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Development and Initial Testing of a Virtual Laboratory for the Build-up and Testing of Microgrid Management Algorithms

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Abstract. In a bid of facilitating the increasing penetration of intermittent and random renewable energies, microgrids along with their management algorithms are becoming crucial assets. To prove their effectiveness, these algorithms need to be tested in real environments and/or laboratories, which can be very difficult in many cases, especially at the initial development stages. To solve this issue, this article proposes the use of a laboratory digital twin, i.e., a virtual laboratory with a behaviour that is similar to that of real installations, aimed at facilitating the development, testing and debugging of microgrids management algorithms. The proposed solution is demonstrated to be safe and complete when it comes to test these algorithms.

Key words. Microgrids, laboratory, digital twin, smart grids, communications.

1. Introduction

According to the International Renewable Energy Agency (IRENA), a microgrid can act as a platform, not only that facilitates the integration of variable Distributed Energy Resources (DERs) in a sustainable, price-competitive and reliable manner, but also as a resource that can provide key services to the main grid **[1]**. Due to the intermittency and stochasticity of renewable energy generation and demand, maintaining grid balance is regarded to as one of the major challenges. In this context, Smart Grid technologies like Energy Storage Systems (ESS), smart control infrastructure and algorithms for energy management systems are expected to play an essential role in the power systems, **[2]**. Moreover, according to the European Technology Platform of Smart Grids, this topic is seen as one of the main Priority Project Concepts of ETIP SNET's R&D implementation plan 2022-2025 **[3]**. Further into detail, some of the complex issues that arise when introducing DER in the existing power grids are efficient control and scheduling algorithm development, as well as designing secure, scalable and standardized data acquisition and communication technologies **[4]**.

It becomes crucial for the electric system of the future to develop microgrids management algorithms. The control system of a microgrid must ensure a secure and stable operation and optimize it from an economical point of view in both islanded and grid-connected modes.

Before transferring a management algorithm to a real microgrid, preliminary adjustments and testing are normally made in a laboratory microgrid. Two standards can be considered at this stage: IEEE 2030.7 related to the specification of microgrid control systems, **[5]**, and IEEE 2030.8 for the testing of microgrid controllers, **[6]**.

By means of the analysed literature, it has been identified that there is little detailed information on virtual microgrid design and implementation, as well as on the technology and methods needed for such laboratory development. Three main kind of virtual microgrid-related publications can be distinguished: 1) publications focused on specific areas/components of the microgrid, 2) publications focused on high-level description of the microgrid implementation and 3) publications focused on independent virtual microgrids (no connected to other microgrids). Among the first ones, **[7]** describes briefly the implementation of a wind energy only virtual microgrid. As to the second ones, in **[8]** a multi-microgrid laboratory is presented with a detailed component analysis but with a brief description of their implementation. Lastly, **[9]** describes a virtual microgrid laboratory for educational purposes. Hence, further detail on individual component and overall system design and implementation is needed for a wider scale deployment of networked virtual microgrid laboratories.

Laboratory microgrids have their own drawbacks and limitations, and it is not always possible to have the adequate DER units to replicate the real-world conditions. To mitigate these problems, this paper proposes the creation and use of a virtual laboratory (see Fig. 1). Some examples of how to interconnect laboratories to take advantage of the different equipment and simulation environments can be found in **[10]** where a Simulation Message Bus (SMB) is used for implementing the interconnection. An alternative approach based on the use of a real-time database with publish-subscribe communication capabilities is used in **[11]** and **[12]**. The work presented in this paper provides additional capabilities such as the possibility to store the data exchanged between laboratories in time series and relational databases, the possibility to use REST API-based communications and dashboard and alerting applications. Indeed, these functionalities provide more flexibility for communicating laboratories as well as added value services (data storage, visualization, etc.). Section 2 presents the general idea of the virtual lab to test different microgrids management algorithms and Section 3 presents the initial testing framework developed in the ENERISLA Project.

2. Virtual lab description

In the ENERISLA Project, a virtual test laboratory for microgrid management algorithms is currently being developed. In this way, different technical partners are free to develop their own tools or modules and communicate and interact with each other, thanks to a "Communications Services Module". Through this module, different other modules run simultaneously in different locations.

