of a company in Pakistan, obtaining consumption profiles of approximately one month so that the user can manage their consumption and save money.

Most of papers reviewed above focus on the application of the technology for a single user, not for a massive number of users, except for [9], however, the communication is simulated, therefore, it was possible to detect a research gap, for the implementation of an AMI in a residential consumer network. On the other hand, some of them calculate and monitor the PF, but do not correct it. Based on these observations, the main contributions in this paper are the following:

- Evaluate the performance of the PF correction system [19] for data acquisition, wireless communication, and data transmission.
- Evaluate the performance of a residential customer network with wireless communication.
- Develop a methodology to simulate the voltage and current variations that may exist for thousands of residential services.
- Evaluate the performance of massive data management using a single data concentrator device using cloud computing.

III. PROPOSED SOLUTION

The PF corrector instrumented transceiver (PFC-IT) is the hardware designed and implemented to acquire the peak voltage and peak current from the residential main electric connection. Using a microcontroller which calculates the time difference between the voltage and current phase to connect a combination of three capacitors directly to the single-phase cables.

This electronic design has an Xbee S2-pro module to transmit and receive digital information into a private wireless network. Fig. 1 shows a simple block diagram of the described PFC-IT

[19], the actual circuit design size is too large to present it in this paper. The microcontroller calculates Δt according to equation (1), the phase angle (φ) in degrees is proportional to Δt, considering 360° for a signal's duty cycle and T is the voltage period in seconds, considering $f = 60\ Hz$.

$$\varphi^0 = \frac{\Delta_t \times 360^0}{T} \tag{1}$$

The signal conditioners block in Fig. 1 preserves the shape, frequency and phase of sensors signals', to adjust their parameters [19]. The microcontroller receives two monopolar voltage signals from the conditioner circuits, in the case of conditioned current signal 5V is equivalent to 50A amplitude. The conditioned voltage signal is 0V for $-127V_{RMS} \times \sqrt{2}$. Those signals are continuously sampled with the 10 bits resolution analog-to-digital converter module (ADC), using two different acquisition channels.

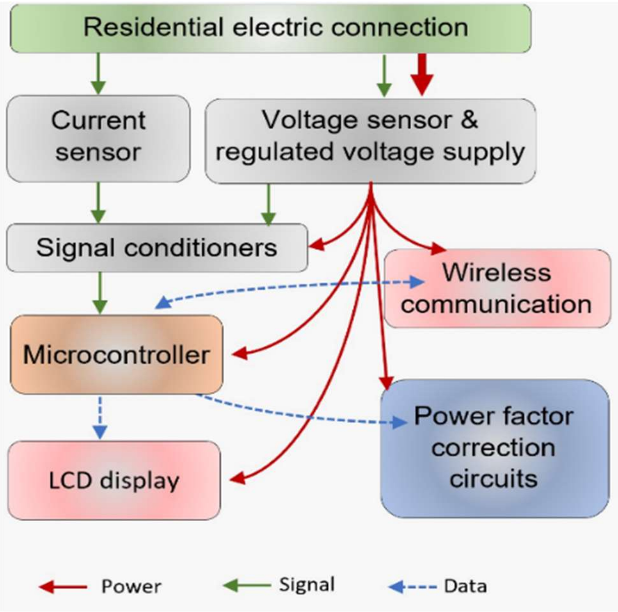


Fig. 1. Block diagram of PFC-IT circuits.

According to the voltage, current and Δt parameters, it is possible to calculate the precise value for the correction capacitor, as shown equation (2).

$$C = \frac{I \times sen(21600 \times \Delta_t)}{120\pi V} \tag{2}$$

The algorithm coded on the microcontroller is a decision tree that uses Δt as an input to estimate the corresponding configuration of connected capacitors to approximate the required capacitance to get the PF above 0.9.

The block shown in Fig. 1 as "power factor correction circuits" consist of three solid state relays to switch eight different configurations as required. Table I represents the switching states and total capacitive effect.

