A Low-Cost Smart Monitoring Device for Demand-Side Response Campaigns

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Abstract The energy transition requires an increasing penetration of renewable resources, particularly at MV/LV levels. The emerging production scheme is characterized by distributed power plants, imposes a capillary control of production and consumption among the distribution network (DN). The implementation of demand-side response (DSR) campaigns is widely seen as a solution that can increase grid stability, but they require a complex and expensive monitoring infrastructure to select the optimal operating point of the production/consumption systems. This paper suggests a cheap and reliable smart monitoring device based on Raspberry Pi technology. The communication infrastructure adopted in the smart building of ASM S.p.A., the distribution system operator (DSO) of Terni city, shows the feasibility of implementing this prototype on a large scale.

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1 Introduction

The penetration of distributed generation among the LV/MV grids and the actual challenge of new electricity-based services, like electric mobility, raised the need for a new grid concept, the so-called smart grid (SG), to manage high fluctuations of production and consumption. SGs require a volume of data to be collected that is increasing tremendously [1], and its secure, efficient, and scalable collection has become a challenging task. The metering infrastructure to monitor DG and loads is requested to be capillary widespread.

In this regard, this paper proposes a cheap and reliable device, based on Raspberry Pi and affordable sensors, for the monitoring of an energy district, in order to implement DSR strategies on a large scale. The feasibility of the monitoring infrastructure for a company building demand is tested in the headquarters of ASM S.p.A., the DSOs of Terni province, in the center of Italy.

As expressed in the literature, SGs represent a significant evolution from traditional power grids, as they allow bidirectional flows of energy and communications. For this grid revolution, a necessary step to be overcome is to monitor the network in detail; therefore, the network must be equipped with a large-scale advanced metering infrastructure (AMI), connected to a data center equipped with computational intelligence technologies and a smart control system, in order to allow accurate and real-time network management [2, 3]. The AMI can be assumed as the developed version of traditional automated meter reading (AMR) and automatic meter management (AMM) systems since it involves several enhanced technologies, such as smart meters (SMs), home area networks (HANs), wide area networks (WANs), or neighbored networks [3, 4]. The capillary monitoring infrastructure is exploited in literature to create services for the DSO and the consumers/prosumers, such as to detect sources of energy flexibility on the territory and to implement DSR or other decision-making mechanisms [5, 6]. Some studies focus on the devices' capability to work with a large quantity of electrical/energy measurements and grid status [7–11]. In [12], smart meters are utilized to provide the grid operators more visibility into the health and operation of their assets (e.g., transformers, lines). In [13], the authors present an original data acquisition and transmission system designed and optimized for online temperature monitoring systems in electric power transformers. In [14], a real-time anomaly detection framework is developed by exploiting data collected at the consumers' premises. In this way, the authors present a system able to detect anomalous events and abnormal conditions. A new method to carry out the load flow analysis in MV networks is presented in [15], based on LV load power measurements applied on an innovative backward/forward algorithm for the power flow resolution. The power quality of public electricity networks is evaluated in [16] through a signal analysis framework based on the data acquisition and transmission of the monitoring devices. Many studies highlight the possibility of building up DSR campaigns to exploit the flexibility derived by the customers [13–21]. In [22], the DSR allows the customers, autonomously or in energy communities, to estimate the baseline price in real time. Based on the estimated price signal, the customers schedule their energy consumption using a cost-sharing strategy to minimize their incommodity level. The authors of [23] suggest an energy management system that runs a simple DSR campaign, considering peak and off-peak rates. Most of the existing studies mainly focus on the theoretical design of DSR schemes and do not verify the proposed schemes through implementation, as underlined in [24].

The activities presented in this paper are carried out and partially financed within the European Union's Horizon 2020 research and innovation program under the IoT-NGIN project [25], which investigates how the diffusion of advanced telecommunication technologies, like 5G, combined with the application of advanced tools of artificial intelligence, can produce significant benefits for the energy system.

The paper is structured as follows: Section 2 illustrates the prototype of smart monitoring device and the telecommunication infrastructure; Section 3 presents the case study of this paper; Section 4 shows the measurement tests in ASM district, and finally, Section 5 concludes the paper.

2 Smart Monitoring Device Components

The smart monitoring device presented within this paper is composed of two Raspberry Pi: a Raspberry Pi 3 model B + and a Raspberry Pi 4. The proposed system monitors four variables: secondary substation temperature, secondary substation humidity, RMS values of voltage and current.

The measurement data are transferred to Raspberry Pi 3 to be stored in and communicated via socket connection provided by a network router (Table 1).