The idea is illustrated in Fig. 1. All individual modules can be run by using real data acquired in real-time from existing facilities, or by emulated data created via simulation. Then, the final objective is to test and coordinate all different modules belonging to different developers.

A. Communications Services Module

One of the main contributions of this system is that it implements a decentralized control approach, as each module is fairly autonomous and complex. However, a common set of communication services is required, in order to enable some higher-level features that depend on the interaction between multiple modules. For example, real-time control processes need to react based on the global system state. These communication services have the following requirements:

- Long-term storage of heterogeneous datasets (e.g., time series data, user credentials, transient alarms).
- Public interfaces based on well-known application-layer protocols that allow for the implementation of multiple communication patterns (e.g., publish-subscribe, request-response, push messaging).
- Advanced visualisation tools that can be leveraged by the end users to easily create bespoke views of the state of the system.
- A scalable system to implement ETL (Extract, Transform, Load) jobs with reasonable latency constraints that can be utilised to extract value from the combination of the datasets of each module.

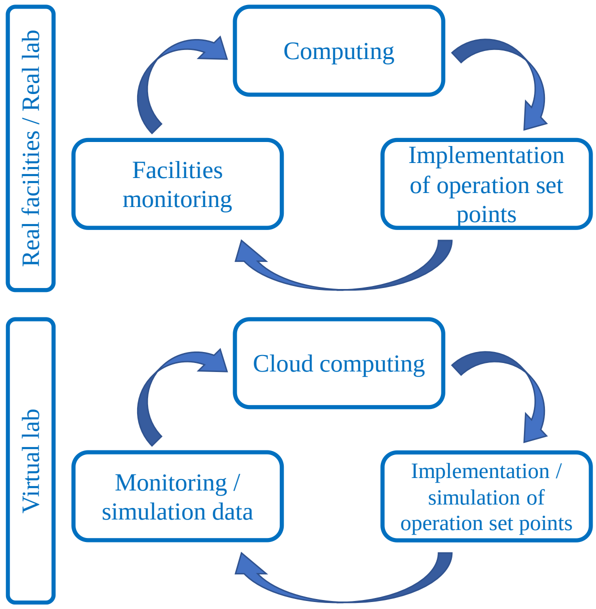


Fig. 1. Real facilities or real lab tests versus virtual lab proposal tests.

Fig. 2 shows the proposed architecture diagram for the communication services. The storage layer consists of a combination of data recordings suited for different scenarios: a time series database for time series data, a database for relational entities and an in-memory cache for volatile data with low latency requirements. Then, a collection of HTTP services is connected to the storage layer, whose design is based on the microservices architectural approach. These services, in turn, implement an ad-hoc business logic, e.g., an API to request long-running processing jobs and retrieve results. An HTTP API gateway serves as the public entry point for the HTTP services, providing centralized features such as rate limiting and authentication. A message broker is also included to enable messaging patterns that are not a good fit for the HTTP protocol (e.g., publish-subscribe). Finally, there is a dashboard and an alerting web application that provides an easy-to-use interface for end users.

3. Initial testing framework

This proposed virtual laboratory is currently being developed and will be tested by four different entities, so that each of them is free to develop any independent microgrid management algorithm or module, which will be subsequently coordinated with the remaining ones to ensure its correct operation prior to the implementation in a real electric grid. Based on this idea and the Communications Module described in the previous section, the following four modules will be tested, in order to verify the correct operation of the proposed virtual lab.

The connection between the four modules is shown in Fig. 3.

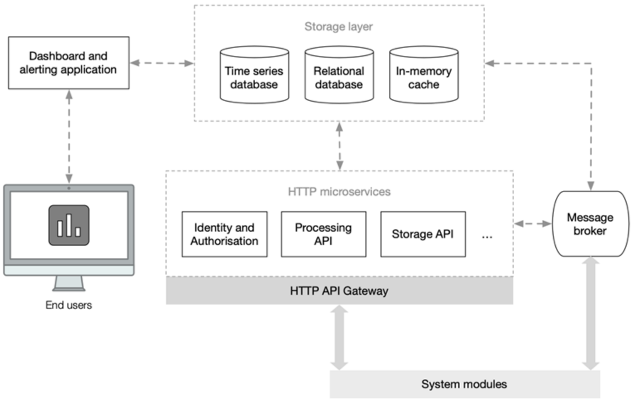


Fig. 2. Communication services module diagram.