According to equation (2), the mesh curve shown in Fig. 3 represents the precise capacitance required for correcting PF=1, it considers a resistive and inductive reactive load connected to the electrical installation [22], [23]. In the same figure, every parallel plane to the Current-Phase time plane, represents the calculated effect for each capacitor's combination. The lower plane represents the effect of the first capacitor connected to the electric connection. This configuration must be selected from the decision tree shown in Fig. 2 when φ is greater than 25.8°, or PF<0.9. The upper plane in Fig. 3 represents the capacitive effect to correct Δt up to 4.16 ms, corresponding to T/4 or φ = 90°. Capacitors commercial values selected are C_1=1.5μF, C_2=2μF and C_3=5μF, to fit closely to the precise capacitance required for correcting at least PF<0.9. C_2 has being created using two capacitors connected in parallel.

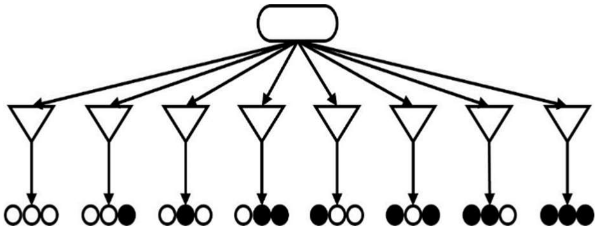


Fig. 2 Diagram of the decision tree algorithm applied by the PFC-IT based on Δt for PF correction [24].

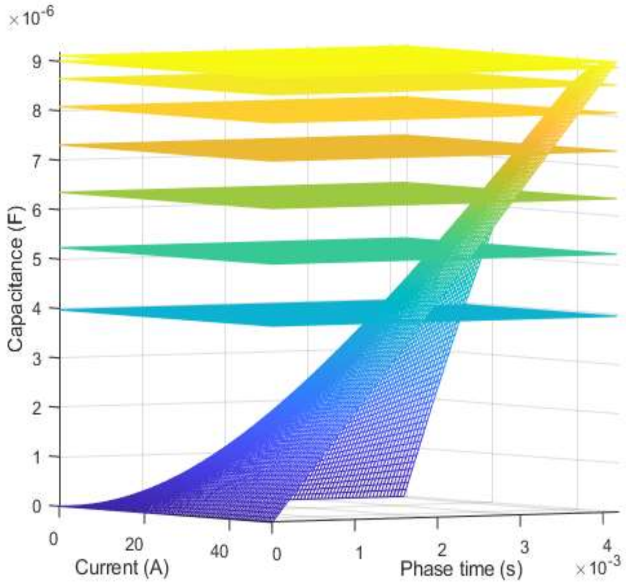


Fig. 3. The calculated capacitance required to correct PF=1 is the mesh grid plot, capacitance planes representing the effect of precise capacitors to correct PF>0.9.

TABLE I
COMMERCIAL CAPACITORS APPLIED FOR PF CORRECTION

Decision tree configuration	C_3=5μF	C_2=2μF	C_1=1.5μF	C_{TOTAL}
0	0	0	0	0μF
1	0	0	1	1.5μF
2	0	1	0	2μF
3	0	1	1	3.5μF
4	1	0	0	5μF
5	1	0	1	6.5μF
6	1	1	0	7μF
7	1	1	1	8.5μF

Fig. 4 shows the capacitance plane as an effect for commercial correcting capacitors. Applying those physical devices, it's possible correct PF>0.9. This configuration requires to adjust the Δt threshold value programmed in the microcontroller to fit with the phase angle φ. This action must be done as fine hardware calibration process.