The Raspberry Pi is a single-board computer that runs the Linux operating system and can be used directly in electronics projects due to GPIO pins on the board [26]. The card also has Wi-Fi 802.11n (150 Mbit/s) and an Ethernet connector, making it easier for the device to connect to the LAN network.

One of the most significant advantages of Raspberry Pi is excellent software support. There are many pre-compiled software packages and a large community of developers online.

In this study, three sensors have been used for measuring different parameters:

- Temperature and humidity sensor: The Sense HAT [28] has been used for measuring temperature and humidity in the secondary substation. The Sense HAT has an 8 × 8 RGB LED matrix, a five-button joystick, and includes the following sensors: (i) gyroscope (ii) accelerometer, (iii) magnetometer, (iv) temperature, (v) barometric pressure, and (vi) humidity.
- Voltage Sensor: A sensor module, namely ZMPT101B, has been used [29].
- Current Sensor: A ROGOWSKI coil has been used for measuring the current [30] (Fig. 1).

Table 1 Features of raspberry pi 3 B+ and raspberry pi 4 [27]

Features	Raspberry Pi 3 B +	Raspberry Pi 4
CPU	Broadcom BCM2837B0 Quad core Cortex-A53 @ 1.4 GHz	Broadcom BCM2711 Quad core Cortex-A72 @ 1.5 GHz
GPU	VideoCore IV @ 250-400 MHz	VideoCore VI @ 500 MHz
RAM	1 GB LPDDR2 SDRAM	1 GB, 2 GB or 4 GB LPDDR4-2400 SDRAM
USB	4 × USB-A 2.0 ports	2 × USB-a 2.0, 2 × USB-A 3.0, 1 × USB-C
Display port	Single full-size HDMI	2 × microHDMI
Connectivity	802.11ac Wi-Fi, 300Mbps Ethernet, Bluetooth 4.0	802.11ac Wi-Fi, Gigabit Ethernet, Bluetooth 5.0
Misc	40-pin GPIO header, 3.5-mm audio port, camera module support, composite video	40-pin GPIO header, 3.5-mm audio port, camera module support, composite video
Programming language	Python is desirable, and C, C + + ruby are preinstalled	Python is desirable, and C, C + + ruby are preinstalled

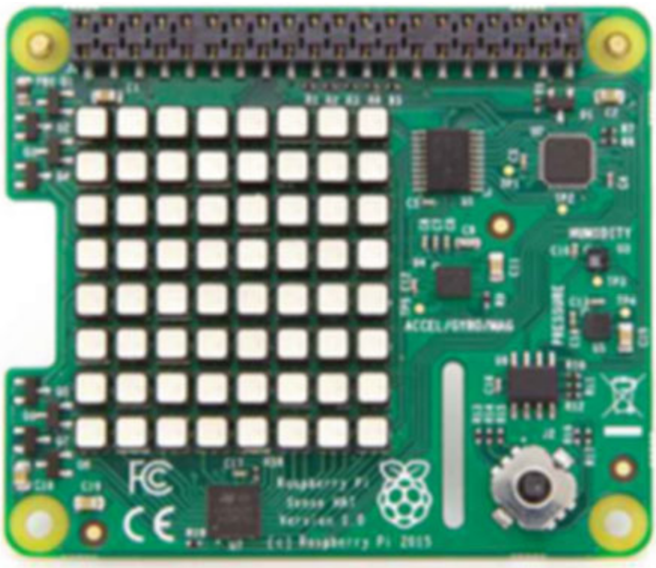


Fig. 1 Sense HAT sensor

The analog-to digital converter, named ADS1115, was implemented to convert the output signal of the sensors [31].

