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Design of a Virtual Power Plant in the presence of microrenewables and electric vehicles in a microgrid concept for real-time simulation as part of a Remote Lab

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Abstract. In the upcoming years, an opportunity for a wide range of electricity management solutions arises, thus several researchers have focused their efforts on studying and analyzing various subjects related to the operation of microgrids, smart grids, Vehicle-to-Grid (V2G), responsive demand, among others. On the other side, especially at engineering courses, these topics are primarily covered from a theoretical standpoint only, without a complementary laboratory approach. To this end, this work considers the development of a small-scale prototype consisting of a set of hardware and software tools that enable the students, either in an undergraduate or postgraduate level, to have a better understanding of the operating principles of these concepts. In this context, various distributed energy resources, including a mini photovoltaic panel, a mini wind generator, a stationary battery, an electric vehicle model, as well as household loads, are collectively run by a central control unit in the form of a Virtual Power Plant. This paper presents the design and development of the hardware and software platform for simulating the operation of a Virtual Power Plant, which serves as the base for a Remote Lab for educational purposes.

Key words

Virtual Power Plant, Remote Lab, Vehicle-to-Grid.

1. Introduction

Over the last decades, significant research efforts have focused on energy sources other than coal, oil and natural gas, since these natural resources are expected to deplete in the foreseeable future. The energy crisis will remain unsolved, unless an efficient approach is used. Besides exploring new energy sources, the current energy consumption has to be well-managed in order to alleviate energy problems. Given that alternative methods for generating electricity have proved to be inefficient when the corresponding resources are subject to depletion, fundamentally the principal method is to manage the efficiency of energy usage. In this context, energy management can be an add-on feature of home automation [1].

Going a step further, many small-capacity distributed energy resources (DER), including generation, storage, or demand units, may be aggregated into one larger system that operates as a single unit [2]. The generators can use both renewable and non-renewable energy sources, while their total capacity can be comparable to a conventional power plant [3]. This concept is often referred to as Virtual Power Plant (VPP) and can be considered as a practical approach to manage these energy sources, which are aggregated mainly in distribution level [4] and are collectively run by a central control entity [5]. In other words, the heart of a VPP is an energy management system (EMS) which coordinates the power flows from the distributed generation installations, controllable loads and storage facilities [6]. It follows that a VPP offers energy supply capabilities within a large area [7], and can replace conventional power plants, while having higher efficiency and flexibility [3].

The objective of this work is the development of a VPP in the form of a small-scale fully-functional physical model for educational purposes in order to better communicate the concepts related to the Smart Grid operation, using renewable energy sources. The VPP is part of a Remote Lab that allows students to remotely configure and perform experiments in real-time conditions. The hardware part contains microrenewable energy sources, energy storage devices, a house with several components, such as lighting loads and various household appliances, as well as an electric car operating in a vehicle-to-grid (V2G) approach. The two main energy sources are solar and wind and they are able to provide with power both the house and the electric vehicle. On the other hand, the whole system is controlled using a software platform that allows for managing the aggregated energy resources.

2. Description of the system

This work involves the development of a prototype that includes a photovoltaic (PV) panel, a wind generator, a stationary battery, an electric vehicle (EV) model, as well as a number of electricity loads, all in small scale. In this context, we consider that the mini PV panel and the electricity loads are components of a Smart House with controllable household appliances. The EV is equipped with a battery pack that can be plugged in the electric system of the Smart House, which in this case can be considered a small-scale physical model of a microgrid. The latter in turn is aggregated with the mini wind generator and the stationary battery, forming a network of distributed energy resources, which are managed by a central control unit, namely the EMS of the VPP. It follows that a number of energy management options arises for both the microgrid (e.g. charge/discharge EV battery and import/export electricity from/to the main grid) and the VPP (e.g. optimal use of the aggregated resources).

The following subsections describe in detail the basic components of the system under study.

A. Smart House

For the purposes of this work, we have chosen to build a scale model of a typical house with 2 rooms (A), 1 WC (B), 1 dining room (C) and 1 standard kitchen (D), according to the dimensions shown in Fig. 1.

