A novel Microgrid Responsive Appliance Controller

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Abstract— **Due to the myriad of devices and loads that are collected under the Commercial Building Energy Management Systems (EMS) focused on the Industry 4.0 paradigm, it is important to ensure their proper electrical operation. The power quality here requires a granular monitoring approach, reaching a point where each device connected to the microgrid can diagnose that its power supply is optimal. Otherwise, it can participate cooperatively in decision-making to avoid faults or blackouts in the microgrid. In this work, we present a novel Controller to make smart appliances responsive to the grid, either autonomously or managed under Demand Response policies. Apart from a TRIAC acting as an AC switch, the main advantage lies in its embedded Power quality internet of things (IoT) sensor. It measures a wide spectrum of electrical disturbances, far exceeding the capabilities of other solutions such as the Grid Friendly Appliance Controller, so it is possible to customize a battery of alarms at will, in e.g. according to IEEE-1547. Moreover, although it can act autonomously, its main mission will be to act in coordination, either cooperatively or under the supervision of the EMS. The IoT platform where the controller would be incorporated is also presented. Finally, two case studies are presented to show their capabilities. With the integration in the microgrid of these distributed sub-metering systems, with wireless connectivity and under standard communication protocols, a further step will be taken in the development of the Digital Energy Platform, and the improvement of the quality of consumption by the user, as well as information support systems for smart meters.**

Keywords— advanced metering infrastructure; energy management system; internet of things; power quality; smart appliances; grid friendly appliance; smart grid.

I. Introduction

The market for large household appliances is expected to grow annually by 1.8% (CAGR 2019-2023), reaching 368 billion dollars in 2023[1]. This increasing pace is being driven by several trends, such as the expansion of digitization in everyday life, the citizen interest in sustainability and the increase in the purchasing power of the average consumer. Meeting these expectations requires investments and economies of scale, but on the other hand, it can bring new opportunities for innovation. Thus, in recent years we have witnessed the appearance and proliferation of what has been called smart appliances (SA). Popularly SAs are recognized for having some electronic processing capability and wireless connectivity. For example, smart washing machines can independently regulate the washing powder and the detergent to be used depending on the weight of the load and the type of fabric. They can also automatically send alerts when the detergent runs out. However, in the energy field, within the framework of Smart Grids (SG), the term "smart" refers to those appliances capable of modulating their electricity demand in response to signal request from the electrical system. Thus, household appliances could incorporate different Demand Response (DR) strategies. DR has already proven to be a resource that the grid operator can use in several ways to provide system reliability, stability, and security services such as voltage and frequency support. Typically, DR policies can be divided into direct (explicit DR) through aggregation or virtual power plants (VPP), or indirect (implicit DR)[2]. Explicit DR (also called incentive-based DR program) is divided into traditional-based (e.g., direct load control, interruptible pricing) and market-based (e.g., emergency demand response programs, capacity programs, demand bidding programs, and ancillary services market programs). On the other hand, Implicit DR (sometimes called price-based DR program) refers to the voluntary program in which consumers are exposed to time-varying electricity prices, e.g. time-of-use pricing, critical peak pricing, and real-time pricing. For the appliances, this would materialize into load-shifting strategies, which shift their operating period from peak to off-peak hours, or load-modulation strategies, which directly reduce or avoid energy use during peak hours.

A different solution is represented by what is known as a grid-interactive or grid friendly appliance (GFA) controller[3][4]. A GFA controller can monitor the frequency of the power supply and shedding the appliance when the under-frequency alarm is triggered, to support the stability of the system. The paper[5] proposes to use appliances equipped with GFA controllers to address this issue under the umbrella of the IEEE 1547-compliant inverters[6], tripping off-line when operating as part of a microgrid in islanded mode.