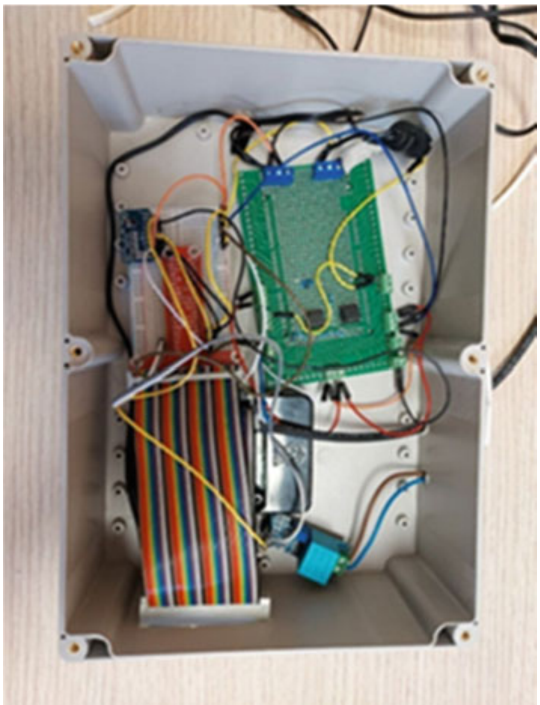
3 TLC Infrastructure

The Raspberry Pi 4 plays the role of a server that receives the measurement data in the form of strings and stores them for future use. Two Python codes were made in the Thonny IDE environment to provide the software required. The "client" code installed in Raspberry Pi 3 reads the measurement data incoming from the sensors, store the data for future use, connects to a given host IP address, and transfers the data in the form of strings via a socket communication. The "server" code establishes a socket communication, binds it to a given port number, and listens to incoming communication. The server receives the measurement data and stores it in the Raspberry Pi 4 storage SD card.

From a software point of view, the Raspberry Pi operating system Raspbian GNU/Linux 9 was adopted. The main benefit of the Raspberry Pi consists of the communication interfaces, such as the secure shell protocol (SSH) and virtual network computing (VNC) utilizing the remote frame buffer protocol (RFB). These may enable both remote wireless access to the PC and wired access to the PC, without the need of connection to a local network with the device to communicate with. In this study, Python programming has been used for measuring temperature and humidity. Socket programming was used to connect two network nodes so that they can interact with one another. One socket listens on a specific port at an IP address, while the other socket seeks to connect (Fig. 2).

The most common type of socket application is client–server applications, where one side acts as the server and waits for connections from clients. The server creates

Fig. 2 Prototype system setup in the outdoor box



the listener socket, while the client connects to the server. The communication system based on TCP/IP socket communication consists of two sides: server and client. The client side is responsible for connecting to the server and transmitting the measured data to the server. The server side is responsible for establishing a socket connection and binding it to a port, receiving measurement data from the client, storing it in the memory of the single-board computer.

The details of the coding of both sides are as follows:

- The client-side Python code is made as follows: (i) defines all necessary libraries and variables, including host (server IP address) and port; (ii) defines functions responsible for reading the sensor measurements and for the communication with the server; (iii) defines a function that writes the measurements into a log file, where each string combines measured variables, date and time of measurement; (iv) then, another function encodes the string containing the measurement variables and sends them via socket communication established before; (v) the measuring, logging combining, encoding, and transmitting functions are put inside an infinite loop to ensure continuity. The measurement granularity is set at every 3 s.
- The server code consists of a series of functions that finally log the information received from the client. (i) The socket communication is created; (ii) it is bound with a pre-defined port number; (iii) the server starts listening to potential client requests; when the signal code is received, the server starts a loop. This loop continuously receives the information, decodes it with UTF-8 (by default), and (iv) logs it into a file opened previously. This file does not have a specific format, but the information received are comma-separated values (CSV).

A diagram representation of the IT infrastructure, described before, is shown in the following figure.

4 Case Study

As a case study, the metering device was installed in Terni DN, with the configuration shown in Fig. 3. ASM Terni grid is managed by its production unit Terni Distribuzione Elettrica (TDE), and it is characterized by three primary substations, feeding about 60 MV lines (at 10 and 20 kV), and about 700 secondary stations. The network extends for 2400 km, 25% of which is at MV level. The DSO is responsible for supplying about 400 GWh per year. More information can be found in [32–35]. In the case study, the device was used to measure ASM's headquarters power connection demand in the LV substation. ASM Terni headquarters comprise (i) a 4050 m^2 three-story office building; (ii) a 2790 m^2 single-story building consisting of technical offices, a computer center, and an operation control center, and (iii) a 1350 m^2 warehouse. The annual building consumption is about 650 MWh, mainly due to lighting, HVAC, and powering computers and data servers, and the district includes a 60 kW PV plant.

