IEEE Open Journal of
Industry Applications

Received 14 April 2025; revised 27 October 2025; accepted 19 November 2025. Date of publication 26 November 2025; date of current version 24 December 2025.

Digital Object Identifier 10.1109/OJIA.2025.3637381

Implementation and Experimental Validation of a PLC-Based Infrastructure for Distributed Generation and Storage Systems Remote Management

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This work was supported by the European Union–Next Generation EU, Mission 4, Component 2 under Grant CUP: B53D23024160001 and Grant B53D23024140001 Fondo per il Programma Nazionale di Ricerca e Progetti di Rilevante Interesse Nazionale (PRIN)–PRIN 2022 PNRR cod. P2022XL9NX, Project title: “Measurement-Based Technique for Renewable Energy System and Their Integration in the Case of Small Island” acronym: MERSIS.

ABSTRACT This article presents new devices and communication architecture for monitoring and controlling distributed generation (DG) and energy storage systems (ESS) in a smart grid. Different communication means, including power line communications, and protocols are presented, which can be adopted for the distribution power system, where DG and ESS are usually connected. The new devices allow the distribution system operator (DSO) to remotely monitor all DGs and ESSs connected to a secondary substation and to remotely interact with each of them with Modbus commands. The proposed communication link was tested, measuring the communication latency, success rate, and bit error rate. Moreover, a test of the whole architecture was carried out, including the power converter and ESS. The results show how DSO can change the power flow, injecting or storing energy in a very short time, confirming the possible contribution of ESS to distribution network management and stability.

INDEX TERMS Communication signal, dispersed storage and generation, energy storage, power line communication (PLC), power system communication, power system measurements, smart grids.

I. INTRODUCTION

Affordable and secure energy is a crucial aspect for creating livable communities while promoting sustainable energy production. This can lead to a significant reduction in the carbon footprint of cities, as well as an increase in the use of distributed generation (DG) from renewable energy sources. In addition, DGs offer an efficient way of providing electricity to rural, remote, or inaccessible areas, especially in developing countries. The ability to generate electricity at the consumer's location and share it in the same area aids in reducing both load demand and network losses, increasing the efficiency of network operations. This paradigm can be effectively exploited only if coherent management of the power grid is implemented, not only in terms of effective planning but also in terms of real-time operation and control. In fact, the widespread adoption of DGs brings unpredictability to energy production since it depends on renewable sources availability (e.g., sun and wind presence). Thus, electrical networks should be correctly managed to make load or energy storage power demand contemporaneous to DG power production, obtaining the balancing of load, storage, and generated power. Otherwise, overproduction from renewable sources could cause networks' instabilities, which are usually solved with DG disconnections.

Handling such sources presents new challenges to the distribution system operator (DSO), requiring a complete reassessment of the electricity network management. New services must be included in the “digital” electrical network management, involving not only the DSO as a unique actor [1], [2]. Many traditional consumers (users) in fact are starting to generate energy (producers) and participating in the energy market, becoming “prosumers,” taking advantage of personalized and customized services [3].

In this context, energy storage systems (ESSs) play a key role in storing extra energy produced by the DG. ESS can effectively mitigate the variability of renewable energy sources, enabling DGs to avoid common issues, such as power flow inversions and undesirable variations in electrical power quantities, due to load and generation mismatch [4], [5]. ESS also encourages prosumers to share energy at various scales (households, virtual power plants (VPPs), microgrids, etc.), empowering smart users to better control energy usage and save costs [6], [7], [8]. Moreover, ESS managed by DSO can contribute to peak shaving strategies, partially moving in time DGs power production when loads' demands are higher.

A reliable measurement and communication infrastructure is required to support these solutions, facilitating grid monitoring and management while ensuring safe operation [9], [10], [11], [12], [13], [14], [15]. The monitoring of loads, generation, and storage is usually performed a posteriori using smart meters remotely questioned via power line communication (PLC) [16]. On the other hand, the remote interaction solutions between the DSO and the distributed energy resources (DERs) are still missing [17]. In fact, DG and ESS are usually connected to the network using an interface protection system (IPS) aimed at disconnecting the power plant when local measurements exceed certain thresholds to avoid islanding conditions. Instead of totally disconnecting DGs during emergencies, as usually done by IPSs, their participation in grid regulation is a more efficient way to control the network. The policies of DSOs and prosumers are critical in this paradigm, aiming to maximize economic gains while ensuring grid safety. From the prosumer perspective, the goal is to minimize the cost of used energy, maximizing the amount of self-consumed energy or to sell the energy when the price is high. On the other hand, DSOs seek to control charging and discharging times of ESSs to maintain system stability and network performance, even at medium-voltage (MV) and low-voltage (LV) levels. Thus, some international standards, such as CEI 0-21, suggest an always-on communication link between DSO and each DG and ESS, which can allow them to participate in frequency, voltage, and power flows regulation [18], [19].

To achieve the goals of proper monitoring, management, automation, and control of the grid, advanced information and communication technology capabilities must be implemented [20], also through the use of MV and LV distribution networks. In this regard, several communication technologies have been proposed in the literature: PLC, wireless, Internet of Energy, optical fibers, etc. [21], [22], [23], [24], [25], [26]. The main challenges when designing communication infrastructure are the installation and service costs (for the provider), especially in geographically vast grids, the requirements in terms of reliability, latency, data rate, cyberattack issues, etc [27]. A thorough review of communication systems for microgrid applications is reported in [28]. It demonstrates how low-bandwidth communications can be suitable for microgrid applications, highlighting the advantages and disadvantages of different technologies considered, i.e., PLC, controller area network, wireless personal area network, cellular network communications, and low-power wide area network and satellite networks. On this framework, PLC can be considered a strong contender to other communication technologies [29], [30] because it has a low installation cost since the power lines are already installed, and there is no need to pay any amount to a communication service provider because DSOs usually own the electrical infrastructure [31]. Besides its wide use for automatic meter reading, PLC technology was tested for various applications on DERs. For example, in [32], an intelligent photovoltaic (PV) module with PLC was proposed using frequency-shift keying modulation. The aim is to reduce the electrical energy losses of PV modules through comprehensive PLC monitoring to have predictive maintenance of a PV system. In [33], a scheme was proposed for locating the faulty PV panel with the help of data collected via PLC. Moreover, PLC finds application in the field of electric vehicles for the exchange of information within the vehicle between the vehicle and the network, facilitating maintenance and diagnosis. In [34], a small-scale autonomous hybrid PV and ESS system was implemented using a PLC link between the energy management system and several battery management systems. On the other hand, no wide applications of PLC were investigated for DG and ESS remote control in MV and LV distribution networks. Moreover, even if some papers propose architecture and control schemes for DG and ESS remote control [27], [28], most of them are not focused on communication issues and no experimental validation of system prototypes based on PLC in an operational environment is available in the literature.