This work aims to design a new controller that combines both approaches expanding their possibilities: it can act on DR schemes as well as monitor power quality (PQ) disturbances for the establishment of a wide and eligible range of alarms and restrictions. The idea is also to connect it to the appliance and be managed by the Energy Management System according to the presented values. Based on a previous Internet of things (IoT) sensor development [7], real-time status information, configuration, consumption data, and

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even diagnostic data from the appliances can be analyzed and recorded while in operation, and simultaneously transferred to the cloud for machine learning processing. The rest of this paper is organized as follows: Section 2 presents a short review of the IoT. Section 3 is devoted to the design of the controller, including hardware devices employed and their configuration and discussing the communications environment. The main features of the developed IoT platform are stated in section 4 and the tests are then discussed in Section 5 and 6. Finally, the conclusions and future work are reported in section 7.

II. INTERNET OF THINGS OVERVIEW.

IoT has become one of the most significant trends in the ICT world. IoT applications are proliferating in all industries. Although there is no universal definition, several authors have provided definitions of the term [8], [9], [10]. The general idea refers to all those everyday objects connected to the Internet.

A. Internet of things communication protocols

Standardization is the current problem with IoT protocols, as there are too many protocols and aspirants to standard. While their consolidation is coming, what is currently being created is more confusion with each new device that comes on the market. There have been many attempts to review all protocols [11], [12], [13]. In the paper [14], the authors even name the technologies of the future as the 5G. In the post, [15], the author makes a good attempt to classify all existing protocols into layers similar to ISO levels of communications. IEEE 802.15.4 and IEEE 802.15.4e are among the most widespread communication protocols: They define access at the physical and access control levels for Wireless Personal Area Networks (WPANs), and they are mainly used for networks with low transmission rates and low power consumption. Based on the standard IEEE 802.15.4 of WPAN, ZigBee is a high-level wireless communication protocol, operating at 2.4 GHz and its bandwidth is up to 250 kbps, to be used in ultra-low power wireless communications. LoRaWan [16] is a non-cellular low-power wide-area network (LPWAN) wireless communication network protocol, particularly intended for low power devices. LoRaWAN is mainly used within the IoT and for connections. Some characteristics are secure bi-directional, low power consumption, long communication range, low data rates, low transmission frequency, mobility and location services. SigFox is also a protocol for IoT which rewards low power consumption, 12-byte messages are used and are valid for networks up to 50 km. One of its main advantages is that has compatibility with major manufacturers in the market. Another option is the use of the existing mobile phone network itself, like GSM, UMTS or LTE network. The main advantage is that can use a network that is already in service, while the main disadvantage is the cost of using a network and that is not oriented to low consumption.

B. Internet of things data protocols

The most commonly used IoT data protocols today are as follows: Message Queuing Telemetry Transport, MQTT (and its variant MQTT-S), SoAP, CoAP, XMPP and REST.

The MQTT[17] protocol permits an extremely lightweight publication/subscription messaging model, using Machine to Machine (M2M) communication mainly with a star network topology. Typically used for bi-directional communications in unreliable networks and battery-powered devices with low power consumption. The MQTT-S variant is useful for devices requiring more time on standby mode, allowing up to ten times more scalable devices.

The SoAP (Simple Object Access Protocol) was created by the UserLand company in 1998. It oversees structuring the message so that it can be sent from or to the server and put it into an XML file. As such, it is not tied to or linked to any programming language. It was highly accepted by companies when it came to light, but today it competes against other more modern languages. SoAP is an information exchange protocol based on XML (extensible frame language used to store data legibly), designed for the Internet, and is used to encrypt information from the requirements of Web Services and respond to messages before sending them to the network. SoAP uses WSDL (Web Service Description Language) which, being an independent platform, is an extension of the XML language that stores and locates Web Service applications.

The CoAP protocol (Constrained Application Protocol) is an improved protocol version from MQTT-S oriented to Web Services instead of messages as MQTT. It also provides support for integration and content discovery, sends and receives UDP packets, and is designed to request and receive information via HTTP with methods like GET, PUT, POST, and DELETE. It also adapts to the node-sensor format with 8-bit controllers and allows the use of 6loWPAN networks that fragment IPv6 packets into small layer frames.

