Sustainable Energy, Grids and Networks 40 (2024) 101530

Contents lists available at ScienceDirect

Sustainable Energy, Grids and Networks

journal homepage: www.elsevier.com/locate/segan

A blockchain-based architecture for tracking and remunerating fast frequency response

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ARTICLE INFO

Keywords:
Islanded power systems
Frequency regulation
Power hardware-in-the-loop
Renewables penetrations
Demand-response
Vehicle-to-grid

ABSTRACT

The increasing penetration of renewable sources introduces new challenges for power systems' stability, especially for isolated systems characterized by low inertia and powered through a single diesel power plant, such as it happens in small islands. For this reason, research projects, such as the BLORIN project, have focused on the provision of energy services involving electric vehicles owners residential users to mitigate possible issues on the power system due to unpredictable generation from renewable sources. The residential users were part of a blockchain-based platform, which also the Distributors/Aggregators were accessing. This paper describes the integrated framework that was set up to verify the feasibility and effectiveness of some of the methodologies developed in the BLORIN project for fast frequency response in isolated systems characterized by low rotational inertia. The validation of the proposed methodologies for fast frequency response using Vehicle-to-Grid or Demand Response programs was indeed carried out by emulating the dynamic behavior of different power resources in a Power Hardware-in-the-Loop environment using the equipment installed at the LabZERO laboratory of Politecnico di Bari, Italy. The laboratory, hosting a physical microgrid as well as Power Hardware-in-the-Loop facilities, was integrated within the BLORIN blockchain platform. The tests were conducted by assuming renewable generation development scenarios (mainly photovoltaic) and simulating the system under the worst-case scenarios caused by reduced rotational inertia. The experiments allowed to fully simulate users' interaction with the energy system and blockchain network reproducing realistic conditions of tracking and remuneration of users' services. The results obtained show the effectiveness of the BLORIN platform for the provision, tracking and remuneration of grid services by electric vehicles and end users, and the benefits that are achieved in terms of reducing the number of diesel generating units that need to be powered on just to provide operational reserve due to the penetration of renewable sources, resulting in fuel savings and reduced emissions.

1. Introduction

The BLORIN (BLOckchain for Renewables INtegration) research initiative, launched in December 2019 and concluded in September 2023, was dedicated to creating a blockchain platform customized for integrating distributed energy resources into the energy market.

Blockchain platforms have the unique ability to simplify interactions between small-scale producers, consumers and prosumers, enabling them to provide network services. The platform designed in the project facilitated the aggregation of residential users for the decentralized provision of Demand-Response (DR) and Vehicle-to-Grid (V2G) services, which are essential for managing demand volatility, particularly in renewable energy generation. DR involves end users by providing a series of strategies to change electricity use in response to price signals or incentives, with the goal to reduce peak demand, improving grid reliability, and reducing energy costs [1]. While, V2G enables electric vehicles to supply or withdraw power from the power network, promoting stability and providing economic benefits to vehicle owners [2]. Through DR initiatives, the developed platform has addressed these challenges by increasing the flexibility of the electricity system and keeping costs manageable, thus facilitating the integration of renewable energy without the need to expand the grid. At the same

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https://doi.org/10.1016/j.segan.2024.101530
Received 4 April 2024; Received in revised form 31 July 2024; Accepted 15 September 2024

time, V2G programs have leveraged the rapid response of charging stations to offer frequency regulation services, using energy stored in electric car batteries to stabilize isolated power grids, such as those on small islands with low rotational inertia. The BLORIN platform was developed to evaluate the effectiveness of DR programs on the island of Lampedusa and V2G on the island of Favignana. Using Hyperledger Fabric, an authorized blockchain platform, participants accessed and managed their transactions through customized Smart Contracts (SCs), which also authenticated data. The modular, configurable, and adaptable architecture of Hyperledger Fabric facilitated the development of applications for different project use cases. Operating as an authorized network, the anonymity of participants was precluded. Consequently, the network operates according to a governance model established to promote trust among participants previously authorized by the local distributor, ensuring the integrity of the network. The blockchain has enabled versatile and efficient interactions between different actors, creating a unique communication environment (single protocol) that connects with local intelligence (such as Energy Management Systems devices) or with measurement systems or even actuators. The use of a proprietary blockchain platform based on HyperLedger Fabric has also given transparency and an equal role to all actors, who have insight into data and the remuneration logic behind business models. The operation of the BLORIN platform for DR is described in [3], the paper [4] describes how the use of blockchain and the BLORIN platform enables residential users' involvement in DR programs to perfectly integrate with the technologies already used for DR. The paper [5] describes the operation of the BLORIN platform for V2G and how the platform enables privacy among users and secure management of sensitive data. The cited papers also include how the transaction are managed, verified, and recorded on the nwtwork.

The present paper explains part of the testing and validation phases of BLORIN's platform for Fast Frequency Response (FFR) services provision. FFR is a balancing service that is available to users that can fully respond to system frequency deviations within 30 s or less, used in power systems with low inertia to improve the control of frequency [6]. In addition, the adoption of FFR in Photovoltaic (PV) and Wind generation together with a widespread implementation of DR programs can provide full regulation even in an extreme situation [7]. From the physical point of view, FFR services carried out using Electric Vehicles (EVs) and energy resources connected to the low-voltage grid (residential users) were emulated considering their dynamic behavior. The experimental setup includes a Power Hardware-in-the-Loop (PHIL) equipment installed within the microgrid of the LabZERO laboratory at the Politecnico di Bari [8]. The setup permits to test both monitoring and control procedures, reproducing real-time response of the V2G and DR resources and emulating the dynamic behavior of the power grids under study. The emulated data were then sent to the BLORIN blockchain platform, through the Bari and Palermo laboratory connection, for tracking the FFR service provided by the users and for their remuneration.

1.1. Motivation of the work

Due to the penetration of renewable sources in small islanded power systems, new problems may appear during operation, related to both dynamic (system safety and stability) and static (congestion and adequacy) issues [9]. In the context of the BLORIN project, the main issue that emerged regarding grid security aspects concerns the possible decrease in rotational inertia in cases of a significant increase in generation from inverter-interfaced renewable sources, due to the consequent reduction in the number of connected synchronous machines [10,11]. Small isolated systems are indeed systems that are natively vulnerable to frequency transients due to the low kinetic energy that can be accumulated by small synchronous machines [12]. In the BLORIN project, it has been hypothesized that, under conditions of recognized vulnerability, additional controls on specific distributed energy resources (ie.: EVs, interruptible or modulable loads), could be activated to provide support to the system's stability during frequency transients. The use of EVs or interruptible/modulable loads as support for frequency regulation following the penetration of renewables was widely analyzed in the literature [13–16]. Most of the papers analyze control strategies for EVs or loads to participate in frequency regulation [17–20]. Other papers [21–24] propose strategies for the control of the number and type of vehicles taking part in the V2G program and modulate their contribution also considering other energy resources or vehicle control strategies to safeguard the health and degradation of batteries [25,26].

Studies show that a relatively small number of V2G recharging stations is sufficient to contribute to a frequency event and that local generation/consumption and thus minimization of electricity transport over long distances provides a highly effective solution for frequency deviation correction. Other papers [27,28] consider the interruptible/modulable load control for frequency regulation. The scientific literature reports that the use of EVs and passive loads can contribute to grid stability in terms of frequency regulation. Besides, most of the papers analyze control strategies to improve the stability of both isolated and interconnected power grids. Other papers explore the effectiveness of blockchain for V2G and DR delivery. For example, in [29,30] the authors propose a blockchain-based transaction system for managing EV charging. While, in [31,32], the authors propose the use of blockchain for secure authentication of vehicle owners for energy trading in a V2G environment, to preserve vehicle anonymity and support mutual authentication between EV, charging stations and aggregators. Regarding the provision of network services such as DR, several authors, such as [33–35], propose the use of a blockchain platform to manage, track, and remunerate the contribution made by generators/loads to DR in a distributed and secure manner. The use of PHIL for the emulation of electrical power systems and especially the study of the problems that can occur as a result of particular events or scenarios is a well-known activity. However, the integration of PHIL systems with blockchain platforms, on the other hand, is a topic not widely addressed. In this context, only a few papers such as [36,37], for example, propose the integration of the two systems, the first one for the implementation of the automated business model within energy communities, while the second for the market supply of reactive power in a trusted and secure way.

Compared to the literature, the integration of the Blorin platform and PHIL setup proposed in this paper demonstrates how blockchain technology, in addition to creating a realistic framework in which FFR services can be applied, tracked, and remunerated, is an enabling distributed technology for engaging end users in the provision of grid services. For this reason, the tests performed and shown in the following sections have a double goal: first, to evaluate the impact of distributed generation on frequency transients and what benefits, in terms of rate of frequency change (ROCOF), maximum under-frequency (nadir), settling time, and stability, can be obtained by using fast frequency reserve and synthetic inertia (SI); and second, to evaluate the effectiveness of the BLORIN platform for aggregating end-users and EVs to provide grid services.

To do this, a network model was developed for the simulation of electro-mechanical transients, to be applied to the case studies of the islands of Favignana and Lampedusa. The dynamic network model was created so that it could be integrated into a PHIL-type real-time simulation. It was developed in the Matlab/Simulink environment to be connected to the Power Hardware-in-the-Loop simulation platform based on the use of an OPAL RT5600 real-time simulator. The created model makes it possible to simulate the behavior of the DR control system, study the influence of control in the charge and discharge cycles of storage systems or V2G recharging stations with EVs, and determine the possible fluctuations of active power exchanged on the system. At the same time, the cited PHIL emulations were connected to the BLORIN platform to fully simulate the user's interaction with the power system and the blockchain. As a result, the main novelties of this work are:

1. The validation of the BLORIN blockchain platform for the involvement of end-users in the provision of grid services, to enable the diffusion of renewable sources into isolated power systems.
2. The evaluation of the effectiveness of the platform in aggregating and coordinating EVs and residential users for the provision of FFR grid services, through Power Hardware-in-the Loop.
3. Implementation of the PHIL tests in a geographically distributed real-time simulation to exploit the physical power equipment available at a remote location.
4. The development of dynamic grid models suitable for real-time simulation of electromechanical transients and PHIL.
5. Development of two FFR use-cases for the islands of Favignana and Lampedusa, and assessment of the impacts of FFR in terms of dynamic response with different technologies, different amount of regulating power and in the presence of the realistic delays and communication systems.
6. Test of different FFR control schemes and identification of possible solutions to ensure a suitable transient behavior.