For these reasons, Artale et al. [35] proposed an enhanced system for real-time power flow monitoring and control for microgrid integration in MV distribution networks. That system was based on a monitoring architecture and embedded control algorithms. In particular, the architecture provided a communication infrastructure based on the use of two devices, an enhanced IPS and an IPS concentrator. The IPS was connected to the power converter of a DG or an ESS, enabling both usual protection features based on local measurements and new communication features for DG/ESS remote monitoring and control by the DSO. The IPS concentrator established point-to-point communication with DG/ESSs by dispatching commands to the connected power converters, thus enabling interaction between the DSO control center and the DG/ESS plants. With the proposed architecture, some new functionalities typical of those of a power plant controller (PPC) can be implemented. Conventional PPC is deployed in utility-scale power plants connected to high-voltage (HV); their operation usually involves interaction with transmission system operators, mostly based on an energy market agreement. On the other hand, the proposed architecture is oriented to LV distribution network implementation, where PPCs would not be an economical and technical viable solution. Moreover, a distinctive aspect of the proposed architecture is the use of PLC, which allows an easy aggregation of all DG and ESS units connected to the LV grid departing from an MV/LV substation, even if they belong to different prosumers. This enables a coordinated control of distributed resources, thus contributing to the distribution network stability.

To cope with the case of already installed DG and ESS and related IPS, in [36], the proposed architecture was enhanced replacing both IPS and concentrator with new devices that have more complex functionalities to meet the requirements of the smart power grid. Specifically, the new architecture and related devices target the following goals.

1) To meet the demand for network monitoring and DG and ESS remote management through an innovative communication bridge, which is able to be interfaced both to commercial IPS and to one or to a group of power converters.
2) To enable better management of distribution networks, thanks to new communication functionalities implemented in a data concentrator to be installed in secondary substations to remotely monitor several DGs and ESSs connected to the same substation and to drive remote commands from the DSO control center to the inverters.

More in detail, to meet these architecture needs, the concentrator, now called the DG/ESS concentrator, includes the old functions of the IPS concentrator [36], and it is also capable of aggregating data from connected DG/ESS plants. In addition, the IPS has been replaced by a remote PLC interface bridge using PLC-PRIME technology, which is added at boot to the DG/ESS concentrator PLC-PRIME subnetwork; it provides for remote monitoring and control of power converters, as well as for communication with commercial interface protection devices (IPDs). These devices can directly communicate with the power converter via serial communication, as in the previous architecture. Furthermore, to cope with a case of a prosumer with multiple power converters, an intelligent electronic device (IED) is presented in this article, which serves as a communication interface for the whole group of power converters. Some preliminary tests on the electronic boards used to develop this architecture were presented in [36]. In detail, a set of representational state transfer application programming interfaces over hypertext transfer protocol (HTTP) was implemented on the concentrator prototype, and HTTP POST calls were used to perform the preliminary laboratory tests.

In this article, the architecture of [36] was experimentally validated by assembling and testing the new devices (concentrator, communication bridge, and IED) with a DG power converter and an ESS. Moreover, the firmware was modified to implement the Modbus protocol to obtain a standardized and more reliable solution. The article describes the Modbus map implemented on the concentrator to group many DGs or ESSs connected to the related portion of LV network. The connection with DG and ESS is guaranteed via PLC, thanks to PRIME protocol, which automatically builds the communication subnetwork at each new device connection. Moreover, the connection to DSOs Supervisory Control And Data Acquisition (SCADA) was guaranteed by implementing the Modbus over TCP/IP protocol. In this way, all the ESS pieces of information are made available at DSOs Human–Machine Interface. Moreover, a user-friendly graphical interface was also implemented in the concentrator. It is available both on the local screen and remotely accessible through the LAN/WAN network. The effectiveness of the proposed architecture and devices was validated through communication and functionality tests, measuring the latency to actuate a remote command on the ESS, the success rate, and bit error rate (BER). These tests were performed both in the laboratory and on-field, interfacing the concentrator prototype with the DSO SCADA. This allows demonstrating the reliability of the developed prototypes in an operational environment. Finally, on-field communication tests were also performed to validate the reliability of PLC communication using the PRIME 1.4 protocol in order to verify its robustness to noise, attenuation, and distortion [37], [38], [39].

The rest of this article is organized as follows. The proposed architecture to connect DG and ESS to the network is introduced in Section II. The main devices are also presented, along with the electronics boards on which they are built. The communication solutions are presented in Section III, including the interfaces and the communication protocols over TCP/IP, PLC, and serial connections. Tests and experimental results, both in laboratory and on-field, are shown in Section IV. Finally, Section V concludes this article.

II. PROPOSED ARCHITECTURE FOR A COMPLIANT CONNECTION OF DG AND ESS PLANT

The proposed architecture is shown in Fig. 1. It is based on the deployment of three core devices, highlighted in green in the figure, to be added to the utility network. The functions to be performed by these devices meet the requirements for the evolution of electrical distribution networks toward the smart grid paradigm.

The architecture aims at managing the distribution network in the presence of a massive amount of DG, introducing a set of signals with the following scopes:

1) to provide voltage, active, and reactive power measurements;
2) to provide network services through appropriate modulation of active and reactive power as required by the DSO;
3) to disconnect the generators in case of remote disconnection signal receipt.