REST (Representational State Transfer), relies on HTTP to exchange information and does not need extra encapsulation to do so. It is lighter and easier to use but with some limitations. Instead of making requests encapsulated in an "envelope SOAP" to request a service for which the WSDL is necessary, in REST the requests are made through the HTTP protocol with GET, POST methods without the need to encapsulate it. It uses a single communication path between the device and the cloud and prioritizes NAT address crossing.

XMPP (Extensible Messaging and Presence Protocol) allows an extensive number of uses, including instant messaging or voice and video calling, redistribution of contents and generalized routing of XML data. Massive real-time scalability for approximately 100,000 nodes. Also used when traffic messages are large and potentially complicated for each device. Also used when extra security is needed.

III. GRID-RESPONSIVE APPLIANCE CONTROLLER

This section describes the proposal of a grid responsive controller (GRAC) which consists of both the developed smart meter and the SA controller shown in Figure 1. The smart meter has been built according to three stages: Signal conditioning based on a voltage divider (voltage measurement) and current transformer (LEM-LA-25P) with shunt resistor (indirect current measurement) on its secondary winding; signal acquisition and processing using a specific-purpose IC for PQ measurements (ADE9000); and data preprocessing and communication through the development kit NodeMCU based on the system on chip ESP12E. The SA controller is based on a CA-CA converter described in [18] which uses a TRIAC as the main switch as well as a specific circuit to detect zero crossings of the power supply. In this case, the control is performed by the ESP8266 system-on-chip. Moreover, both devices have a message queuing telemetry transport (MQTT) protocol interface thanks to this systems-on-chip which makes possible real-time communication with any other node of the network.

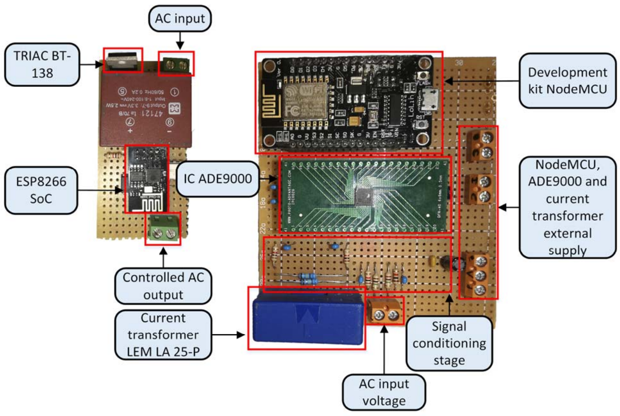

Figure 1. Developed modules.

IV. THE INTERNET OF THINGS PLATFORM DEVELOPED

The IoT platform depicted in Figure 2, besides the previous GRAC, is made up of the application developed in [19] although, this case goes beyond a simple simulation case study as the EMS plays an active role by being integrated as one extra node in the network that also uses the MQTT protocol in the transport layer to allow a link with the FIWARE ecosystem [20] which is an open-source framework that is widely used to develop smart solutions.