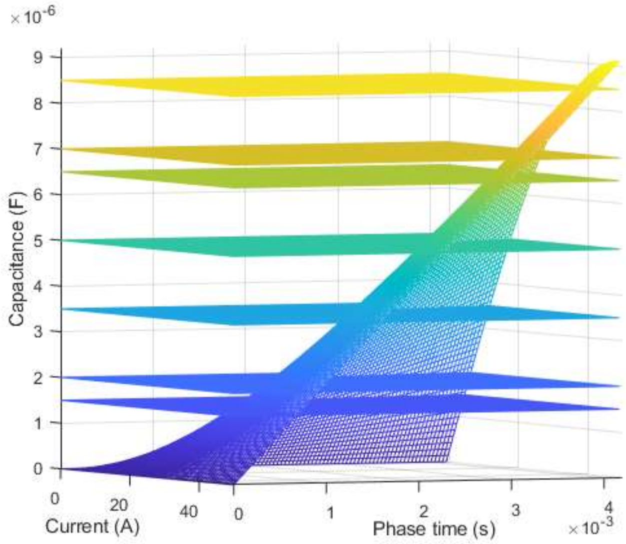


Fig. 4. Capacitance planes representing the effect of commercial capacitors to correct PF>0.9.

This PFC-IT automatically repeats the described sequence and verifies if there is some request from the coordinator node to transmit actual collected data. Fig. 5 shows the flow diagram of the PFC-IT operation [19].

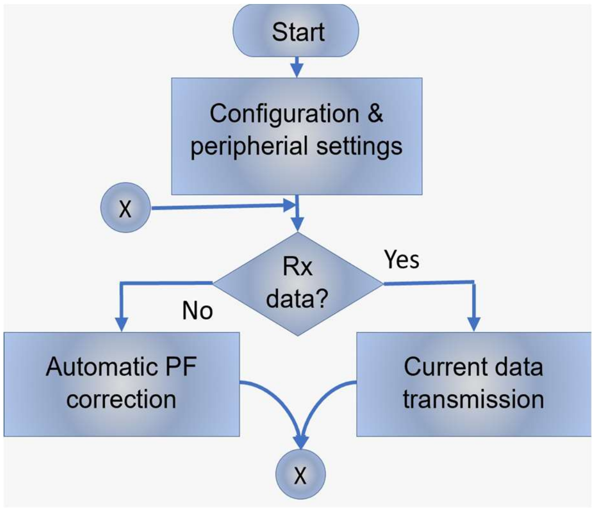


Fig 5. Flowchart of the PFC-IT automatic operation.

The described process for PF correction is an alternative to improve energy efficiency, however, the PFC-IT is integrated as part of the proposed system. A Raspberry Pi 3B+ has the role of Data Processing and Management Coordinator Node (DPM-CN), in charge of wireless communication with the PFC-IT, through Xbee S2-pro modules to process and backup parameters in a DB through an internet service. Fig. 6 shows the proposed AMI and the recommended implementation of the PFC-IT in a residential single-phase service [19].

The DPM-CN uses a communication module configured as *coordinator* to perform packet routing on the private wireless network. The PFC-IT communication modules take the role of *end device*, sending and receiving data through the coordinator [25].

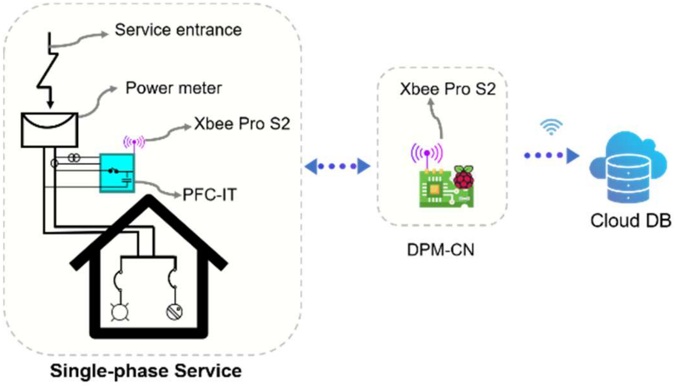


Fig. 6 Scheme of proposed AMI, the left block represents one PFC-IT connected in one residential service, the block on the right represents the operation of one DPM-CN and its communication functions.

DPM-CN establishes communication with the PFC-IT through an identification (ID) code, in this case is the same client number defined by the service provider. The baud rate used was the standard 9600 bps, however, it is not limited.