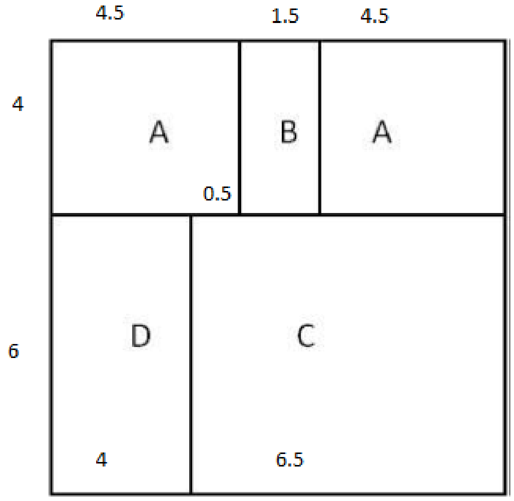

Fig. 1. Layout and dimensions of the physical model of the Smart House.

It is considered that each space of the real house is equipped with its individual components, as stated below [8]:

A) Each room has a surface of 18 m^2, heating and cooling loads from 3 to 720 W, as well as lighting and general loads between 5 and 225 W.

B) The WC has a surface of 6 m^2 with lighting and general loads between 0 and 75 W.

C) The dining room has a surface of 39 m^2, heating and cooling loads from 3 to 2000 W, as well as lighting and general loads between 5 and 625 W.

D) The kitchen has a surface of 24 m^2, lighting and general loads between 5 and 200 W, as well as a washing machine with 3300 W rated power.

Totally, the following loads are considered:

1) *Heating and cooling system*: 6 to 2720 W.
2) *Lighting and general loads*: between 15 and 1125 W.
3) *Remote controlled appliances*: 3300 W.

The electric system of the Smart House is modelled as a DC circuit with a scale factor 1:680, resulting to following assumptions for the scaled power consumption of the corresponding loads:

- *Heating and cooling system*: 13,24 mW - 5,06 W.
- *Lighting and general loads (A)*: 7,35 mW - 330,88 mW.
- *Lighting and general loads (B)*: 0 W - 110,29 mW.
- *Lighting and general loads (C)*: 7,35 mW - 919,12 mW.
- *Lighting and general loads (D)*: 7,35 mW - 294,12 mW.
- *Remote controlled appliances (washing machine)*: 4,85 W.

At this point, it is important to note that the heating and cooling loads installed at the rooms and the dining room operate synchronized in the form of a centralized heating and cooling system, while the washing machine can be controlled remotely in order to schedule its operation at the most beneficial instant during the day.

B. Electric Vehicle

Generally, electric cars are automobiles that use electrical energy to drive one or more electric motors, which are mechanically coupled to the wheels. In the context of this work, we consider an electric vehicle (EV), such as a plug-in hybrid electric vehicle (PHEV) or a battery electric vehicle (BEV), equipped with an onboard battery system that can be connected to an external electric power source, e.g. a power plug. We further assume that the electric vehicle operates under a V2G approach (Fig. 2) in order to optimize the energy consumption at the Smart House. The V2G concept is an approach that allows an electric car to be plugged in and communicate with the power grid to sell demand response services by either delivering electricity into the grid or by throttling its charging rate. Since most vehicles are parked for more than 95 percent of the time, their batteries could be used to let electricity flow from the car to the power lines and back [9], in our case to the Smart House.

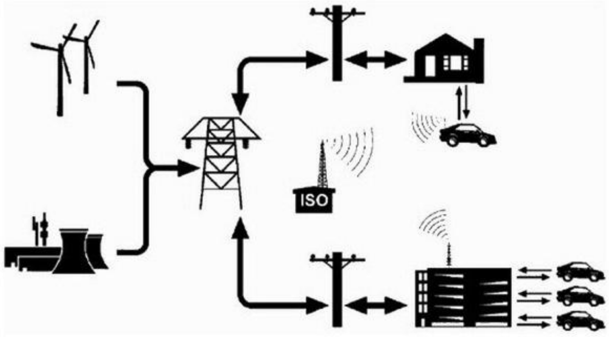

Fig. 2. The vehicle-to-grid (V2G) concept [9].