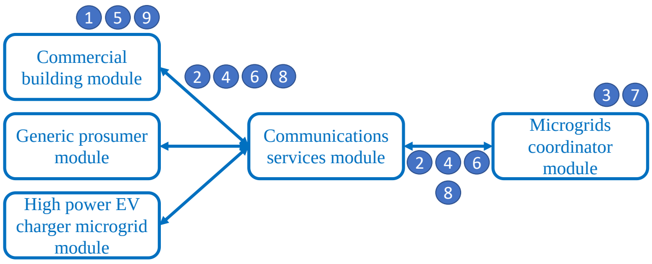


Fig. 3. Simulation framework working scheme.

A. *Commercial Building Module*

The prosumer management module for the tertiary sector is aimed at calculating the optimal economic operation of a generic commercial consumer, in both connected and islanded mode, by using its flexible or manageable resources, such as EV charging facilities, HVAC, electrical energy storage and renewable generation assets. This module is being conceived for using real data from an office building. This module works in two stages: in the first stage, the electrical consumption of thermal loads (HVAC) is modelled using neural networks with their consumption being optimised using genetic algorithms; in the second stage, an integer linear problem is formulated to be solved using the GUROBI solver, in order to optimise the operation of the rest of the installation's flexible resources.

B. *Generic Prosumer Module*

This generic prosumer management module has been implemented through two sub-modules:

1. Prosumer aggregation sub-module for the optimal generation of flexibility offered by an aggregator managing the flexibility of small and medium scale DER units. The objective of the sub-module is to create flexibility bids (upwards and downwards volumes with prices) to solve potential power over-flows through the network lines and transformers as well as potential voltage limit violations. The sub-module implements flexibility models for the following DER units: heat pumps, batteries, and photovoltaic installations. These flexibility models incorporate the technical characteristics of the DER units, as well as the end user preferences and limitations. The bidding strategy is implemented by means of an optimization model (MILP), whose objective is to maximize the incomes from participating in the potential flexibility markets.
2. Control sub-module is in charge of delivering the set points to the managed DER units in real-time, in order to comply with the market agreements. The operation component is implemented by means of a Model Predictive Control approach that considers the actual status and behaviour of the DER units as well as the flexibility to be deployed in a certain time horizon.

C. *High-Power EV Charger Microgrid Module*

This module aims to manage the power flows of a fast and ultra-fast charging point for electric vehicles equipped with distributed storage and solar PV generation. Therefore, the aim of this module is to manage a charging point in a versatile and modular way, taking into account the possibility of supplying an ultrafast charge or multiple fast charges, alternatively, and the eventual integration of a distributed generation point (photovoltaic plant) serving the same charging station. Under this scenario it is assumed that this management module can virtually operate from the Energy Management System of the installation. The main functionalities of the module are indicated:

- Peak shaving function (main function): consists of discharging the battery to meet a stochastic vehicle charging demand while not exceeding the Point of Common Coupling (PCC) power capacity. Therefore, the battery would back grid power up and would avoid/postpone PCC capacity upgrade. While not providing the service it would be charged either from the grid or the local PV generation.
- Optimised: Battery charging/discharging can be managed on the basis of a series of additional criteria based on the specifications of the cell given by the manufacturer, but this requires predictions of the use of the charging points.
  - Optimal sizing of the storage system according to parameters like stochastic EV charging profiles, cell parameters and the PCC capacity.
  - Optimisation of PV self-consumption in case there is an associated PV installation prioritising EV charging demand and, in such absence, battery charging.
- Advanced: Provision of flexibility services to the local grid/microgrid, in periods where there is no demand for electric vehicles, i.e. the battery is available to provide services to the grid as congestion management or node voltage regulation to the local grid.