When the PFC-IT is requested from the DPM-CN, it sends its data packet comprising 18 ASCII code bytes, with the following structure: four bytes for the peak voltage digital conversion, four bytes for the peak current digital conversion, six bytes for the Δt and one byte to indicate the combination of capacitors for power correction (from 0 to 7 accordingly), space-separated each other.

0919 0217 0.0045 0

The DPM-CN receives and interprets the data frame through a Python script, then V_{RMS}, I_{RMS}, Δt, PF, active power (P), reactive power (Q) and apparent power (S) are calculated. These critical parameters are stored in a cloud DB through an internet service. For this process, a NoSQL DB was designed in Google Firestore Cloud, which is characterized by being targeted to IoT, mobile or Web projects [26]. This is part of the Cloud Computing concept as it provides the user with infrastructure and computing resources that adapt to the needs of the project [26],[27].

Fig. 6 shows the structure of the DB designed for this process and shows the information is organized by the identifier that corresponds to the PFC-IT. The DB records the critical parameters calculated, as well as the date of reading.

To evaluate if information backup in the cloud DB was correct and to verify its availability, a web page was developed using the open-source Django framework, which is characterized by its compatibility with other frameworks, provides security tools, is scalable and versatile to adapt to any kind of project [28].

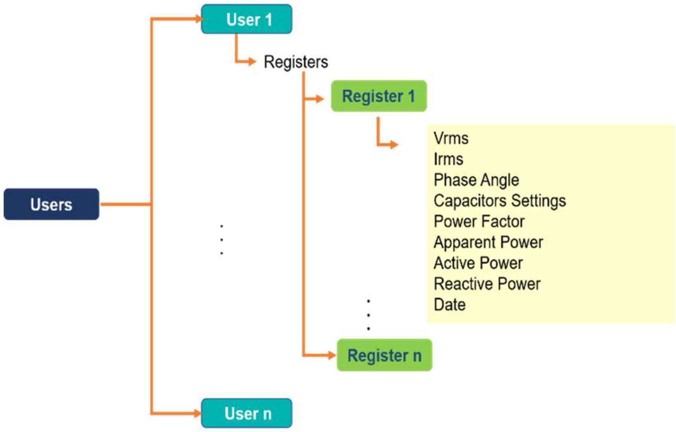


Fig.7 Structure of the cloud NoSQL database.

IV. MASSIVE IMPLEMENTATION SIMULATION

The implementation of this proposal for thousands of residential customers is part of the objective, however, there is not physically a massive number of PFC-IT, so ten thousand groups of data for the same number of devices were simulated in Matlab and applied the same mechanism for its operation described in section III, each one identified with a unique ID. In order to create a simulated scenario of consumption habits, taking into consideration that the statistical trend of the data can be replicated, it has been proposed to use random distribution models with the following characteristics: Assuming that the behavior of electrical energy consumption is unpredictable, due to several factors such as the number of inhabitants, number of appliances, different routines, social events, weather, etc. [29], it was necessary to simulate this data variability. The random values were generated for peak voltage, peak current and Δt, but in a controlled procedure considering the voltage and current conditions in a residential installation in Mexico. To achieve this objective, some Matlab statistical distribution functions for the generation of random numbers were used, which are described below.

Peak Voltage

The optimum distribution peak voltage must be 179.6 volts, considering voltage drops (-5%) or overvoltage due to poor regulation (+5%), as established by the Federal Electricity Commission (CFE) and the Mexican Official Standard [30]. For represent this peak voltage variation, the normal distribution random number function was used, defined by equation (3), since the histogram's left-end would represent the voltage drops, the right-end of the histogram in Fig. 7 are the overvoltage representation, most of data would be very close to the mean representing the optimum peak voltage ($127v \times \sqrt{2}$).

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{3}$$

Where μ is the mean, x the vector of the calculated data and σ the +5% and -5% of the optimum voltage.

In Fig. 8 the abscissa axis represents the range of the peak voltage variation, and the ordinate axis represents the number of users.