The remote disconnection command is already defined in reference standard, such as CEI 0-21 in Italy, but the related communication issues are still under investigation. In summary, the proposed system can support functionalities, such as remote active and reactive power control, remote variation of operation curves (as those suggested by standards, such

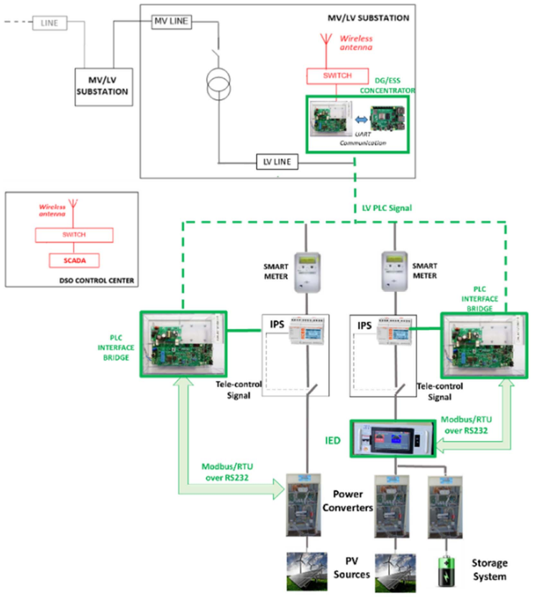

FIGURE 1. **Proposed PLC communication link for DG and ESS connection to LV network: in green, the developed devices for implementing the architecture.**

as CEI 0-16/0-21), real-time monitoring (e.g., battery state of charge (SoC), generated or exchanged power monitoring), islanding detection, and remote disconnection. Those functionalities are included in some standards, but to be manually activated based on the grid code to help voltage and frequency regulation at the point of common coupling. The proposed solution aims to fill this gap, proposing the possibility to remotely change the above-mentioned regulation functionalities by means of the proposed new devices. On the other hand, other functionalities typical of PPC implementation at HV level (such as certified grid code compliance, market participation, and VPP aggregation) are not currently targeted by the proposed solution, which instead is focused on providing a cost-effective solution for LV distribution networks.

To meet the above requirements, the following three devices were developed:

1) a DG/ESS concentrator;
2) a PLC interface bridge;
3) an IED.

The innovative functionalities of the above devices will be described in detail as follows.

A. DG/ESS CONCENTRATOR PROTOTYPE

The *DG/ESS concentrator* prototype, to be deployed within a secondary MV/LV substation, was built by combining the EVALKITST8500-1 electronic board and a Linux-based single-board computer (LSBC) [36]. The Raspberry Pi-3 has been chosen as an on-board computer for two practical reasons: cost effectiveness for rapid prototyping and widespread market availability, which facilitated iterative development and testing. Both boards are assembled inside a metal box, as shown in Fig. 2. In addition, local user interaction with the device is possible, thanks to a touchscreen display on the front panel controlled by the LSBC for debug and test purposes.

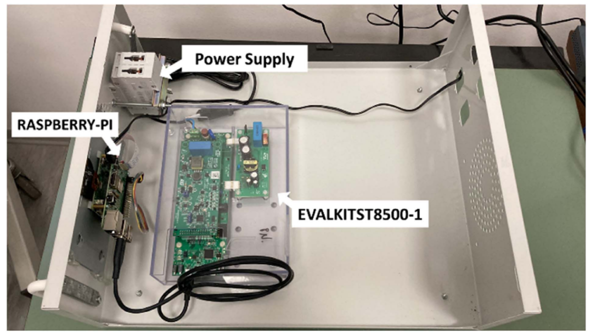

FIGURE 2. **In-house assembly of the DG/ESS concentrator prototype.**

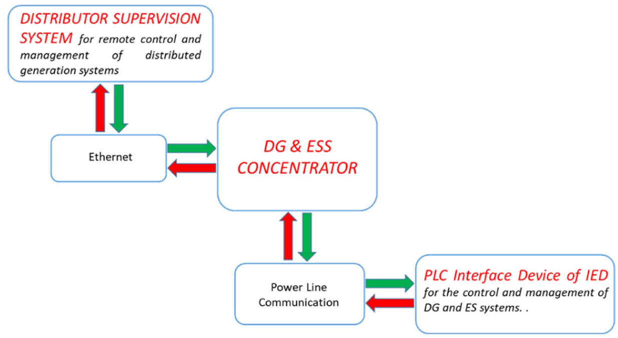

FIGURE 3. **Functional block diagram of the DG/ESS concentrator prototype.**

The DG/ESS concentrator performs the following functionalities.

1) Supervision and aggregation of DG and ESS plant data by querying IEDs connected to power converters.
2) Parsing, wrapping, and routing of control and management messages to and from DGs and ESSs.
3) Management of PLC network based on a defined protocol.

The interactions of DG/ESS concentrator prototype with the other devices in the architecture are shown in the functional block diagram of Fig. 3. The DG/ESS concentrator is connected to DSO LAN via Ethernet interface and to the PLC LV network via PLC interface. In detail, the Ethernet interface allows the DSO to query, through his own network, the DG/ESS concentrator about the status of the DG and ESS plants; moreover, it also allows to forward the configuration commands to change the operating modes of power converters, according to the actual network needs. Both interfaces are managed by the LSBC. According to the messages received from the DSO, LSBC can transfer commands to an IED system connected to DG and ESS plants on the LV network by configuring and managing the EVALKITST8500-1 board and exploiting the PLC technology. This enables DSO to remotely control DG and ESS plants. Since the wireless connection and several Ethernet-based devices are involved in the proposed solution, cybersecurity is a critical concern

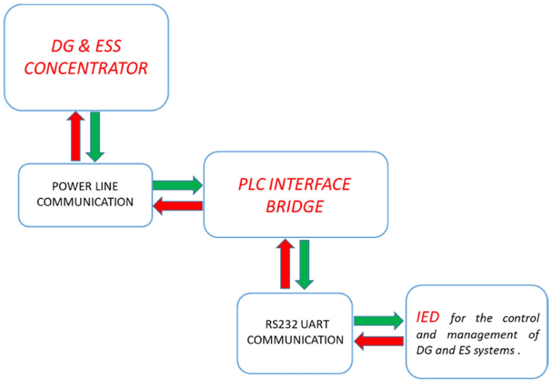

FIGURE 4. **Functional block diagram of the PLC interface bridge prototype.**

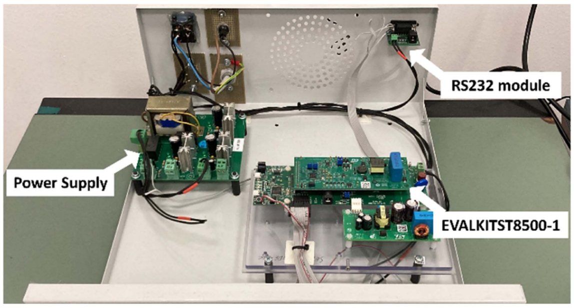

FIGURE 5. **Assembly of the PLC interface bridge prototype.**

within the power distribution network where the solution is deployed. The prototype operates within the DSO MV/LV substations, which are connected to the control center through dedicated wireless bridges. These substations are a part of a private, segmented subnetwork with no Internet access, and all traffics are managed via network address translation under the direct supervision of the DSOs Information Technology department. This ensures compliance with enterprise-grade security practices, including firewalling, intrusion detection, and continuous monitoring. While the prototype, therefore, benefits from the existing security framework of the DSO, future industrial-grade implementations will also incorporate device-level measures, such as secure authentication, encrypted communications, controlled update mechanisms, and alignment with standards, such as IEC 62443.