D. *Microgrids Coordinator Module*

The microgrid Coordinator Module consists of a set of algorithms that, based on the description of the grid and forecasts of its use provided by the other modules, anticipates problems (congestion and/or voltages outside the norm, etc.) and proposes solutions based on the management possibilities of the available distributed resources. The main functionalities of the module are:

- Calculation of the future state of the network and early detection of problems (congestions and/or voltages outside the norm, etc.). This detection involves locating the element experiencing the problem (transformer, line, or network node) and its severity. This last classifies the network status according to a colour code or traffic light:

  - Calculation of the network status over a 24-hour horizon in 15-minute steps.
  - Updating or recalculation every 15 minutes ("sliding" horizon)
  - Classification of future network states according to a "traffic light":
    - Green, all nodes and buses operate between standard limits
    - Yellow, situation close to exceeding the system limits (component limits or standards limits)
    - Red, system limits are exceeded

- Choice of the optimal solution to solve this problem. Based on the management possibilities of the elements connected to the network, this module generates the operating instructions for these devices to solve or at least reduce the expected problem.
- Communication with consumers, prosumers and generators connected to the grid that the module manages in order to know their possibilities to provide flexibility and activate them to support in the operation of the grid.

E. Simulation framework

The "Commercial Building Module", the "Generic Prosumer Module" and the "High-Power EV Charger Microgrid Module" are implemented in different servers or locations, as if they were tools provided, or run by different Service Providers working for the real consumers connected to the same distribution network. This situation will be very likely in the future. In this way, it is possible to check how different algorithms, developed and executed by different actors, can work in a coordinated way to ensure the correct operation of each microgrid, as well as a correct coordination between them.

The "Microgrids Coordinator Module" runs on a different server, as if it was the tool that a DSO would use to monitor the operation of the network, detect problems before they occur and solve them by means of the flexibility that consumers can offer. The working scheme of the simulation, which is repeated every 15 minutes, is shown in Fig. 3.

The "Commercial Building Module", the "Generic Prosumer Module" and the "High-Power EV Charger Microgrid Module" calculate the optimal economic operation for the next 24h in 15-minute steps. The Commercial Building Module will use real data from an existing building, whilst the rest of the modules will use synthetic data. Usually, in a real microgrid, these operation setpoints would be applied to the manageable devices.

1. Local modules send working profiles (grid interaction profiles, the demand and/or generation added curves) to the "Microgrids Coordinator Module" through the "Communications Services Module".
2. "Microgrids Coordinator Module", which knows the complete description of the grid being managed, runs simulations and power flows using forecasted working profiles for all customers connected to the grid to detect any grid issue. If no problem is detected (green state), no extra action is taken. If a problem is foreseen (yellow or red state), the congestions of voltage deviations are spotted and the most suitable prosumers to provide flexibility are chosen.
3. "Microgrids Coordinator Module" asks through the "Communications Services Module" to the chosen prosumers for flexibility.
4. Chosen prosumers calculate their flexibility possibilities and cost for the needed moment.
5. Inquired prosumers send their flexibility possibilities to the "Microgrids Coordinator Module" through the "Communications Services Module".
6. The "Microgrids Coordinator Module" chooses the best technical and economical solution for the grid operation from among the communicated flexibility possibilities.
7. The "Microgrids Coordinator Module" sends through the "Communications Services Module" operation set points.
8. Local modules incorporate, if requested, operation set points to the next optimal operation calculation steps.

F. First tests

In order to check the correct performance of the proposed idea, several tests have been carried out, from independent and basic tests for each individual module, to communication and cooperative tests between modules. For the cooperative tests, a virtual low-voltage distribution grid has been created by changing part of the actual consumption data of the real grid for profiles generated by the developed and tested modules. The High-Power EV Charger Microgrid Module and the Commercial Building Module have created specific consumption profiles while the Generic Prosumer Module has created the rest of consumption patterns of the grid.

The High-Power EV Charger Microgrid Module considers as input data the EV demand, the battery specification cell data, PV forecast production performing simulation per minute for a day. The energy management acts as a peak shaving strategy, charging the battery (from the grid or/and PV) when there is no EV demand and discharging the battery when there are vehicles charging (from the grid or/and PV), preventing the maximum power consumed from the network from exceeding a certain limit, and thus contracting less power as illustrated in Fig. **4**. In the upper side of the figure, it can be seen the power exchanges of the EV charge station and SoC of the static batteries and in the lower side voltage and currents in the static storage system. The red line in the upper side of the figure represents energy demand from the grid, used for the cooperative tests.