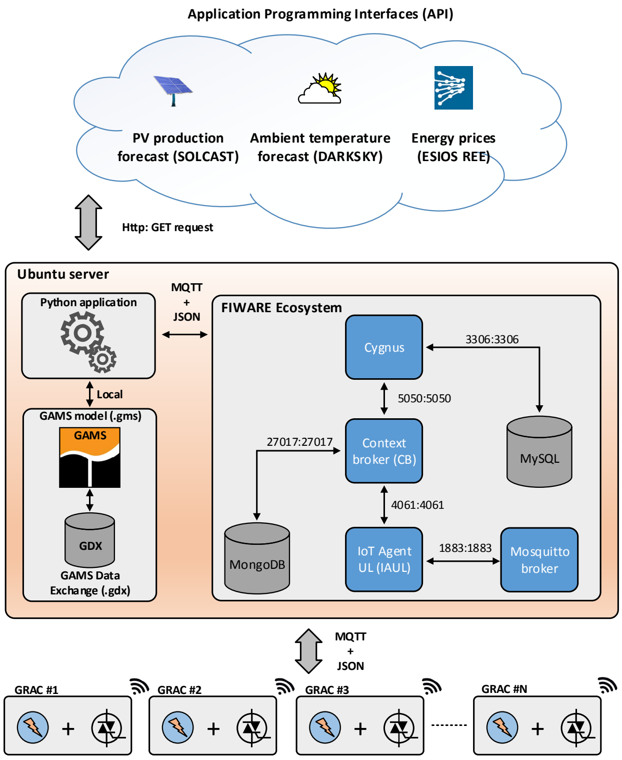

Figure 2. Block diagram of the IoT platform.

Such a framework enables the assembly of many services together as well as with other third-party platforms to promote interoperability among tools. For this research, a basic smart solution of six services has been launched using the container technology provided by docker [21]. These services include the core of any FIWARE-based solution which consists of an instance of the MongoDB database and the so-called context broker (CB) that exchange data through the next generation service interface (NGSI) protocol [22] as well as with any other container. While this database stores all the defined entities (understood as a thing representation), their attributes structure and the last value of them even other information on the relationship of containers, the CB manages these data.

Besides this core, a MySQL database, a connector in charge of persisting certain sources of data into third-party databases called Cygnus, a mosquito MQTT broker, and the intermediary between the CB and this broker known as IoT agent UL (IAUL) can be found in this solution. The fact that both databases have been used is due to their different data persistence, as MongoDB only stores the last value of any attribute while MySQL stores the whole time-series.

V. A CASE STUDY OF THE PLATFORM CAPABILITIES

This section proposes a case study in which the abovementioned EMS deals with the different SAs and the available energy resources such as the photovoltaic system (PV) and the energy storage system (ESS) to optimize the cost of energy. Hence, each SA has been planned as follow: the tumble drier has been fixed at 22:00 hour with the washing machine and dishwasher scheduled from 12:00 to 19:00 and from 9:00 to 18:00 hours respectively. Furthermore, a tariff with hourly discrimination provided by the Spanish transmission system operator (TSO), $Pr\ (t)$, (red plot of Figure 3d), the estimated PV production depicted in the orange plot of Figure 3d for a 2 kW system, $fpv\ (t)$, and the ambient temperature forecast. $Tamb\ (t)$, as well as the example of hot water consumption, $Vp\ (t)$, used by the electric water heater (EWH) and shown in Figure 3 (blue and purple plots respectively). All these foreseen power and temperature profiles and the energy prices are given by the specific purpose APIs that are integrated into the EMS. Finally, the developed EMS also considers the power that cannot shift, $Pns\ (t)$, but has to be taken into account for the global balance, thus, the red plot of Figure 3a shows an example of non-shiftable consumption that was measured in one circuit of our laboratory using the GRAC and will be used as an input of the system. To this time series also has been added the SA that has not been scheduled (tumble drier al 22:00).

The first result of the optimization is the time in which the SAs are launched, in this sense, the output of the EMS is the blue plot of Figure 3a, $Psa\ (t)$ that concludes the washing machine and the dishwasher have to be launched at 15:00 and 9:00 respectively to operate within the optimal area. The green line shows the power that is injected $Ppv\ (t)$ from the estimated one $fpv\ (t)$.

Figure 3b displayed the water heater behavior by showing its consumption $Pnwh * Xwh(t)$ in orange, where $Pnwh$ refers to the nominal power of the heating element and the temperature inside the tank $Twh(t)$ in red that was bounded in the range 70-90 ºC. An important detail is the amount of energy taken by this appliance (which can be estimated graphically by regarding the area under this first curve) in both periods: From 22:00 to 12:00 this energy is greater, however, the prices drop what brings out the strategy followed by the EMS to use most of the energy in the cheapest period. $Twh(t)$ remains within the established margin and behaves depending on the consumption and also inversely concerning the hot water demand.