The paper is organized as follows. Section 2 describes the BLORIN blockchain for the provision of FFR through V2G charging stations and passive loads control. The FFR service remuneration through the BLORIN platform is presented in Section 3. Section 4 describes the LabZERO and the equipments used for the PHIL emulation. Section 5 shows the results. Section 6 describes the overall architecture for PHIL emulation and integration with the BLORIN network by connecting the laboratories in Bari and Palermo.

2. The BLORIN blockchain for fast frequency regulation

The integration of blockchain technology into the energy sector aligns perfectly with the growing trend toward distributed generation, promoted by photovoltaic plants, other distributed generators, and Internet-of-Things (IoT) devices within generation systems. This innovative technology has numerous advantages that address the challenges inherent in integrating renewables and managing distributed generation. Blockchain facilitates the aggregation of local energy resources, including PV plants, household batteries, EVs, and passive users, enabling their participation in capacity and balancing markets. This technology can thus facilitate the delivery of ancillary services from distributed units, enabling the active participation of distributed generators and IoT devices in grid management. These ancillary services include backup power supply, frequency regulation, and grid balancing. Another important aspect is security in recording and sharing of real-time energy data. The blockchain enables indeed better supervision and coordination of energy processes, improving grid efficiency and resilience. Finally, the use of blockchain can eliminate or reduce the need for third parties in energy services by enabling direct transactions between energy producers and consumers. This can reduce the cost of energy and improve the overall efficiency of the energy market. In a nutshell, the use of this technology in the energy sector offers opportunities for greater decentralization, active and transparent participation of end users, and more efficient and resilient management of distributed generation.

But there are limitations of both a regulatory, technical and social nature that to date make its deployment difficult. Current Italian regulations do not allow the aggregation of resources of less than 1 MW, there is a lack of regulation of both the energy services that end users can provide and the use of the blockchain itself, the available regulating power is a variable data that depends on the behavior of users, the use of blockchain can be expensive as it requires advanced technical infrastructure and continuous maintenance, and finally being a complex technology and not easily understood by the general public the lack of knowledge and training limits its large-scale adoption.

For these reasons, it is important to note that the transition to a blockchain-based energy system requires appropriate technological, regulatory, and infrastructure development, as well as solving some privacy and data security challenges. To demonstrate technical feasibility while ensuring the data privacy of blockchain technology, a platform based on this paradigm was implemented in the BLORIN project [38]. The platform supported the provision of energy services by residential users through V2G and DR programs in the islands of Favignana and Lampedusa. In the islands, electricity is supplied by diesel generators, thus strongly linking the benefits of V2G and DR programs to the reduction of fuel consumption and mitigation of frequency fluctuations problems due to renewable penetration. Traditionally, the algorithms for executing V2G or DR programs are centrally managed by a third party and reside on a proprietary cloud. Thus, users do not have full transparency on how these services are managed. In BLORIN, in contrast, these algorithms are shared among users and reside in the BLORIN network inside a dedicated channel accessible only by users participating in the service. The Fig. 1 shows the network architecture implemented to test the V2G program in Favignana and the DR program in Lampedusa.

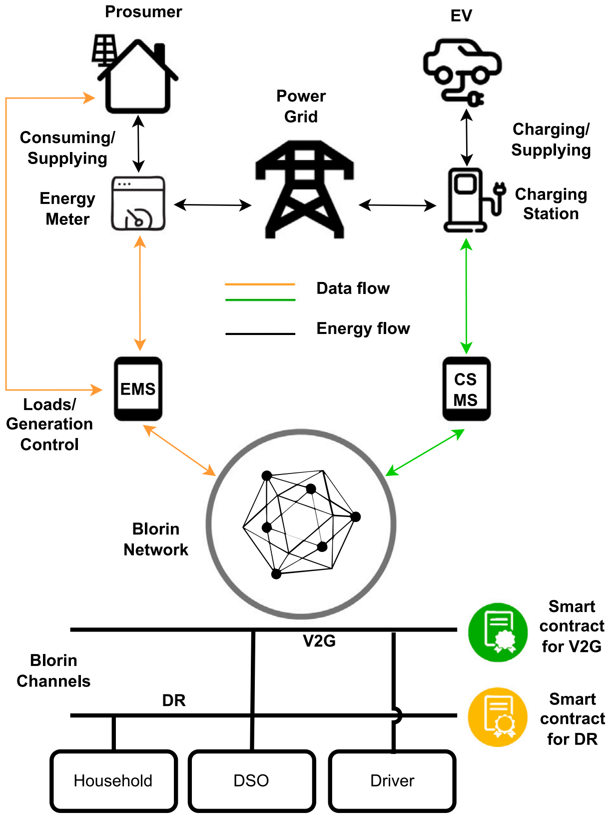

Fig. 1. BLORIN network architecture.

As introduced in Section 1, the BLORIN platform was developed on Hyperledger Fabric technology. At the center of a Fabric network are SCs, custom code designed to execute the logic of various transactions and ensure the integrity of each transaction submitted by network participants. These SCs serve as tools that enable users to interact with the blockchain. Every action within the BLORIN network, from simple queries to more complex transactions, is executed through these SCs. Regarding privacy within the blockchain structure, Hyperledger Fabric facilitates the division of the blockchain into distinct sections known as “channels”. Channels enable data segregation and privacy, allowing users to communicate securely. Data shared within a specific channel is accessible only to participants in that channel, and transacting parties require proper authentication to interact with it. Hyperledger Fabric offers the flexibility of setting up multiple channels within a single network, allowing different groups of participants to maintain separate transaction logs. For the project objectives, illustrated in Fig. 1, two separate channels were used for V2G and DR. A dedicated SC was developed and deployed on each channel, customized to perform transaction logic and related services. Access to data was governed by participants' roles within the platform and their corresponding authorization to subscribe to specific channels. For example, the driver of an electric vehicle could only access the *V2G channel*, while he could not access data in the *DR channel*. In contrast, the network operator (Distribution System Operator - DSO) or electric service provider could access both the *V2G* and *DR channels*.

2.1. V2G application

The delivery of V2G services requires a bidirectional smart charging station. Within the BLORIN project, a bidirectional charging station was installed in Favignana and used as a charging station for the vehicles involved in the experimentation. Among these vehicles, a Nissan e-NV200 van was equipped with an onboard experimental setup for monitoring features related to the vehicle mobility phases (which are out of the scope of this paper), as described in [39]. Below are listed the features of the bidirectional charging station:

- Connection: IEC EN 62196-3 configuration AA (CHAdeMO);
- Supply voltage: 400 V three-phase AC;
- Maximum input/output power: +10 kW/−10 kW;
- Maximum DC current: +28 A/−28 A;
- DC output voltage range: 50–500 V;
- Minimum efficiency: 94%;
- Connector or plug type: IEC EN 62196 AA configuration;
- Communication protocol: CHAdeMO, RS-485, Modbus TCP/IP. OCPP+V2G, 4G, Ethernet (at least two of these types);
- Certifications: CHAdeMO, ISO 9001, ISO 14001, EMC Directives (61000-6-1, 61000-6-3, 61851-21-2); LVD Directives (61851-1, 61851-23, 61851-24).

The communication protocol is indispensable for controlling the recharging station, and its charging and discharging phases, thus allowing to enactment of various energy services.

The most common protocol for V2G recharge stations is the OCPP, Open Charge Point Protocol. The latter sets some rules for data exchange between the control system and the charging infrastructure. In this context, data are the values of the power injected or absorbed, as well as the State of Charge (SoC) of the car battery. OCPP has been developed in recent years by the Open Charging Alliance to enable operators, network managers, or aggregators, to monitor, authorize, or start/stop a charging phase and to modify some important parameters of the charging station to provide some required energy service to the grid [40,41].

Based on these data and parameters, the control system elaborates commands to be sent to the charging point, regarding charge and discharge cycles. Using the same mechanism, algorithms for FFR are also implemented, and these are necessary for primary regulation following changes in the grid frequency. Once the technical characteristics with which the charging point must be equipped were defined, the bidirectional charging point produced by AME (Applied Micro Electronics), a U.S.-based company with European headquarters in the Netherlands, was chosen; the model is the 10 kW AME V2G Charger, designed for Smart Charging and V2G applications, also prepared for the use of generic storage systems and inverter operation in coupling with photovoltaic systems.

Fig. 2 shows the AME V2G charging point installed in Favignana in front of the SEA office building.

The charging point meets the requirements already outlined. In particular, it is configured with OCPP protocol version 1.6, features both a CHAdeMO and CCS Combo 2 connector, and is also equipped with power and frequency meters for load management and primary regulation such as FFR.

Fig. 2. AME V2G charging point, operated by SEA S.p.A. (DSO in Favignana) and installed in Favignana as part of the BLORIN project.

Fig. 3 shows the main elements of the AME charging station installed in Favignana. The charging station can be schematically divided into three main parts: the first for exerting control by the system operator, the second for communication with the user, and the third for power exchange between the vehicle and the power grid.