B. PLC INTERFACE BRIDGE PROTOTYPE

The second innovative device in the proposed architecture is the PLC interface bridge prototype. It is designed to be deployed near the IED device of DG or ESS power converters connected to the LV network.

The main function of this device is to give IED the ability to communicate over the PLC network by forwarding messages to and from the DG/ESS concentrator. The interactions of the PLC interface bridge with other devices in the architecture are shown in Fig. 4.

The PLC interface bridge prototype was built by using a hardware platform of the EVALKITST8500-1 type, on which a custom-designed firmware was implemented, assembled with a power supply and an RS232 interface board, as shown in Fig. 5.

By exploiting the EVALKITST8500-1 PLC technology, the power converters of DG and ESS plants can be controlled and monitored by the DSO, thanks to the capability of receiving directives provided through the concentrator via a PLC signal injected into the LV network cables.

Commands and data exchanged with the IED of DG and ESS power converters are sent via a serial connection on RS232. The PLC interface bridge can also be connected to a commercial interface device (i.e., an anti-islanding protection device). In this last case, PLC interface bridge handles the remote disconnection signal via a digital output pin of the EVALKIST8500 (sent to a digital input of the protection).

C. IED PROTOTYPE

The IED is designed to coordinate command and control from an external utility to a group of power converters. The primary scope of the IED is to virtualize the power plant (that can be composed of heterogeneous energy sources) and to expose a single, coherent interface. The IED is topologically placed as a middle layer between the distributed generators and the external interface device. The IED is also responsible for monitoring ancillary plant parameters (e.g., solar irradiance, temperature, wind speed/direction, and so on) and logging all the collected information for future analysis.

The IED is deployed on the field after a configuration stage that is executed in the design phase of the plant. In the configuration step, every energy source or storage system that should be controlled by the IED is added to the device, specifying all the relevant parameters (such as battery type, storage capacity, and peak PV production energy). With these parameters, the IED can expose to the DSO a consolidated view of the plant with all power converters aggregated as sources or storage systems. In this way, the DSO can send standardized Modbus commands to the IED, which, in turn, translates them into Modbus commands for each power converter. The Modbus map of the IED is shown in Table 1.

In detail, the following pieces of information are stored:

1) operating modes of the sources (PV plants in the considered case);
2) instantaneous power value of the sources;
3) SoC of the ESS;
4) state of health (SoH) of ESS;
5) operating modes of ESS;
6) operating modes of ESS power converter;
7) instantaneous power value for the ESS;
8) nominal PV inverter power value;
9) nominal ESS converter power value;
10) nominal ESS energy value;
11) contactor status for the remote disconnection.

These pieces of information are stored on 16-bit registers (also named “word”). For some information, such as the instantaneous powers, two registers are requested.

TABLE 1. IED Memory Map of DG and ESS Functional Parameters

Register Description	Start Address	Register Type
PV Inverter operational mode	0×00	R/W
PV instantaneous power_MSWord	0×01	R/W
PV instantaneous power_LSWord	0×02	R/W
ESS SoC	0×03	R
ESS SoH	0×04	R
ESS operational mode	0×05	R/W
ESS Inverter operational mode	0×06	R/W
ESS instantaneous power_MSWord	0×07	R/W
ESS instantaneous power_LSWord	0×08	R/W
PV Nominal Inverter power_MSWord	0×09	R
PV Nominal Inverter power_LSWord	0×0A	R
ESS Nominal Inverter power_MSWord	0×0B	R
ESS Nominal Inverter power_LSWord	0×0C	R
ESS Nominal Energy_MSWord	0×0D	R
ESS Nominal Energy_LSWord	0×0E	R
Contactor Status	0×0F	R/W

III. PROPOSED COMMUNICATION SOLUTIONS

The proposed architecture makes use of the three devices described above, and it allows exploiting the potential of different communication means, i.e., Ethernet, PLC, and serial communications. The related communication protocols are described in the following. This choice comes from the need to ensure not only a high degree of reliability and stability of the communication link, which extends from the DSO to each connected DG and ESS plant, but also the reduction of management and installation costs related to industry standards.

A. DSO-DG/ESS CONCENTRATOR COMMUNICATION PROTOCOL: MODBUS TCP/IP

To standardize the use of DG/ESS concentrator toward the most common industrial SCADA systems used by DSO, the Modbus TCP/IP protocol was exploited to interface DG/ESS concentrator to the Ethernet network. The implementation of this protocol is handled by the firmware implemented into the LSBC. In this way, the DG/ESS concentrator is considered by SCADA systems as a slave Modbus device.

The DG/ESS concentrator implements a memory area divided into blocks that can be read and written. Each memory block contains information about the individual DG or ESS plant connected to the LV network downstream of the secondary MV substation. The number of devices connected to the concentrator is stored in the first Modbus register made available by the DG/ESS concentrator. This 16-bit register with address 0×00 is referred to as the availability register (AR). Each bit of the AR indicates the presence or absence of a plant connected to the DG/ESS concentrator and, thus, to the LV network. Specifically, if the bit is equal to 0, this means that the plant is not connected; otherwise, if the bit is equal to 1, the plant is connected. Each DG or ESS plant connected to the LV network is associated with a memory block, as shown in Table 1, with, in addition, a register to store the time of last information update for the connected plant.

A plant connected to the LV grid can consist of an energy source (in the considered case, a PV plant) and an ESS, only a PV plant, or only an ESS plant. In the case of the last two configurations, the absence of either the PV plant or the ESS involves storing the default value 0×FF in the associated registers. The DSO supervisory system can address its write or read commands according to the Modbus TCP/IP protocol to each memory block based on the status of the AR register bits.

A Modbus write operation to one or more registers of a memory block generates a PLC transmission of the new parameters from the DG/ESS concentrator to the associated plant power converter. In this way, therefore, remote control of the DG and ESS plants by the distributor is realized.

B. DG/ESS CONCENTRATOR–PLC INTERFACE BRIDGE COMMUNICATION PROTOCOL: PRIME 1.4

The communication between DG/ESS concentrator and the PLC interface bridge exploits the PLC technology through the PRIME 1.4 protocol. The physical specification of PRIME 1.4 uses the frequency band from 41.992 to 471.679 kHz, divided into eight channels. These channels can be used independently or combined to obtain a unique transmission/reception band [40]. In detail, the PRIME 1.4 protocol is implemented on the respective EVALKITST8500-1 boards that exploit the single-channel communication feature. The use of this protocol allows mapping the physical power grid into a set of PRIME subnetworks. Each subnetwork is composed of an MV substation and the DG and ESS facilities that become the nodes of the PRIME subnetwork.