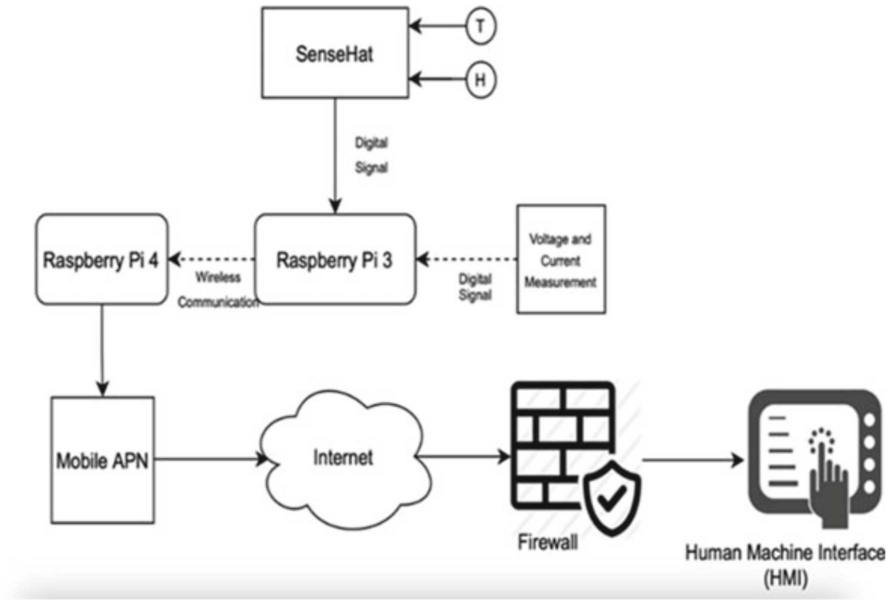


Fig. 3 IT infrastructure of the proposed monitoring device

An expansion board was considered to make the sensors accessible to the measurement place to realize the system, and an outdoor box was used to protect the systems from environmental hazards. For this project, the monitoring device was turned on for about one month, and then, the measurement data were collected via VNC remote control. The following figures illustrate the prototype device installed at the secondary substation at TDE DN. For installing the system in the secondary substation of TDE, an indoor box was used, as represented in Fig. 4.

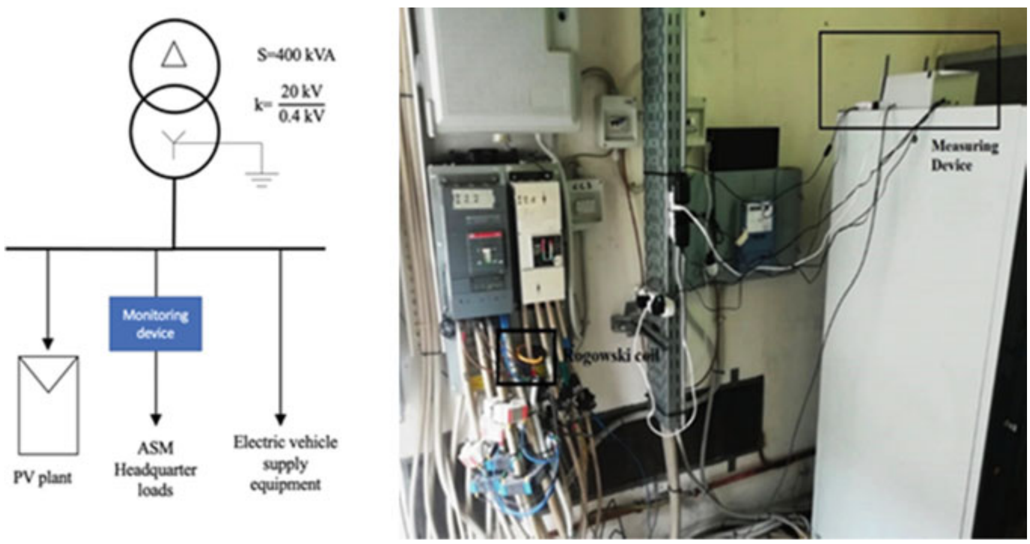


Fig. 4 Location of the measuring device in the terni electricity grid

In the study, we used a laptop to control and monitor data obtained from a Raspberry Pi through a Wi-Fi connection to achieve the goal of remote-mode communication. As a result, joining the Raspberry Pi to a Wi-Fi network is possible by determining its IP address using a sophisticated IP scanner, and then, the graphical user interface is accessed using the virtual network computing (VNC) server software.

5 Results

An example of the acquired data in real time at the secondary substation of the ASM district is illustrated in Fig. 5.

As expressed in Section 2, measured data concern secondary substation temperature in °C, secondary substation humidity in %, RMS value of voltage, expressed in volt, at LV level for ASM district load and RMS value of current, expressed in ampere, at LV level for ASM district load.