The AME charging station in Favignana exchanges data with the BLORIN network through the Charging Station Management System (CSMS), see Fig. 1, which communicates with the Charging Station using the OCPP 1.6 protocol. The use of this protocol allows the collection of data charge/discharge cycles, the management of various charging profiles, the acquisition of a complete vehicle history and the definition of particular parameters useful for the delivery of energy services.

With a view to primary frequency regulation, the parameters of interest are:

- *FFRPowerPositive/Negative*: allows to set the power [W] that the charging point provides during FFR;
- *FrequencyDeviationHigh/Low*: allows to set the frequency threshold [mHz] above which the charging point provides the maximum power set;
- *DeadBandHi/Low*: allows to set the dead band [mHz] in which the charging point does not provide regulation.

By appropriately setting these values, different control strategies for frequency regulation can be implemented. In the present case, the above parameters are set by the power system operator, based on the possible disturbances that may occur due to renewable generation, through the SC running on the V2G channel of the BLORIN platform.

2.1.1. BLORIN platform operation for FFR through V2G

Since primary frequency regulation is an event that starts and ends in a few seconds, the regulation parameters of charging stations

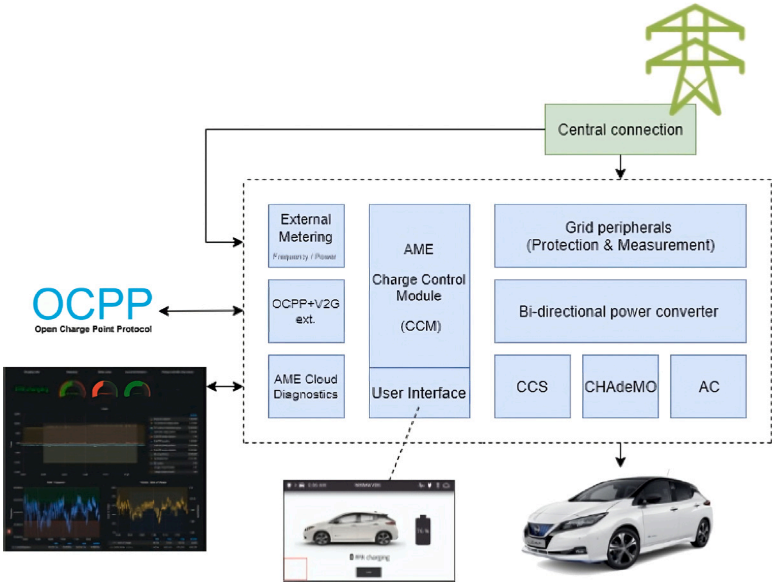

Fig. 3. AME charging station main elements.

described before are set 'a priori' based on possible expected disturbances and based on the time of the year, given the high variability of the island's consumption due to seasonality. As shown in Fig. 1, the charging stations are physically connected to the power grid. While the connection with the BLORIN blockchain platform is implemented through the CSMS, which accesses the charging stations by obtaining the data for the single V2G event and storing it on the V2G channel of the blockchain.

An identifier assigned to each EV allows the SC operating on the V2G channel to compile complete data relevant to it. To obtain data from the EV during the energy input and consumption phases within the grid, querying the charging station is a successful method. The data collected from the charging station through the Charging Station Management System (CSMS) is then transmitted to the BLORIN blockchain platform through the SC for validation. The SC for V2G is engineered to run the logic and scenarios for Frequency Response Reserve (FFR) event monitoring. The initial phase involves monitoring the Gear parameter of the vehicle, which determines whether the vehicle is parked (Gear = 0), stationary (Gear = 1), or moving (Gear > 1). When the vehicle is parked, the Plug State parameter allows checking the connection status to the charging station (Plug State = 2 for connected, Plug State = 0 for disconnected). During connection, various parameters such as battery temperature, ambient temperature, changes in the vehicle charge profile, battery health status (SoH), and voltage applied to the battery pack cells are monitored. These parameters help determine whether the vehicle battery is under stress or aging. While the vehicle is connected to the charging station, the direction of energy flow (injected or consumption) determines if the vehicle is participating in an over-frequency or under-frequency event. This data is continuously recorded in the dedicated V2G channel, facilitating comprehensive tracking of all events affecting the vehicle and accounting for the duration spent in each state. Additionally, this information is utilized by the SC to compute user remuneration resulting from participation in regulation activities.

2.2. DR application

In Lampedusa, the BLORIN platform has been deployed to implement DR services by consolidating simple consumers or prosumers into virtual clusters residing on the island. The BLORIN platform was seamlessly integrated with household consumers, allowing for the management of their loads through a purpose-built Energy Management System (EMS) device, utilizing smart plugs as actuators. The EMS serves as the central system facilitating monitoring and control of passive household loads and communication with the BLORIN platform, as depicted in Fig. 1. Installed directly within the user's home, the EMS resides in a dedicated electrical switchboard and comprises a data processing controller, an energy meter, and a circuit breaker. Furthermore, the EMS functions as a blockchain client, facilitating communication with the BLORIN platform, receiving DR requests from the blockchain, and providing power consumption/generation data for Baseline calculation and service quantification. The DR program's logic is implemented through a dedicated SC, which also delineates the roles of various actors within the BLORIN network. In this context, the involved actors include the Distribution System Operator (DSO) and users opting to participate in the program by offering their flexible loads or generation/storage systems. Unlike the conventional approach where DR event execution is initiated by the network operator and communicated to home users via an aggregator, the BLORIN platform enables direct interaction between the network operator and home users, with aggregation executed through SCs [42]. Acting as the intermediary and aggregator, the blockchain and its SCs facilitate power request sharing, verify user responses, and transparently and reliably compensate them based on their contributions. Overall, the integration of the BLORIN platform with the EMS and smart plugs in Lampedusa has proven to be an efficient system aimed at enhancing energy consumption efficiency through the consolidation of consumers and prosumers into virtual clusters. Direct load control via the EMS has bolstered the flexibility and responsiveness of the island's energy infrastructure during DR events.

2.2.1. BLORIN operation for FFR through DR

DR is an important tool that can help maintain the proper operation of the power system following RES penetration, as it allows for balancing energy supply and demand at different time scales. The BLORIN network allows the aggregation of users transparently and without the need for an aggregator, generating virtual load/generation clusters that can provide flexibility to the power grid. When a request to increase or decrease the load is notified on the blockchain, the EMS sees this request and turns one or more loads on or off according to the users' needs. These user loads are supplied and controlled through smart plugs. Experiments carried out to test the feasibility of DR through the BLORIN network have shown that the response time of loads following a DR request is in the order of a few seconds. This completely satisfies the requirements for DR [43], but may not be sufficient for frequency regulation, as this service requires a power device to be able to detect and react to frequency changes very rapidly, within a few hundred milliseconds from the beginning of the transient event. To provide frequency regulation, it is thus necessary to equip the EMS with a grid frequency metering system to enable the disconnection of some loads when required. Using a voltage transducer, it is possible to provide the grid voltage signal directly to the EMS, which through appropriate software calculates the RoCoF and processes the control action of the loads connected to the EMS itself [44]. Assuming the presence of massive renewables installations, when there is a rapid decrease in production, and thus of frequency, the EMSs installed inside the homes instantaneously disconnect one or more loads thus contributing to regulation. In this way, residential users can contribute to the primary frequency regulation. The data recorded during the event are sent to the BLORIN platform, which processes them through a specific SC for validation, storage, and finally remuneration for the service provided.

3. FFR service remuneration

3.1. Italian energy market overview

The Italian electricity market is divided into a spot electricity market and a forward electricity market. The Spot Electricity Market is composed of:

- Day-Ahead Market (DAM),in which market participants trade hourly blocks of electricity for the next day by submitting bids in which they indicate the quantity and the maximum/minimum price at which they are willing to buy/sell.
- Intraday market, which allows operators to make changes to the schedules defined in the DAM through additional offers to buy or sell.
- Auxiliary services market, called in Italian “Mercato del Servizio di Dispacciamento” (MSD). Through this market, *Terna S.p.A.* (the Italian Transmission System Operator - TSO) procures the resources necessary to manage and control the system (intrazonal congestion resolution, power reserve creation, real-time balancing).

Frequency regulation service is included within the MSD. The provision of the system’s reserve capacity is a fundamental part of a well-functioning power system, as it is necessary to ensure a real-time balance between electricity generated and consumed, avoiding risky frequency deviations.

Until 2017, only generation units with an installed capacity of more than 10 MVA and technically capable of effectively and predictably modulating their output (so-called “Relevant Units”) could participate in the MSD and primary frequency regulation. From 2017 to 2018, several pilot projects were started for the inclusion in the MSD of virtual consumer, production, and relevant units not subject to mandatory qualification, and storage systems functional to electric mobility [45].

Until 2014, Relevant Units were obligated to provide primary frequency regulation (FCR) without receiving any remuneration. As of November 1st, 2014, with the technical document “Allegato A73” [46] Terna S.p.A. also established a mechanism for valuing the energy supplied by Relevant Units qualified for primary frequency regulation.

In 2020, ARERA Resolution 200/2020/R/eel approved the rules for the provision of the ultrafast frequency regulation service proposed by Terna S.p.A. with the pilot project “Fast Reserve” [47]. The project proposes a service distinct from the primary control service but closely coordinated with it to assist dynamic frequency stability. Specifically, the Fast Reserve is bidirectional and consists of providing a continuous and automatic response in active power, proportional to the frequency error, within 1 s of the event that resulted in service activation and a response start-up time within 300 ms. The required power profile must be maintained for at least 30 s and must subsequently ramp linearly in 5 min until the activated contribution is annulled. Aggregates of devices, possibly coinciding with a single device, referred to as Fast Reserve Units, including stand-alone generation units, load units, storage systems, or generation units mixed with load and/or storage units, may participate. Participation requires a rated power between 5 MW and 25 MW, to respond within 1 s of the frequency deviation event, as well as to ensure a minimum service delivery duration at full power of 15 min both up and down. Fast Reserve participants are rewarded through a tariff that varies hour by hour and depends on the energy exchanged by the unit for service provision and the hourly price of energy related to the DAM.