In detail, by exploiting the PRIME protocol features, the DG/ESS concentrator manages the PRIME subnetwork from the MV substation, and it is responsible for managing all connections between DSO and the end-user nodes. For the PRIME 1.4 protocol, the EVALKITST8500-1 managed by the LSBC of the DG/ESS concentrator acts as the base node (BN), while those of the PLC interface bridges of the various DG and ESS plants act as the service nodes. To be able to communicate, service nodes must register with the subnetwork of a base node. Taking the advantage of this feature, each time a new plant is connected to the LV network, the PLC interface bridge sends a registration request to the base node or DG/ESS concentrator network.

In addition to containing the *Connection Handle* and *EUI48*, i.e., the identification and addressing parameters of a node proper to the protocol, the request message also carries information about the connected DG/ESS plant. A successful registration of a service node (SN) means that a new plant is connected, and the DG/ESS concentrator updates its Modbus registers. Specifically, the DG/ESS concentrator will change the status of the AR by setting one of its bits to 1 and by filling in a memory block, from among those available, with information about the new connected plant.

TABLE 2. Sync Set Time Stamp Frame Format

Byte 0	Byte 1	Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7
0×32	Week Days	Number of Day	Month	Year	Minute	Second	Sub seconds

TABLE 3. Channel Configuration Frame Format

Byte 0	Byte 1	Byte 2
0×08	Channel number	Padding

The messages that the DG/ESS concentrator exchanges with the various PLC interface bridges through the PLC link concern the following frames.

1) *Sync* frame.
2) *Sync Set Time Stamp* frame.
3) *Channel Configuration* frame.
4) *Contactor command* frame.
5) *Set Status* frame.
6) *Get Status* frame.

The *Sync* frame is sent from the DG/ESS concentrator to the PLC interface bridge to notify the start of clock synchronization operations. When this frame is received, the PLC interface bridge replies by sending a frame starting with the hex 0×31 identifier. In this way, after several transmissions, the DG/ESS concentrator will be able to determine the average latency of the communication channel.

The *Sync Set Time Stamp* frame is sent from the DG/ESS concentrator to the PLC interface bridge; it contains the clock setting that must be set on the PLC interface bridge, considering the latency of the channel. The *Sync Set Time Stamp* frame format is shown in Table 2. The *Sync* frames transmission trail can be used, counting successful transmissions over failures, in order to evaluate the channel performance. This new functionality implemented in the concentrator allows the communication channel of the connected PLC interface bridge to change. This allows verifying the performance of each channel and choosing the best one to be used.

The *Channel Configuration* frame is sent from the DG/ESS concentrator to the PLC interface bridge to change the communication channel on which PLC transmissions occur. The channel can be chosen from among the eight available ones according to the frequency range defined for the PRIME protocol. The *Channel Configuration* frame format is shown in Table 3.

When the *Channel Configuration* frame is received, the PLC interface bridge sets the PLC modem of EVALK-ITST8500 with the new received transmission channel value and, before that, it sends an acknowledgment (ACK) message to the DG/ESS concentrator. When the ACK is received, the channel is switched at the concentrator and a new registration phase begins.

The *Contactor Command* frame is sent from DG/ESS concentrator to the PLC interface bridge to toggle the contactor of the IPD for the connection or disconnection of the DG/ES systems from the utility network. When the PLC interface bridge receives the *Contactor Command* frame, it handles, via a digital pin, the disconnection to the IPD, which commands the disconnection or connection of the generation/storage system to the DSOs electricity network.

The *Set Status* frame is sent from DG/ESS concentrator to the PLC interface bridge to change the configuration of the power converter that manages the DG/ESS. The received format is different, depending on whether the configuration concerns the generation system (PV) or the storage system (batteries). The *Set Status* frame for configuring the power converter connected to a PV or storage system is stored in three bytes, and it contains one of the operating modes, which are defined by the reference standard, and the instantaneous power value at which the system must operate.

The *Get Status* frame is sent from DG/ESS concentrator to the PLC interface bridge when the operational status of the DG and storage system is required. After receiving a *Get Status*, the PLC interface bridge requests the status of the plant by forwarding a message to the IED of the generation/storage system. When the PLC interface bridge receives the information from the IED, it replies with a hex 0×21 byte followed by all the information about the status of the connected DG/ESS plant. The information contained in these bytes is the information that will be stored in the memory blocks that the DG/ESS concentrator will provide for each connected DG or ESS system.

C. PLC INTERFACE BRIDGE–IED COMMUNICATION PROTOCOL: MODBUS RTU OVER RS232

Communication between the PLC interface bridge and IED is achieved by means of RS232 serial communication based on the Modbus/RTU protocol.

After undergoing a parsing operation, messages received via the PLC link from the PLC interface bridge, specifically *Set Status* and *Get Status* messages, are encapsulated (wrapped) according to the Modbus/RTU protocol, and they are sent to the IED of the DG/ESS system.

For a received Set Status message, a write message is sent using *FUNCTION 16* of the Modbus/RTU protocol. In this way, it is possible to write to the IED registers containing the configuration of the generation and storage systems and to the respective registers containing the instantaneous power value. This configuration will then be transferred from the IED to the power converter, which will operate in a mode characterized by the new operating parameters.

For a received *Get Status* message, a read message is sent instead. The request to read the status of the devices connected to the DG/ESS systems is realized through *FUNCTION 4* of the Modbus/RTU protocol. By means of this request, it is possible to trace back all information about the status of the generation/accumulation systems contained in a dedicated memory area of the IED. The requested information is sent to the DG/ESS concentrator by the reverse path of the communication link, which, in turn, will make it available to the distributor's SCADA system.

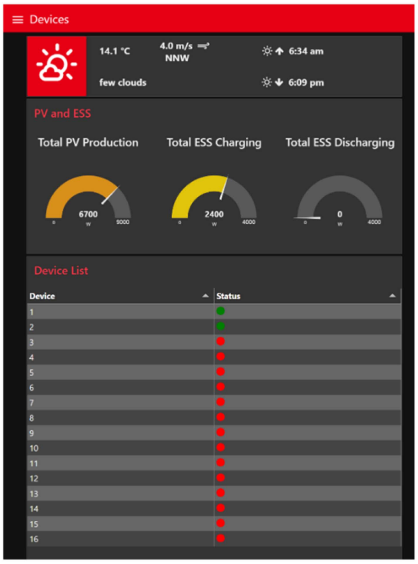

FIGURE 6. Graphic user interface home page on the concentrator.