According to Figure 3c, the ESS is very useful and contributes to increasing the flexibility of the power system in those periods where may be attractive to store the excess of energy or use it since it is widely employed. These plots show the evolution of the power used by the ESS and its state of charge (SoC) which are symbolized by $Pess(t)$ and $SoC(t)$ respectively. It is also important to note that the initial and final SoC is equal to avoid reaching the lower limit or allowing total discharge at the end of the day. Finally, Figure 3d shows the total consumption besides the prices of energy.

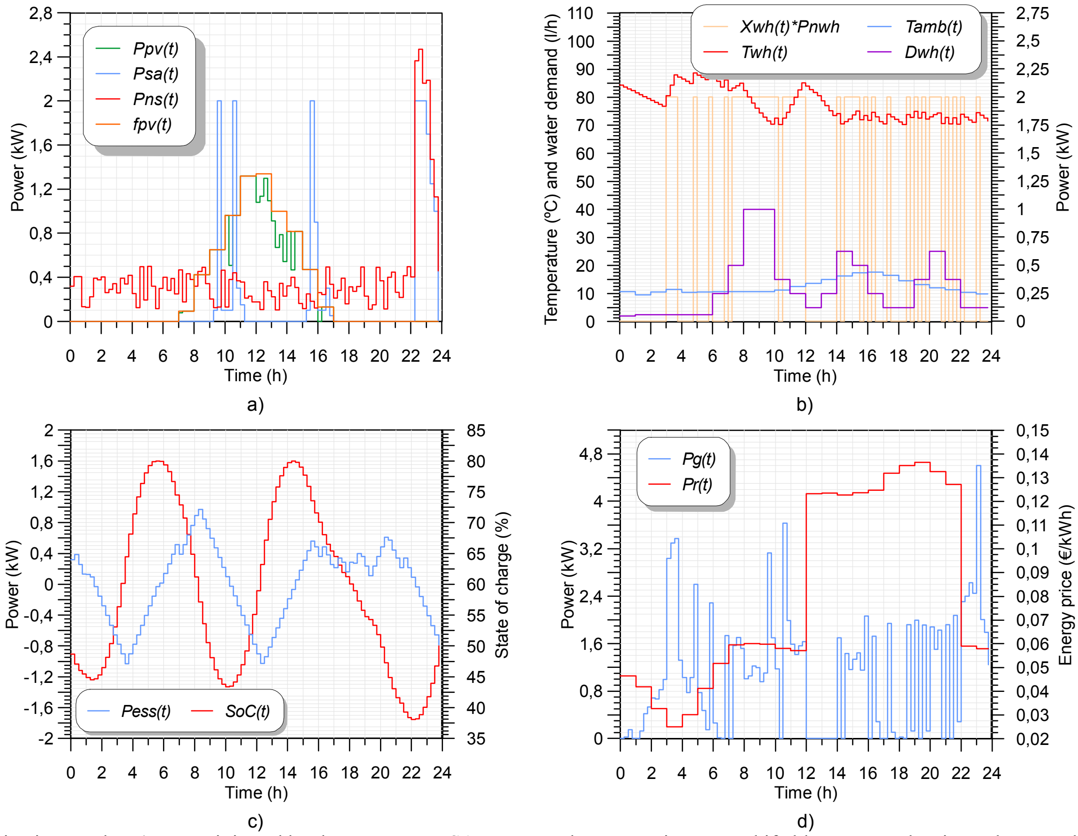

Figure 3. Optimization results: a) Power injected by the PV system, SA aggregated consumption, Non-shiftable power and estimated PV production b) EWH behavior: consumption, ambient temperature, water temperature, and hot water demand, c) ESS performance: Power and SoC and d) aggregated consumption and energy prices.