Due to the increasing presence of non-programmable renewable power plants, the Integrated Electricity Dispatch Text (TIDE) was approved with the ARERA Resolution 345/2023/R/eel. Starting in 2025, it will allow full participation of renewables, distributed generation, storage systems, and consumers in the electricity system. The TIDE eliminates the minimum power limit for participation in the services market and terminates the pilot projects started by Terna S.p.A. in past years. In this way, the energy resources involved in the BLORIN project can realistically participate as aggregate resources in the regulation services market able to provide support for ultrafast frequency deviations.

3.2. Smart contract for FFR remuneration

As already introduced in Section 2 and explained through Fig. 1, during V2G and DR events for FFR, data collected from charging stations and EMSs are sent to the BLORIN network, which processes them through specific SCs and stores them within the dedicated channel. The SCs, in addition to validating the data received also calculate the remuneration of the users who participated in the FFR event. In particular, the same method used by Terna S.p.A. for Fast Reserve was used for remuneration. Through proper APIs, the blockchain acquires the zonal prices of Sicily relative to the DAM every day from the Energy Market Operator’s website. At this point, when there is a sudden reduction/increase in production from the renewable plants, the V2G charging stations in Favignana and the EMSs in Lampedusa take action to provide FFR service. In the case of V2G, the charging station sends the energy input or output during the FFR to the BLORIN network, while in the case of DR, the EMS registers and sends to the BLORIN network the (negative) energy variation sustained to participate in the event. Then, the SC calculates in terms of energy tokens the remuneration of each user using the energy committed during the FFR event. During the field tests, it was possible to verify the users’ interaction with the BLORIN network and the effectiveness of the FFR services implemented by the SCs. However, due to the small number of charging stations in Favignana and residential users involved in Lampedusa, an integrated framework using PHIL and the BLORIN blockchain platform was set up for testing realistic scenarios. The framework is described in the following sections.

4. Experimental tests

The BLORIN project included an experimental validation of the proposed FFR methodologies. Unfortunately, given the limited number of flexible resources that were available to participate in the tests (in Favignana there are only a few EVs and just one bidirectional charging station, whereas in Lampedusa only a few residential loads have been equipped with blockchain-ready EMS devices), the assessment of their potentials in controlling the frequency transients was evaluated through PHIL simulations.

PHIL tests were conducted through the microgrid and the instrumentation available in the LabZERO laboratory [48] at the Poliba. The validation of V2G and DR actions has been carried out defining possible future scenarios characterized by a high penetration of RES and very low rotational inertia. The response of these resources was emulated

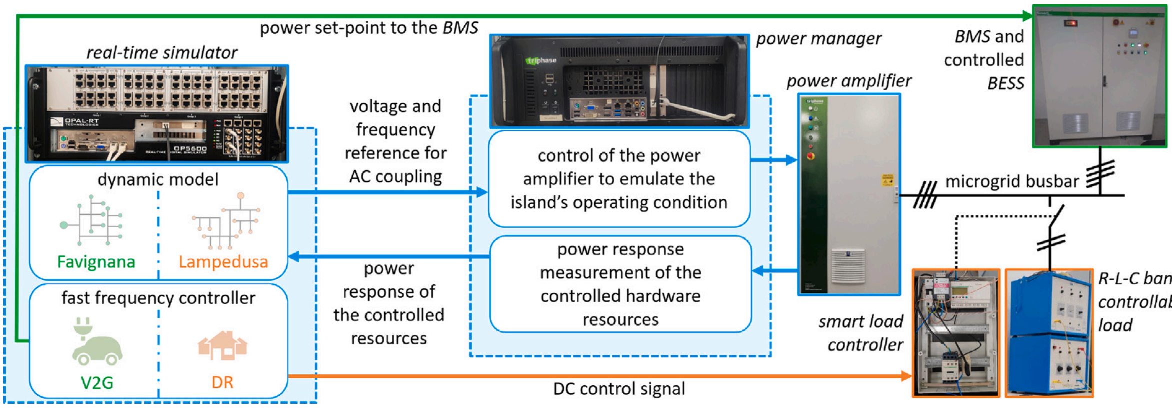

Fig. 4. Experimental set-up for PHIL simulations: blue indicates the devices and connections used in all tests performed, green indicates the devices and connections used during validation of the V2G action, and orange indicates the devices and connections used during validation of the DR action. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

using different power hardware resources available in the microgrid LabZERO.

The PHIL set-up used for this experimental validation is schematically shown in Fig. 4. A real-time simulator (RTS) OPAL OP5600 is used to solve the dynamic grid models and elaborate the FFR control laws to be implemented on the distributed resources. The RTS is coupled with the microgrid using the switching power amplifier Triphase PM15A30F60, programmable on all four quadrants. The amplifier is controlled by a dedicated power manager which exchanges synchronized real-time data with the RTS using fiber optics. The power amplifier is run using a voltage source control mode and programmed to replicate voltage and frequency conditions measured at a specific node of the simulated grid. This voltage is applied to the physical devices under test (DUT).

The tests on Favignana island were conducted using a three-phase $LiFePO_4$ Battery Energy Storage System (BESS) to emulate the behavior of a V2G electric vehicle. The BESS was controlled by its Battery Management System (BMS) which received time-variant active power set-points from the FFR controller emulated by the RTS. Control signals generated by the RTS were read and sent to the BMS using Modbus TCP/IP. The tests on Lampedusa island involved the use of a set of R-L-C controllable load banks as DUTs. The loads were controlled though a smart load controller (Schneider Zelio Logic SR3) which received switching signals from the simulated FFR controller. Controls were sent using a hardwired DC voltage signal from the analog output of the RTS to the inputs of the load controller.

4.1. FFR through V2G test case

Efficacy and feasibility of FFR through V2G were demonstrated considering an increasing potential number of EVs connected to the Favignana power system and available to the control. The MV primary distribution network in Favignana consists of 46 buses at a nominal voltage of 10 kV. The primary distribution makes use of three radial feeders, all of which connected to the power plant station where all generation units are is located. With a total installed capacity of about 18 MVA, the system is capable of covering the summer peak load (about 9 MW) with sufficient adequacy margins.

A dynamic model of the Favignana power grid was built using Matlab/Simulink. The model allows to represent electro-mechanical transients and can be used to obtain in real-time the voltage and frequency trajectories that can be experienced following a sudden event. The implementation of the model in a PHIL environment allows to embed in the simulation the actual real-time dynamic response of the power hardware resources, currently available at LabZERO microgrid. It must be noted that RTS is characterized by strict computational limitations which can constraint size and resolution of the simulation. For this reason, the adopted model was suitably simplified.

The network model used for simulations is shown in Fig. 5. It consists of 16 equivalent MV buses, which resulted from the aggregation of the downstream paths of laterals. This kind of simplification allows to reduce the computational burden of the real-time simulations, without heavily affecting the system behavior, as discussed in [49]. Each distribution line was modeled using the Simulink three-phase PI model (Three-Phase PI Section Line). The diesel power plant is represented by an equivalent synchronous generator. A sixth-order differential equations model was adopted, plus a model of exciter and governor. The synchronous generator is connected to the MV grid via a 0.4/10 kV equivalent step-up transformer. Controllers for excitation and governor functions are adapted to the overall equivalent rated power, which depends on the number of active diesel groups. In order to simulate low inertia conditions, total rotational inertia was set to 0.5 s.

Because of the strict time requirements imposed by the real-time simulation, in these tests, the behavior of RES and dynamic loads was modeled using a novel *p*-*q* theory-based dynamic load model, recently proposed by some of the authors in [50]. Thanks to its innovative formulation, the model is characterized by a computational burden much lighter than the one of the blocks available in Simulink library. The adoption of the *p*-*q* theory-based dynamic load model allowed to improve the complexity of the power system, while increasing the number of connected DERs, without incurring in overruns. The model is general enough to describe the behavior of any kind of load including constant-power loads, dynamic loads, or equivalent loads which can describe the response of DERs equipped with interface control systems (for example also RES plant and their interface controllers). Further detail on this load model can be found in [50,51].

Fig. 6 shows the FFR control scheme proposed to control V2G EVs. The FFR control scheme generates a variation of the active power set-point of the controlled V2G EVs (ΔP), according to the instantaneous measures of frequency and RoCoF. The variation ΔP is the sum of two separate contributions, one proportional to the frequency variation (as in primary regulation or PR), and one proportional to the frequency derivative (synthetic inertia or SI).

The whole control scheme was normalized with respect to the rated power of the controlled resource. A 5% droop was set to the PR controller ($K_{PR} = -20$), whereas the synthetic inertia was set to obtain a per unit value of 3 s ($K_{SI} = -6$).

The model includes a first low-pass filter needed to filter frequency measurements and a second low-pass filter used to avoid sudden changes in the inertia controller. Both filters were chosen first-order with time constants (T_1 and T_2, respectively) set at 40 ms.