D. MODBUS TCP/IP CLIENT BASED ON NODE-RED SOFTWARE

To emulate a SCADA system that could be used to query the DG/ESS concentrator, a Modbus TCP/IP client was implemented through *Node-RED* software, along with a dedicated graphical user interface (GUI). The client was implemented on the same LSBC used for the DG/ESS concentrator; a user can locally interact with it through the touchscreen display on the device or remotely hit the LAN IP address of the board computer where the same web GUI is exposed. The querying of the DG/ESS concentrator by the *Node-RED* client has a cycle of 1 s. From the touchscreen display, the user can also address and launch Modbus TCP/IP commands for reading DG/ESS concentrator memory blocks related to the information of connected DG/ESS plants. When the devices are turned ON, the bridge interface PLCs proceed to request registration to the PRIME network of the base node, i.e., the DG/ESS concentrator, providing information about the connected plants. Through the GUI, the *Node-RED* client allows displaying the registered devices associated with the connected plants, as shown in Fig. 6. The registered PLC interface bridges are indicated through the green color of the LEDs. In addition, the same screen shows a three-gauge widget that provides a visual representation of the global information of the entire generation and storage system connected to the LV network downstream of the secondary substation, where the DG/ESS concentrator is located.

IV. EXPERIMENTAL TESTS AND RESULTS

A. LABORATORY TESTS

The main goal of these tests was to verify the communication link reliability and stability at each point in the communication chain by excluding possible interruptions under normal working conditions. The tests were performed in the laboratory using the test setup, as shown in Fig. 7.

FIGURE 7. Configuration setup of lab test.

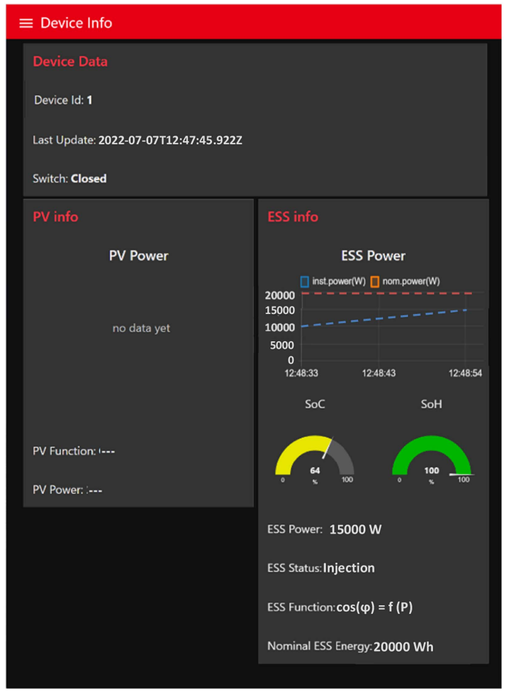

FIGURE 8. *Device 1 info* on the concentrator graphic user interface.

The experimental setup involves an IED with its respective PLC interface bridge, which is polled by a DG/ESS concentrator. The IED controls a 20-kW bidirectional power converter connected to a 20-kWh battery. By clicking on the main screen of the Node-RED client at the registered devices, a new screen opens, showing all the specific information about the connected system. The information displayed is updated cyclically after each response by IED to a Modbus TCP/IP read message forwarded by the Node-RED client. In the case of the developed test setup, the IED was identified as Device 1. By clicking on the graphical interface, it is then possible to open a new screen, as shown in Fig. 8, where all the plant data are present. In the screenshot of Fig. 8, it is possible to see the nominal power output of the system (20 kW) and the instantaneous power value injected by the converter. In particular, the ESS system is injecting an instantaneous power value of 15 kW. The instantaneous power value read via Modbus is measured by a wattmeter installed inside the converter.

TABLE 4. Measurement Accuracy of Lovato DMG100

Temperature	+23 C° ± 2 C°
Voltage (phase to neutral)	± 0.5% (50…415V~) ± 0.5 digit
Voltage (phase to phase)	± 0.5% (90…720V~) ± 0.5 digit
Current (CT /5)	± 0,5% (0,1…1,2In~) ± 0.5 digit
Active Energy	Class 1(IEC/EN 62053-21)
Reactive Energy	Class 2 (IEC/EN 62053-23)

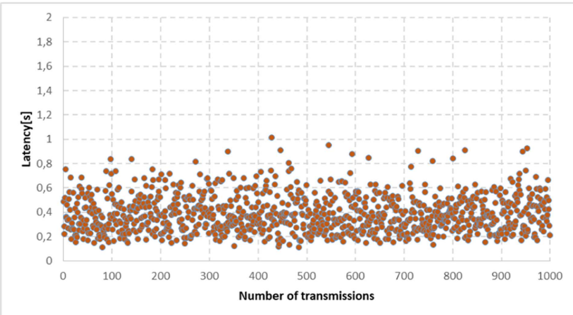

FIGURE 9. Latency values of 1000 transmissions for channel 3.

The wattmeter is the Lovato DMG110, whose measurement characteristics are given in Table 4.

The same screenshot shows other useful information, such as the mode of operation of the ESS power converter. Specifically, the ESS power converter is working with a $cos(\varphi) = f(P)$ work curve, i.e., with power factor as a function of the power supplied by the converter. This work curve refers to one of those given in the Italian standard CEI 0-21 [18]. SoC, SoH, and battery power rating are also reported for the ESS. The cyclic updating of information on the various screens, confirmed on the display by the time update of the last status of the connected devices, demonstrates the overall stability of the entire communication link from the Modbus TCP/IP client to the IED and vice-versa.

Moreover, to verify the link stability and reliability, some tests were carried out in both the high and low parts of the PRIME frequency band. The low band test was done on channel 3 (151–198 kHz) to avoid interferences with other lower frequencies PLC signals, used by smart meters. The high band test was done using channel 8, i.e., the highest in terms of frequency range (424–471 kHz). A single test consisted in sending 1000 Sync Frames with a 500 ms gap between each frame. A multiple retransmission system was also implemented in case there was no response to the current message from the bridge PLC (three retransmissions). In case of no response after the packet retransmissions, the channel is considered mute, and the procedure stops. For each trial, all retransmissions by the concentrator were recorded. At each sent frame corresponded a reply from the remote unit and the round-trip time was calculated at the concentrator. The latency for each Sync Frame was evaluated as half of the round-trip time. The recorded latency measurements are shown in Figures 9 and 10. The results are also summarized in Table 5. For both channels, the success rate was equal to 100%, against a reasonably low number of retransmissions. The latency values (min, max, and mean) were also comparable for both cases.