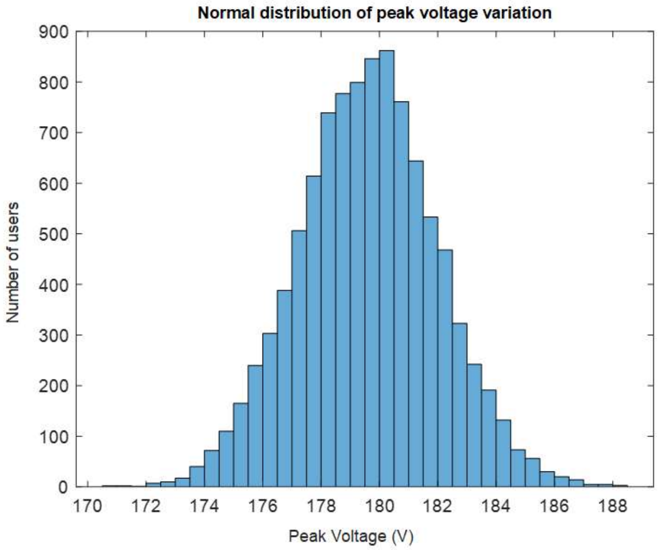


Fig.8 Ten thousand random numbers generated for simulating the same number of voltage measures using normal distribution.

Peak Current

Due to its constant variability, the peak current depends entirely on the customers' consumption habits. Ten thousand random data were generated using the Chi-square distribution for the peak current variation, because the bias of the curve depends on the degree of freedom (DOF) admitting only positive values [31]. This flexibility allowed generating a simulated consumption profile, considering that the PFC-IT supports a maximum of 50 A and that on average a residential customer demands between 8 and 10 A. This distribution is based on equation (4).

$$p = \int_0^x \frac{t^{(v-2)/2} e^{-t/2}}{2^{v/2}\Gamma(v/2)} \tag{4}$$

Where v represents the DOF in this case the value is 6. $\Gamma(\cdot)$ is the Gamma function, x is the maximum value of current, t represents the bias users' vector and p represents the discrete vector of random numbers.

Fig. 9 shows a histogram of the variation of the peak current, where some users are concentrated below the average or even down to zero amperes, on the histogram's right side are the users that their consumption is above 20 A and most of the users are concentrated in the highest part of the curve very close to the average peak current.

Phase Time

For the simulation of the phase time (Δt) variation, a Weibull distribution was used to establish a very marked tendency towards the histogram's left side, to represent more of the users

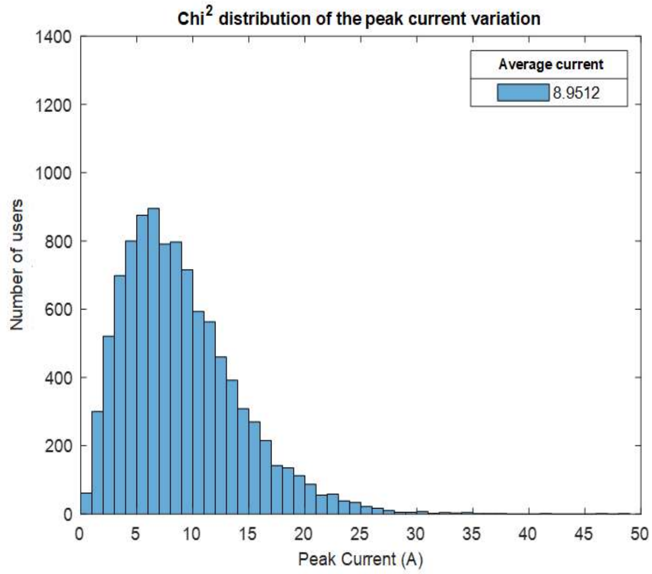


Fig. 9. Histogram of peak current variation.