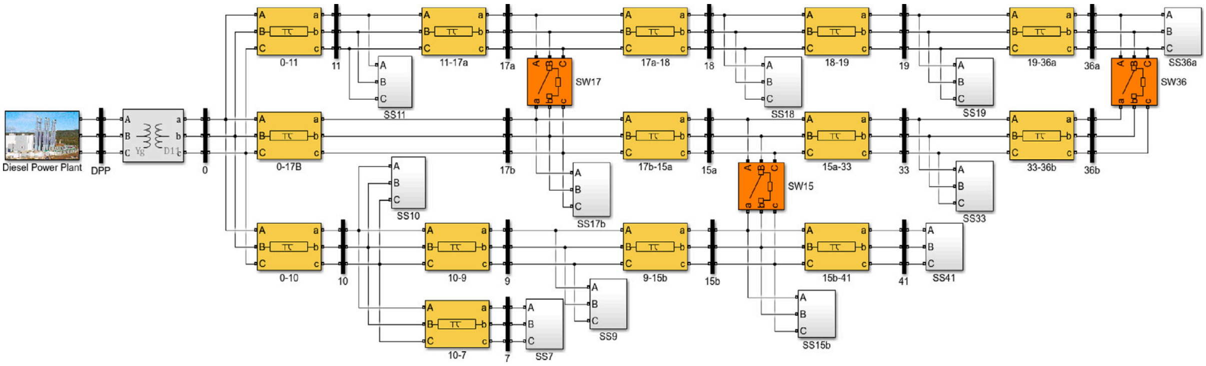

Fig. 5. Favignana island grid model developed on Matlab/Simulink environment.

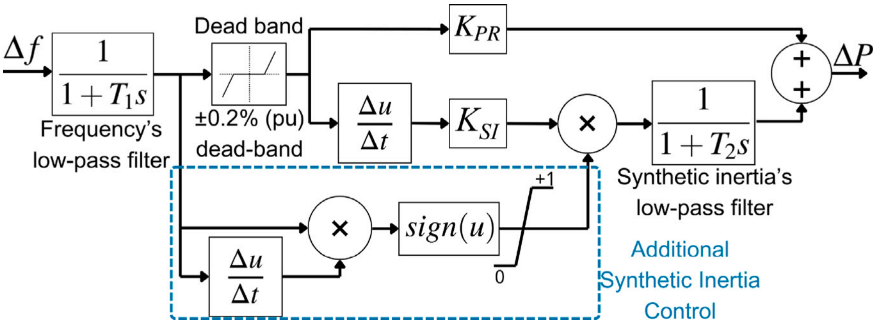

Fig. 6. V2G fast frequency response control scheme.

This time constant of the filters is chosen as a suitable value to filter out the noise in the measurement and to contain possible jumps in the frequency signal [52].

In addition, to avoid the activation of the controllers in the case of small frequency fluctuations, a dead band on frequency deviation of $\pm 0.2\%$ ($\pm 100\,\text{mHz}$) was introduced. This dead band value takes into account the high-frequency volatility that can be experienced in non-synchronous electrical systems with very low rotational inertia.

To improve the effect of SI control, an additional control was introduced. This additional control is based on the synthetic inertia controllers developed by the authors in [53,54], and allows to suppress the inertial response when it is not necessary.

The concept behind the proposed additional *SI* control can be summarized in a simple *if* statement:

$$\begin{cases} if \quad \Delta F \cdot dF/dt > 0 \\ \quad SI\ control\ ON \\ else \\ \quad SI\ control\ OFF \end{cases}$$

This logic has been implemented as shown in the proposed control scheme (Fig. 6), where the inertial contribution is enabled only when Δf and its derivative (Rate of Change of Frequency - RoCoF) are concordant. As it will be shown in the experimental results, this additional control permits to reduce the settling time and improve the overall system transient stability.

4.2. FFR through DR test case

The validation of FFR contribution provided by DR was assessed by considering a plausible scenario with 400 residential buildings equipped with the EMS on the island of Lampedusa. In this island, the primary distribution system operates with a nominal voltage of 10 kV. The network develops starting from a main substation which connects a conventional power plant to the whole grid. Primary distribution is organized in four radial feeders, and a total number of 64 MV buses. The generating units at the power plant have a total capacity of about 8 MVA, which is adequate enough to supply the summer peak load.

The overall grid model of the distribution network on Lampedusa Island is shown in Fig. 7.

As in the previous case, a simplification of the overall Lampedusa power system was needed to satisfy RTS constraints. Computational complexity was further reduced thanks to the adoption of the above-mentioned *p-q* theory-based dynamic load model to represent all flexible resources.

As for the Favignana Island grid model described in Section 4.1, the diesel power plant was modeled as an equivalent synchronous generator with controllers for excitation and governor functions. In order to simulate low inertia conditions, total inertia was set to 0.5 s. The generator was connected to the MV grid via a 0.69/10 kV equivalent step-up transformer.

To generate the DR control action, a simple load-shedding control scheme was implemented, which, for the sake of brevity, is not schematized. The simulated controller disconnects the load instantaneously when the minimum frequency threshold of 49.5 Hz is reached.

5. Test results

5.1. Fast frequency response control of V2G EVs in Favignana island

The scenario assumed for these tests can be described as follows. Initially, at an instant $t_0 = 0^-$, the system was stable and characterized by a total consumption of 1.098 MW. The overall PV production was 677 kW, whereas the power plant supplied the remaining 431 kW. It was imagined that starting at $t_0 = 0^+$, a sudden clouding event caused a severe generation reduction on the largest-sized PV plant. In one second the active power produced by this plant was brought from 339 kW to 34 kW, giving rise to an under-frequency event.

In the first test, 20 V2G EVs were assumed to be connected and available to FFR during the frequency transient. The nominal power

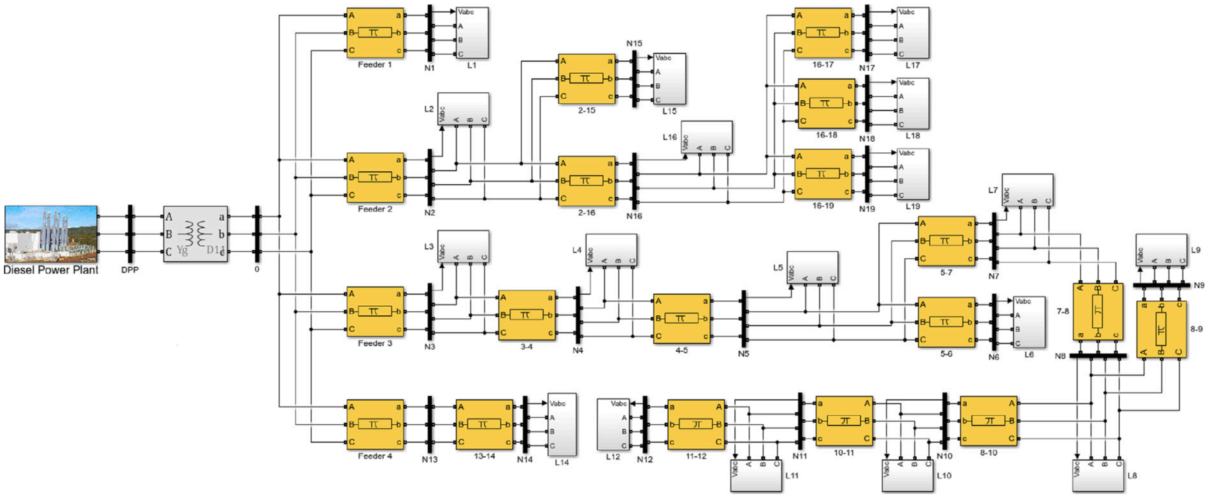

Fig. 7. Lampedusa island grid model developed on Matlab/Simulink environment.

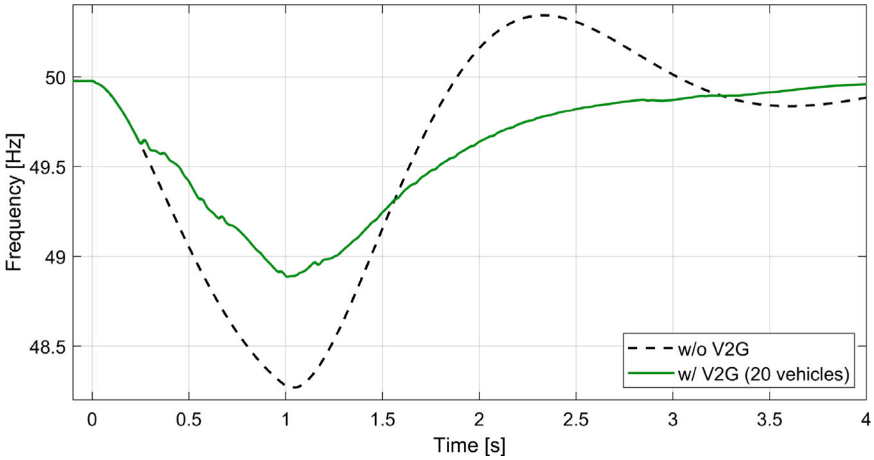

Fig. 8. Frequency behavior with and without the FFR contribution of 20 V2G EVs.

of each V2G pedestal was assumed to be 10 kW, as the charging station was installed in Favignana. It was assumed that all EVs were at 50% of their storage capacity and in standby (no active power exchanged). This last hypothesis permits to better evaluate the effect of the V2G's contribution during frequency events, maintaining the same initial condition, even when a growing number of connected vehicles is simulated.

Fig. 8 compares the frequency trajectory obtained with and without the FFR of the EVs. In the PHIL test, the response of the EVs was emulated through the real-time control of a physical battery. Thanks to the FFR contribution, a significant reduction (−36%) of the maximum frequency excursion was obtained, with the nadir increasing from 48.27 Hz to 48.89 Hz. A clear improvement was also obtained regarding the average RoCoF after contingency. The average RoCoF, calculated as the frequency excursion between $t_0 = 0^+$ to reaching half of the maximum frequency excursion (0.46 s and 0.48 s, w/o and w/ FFR respectively), was reduced by 38%, from 1.87 Hz/s to 1.16 Hz/s. Also, it should be noted how the FFR control allowed to better damp the frequency oscillations and almost cancel the frequency overshoot.

The active power trajectories are shown in Fig. 9, where the active power production of the generation plant is shown for both cases (with and without FFR). The figure allows to observe how, thanks to the FFR contribution of V2G, the transient response of the diesel generator was reduced in both terms of intensity and acceleration. This means that a lower operating reserve is needed from the power plant, and therefore a smaller number of generators can be employed to ensure security. Reducing the number of active diesel generators generally results in fuel savings and CO_2 emission reduction, since the generators can work closer to their maximum efficiency operating point.