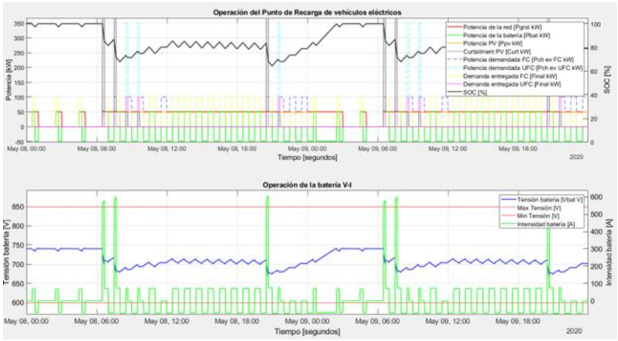


Fig. 4. Operation example of the High power EV charger microgrid module.

Different technologies, such as electric vehicles (EVs), photovoltaic systems (PVs), HVAC units, and battery energy storage systems (BESS), were allocated to a group of 160 residential users who also had installed dryers, washers, and dishwashers to respond to flexibility offers.

As starting point, the Optimization Module of the Generic Prosumer Module, described in section *B.1*, was used to generate the power generation and consumption baselines for all the technologies per end-user, considering the day ahead prices from OMIE (Operador del Mercado Ibérico de Energía in Spanish) and the time series of irradiance and temperature from a city in Spain for a sample day. An hourly sample period for a 24 h interval was used.

Fig. 5 shows the response of an end-user optimized according to day-ahead electricity prices but still fulfilling the end user comfort and needs.

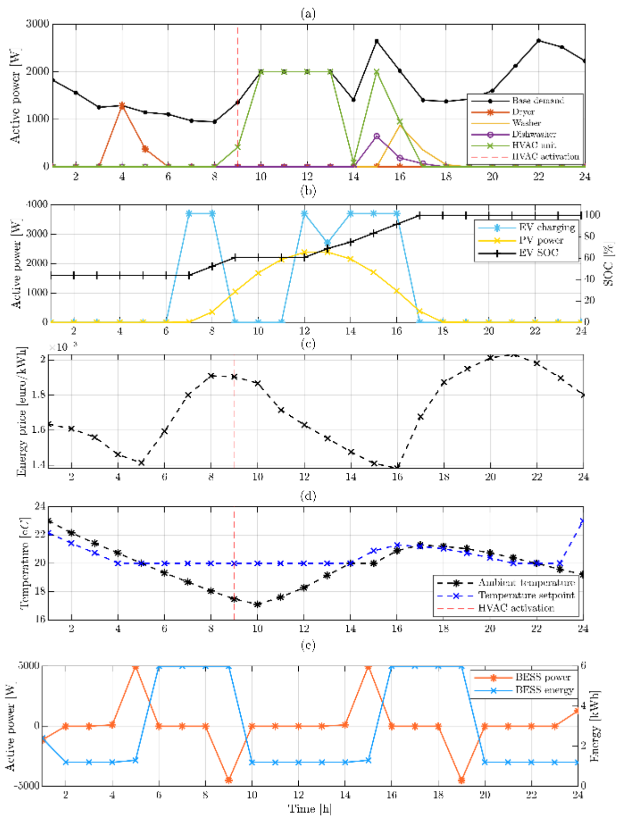
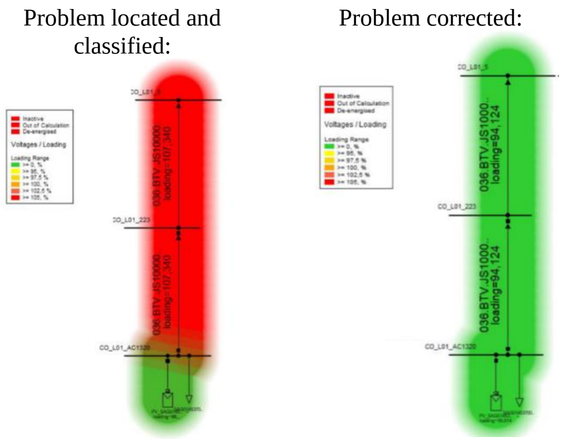


Fig. 5. Flexibility profiles for an end-user: (a) activation of HVAC and appliances, (b) EV charging and PV power available, (c) Energy prices to provide flexibility, (d) ambient and setpoints temperatures, and (e) BESS power and energy.