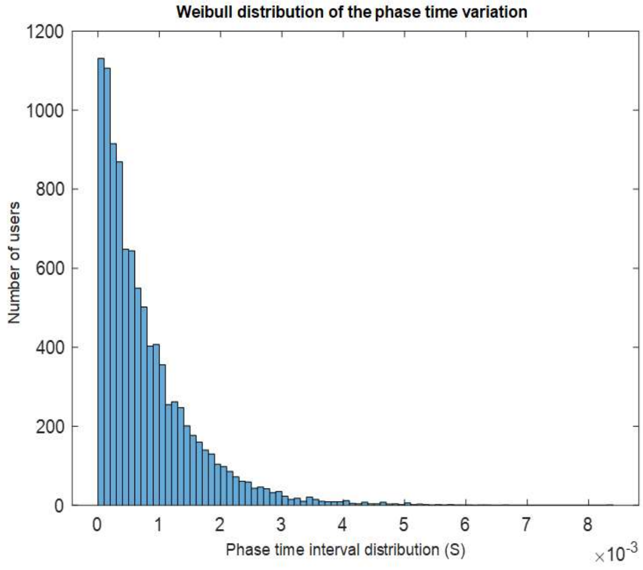


Fig. 10 Histogram of random phase time (Δt) variation, bars closer to zero seconds, correspond to PF closer to 1.

with a minimum Δt between voltage and current signal. The statistical distribution through its shape parameter provides the possibility to adjust the curve, distributing the random numbers according to the needs. This distribution is calculated by equation (5).

$$F(t) = 1 - e^{\left[-\left(\frac{t-\delta}{\theta}\right)^{\beta}\right]} \qquad (5)$$

Where, $F(t)$ is the value of the calculated phase time, $\theta = 1$ represents the scale value, δ is the shape value (+1), and β is the threshold parameter, in this case equal to ten thousand.

Capacitors Configuration

When PF correction is required, capacitors configuration is determined by the decision tree shown in Fig. 2, using Δt as the input. Table I shows the capacitors commercial value and figure 4 the capacitive effect produced for each configuration.

Data Flow for Massive Operation

The proposed data flow for the simulated massive operation in a private wireless network is shown graphically in Fig. 11, where the DPM-CN (*coordinator*) sends a request in an orderly manner to each of the PFC-ITs (*end device*) through their ID, only the chosen client responds with their data frame, to be processed and stored in the cloud, as described in section II.

All described process was executed twice, the first one without PF correction, with the value of the capacitor's combination being zero, and the second one on the same simulated data, but with PF correction, as described on Fig. 4.

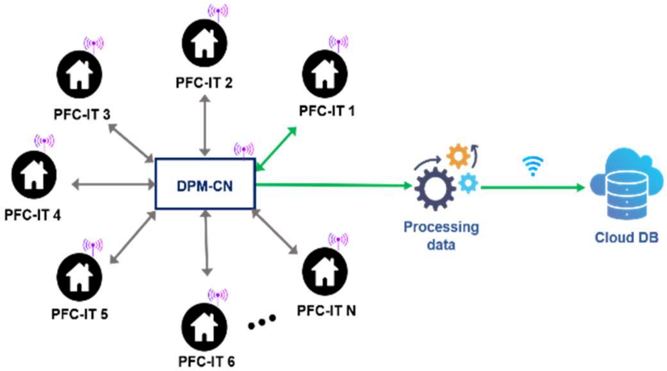


Fig. 11. Diagram of the wireless network operation, PFC-IT as end devices and one DPM-CN as one network node and manager.

V. Results

Communication trials using the Xbee Pro S2 module, between the physical PFC-TI and the DPM-CN, were presented stably without data loss. Communication between the DPM-CN and the multiple PFC-TI simulated in Matlab took 26.6 ms per request and response. The time consumed from the data processing in the DPM-CN to the backup in the cloud DB was 31.4 ms. Trials of communication process took 58.0 ms per residential client. Massive communication for ten thousand simulated clients spent about 55 minutes. It means the internet latency was around 4.6 ms per user.

According to the results of authors in [19], two Xbee Pro S2 modules transmitted ASCII data bidirectionally in line-of-sight, maintaining stable communication along 500 m. Based on these results, a circumference with a radius of the same length was located and plotted on the Google satellite image, in a densely populated urban area from Pachuca city, Hidalgo, Mexico, to estimate the number of dwellings in this area. The National Institute of Statistics and Geography (INEGI-Mexico) was consulted in the same way, resulting in 2905 dwellings [32]. Fig. 12 shows the wireless communication coverage.