Further, PHIL tests were carried out considering the growing number of available EVs. These tests are based on the same scenario precedently described and aim to observe how the power capacity of FFR resources can affect frequency transients. Fig. 10 collects the frequency trajectories obtained by increasing the number of enabled vehicles from 0 to 35. The increase in controlling resources improves the overall transient response. However, with a number of 30 or more vehicles, the frequency trajectory starts to show a poorly damped oscillating behavior due to the delays introduced by communication and control. A higher sensitivity to measurement noise is also clearly shown.

Table 1 compares the responses obtained considering a different number of controlled EVs. Results are expressed in terms of typical metrics used to evaluate frequency transient response. It can be observed that, even with just 5 vehicles, the frequency excursion can be reduced by 13% and the average RoCoF by 12%, together with significant reduction of overshoot (−62%) and settling time (−5%). Performances improve even further as the number of vehicles increases up to 25 EVs. Adopting 30 vehicles can provide further improvements in terms of RoCoF or frequency deviation, although some poorly damped oscillating modes can arise, affecting the settling time. These oscillations can be observed in Fig. 10 and are particularly visible when 30 and 35 EVs are used. Based on these observations, it can be inferred that

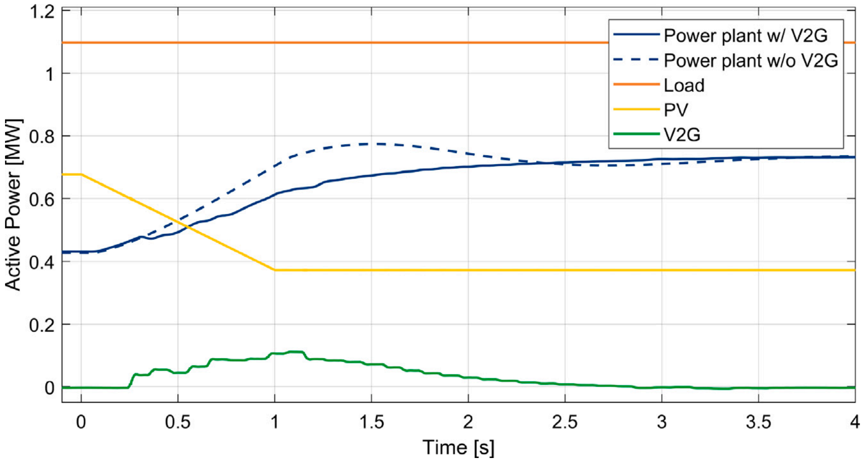

Fig. 9. Active power behaviors with and without the effect of 20 V2G EVs.

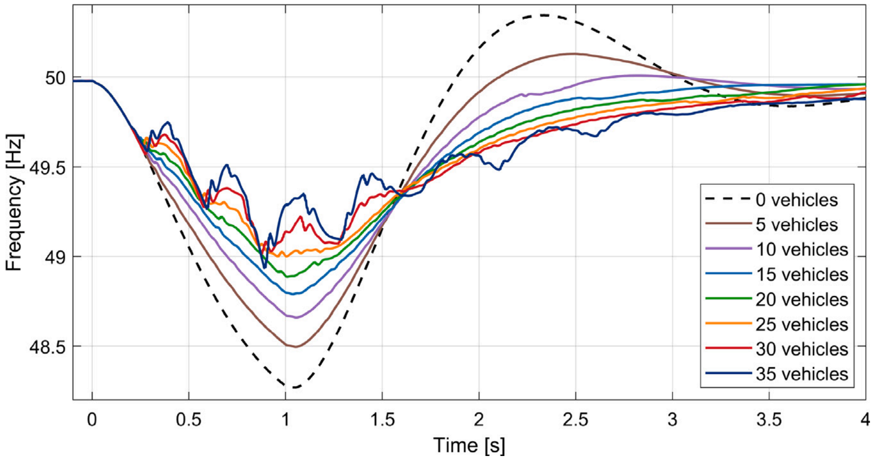

Fig. 10. Frequency behavior for different numbers of connected V2G EVs.

Table 1
Frequency response indicators for different number of connected V2G EVs.

	0 V2G	5 V2G		10 V2G		15 V2G		20 V2G		25 V2G		30 V2G		35 V2G	
Nadir	48.27	48.50		48.66		48.79		48.89		49.00		49.02		48.94	
Max $f_n - f$	1.73	1.50	−13%	1.34	−23%	1.21	−30%	1.11	−36%	1.00	−42%	0.98	−43%	1.06	−39%
RoCoF	1.87	1.64	−12%	1.43	−24%	1.27	−32%	1.16	−38%	1.06	−43%	1.01	−46%	0.75	−60%
Overshoot	50.34	50.13		50.01		50.00		50.00		50.00		50.00		50.00	
Max $f - f_n$	0.34	0.13	−62%	0.01	−97%	0.00	−100%	0.00	−100%	0.00	−100%	0.00	−100%	0.00	−100%
Settling time	4.08	3.86	−5%	2.25	−45%	2.77	−32%	3.37	−17%	3.64	−11%	3.95	−3%	4.41	+8%

performances can be improved by FFR on EVs only up to a certain amount of controlled resources (in this case about 20 or 25 vehicles). Nevertheless, despite the oscillations, the system remained stable even in the presence of the highest number of EVs, thanks to the additional SI control described in the previous Section 4.1. This conclusion can be affirmed based on the results shown in Fig. 11, where the frequency responses obtained with and without the additional SI control have been compared. Without the additional control, the SI would have lead to unstable conditions. Instead, the additional SI control mitigates the effects of measurement and control delays, favoring a higher penetration of flexible distributed resources in frequency regulation.

Further tests were carried out in order to investigate the performances of different FFR control schemes. The proposed control scheme (see Fig. 6) is general enough to allow both PR and SI control, or a combination of the two. Fig. 12 shows the frequency responses obtained considering different combination of the FFR controls. The tests were conducted using a same scenario, characterized by 20 enabled EVs. The impact of each control can be observed and compared with the base case (no FFR control of EVs). From the trajectories shown in Fig. 12, PR control appears more stable compared to SI control. This result is due to the fact that the RoCoF changes faster than the frequency deviation. The PR control has no impact on the initial RoCoF but reduces significantly the frequency overshoot and the settling time after the disturbance. Conversely, the SI control can improve RoCoF but leads to a longer settling time and increased frequency overshoot.

Performances can also be quantified using the transient response metrics in Table 2. In general, a net quantitative comparison between PR and SI control is not really possible because of their different nature and concept. PR control can improve Nadir, frequency deviations and settling time, but not the RoCoF which, instead, can be improved only thanks to SI. Results confirm that the adoption of an additional SI control can only bring improvements, since it allows to mitigate the

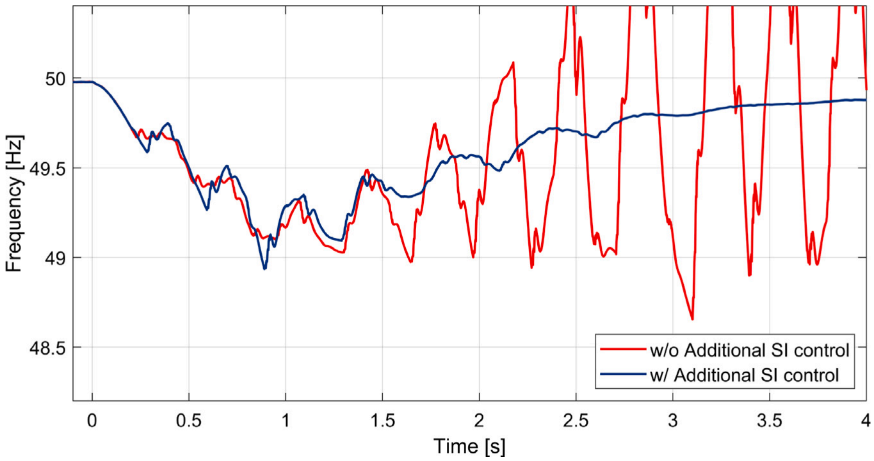

Fig. 11. Frequency behavior with 35 V2G EVs, with and without the additional SI control.

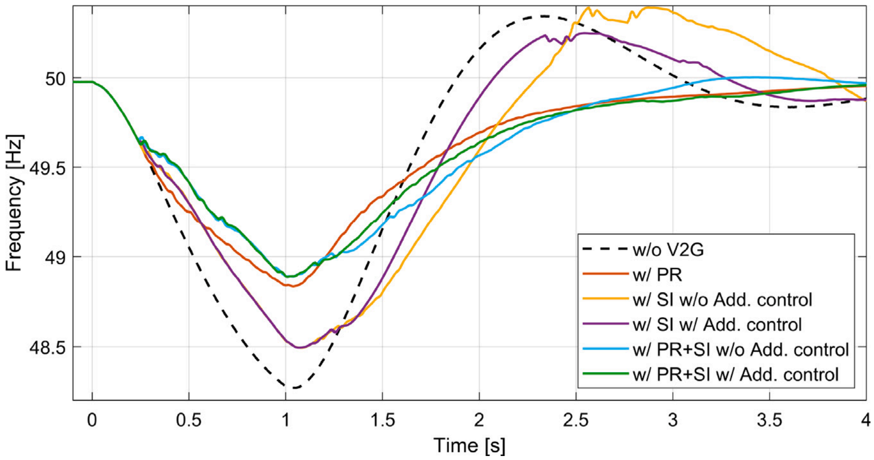

Fig. 12. Contribution to frequency regulation obtained by considering the different parts of the proposed FFR controller taken individually (20 V2G EVs connected).