In Fig. 5(a), the activation of the dryer, washer, and dishwasher occurs during low-price hours. The HVAC unit was programmed to be activated at 9:00 h no matter the energy price if the ambient temperature was below 20ºC, as shown in Fig. 5(c) and (d). Once this temperature level is reached, the HVAC unit continues working until it gets to 23ºC, i.e., the comfort temperature. However, if the energy price becomes expensive, the unit is turned off. Fig. 5(b) shows that the initial charging of the EV is in a high-price period, but the following bulk charging ends with the lowest energy price. In Fig. 5(e), it can be observed that the BESS starts charging when the energy prices are low and discharging when these are high.

The objective of the "cooperative" tests is to evaluate the simulation framework described in section 3.E. For these tests, the Microgrids Coordinator Module receives as inputs the consumption/generation profiles (interaction with the grid in short) calculated by the other evaluated modules and runs power flows to detect problems. In the simulated case, a moment with congestion due to excess generation is detected and it is subsequently established that the commercial building is the most appropriate to reduce this problem. By using the process described in section 3.E, it is asked for flexibility possibilities and it responds with a flexibility profile. The process is closed when the Microgrids Coordinator Module "buys" a flexibility of this consumer to avoid problems. In the case studied, an excess generation is detected and is solved by means of the appropriate curtailment of the PV generator of the commercial prosumer, thus avoiding any problem in the network (Fig. 6).



Element	New set-point change (&)
SAG0145370047	+10%
PV_SAG0145370047	—15%

Fig. 6. Microgrids Coordinator Module solving a congestion generated by PV generation excess.

The final tests carried out are related to the "Communications Services Module". Independent tests have been carried out in the software engineering domain to ensure the correct exchange of information. In the cooperative tests, this module has also been tested. A series of experimental tests were conducted to demonstrate the capabilities of the virtual laboratory. The tests were based on a dataset containing time series data describing an instance of a real load data. In this case, the virtual lab was instrumental in enabling seamless sharing of information between nodes located in separate geographic locations. More specifically, the virtual laboratory enabled researchers to:

- Share information by adopting the publish-subscribe messaging model, which is especially adequate when multiple consumers need to access data as it is produced with minimal latency.
- Visualise information that is kept in a time series database for long-term storage. There is a service that automatically communicates with the messaging broker in order to interconnect both services, that is, the messaging broker acts as a data source while the time series database acts as a data sink. The dashboard application provides users with the ability to build ad-hoc visualisations using advanced Web components.
- Query the time series database API to retrieve and process historical information. For example, users can download datasets serialised in CSV format, which are automatically aggregated in the server depending on the requested resolution.

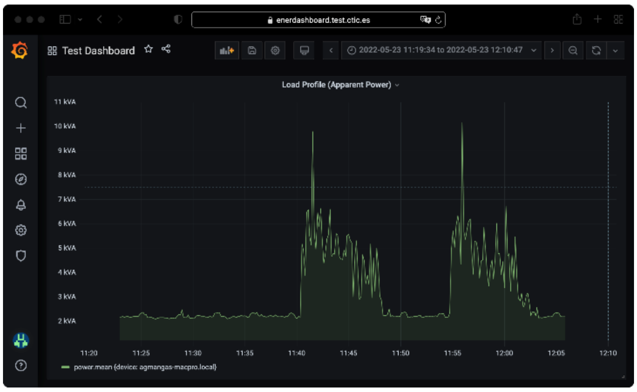


Fig. 7. Screen-shoot of the information uploaded to the platform along tests.

4.Conclusion

Due to the increasing penetration of intermittent and random renewable energies, microgrids management algorithms become crucial for the electric system of the future. These algorithms have to be tested in real environments, in real facilities, or as close to the real world as possible, laboratories. This is very difficult in many cases, especially in the initial stages of the development of these control systems. As a potential solution, this article proposes the use of a virtual laboratory, with a behaviour similar to that of real installations. With this objective in mind, a virtual laboratory for the development, testing and debugging of tools for the management of microgrids has been presented in this document. The proposed strategy is considered safe and efficient for the proposed objectives.

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