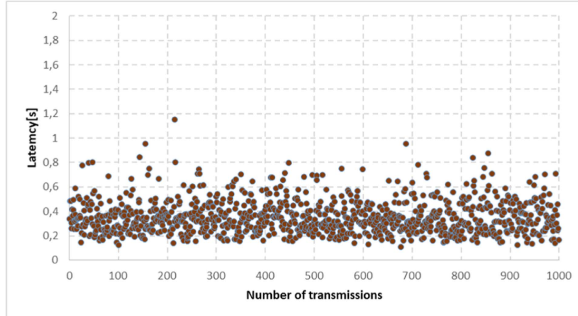

FIGURE 10. Latency values of 1000 transmissions for channel 8.

TABLE 5. Latency Results

CH.	n. Retrans-missions	Success Rate %	Min Latency [s]	Max Latency [s]	Mean Latency [s]	Std Dev
3	22	100	0.111	1.010	0.385	0.153
8	26	100	0.108	1.149	0.353	0.139

CH: Channel used for the transmission, n. Retransmissions: Number of packets retransmitted, Success Rate %: Percentage of received packets over transmitted packets, Min Latency: Minimum latency recorded, Max Latency: Maximum latency recorded, Std Dev: Standard Deviation.

Furthermore, to comply with the requirements of the CEI 0-21 standard, the possibility of storage system power regulation was verified by using an external command from the distributor. In more detail, the DSO can increase or decrease the active power injected or stored by remotely commanding the power converter. This was achieved by measuring the time elapsed between the instant when the distributor sends the remote command (in our case, from the PLC concentrator) and the instant of changing of storage system operating mode, from injection into storage or vice-versa. According to the CEI 0-21 standard, the described time interval must not exceed 50 s. Laboratory tests were carried out by using the setup, as shown in Fig. 11, which involved the use of an oscilloscope to which a voltage probe and a current clamp were connected. A digital pin of the PLC modem, controlled by the LSBC, was used to identify the instant at which the concentrator sent out the PLC frame containing the command to control the operation mode of the storage system. The logic level of this digital pin was changed from low to high and it remained in high status for the duration of the transmission of a PLC frame. The logic level of the digital pin was displayed on the oscilloscope's CH1 via the voltage probe. A current clamp was connected to CH2 of the oscilloscope to display the current injected or drained from the storage system. On the oscilloscope, the change from a negative to a positive value of the current allowed identifying the instant at which the storage system changed its mode of operation (injection or storage), following the reception of a remote command. The acquisition of the two signals on CH1 and CH2 of the oscilloscope allows measuring the time delay between the two events, as shown in Fig. 12. The test was repeated 100 times, and the results are shown in Table 6. The results obtained are well within the limits of the CEI 0-21 standard.

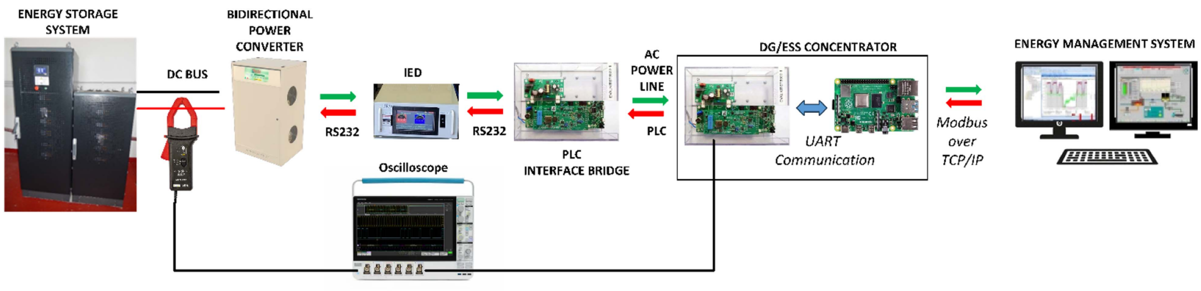

FIGURE 11. Lab setup for time delay measurement of power converter remote control.

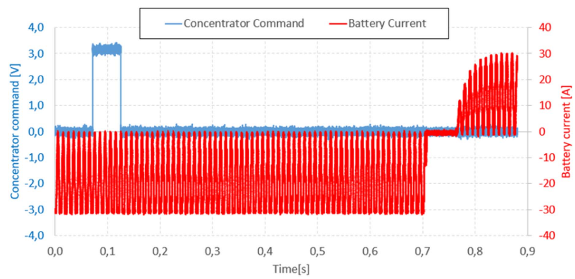

FIGURE 12. Delay measurement between the instant of command sending from the concentrator and the instant of change of storage system operating mode from generating (negative current) to absorbing (positive current).

TABLE 6. Remote Command Delay Measurement Results

Min Latency[s]	Max Latency[s]	Mean Latency[s]	Standard deviation
0.484	1.259	0.806	0.230

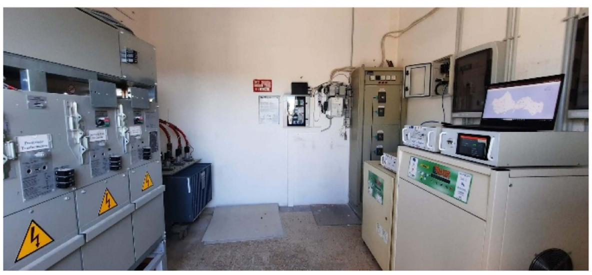

FIGURE 13. Concentrator, PLC interface bridge, IED, and power converter deployed in MV/LV substation.

B. ON-FIELD TESTS

Field tests were conducted on an LV line of the power distribution network of the island of Favignana. In detail, by deploying the concentrator in the MV/LV secondary substation (see Fig. 13), two types of communication tests were conducted: the first by connecting the bridge together with the IED inside a secondary substation; the second by connecting them to an LV distribution cabinet 200 m from the secondary substation.

In the first test, the communication between the SCADA control center and a storage system was verified, sending a command from the SCADA control panel via a Hyperlan connection to the concentrator and then via PLC to the IED

FIGURE 14. Battery of 20 kWh ESS.