The random data generation based on statistical distributions was performed, as described above, for each parameter (peak voltage, peak current and Δt). The number of bytes established for each data frame was packed without loss nor values outside the established ranges. This process allowed an accumulation of information for the comparison of scenarios with and without PF correction.

In this sense, Fig. 13 shows the histogram of the peak current variation without PF correction, average current is about 8.9 A and the maximum number of services is around 900. Fig. 14

Fig. 12. Wireless communication coverage in a densely populated urban area.

shows the same parameter, but with PF correction, the average current dropped to 6.3 A and the maximum number of services is around 1200. It means the reduction of the average current per service, and the increment of efficient consumers without disconnecting the installed load.

Numerically the current reduction rate is about 29%, the consumed power will decrease and consequently, the cost for the user.

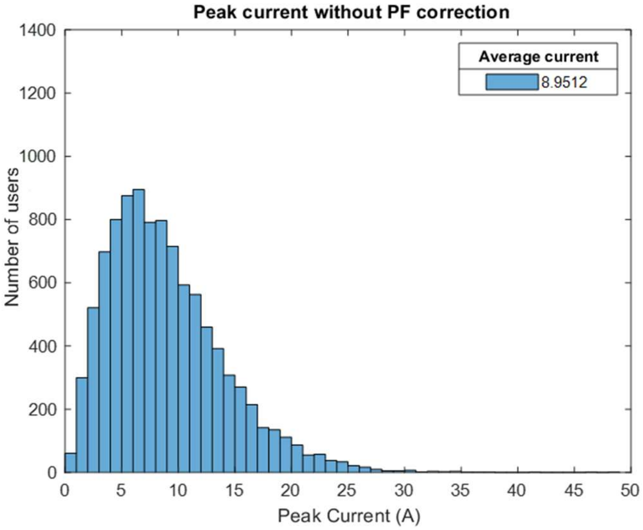


Fig. 13. Peak current without PF correction.

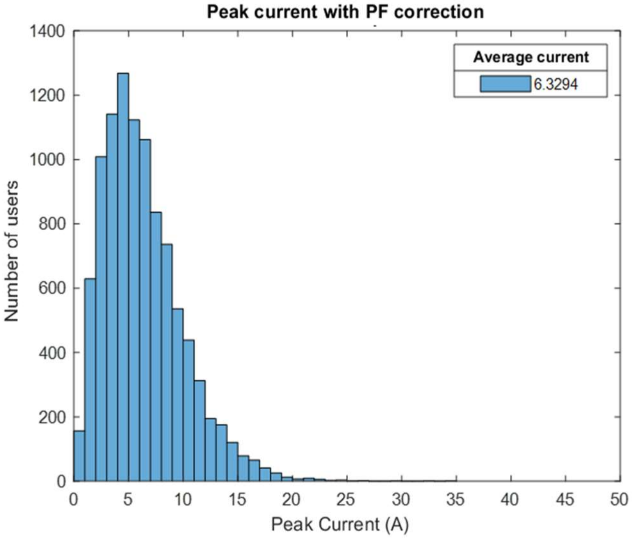


Figure 1Fig. 14. Peak current with PF correction.

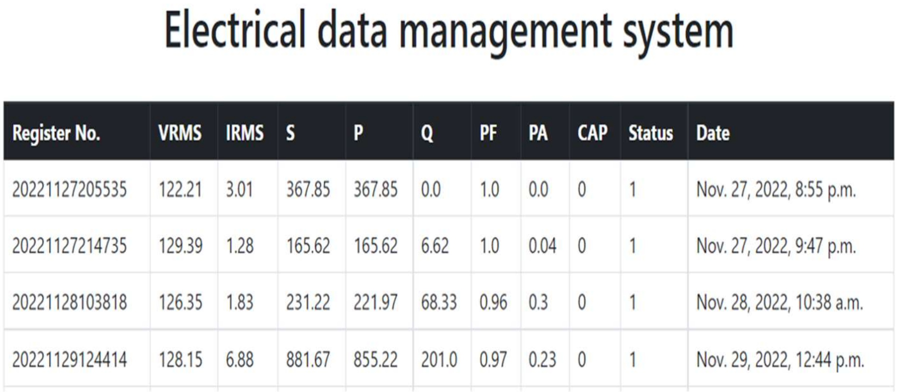
Fig. 15 displays a query for four cloud computing services. It shows the user's ID, calculated parameters from DPM-CN, and the registration date and time.