As can be seen from Fig. 6, during the period under consideration the voltage is always between 242 and 231 V, i.e., in p.u. between 1.05 and 1.004. The current, on the other hand, varies more, ranging from around 30 A to almost 150 A. The acquired data concern the electrical quantities of the line connecting ASM's headquarters with the secondary substation; therefore, the trend of the curves is very jagged, due to variegate types of loads and the power generation from the PV system. The granularity of the data is 15 s, feasible to the DSR campaigns implementation.

data_15_10_2021

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2021-09-23 10:21:12,29,37,239.51403656505585,40.1972824953052
2021-09-23 10:21:26,29,37,239.82274390654243,38.93296867192161
2021-09-23 10:22:33,29,37,240.3474700576363,42.21117569569517
2021-09-23 10:22:47,29,37,239.00793418050074,40.23104098145572
2021-09-23 10:23:02,29,38,238.31501135365946,39.15485411979299
2021-09-23 10:23:16,29,37,239.48577039056943,39.93262340006662
2021-09-23 10:23:31,29,37,238.49442938463707,38.603692179645854
2021-09-23 10:23:45,29,37,238.90276432628542,37.22508349559887
2021-09-23 10:24:00,29,37,238.19811748901233,37.3552128854603
2021-09-23 10:24:14,29,37,238.54942985573766,38.37223022482295
2021-09-23 10:24:29,29,37,238.0155156038472,46.1199100040364
2021-09-23 10:24:43,29,37,239.37166755968886,38.06815265017782
2021-09-23 10:24:58,29,37,239.07219335979914,46.56811708847692
2021-09-23 10:25:13,29,37,239.51138850358586,49.727492489575106
2021-09-23 10:25:27,29,37,240.10053954860751,45.692576342388165
2021-09-23 10:25:41,29,37,240.20968429110036,38.30766390979444
2021-09-23 10:25:56,29,37,239.76275567087094,38.26686635963246
2021-09-23 10:26:10,29,37,239.11751438038112,46.9255979546912
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Fig. 5 Data sample

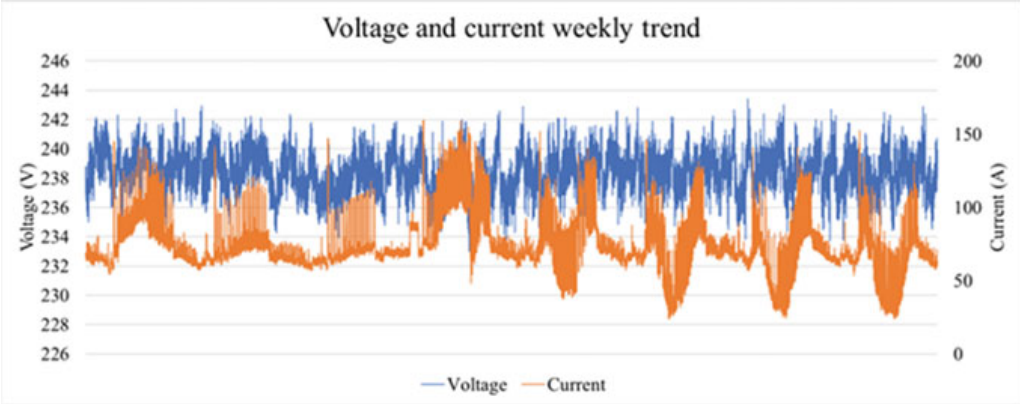

Fig. 6 Voltage and current measured at the ASM secondary station by the proposed monitoring device in the week of 24/09/2021–01/10/2021

6 Conclusion

The paper shows the realization of a simple and cost-effective monitoring device, easily applicable on a large-scale DN and whose data can be accessed just through a simple Internet connection. The implemented device was installed and tested within a secondary substation of ASM grid, monitoring the consumption of the ASM district for a short period of analysis.

A capillary knowledge of consumption/production profiles of LV/MV customers allows to enable the adoption of innovative strategies, which will play an increasingly important role in the energy transition. DSR and the implementation of flexibility tools, such as storage systems and smart electric vehicle charging stations, require the monitoring of the network in near real time.

The large-scale introduction of these technologies results extremely expensive for DSOs in case of adoption of complex monitoring infrastructure. Indeed, an economical, simple, and reliable device, such as the prototype presented in this article, could represent the optimal solution for enabling these new services, avoiding the possibility to carry on more accurate analysis that should require huge amount of data flow.

For future research, the authors are investigating the possibility to increase the adoption of such devices in ASM DN also implementing AI-based and machine learning tools for analytics purposes. In addition, the amount of data to be transmitted will be discussed, trying to adopt some techniques to limit the flow of data to be transmitted to the DSO.

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