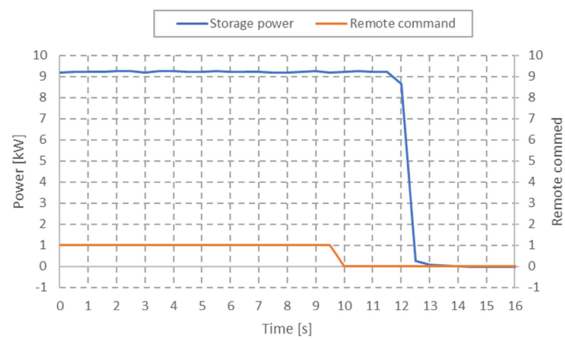

FIGURE 15. Latency measurement of remote-control command of ESS.

connected to the power converter. This last is connected to a 20-kWh storage system, as shown in Fig. 14. From the SCADA monitoring interface, it is possible to measure the time interval between the instant of command sending to the converter and the instant of power changing of the battery. In particular, a test was carried out by sending a command to change from an absorbed power of 9.2–0 kW. Fig. 15 shows the command signal changing from 1 to 0 and the power measured by the power quality analyzer connected in the secondary substation. From the figure, it can be observed that the latency time between the command sent by the SCADA and the instant when the delivered power drops to 0 kW is less than 4 s (including the measured times, as shown in Fig. 12). The result obtained is, therefore, well below the maximum time required by the CEI 0-21 standard.

TABLE 7. BER Test: 1000 Transmitted Packet With 102 000 Payload Bits

	BPSK				8PSK			
CH	Rx Pkt	Rx Bit	Wrng bits	BER	Rx Pkt	Rx Bit	Wrng bits	BER
1	988	102000	24	2,35 E-04	0	32232	1931	5,99 E-01
2	1000	102000	0	0	706	102000	775	7,60 E-03
3	998	101796	0	0	996	102000	5	4,90 E-05
4	999	101898	0	0	837	102000	325	3,19 E-03
5	1000	102000	0	0	1000	102000	0	0
6	999	102000	1	9,80 E-06	999	101898	0	0
7	1000	102000	0	0	983	102000	19	1,86 E-04
8	999	101898	0	0	997	102000	3	2,84 E-05

CH: Channel used for the transmission, Rx Pkt: Number of received packets, Rx Bit: Number of received bits, Wrng bits: Number of wrong bits, BER: Bit Error Rate.

In the second test, the BER was measured for the eight available channels of the PRIME 1.4 protocol by transmitting 1000 packets and using BPSK and 8PSK modulations. The concentrator remained in the secondary substation, while the PLC interface bridge and the IED were connected to an LV shell about 200 m away from the substation. The results, as listed in Table 7, show that, for BPSK modulation, BER is almost zero for all eight channels, whereas for 8PSK modulation, BER is close to zero for the higher channels (CH3–CH8). This is certainly due to the lower immunity of 8PSK modulation to noise and disturbances present at lower frequencies (CH1 and CH2).

V. CONCLUSION

In this article, a monitoring and management architecture is proposed, which makes use of some innovative equipment and solutions to meet the requirements of the future smart grid. The solution is tailored to LV distribution grids, filling a gap in the control framework of smart grid implementation at all voltage levels. The proposed solution can provide some PPC-like capabilities at LV level, offering a practical way of interacting with small-scale distributed resources for their integration into DSO operations.

In detail, the remote monitoring and control of DGs and ESSs connected to LV distribution networks have been studied and developed by using new IEDs. These devices, named DG/ESS concentrator, PLC interface bridge, and IED, have been conceived to be deployed at precise points in the utility network, without the need of making any changes to the network itself and in compliance with the relevant standards on DGs/ESSs connection to the grid. Because the developed solution relies exclusively on common, portable software technologies and on a standard network interface, the design is hardware agnostic: any industrial-grade SoC or single-board computer that can run Python and Node-RED (or containerized equivalents) and offers an Ethernet interface can be used as a drop-in replacement. The communication protocols that have been implemented on the developed devices are those of industry standards so as to ensure the feasibility and scalability of the communication link. The DG/ESS concentrator, deployed in an MV substation, exploits the consolidated Modbus TCP/IP protocol to enable the distributor to communicate by interfacing with widespread SCADA supervisory systems. Commands forwarded by the distributor are, in turn, addressed by the DG/ESS concentrator to the DG and storage facilities. PLC interface bridges must be deployed in this part of the power grid; they allow communication with the IEDs that control the power converters connected to DG and ESS plants. PLC technology was exploited for communication between DG/ESS concentrators and the PLC interface bridges by employing the PRIME 1.4 protocol. The establishment of the PRIME network is performed automatically and has a tree structure, where the BN, i.e., DG/ESS concentrator, manages the network consisting of many SNs, i.e., PLC interface bridges. These protocol features greatly facilitate the deployment of a large number of devices and they smartly implement LV mapping from the perspective of communication network configuration. For interfacing with the outside world, a Modbus TCP/IP client was implemented using Node-RED software. By polling DG/ESS concentrator, the Modbus TCP/IP client made it possible to verify the proper functioning of the entire communication link in both directions, i.e., from DG/ESS concentrator to power converter IEDs and vice-versa. The results obtained in the tests show the high levels of stability and reliability of the communication link, which were obtained with the use of low-cost commercial boards, thanks only to the implementation of new firmware. In addition, the choice of communication protocols, particularly that of the PRIME 1.4 protocol, makes it easy to cope with the randomness of the network due to continuous reconfiguration for the connection of new generation or storage plants. These aspects can be considered critical for better control and optimization of the management of DG and ESS systems, thereby increasing the efficiency of network service provisions.

In conclusion, the proposed solution has some practical benefits if compared with the conventional PPCs: the economic feasibility, avoiding the complexity and cost of industrial-grade PPCs not compatible with the application in LV networks; the scalability guaranteed by the use of PLC, which can be easily implemented because the infrastructure, i.e., the power lines, is already owned by the DSOs; the capillarity because, thanks to the proposed PLC infrastructure, all prosumers connected at LV level can be easily reached from the concentrator of each secondary substation; and the interoperability because the proposed communication protocols enable easy integration with higher level DSO systems. Even if the actual capabilities are limited compared with utility-scale PPCs, the proposed devices are designed to be upgraded. In future work, the firmware could be updated to implement new functionalities, such as VPP and ancillary service, when they are standardized for LV networks.

ACKNOWLEDGMENT

The authors would like to thank the Engineers of Layer Electronics S.r.l., Italy, for their support in communication interface development and especially M. Fiorino, A. Culcasi, N. Giuffrè, and G. Del Mastro, and STMicroelectronics for their scientific and technical support.

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