VI. PROTECTIVE FUNCTIONALITY PROVIDED BY THE DEVICE

A laboratory setup has been configured and used in the calibration process, concretely, the Fluke 5522A Multi-Product Calibrator [23] and a test bench composed of the Programmable Power Source California Instruments 9003iX [24] and the programmable load California Instruments 3091LD [25] for testing the measurement system in different supply and load conditions. To manage the information, a basic data acquisition and monitoring system have been designed over LabVIEW and communicated with MQTT protocol over a local network.

A. RMS, Power and Energy Monitoring.

The main variables controlled by a Smart Meter focused on energy billing are voltage and current RMS values, power and energy monitoring. Based on that, a scheduled setup was done for describing the quality of the measurement done by the EPQS. The programmable power source was configured with different voltage steps, varying from 228.5 to 237 V for 4 hours. Moreover, the programmable load was also configured in different tPF and current consumed steps for the same time. The results of the RMS measurements calculated over 200 ms windows is shown in Figure 4. The overvoltage and current present a 3% maximum error when the measuring system is stabilized after 20 minutes.

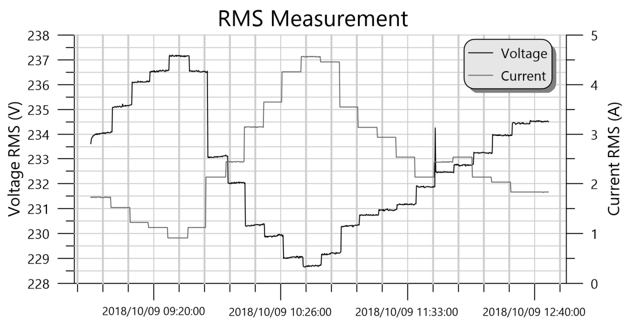

Figure 4. Voltage and Current RMS measurements.

According to the tPF set and voltage and current setpoint waveforms configured in both programmable power source and load, the resultant power components (active, reactive and apparent powers) are displayed in Figure 5. The apparent power is the squared sum of both active and reactive power. During all the experiment the reactive power is inductive active power (positive) as it was configured in the tPF (inductive in the whole test). The IC ADE9000 calculates the energy by the integration of the power in a constant interval (1.024 s). The active, reactive and apparent energies are shown in Figure 6.

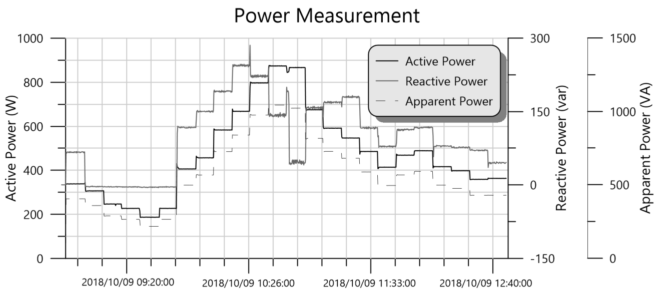

Figure 5. Power components measurements.

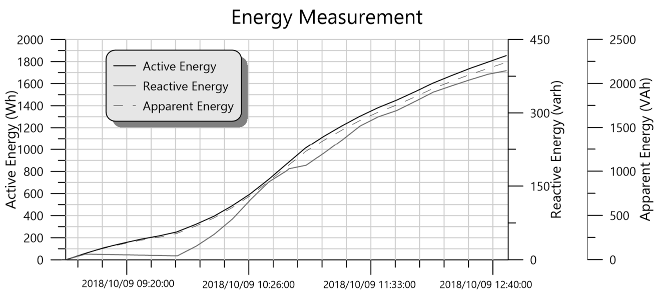

Figure 6. Energy components measurements.