V2G vehicles are capable of providing power to help balance the electricity load demand by "filling the valleys", i.e. charging at night when demand is low, and "shaving the peaks", i.e. sending power back to the grid when demand is high. Moreover, they offer new ways to provide regulation services (keeping voltage and frequency stable) and spinning reserves (meet sudden demands for power), in which power must be delivered upon request within short periods of time, e.g. minutes or seconds [9]. Towards this direction, the electric vehicles in the not-so-distant future could buffer renewable power sources, such as wind power, and effectively stabilize their intermittency, for example, by storing excess energy produced during windy periods and providing it back to the grid during peak demand periods [10].

To simulate the operation of a real EV in small scale, a physical model is constructed, consisting of the chassis from a modelism car and an electric motor connected with a battery pack. The technical characteristics of the electric motor employed for the purposes of this work (Fig. 3) are detailed in Table I.

Fig. 3. Electric motor of the EV model (retrieved from [11]).

Table I. – Technical characteristic of the electric motor for the EV model (retrieved from [11])

Rated voltage	DC 12V
Rated current	50 mA
Rated torque	2,79 kg*cm
Rated speed	45 rpm
Shaft size	7*5 mm / 0,3”*0,2” (L*D)
Motor body diameter	32 mm / 1,3”
Mount hole diameter	3.4 mm / 0,13”
Total size (included pin)	49 x 54mm / 1,9”*2,1” (L*W)
Material	metal, electronic parts
Color	silver tone
Weight	102 g

The EV battery is connected to the electric system of the Smart House through wires, providing the required electrical connection that allows the EV to interact with the Smart House under the V2G approach and to supply extra power during times of peak demand. Table II shows the technical characteristics of the EV battery, which serves as a local electricity storage option when the EV is present at the Smart House.

Table II. – Technical characteristics of the battery for the EV model (retrieved from [12])

Nominal voltage	12V
Nominal capacity	0,8 Ah at 20 hours
Height	63 mm
Weight	0,35 kg
Lifespan	5 years
Recharge under storage (< 20 ºC)	Every 9 months
Between 20 and 30 ºC	Every 6 months
Between 30 and 40 ºC	Every 3 months

C. Microrenewables

To power the whole system in a green energy environment, two types of renewable energy are used, namely solar and wind energy. Taking into account that this work involves the implementation of a maquette, it follows that the devices used for generating electricity are in mini scale.

1) Solar energy

Solar photovoltaic (PV) cells convert sunlight energy into electricity through the photovoltaic effect. A single cell can only produce low DC voltage, however a group of PV cells can be connected in series and/or parallel to form a module, which is the building block of larger systems, such as PV panels and/or arrays. For the VPP application, a small monocrystalline silicon module capable of generating power of 10 W and output voltage of 12 V is mounted at the roof of the Smart House. Table III shows the technical specifications of the PV module and the accompanying charge controller (Fig. 4).

Table III. – Specification sheet of the PV module with charge controller (retrieved from [13])

Model number	SLP-005	Material	Monocrystalline silicon
Size	302*366*23 mm	Max. Power	10 W
Item	Mini mono PV panel	Power	10 W
Operating voltage	18 V	Cells	Monocrystalline silicon cell
Operating current	5.55 A	Warranty time	3 years
Application	Supply power for 12 V battery	Certificate	CE, TUL etc

Fig. 4. PV module with charge controller (retrieved from [13]).

1) *Wind energy*

Wind turbines use the wind flow to produce electricity through a rotor with blades that drives a generator and they are generally divided into two basic categories in terms of the orientation of their rotational axis, namely horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT). The former ones are more common implementations that typically have the rotor shaft and the generator mounted at the top of a tower and, because of their design, they need to be pointed into the wind direction using special equipment. On the contrary, the rotor shaft of a VAWT is mounted vertically, allowing effective operation under highly variable wind direction conditions, such as those in urban environments. To this end, a VAWT with 10 W nominal power and 12 V output voltage was chosen for the VPP lab application (Fig. 5). The detailed technical specifications of the mini wind turbine are presented in Table IV.