VI. CONCLUSION

The installation of PFC-IT in dwellings for urban places allows electricity service providers to obtain consumption data remotely and preserve those registers for billing or analysis. With this data, the provider can make informed decisions and improve energy generation efficiency. The massive implementation of this technology could reduce pollutant emissions into the atmosphere, contributing to the fulfillment of SDG 7 [21]. The PF correction allows to contribute to energy saving and efficiency because several houses in Mexico [33] commonly are installed as convenience stores, sewing workshops, etc. which require inductive loads for economic production.

A single DPM-CN can cover at least two thousand dwellings in line-of-sight for consumption data management of a densely populated urban area, with an XBee Pro S2 module. In this case this affirmation does not suppose interference or signal attenuation due to obstacles or meteorological conditions. Successful access to the internet service depends on the internet connection and bandwidth. In this experiment, just a cable connection was used without redundant internet service.

Compared with the system presented by [13], the present AMI can measure consumption electrical parameters, but it's not designed for load disconnection. In the same way, authors in [14] implemented a Raspberry pi computer to store batteries' electrical parameters, the user could consult those data through an internet connection. The proposed AMI in this paper collects and uploads the consumption electrical data in a web service, the Raspberry pi computer used here just manages information from the group of end devices belonging to the private wireless network. The system described in [15] is similar to the present AMI but their main goal is to verify the consumed kWh in a single building to disconnect the load when limit has been passed. According to authors in [16], they used a microcontroller to acquire electrical parameters from one single service, then information is sent to a DB. The user could access to those data through a mobile app. Their system requires one Wi-Fi internet service per microcontroller. Like the system in [17], authors sent electrical measurements to an open-source platform using the 5G communication network for a single user. In the same way authors in [18] applied smart meters to send information to a smartphone, their objective was implementing algorithms to efficiently locate smart sensors.



Electrical data management system

Register No.	VRMS	IRMS	S	P	Q	PF	PA	CAP	Status	Date
20221127205535	122.21	3.01	367.85	367.85	0.0	1.0	0.0	0	1	Nov. 27, 2022, 8:55 p.m.
20221127214735	129.39	1.28	165.62	165.62	6.62	1.0	0.04	0	1	Nov. 27, 2022, 9:47 p.m.
20221128103818	126.35	1.83	231.22	221.97	68.33	0.96	0.3	0	1	Nov. 28, 2022, 10:38 a.m.
20221129124414	128.15	6.88	881.67	855.22	201.0	0.97	0.23	0	1	Nov. 29, 2022, 12:44 p.m.

Fig. 15. Shows an example of an information query that is stored in the Cloud DB.

The proposed AMI in this paper was designed to collect wirelessly electrical data, reduce the PF loss in each service and upload the massive information throughout one single manager node to a DB. All collected data might be used for modelling statistical tendency, as needed in the demand-side management.

Compared with different commercial systems [34], [35] designed to improve PF and energy quality, the system presented in this paper is different because the PF is corrected applying reactive load to modify the phase-time of current signal consumed by the user (residential medium voltage), not on the distribution primary-side (distribution high voltage).

On the other hand, in this paper there was no resonance nor harmonic analysis. These issues are part of further research objectives, as well as the modelling techniques for consumption tendency and smart prediction.

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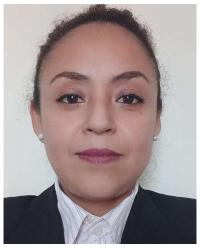

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