Table 2
Frequency response indicators obtained by considering the different parts of the proposed FFR controller taken individually (20 V2G EVs connected).

	w/o V2G	w/ PR		w/ SI		w/ SI		w/ PR+SI		w/ PR+SI	
				w/o Add. control		w/ Add. control		w/o Add. control		w/ Add. control	
Nadir	48.27	48.84		48.49		48.49		48.89		48.89	
Max $f_n - f$	1.73	1.16	−33%	1.51	−13%	1.51	−13%	1.11	−36%	1.11	−36%
RoCoF	1.87	1.61	−14%	1.42	−24%	1.42	−24%	1.15	−39%	1.16	−38%
Overshoot	50.34	50.00		50.40		50.25		50.00		50.00	
Max $f - f_n$	0.34	0.00	−100%	0.39	+15%	0.25	−26%	0.00	−100%	0.00	−100%
Settling time	4.08	3.08	−25%	5.00	+23%	4.29	+5%	3.80	−7%	3.37	−17%

side effects of the SI control. As shown in Table 2, comparing the cases with and without the additional control (SI w/ and w/o Add. control), the frequency overshoot changed from a 14% increase to a 27% reduction compared to the base case, while the settling time (defined as the time to return within the ±100 mHz dead-band) was significantly reduced, going from +23% to +5%.

In conclusion, by adopting the proposed controller that incorporates both types of control (PR and SI), it is possible to achieve a frequency response that includes the positive aspects of both. This can be observed from the frequency response in Fig. 12 and through the quantitative analysis in Table 2.

5.2. Fast frequency response control of demand response in Lampedusa island

The tests assume that, at the time $t_0 = 0^-$, the total consumption of the island was 8.531 MW, including 600 kW of dispatchable load (400 household boilers). At that time, the total PV production was 1.5 MW while the power plant supplied the remaining 7.031 kW. At the instant $t_0 = 0^+$, a sudden clouding event caused a reduction from 100 to 10% of PV production in 1 s, leading to an under-frequency event.

As described in Section 2.2, the domestic loads are controlled through a smart plug able to connect or disconnect the load. Therefore, in this case, the DR is controlled through an automatic load shedding control scheme. The domestic loads are disconnected when a frequency deviation threshold is reached.

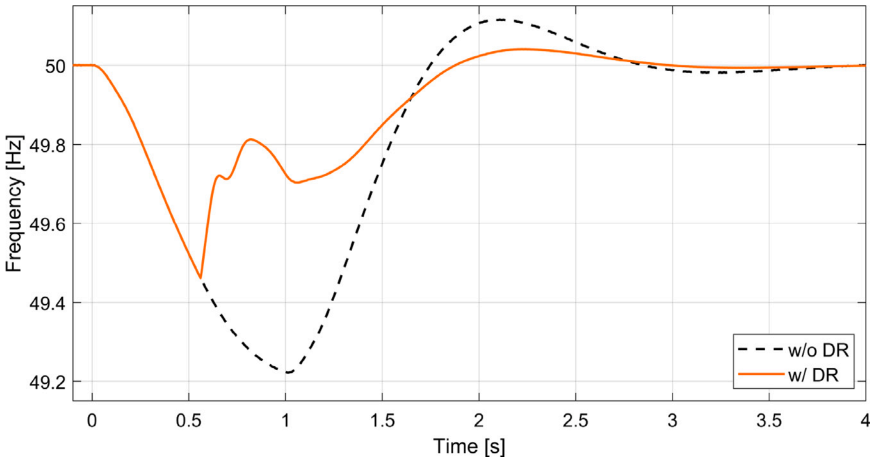

Fig. 13. Frequency behavior with and without DR.

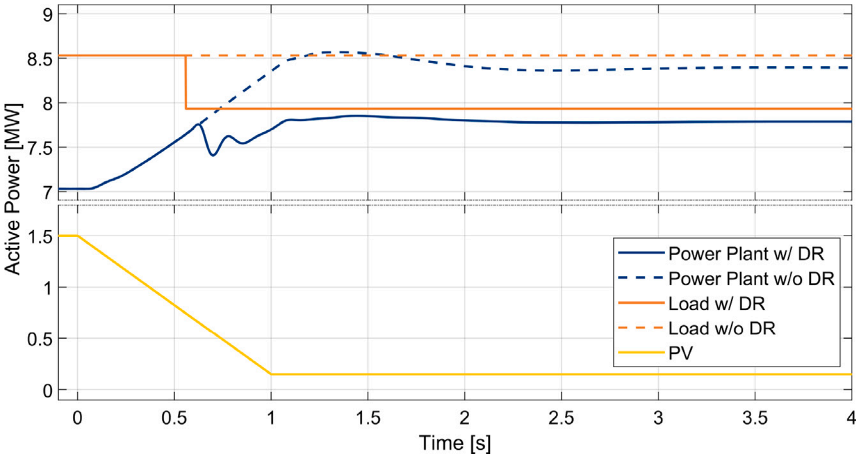

Fig. 14. Active power behaviors with and without DR.

Table 3
Frequency response indicators for varying numbers of controlled boilers for DR service.

	0 boilers	100 boilers		200 boilers		300 boilers		400 boilers		500 boilers		600 boilers		700 boilers		800 boilers	
Nadir	49.22	49.35		49.46		49.46		49.46		49.46		49.46		49.46		49.46	
Max $f_n - f$	0.78	0.65	−17%	0.54	−31%	0.54	−31%	0.54	−31%	0.54	−31%	0.54	−31%	0.54	−31%	0.54	−31%
RoCoF	0.93	0.90	−3%	0.85	−9%	0.85	−9%	0.85	−9%	0.85	−9%	0.85	−9%	0.85	−9%	0.85	−9%
Overshoot	50.12	50.09		50.08		50.06		50.04		50.03		50.08		50.21		50.34	
Max $f - f_n$	0.12	0.09	−25%	0.08	−33%	0.06	−50%	0.04	−67%	0.03	−75%	0.08	−33%	0.21	75%	0.34	183%
Settling time	2.28	1.63	−29%	1.62	−29%	1.62	−29%	1.61	−29%	1.58	−31%	1.50	−34%	0.99	−57%	1.17	−49%

The frequency trajectories obtained with and without the DR load shedding scheme are depicted in Fig. 13. The DR intervention threshold, set at 49.5 Hz, was reached after approximately 0.52 s, whereas the interruptible loads were physically disconnected few cycles after that the triggering signal was sent to the smart load controller.

As observed in the figure, the DR allowed the frequency to stay quite above the chosen limit of 49.46 Hz, in contrast to the base case (no DR) where a nadir of 49.22 Hz was reached. Furthermore, the DR helped to reduce frequency oscillations during the transient and the overshoot, with a 67% reduction (approximately from a peak of 50.12 Hz to 50.04 Hz).

The active power trajectories experienced during the transient are shown in Fig. 14. It can be observed how the intervention of DR reduced the operating reserve that the generation plant of the island has to provide to cope with this kind of event. This results in a reduction of the number of diesel-generating units that need to be switched on during operation just to provide an operating reserve, with consequent fuel savings and emissions reduction.

The PHIL test was carried out considering a varying number of controlled boilers, in order to show how the amount of enabled DR resources affects system response. Fig. 15 gathers the trajectories obtained considering a number of boilers varying from 0 (no DR) up to 800. Table 3 shows the main transient response performance indices. The DR service provided a significant improvement in frequency dynamics even with a small number of enabled boilers. With only 100 boilers (about 15 kW) it was possible to reduce the frequency excursion by 17% and the RoCoF by 3%, along with a significant reduction in settling time (−29%) and overshoot (−25%). The best result was achieved with 500 enabled boilers (750 kW), obtaining a 31% reduction in frequency excursion and a 9% reduction in RoCoF, as well as a 75% reduction in overshoot and a 31% reduction in settling time. It can be observed that an excessive number of enabled resources (from 600 boilers onwards) leads to an over-frequency, which in some cases can result in a frequency behavior worse than that caused by the contingency occurring on the grid.

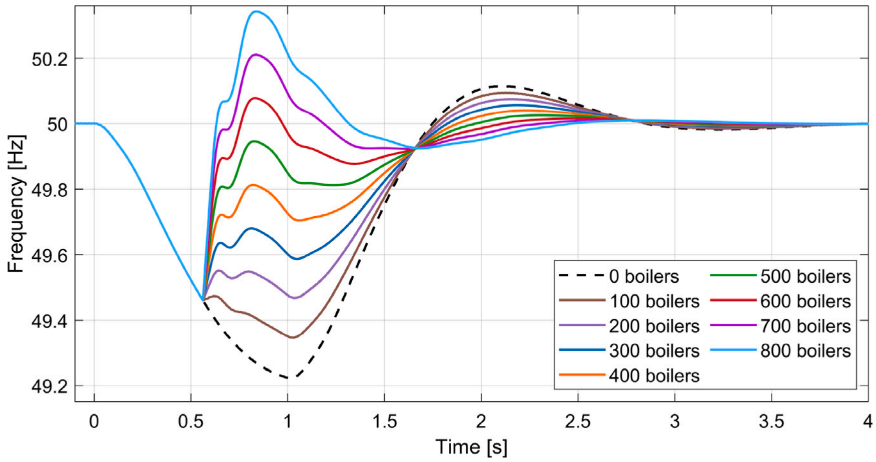

Fig. 15. Frequency behavior for different numbers of controlled boilers for DR service.

From these results, it can be concluded that the optimal number of boilers to enable for providing the DR service on the island under study is about half the power produced by non-programmable RES on the island. Indeed, in this case study, a reduction of 1.35 MW in 1 s was assumed, and the best result was obtained by disconnecting 0.75 MW of load.