Fig. 5. Mini vertical axis wind turbine (retrieved from [14]).

Table IV. – Technical characteristics of the mini vertical axis wind turbine (retrieved from [14])

Nominal power	10 W
Wind power range	9-44 mph
Optimal wind speed	22 mph
Maximal wind speed	89 mph
Exit DC voltage	12 V
Turbine diameter	12”
Sheet length	12”
Turbine height	30 cm
Tower height	18 cm
Net weight	3 kg

D. *Electricity storage device*

Generally, the operation of the renewable generators considered in this work is subject to randomness, uncertainty caused by meteorological factors and intermittence due to diurnal and seasonal variation of solar radiation and wind [15]. On the other hand, the electricity consumption in a typical residence has a different pattern. In our application, we consider that the electricity demand follows an increasing trend and reaches its peak during the afternoon and evening hours, when most people return from their work and most household appliances are in use. To this end, the battery storage system illustrated in Fig. 6 is employed to balance the effects from the variation of electricity consumption and the intermittent power sources. Accordingly, the electricity storage device is expected to store excess energy and deliver it back to the system when the supply from the microrenewables is not sufficient to meet the load demand. The characteristics of the battery are presented in Table V.

Fig. 6. Battery storage system (retrieved from [16]).

Table V. – Technical characteristics of the battery storage system (retrieved from [16])

Nominal voltage		12V
Nominal capacity (10 hour rate)		70Ah
Type	Valve regulated gel battery	
Internal resistance	full charged battery 25 ºC	≤6.0mΩ
Self-discharge 25 ºC capacity	after 3 month storage	90%
	after 6 month storage	80%
	after 12 month storage	62%
Dimensions	length	260 mm
	width	169 mm
	total height	211 mm

E. *Measuring instruments*

In contrast to the traditional approach, where the DER units are not transparent to the system operators and other market players, the VPP concept is a means of enhancing the visibility and control of DER [17]. This implies that a number of sensors and/or smart meters provide the VPP with the required information regarding the operational status of each unit. For the purposes of the VPP physical model, typical multimeters are installed at the Smart

House, the EV and each power resource to measure electricity generation and consumption, while a temperature probe is used for monitoring the temperature at the rooms and the dining room of the Smart House.

F. Software platform

Given that the central idea of the VPP concept is to enhance the control over the aggregated energy resources, the core component of the VPP is an energy management system (EMS) that coordinates the power flows from the distributed generators, controllable loads and storage devices [6]. The control unit monitors the current status of the network and manages the aggregated resources through advanced ICT infrastructure in order to remotely dispatch and optimise their operation [6]. Accordingly, the operation of a VPP is primarily based on software systems [18].

In the context of our work, a software platform with feature-rich capabilities is under development, allowing a wide range of options for the energy management of the system under study. Along these lines, the students have the opportunity to experiment with a number of parameters, such as temperature and lighting settings at the Smart House, and monitor the response of the VPP components. To this end, a user interface is responsible for the display of real-time measurements as well as the parameterization of the system components.

3. Concluding remarks

This paper presents the theoretical framework and implementation issues for the development of a physical scale model of a VPP for educational purposes. Specifically, this work involves the use of different renewable energy sources, namely a small PV module and a mini wind turbine, as well as electricity storage devices in order to provide all the components of a Smart House with power. In this context, a plug-in EV equipped with a battery serves as a non-stationary electricity storage option, having the capability to provide its power when it is considered as parked and thus connected to the electric system of the house, while there is not sufficient power to supply the electricity demand. In addition, a software platform is responsible for controlling the power consumption of the house, the energy generated from the renewable energy sources and the electricity storage from the battery systems.

The prototype considered within the frame of this work simulates the operation and use of distributed energy resources from a centralized energy management system, which plays the role of a VPP. The small-scale physical model is considered as a part of a Remote Lab that aims to familiarize both undergraduate and postgraduate students with the working principles of a VPP, combining research, theory, and practice in energy systems courses.

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