B. *THD, tPF, and Sag/Swell Monitoring.*

The tPF has been configured as a control parameter of the load adjustment within the experiment, varying between 0.8 and 0.86. The programmable load California Instruments 3091LD, to set the tPF, distorts the current waveform with the inclusion of harmonics and their shift to achieve the desired power factor. Figure 7 shows the tPF and THDV and THDI both expressed in percentage of the fundamental. The THDV was set to 0 in the AC Power Source (so that, a pure sinusoidal voltage waveform), and as the tPF was varying during the experiment, the THD of the current does too. By observing the tPF and THDI curves in Figure 7, the correlation between both variables can be appreciated. An increase in tPF implies a reduction in THDI, which by definition is mathematically consistent due to the definition of both PQ parameters.

With regards to the protection functionality, the device can provide its commands and alarms according to the response times specified in the relevant regulations. In our case, a set of algorithms has been planned to supervise the operating conditions for each appliance. In this way, the corresponding commands and signals are generated and sent to the EMS when the corresponding thresholds are exceeded or even perform a disconnection if it is understood that the load being supplied may be permanently damaged. The standards to which reference could be made are IEC 61727, IEC 62116, VDE 0126-1-1, IEEE 1547 and IEEE 929.

Accordingly, Figure 8 depicts 26 voltage events carried out by the aforementioned programmable power source and detected by the proposed device. Moreover, these voltage sags and swells have been overlapped on the previous standards about PQ and safety operation in distributed generation systems. Although most of these disturbances are in a safe operating area when IEEE 929 or IEC 61727 are considered, IEEE 1547 and VDE V 0126-1-1 are more restrictive and would thus trigger an alarm in our device.

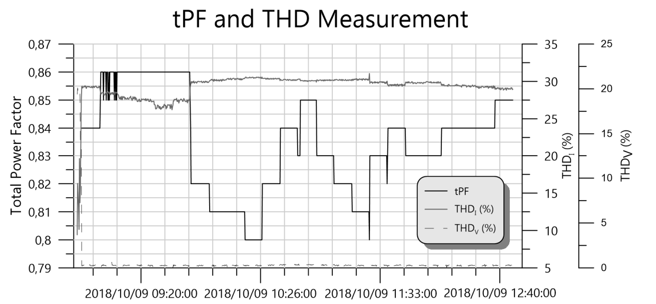

Figure 7. tPF, Voltage, and Current Total Harmonic Distortion measurements.

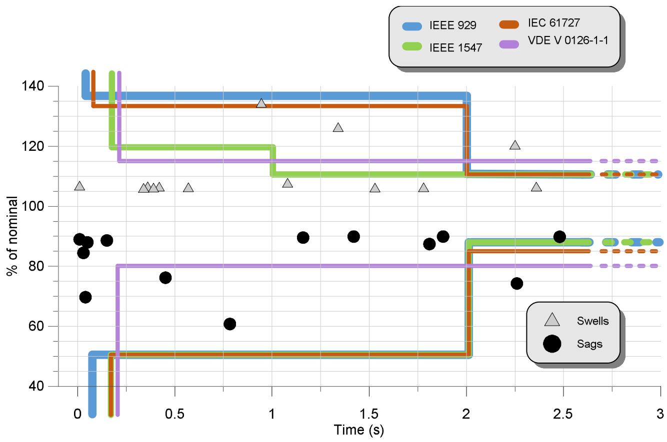

Figure 8. Sags and swells compared to several standards.

VII. Conclusion

Responsive appliances are those that, first, represent a significant load that can be reduced, increased or moved over time, to provide useful support to the power grid, second, provided that the change in its operation is acceptable to the customer, if not imperceptible, and third, are capable of responding to price, demand or certain grid conditions. This paper resolves many of the technical issues related to the design and construction of these devices, presenting a universal and ambivalent solution as demonstrated by the high-end IoT device, which can communicate and respond to information from the external environment within the framework of a cloud platform. While there are social, political and economic barriers to the widespread acceptance and adoption of these flexible loads in the marketplace, they need to be addressed and reasonable approaches to overcome them.

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