6. Overall architecture for PHIL environment integration with the Blorin network

To test the effectiveness of the BLORIN network for FFR service tracking and remuneration, the PHIL simulation setup described in the previous section was interfaced with the blockchain-based BLORIN network. In this way, it was possible to co-simulate, as realistically as possible, the entire control and measurement chain used to enable FFR in the islands of Favignana and Lampedusa. The real-time response of the power hardware equipment, used to emulate the V2G charging stations and home users, has been sent from Bari to Palermo through a connection established between the two RTSs at LabZERO and SMGLab, respectively. The connection between the RTSs makes use of a dedicated VPN tunnel, with an *IPsec* key to ensure security.

This procedure has already been tested and validated by the author in [55].

Fig. 16 shows the general architecture developed for connecting the PHIL setup in Bari with the BLORIN network. No electrical model has been implemented within the SMGLab RTS, which just received the emulated charging stations or home users' data and forwarded it to the Blorin network. Specifically, in addition to the identification data of the emulated users, data on the energy committed during FFR events for each user are sent to the blockchain. These data are processed by the SCs running on the dedicated channel (Fig. 1) who evaluate users' remuneration. Although this setup does not constitute a remote co-simulation *per se*, it allows to appreciate the advantages of geographically distributed real-time simulation since the entire complex cyber–physical system was emulated without the need of exchanging relevant pieces of hardware or software, nor specific technical competences [56]. LabZERO devices were connected to the BLORIN network even without the need to install a blockchain node in Bari.

The following Table 4 shows the remuneration of each user for the energy contribution provided during the case studies presented in Section 5 evaluated through the SC running on the BLORIN platform implementing the same remuneration method proposed by *Terna S.p.A.* for Fast Reserve.

The table is divided into two parts: the first shows the input data of the SCs, while the second shows the results of the calculations performed. The input data required for the calculation of user remuneration are the price of energy relative to the DAM at the time when the event occurs and the energy contribution provided by EVs or home users during the FFR event.

Table 4
User remuneration for FFR event on a summer day.

SC input data	
Coefficient	Price [€/MWh]
$P_{DAM,Z}(h)$	126.67
Energy contribution for FFR event	
V2G [Wh/vehicle] 1.969	DR [Wh/user] 3.508
SC Remuneration evaluation for FFR event	
V2G [€/vehicle] 0.0017 - for up event 0.00077 - for down event	DR [€/user] 0.00027 - for down event
V2G [token/vehicle] 0.26 - for up event 0.092 - for down event	DR [token/user] 0.134 - for down event

The $P_{DAM,Z}(h)$ is the energy price on the DAM in Sicily referred to 12/07/2023 at 10:00 a.m., the date and time when the events described in Section 5 were assumed. Whereas, the energy contributions provided by EVs and home users are those emulated through PHIL in the scenarios described in Section 5 and sent to the Blorin network through the architecture shown in Fig. 16. The second part of Table 4 shows the calculation performed by the SCs.

In the V2G case, both UP and DOWN events were considered, while for the DR case, only the DOWN event was considered.

As can be seen from Table 4, the contribution in energy provided during the FFR is very small; this is due to the short duration of the transient (about 5 s). This result is positive because it means that participation in regulation does not negatively affect vehicle charging and residential users' habits. However, because of the small contribution in energy, there is also a small contribution in remuneration. Therefore, in the BLORIN network to incentivize users to participate in these events, a multiplier coefficient of 120 for EVs and 500 for home users was considered for token calculation. Thus for the simulated event, each EV would earn 0.26 tokens for the UP event and 0.09 tokens for the DOWN event, while each home user would earn 0.134 tokens.

As can be seen from the results obtained in terms of individual user remuneration, the method used does not provide large profits. However, this result was expected since the chosen method is based on the quantity of energy provided during regulation. To better incentivize users to provide this service, it would be necessary to develop an innovative tariff scheme that also takes into account the contribution made in terms of synthetic inertia. This aspect is not analyzed in this

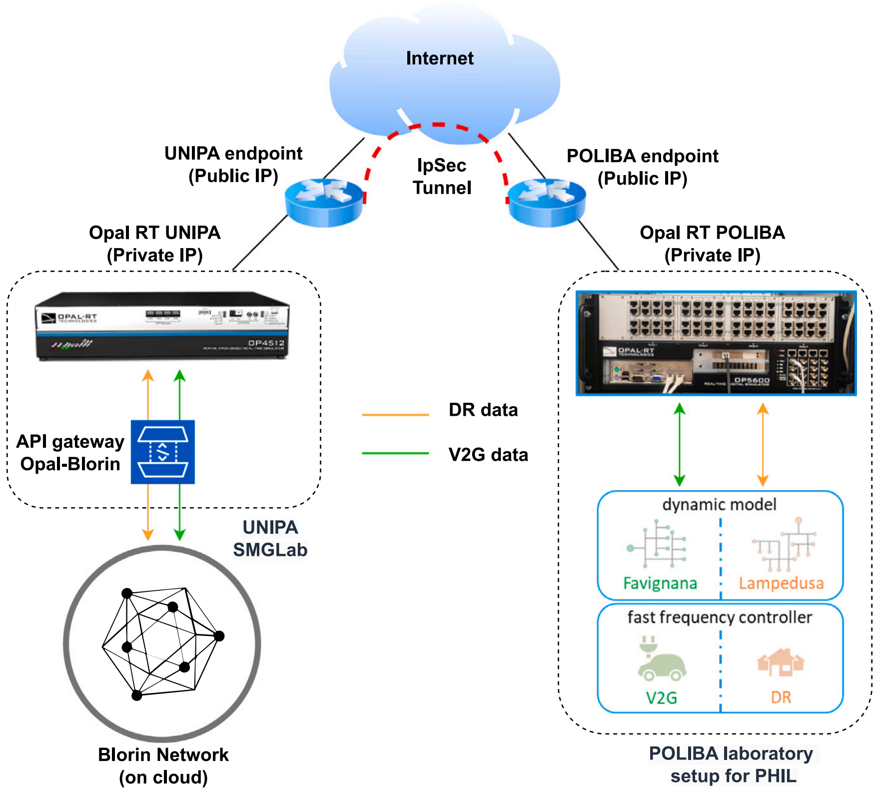

Fig. 16. PHIL setup integration with the BLORIN network.

paper as the main purpose is to test the interconnection of the PHIL environment with a blockchain network, but it will be addressed in future developments.

7. Conclusion

This paper outlines part of the experimental activities carried out during the BLORIN research project, which focused on solving the challenges introduced by the increasing penetration of renewables in isolated power systems, particularly those powered by a diesel power plant, such as in small islands. The main problems identified include the need for stability and rapid frequency control due to the unpredictable nature of renewable generation. To this end, methodologies for FFR were proposed during BLORIN project activities, using V2G or DR programs. Unfortunately, due to the limited number of flexible resources physically available to participate in the tests, their dynamic behavior was emulated in a PHIL environment using the equipment installed at the LabZERO laboratory of Bari Polytechnic University. The activities described demonstrate a holistic approach to addressing the challenges of integrating renewable sources into isolated energy systems, with a focus on testing conducted using advanced simulation techniques such as PHIL and a blockchain-based platform.

Results obtained through PHIL emulations showed that in the case of providing FFR through V2G, the contribution of 20 EVs allows a reduction of nearly 36% of the maximum frequency excursion caused by the sudden reduction of 300 kW of PV generation. Increasing the number of EVs results in an improvement of the overall transient response. However, with a number of 30 or more EVs, the frequency pattern starts to show poorly damped oscillatory behavior due to the delays introduced by communication and control. Despite the oscillations, the system remains stable due to the additional SI control described in Section 4.1.

Moreover, tests conducted using different types of V2G FFR controllers have shown how the proposed control scheme includes all the advantages of the classical primary regulation and synthetic inertia control laws in terms of system stability and frequency response metrics. While in the case of FFR provision through DR, the instantaneous load reduction sustained by 400 domestic users (600 kW) following the sudden reduction of 1.35 MW of PV energy allowed the frequency to remain quite above the chosen limit of 49.5 Hz, in contrast to the base case (without DR) where a nadir of 49.22 Hz was reached. In addition, DR helped reduce frequency oscillations during transient and overshoot, with a reduction of 67%.

By varying the number of DR-enabled users, an indication of the optimal number of users to be enabled to provide this service was obtained, approximately equal to half of the power produced by the non-programmable power plants on the island. The results obtained in both tests, underlined the importance of a correct quantification of the amount of FFR control resources. This is clearly a function that can be developed at centralized level so that only the needed resources are enabled, for example through real-time smart contracts which can be easily managed by the blockchain platform.

The use of V2G and DR to provide FFR allows for a reduction in the operating reserve that the island's generation plant must provide to meet the variability of renewable sources. This results in a reduction in the number of diesel-generating units that must be turned on during operation just to provide an operating reserve, resulting in fuel savings and reduced emissions. Finally, connecting the two laboratories has improved the realism and completeness of the experimental setup by enabling the connection of the PHIL test facility to the BLORIN network for a realistic assessment of tracking and rewarding users for their contribution.

In future works, more detailed studies will be carried out regarding:

1. the centralized coordination of distributed resources throughout the grid, based on real-time measurements;
2. the development of innovative tariff schemes that also consider the contribution of users in terms of synthetic inertia;

3. the further development of existing regulations and their possible integration to include EVs and DR in power system ancillary services;
4. the testing of the availability and integration of other technologies, such as hydrogen wind power.

CRediT authorship contribution statement

Giuseppe Sciumè: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Cosimo Iurlaro:** Writing – original draft, Methodology, Data curation, Conceptualization. **Sergio Bruno:** Writing – review & editing, Validation, Methodology, Conceptualization. **Rossano Musca:** Supervision. **Pierluigi Gallo:** Supervision. **Gaetano Zizzo:** Validation, Supervision. **Eleonora Riva Sanseverino:** Writing – review & editing, Validation, Supervision. **Massimo La Scala:** Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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