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Design, architecture and implementation of a residential energy box management tool in a SmartGrid

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ABSTRACT

This paper presents the EB (energy box) concept in the context of the V2G (vehicle-to-grid) technology to address the energy management needs of a modern residence, considering that the available infrastructure includes micro-renewable energy sources in the form of solar and wind power, the electricity loads consist of "smart" and conventional household appliances, while the battery of an EV (electric vehicle) plays the role of local storage. The problem is formulated as a multi-objective DSP (dynamic stochastic programming) model in order to maximize comfort and lifestyle preferences and minimize cost. Combining the DSP model that controls the EB operation with a neural network based approach for simulating the thermal model of a building, a set of scenarios are examined to exemplify the applicability of the proposed energy management tool. The EB is capable of working under real-time tariff and placing bids in electricity markets both as a stand-alone option and integrated in a SmartGrid paradigm, where a number of EBs are managed by an aggregator. The results obtained for the Portuguese tertiary electricity market indicate that this approach has the potential to compete as an ancillary service and sustain business with benefits for both the microgrid and residence occupants.

1. Introduction

The shift towards small scale distributed generation of electricity is indicative of the major changes that are taking place on energy generation, distribution and storage technologies [1]. Over the years, considerable research efforts have focused on exploring technically feasible and practical solutions for integrating the decentralized generation units into the main grid [2–6]. Prominent among them is the microgrid concept, with multiple benefits to customers, electricity utilities and society in general, including economic advantages, reduced environmental impact, as well as enhanced reliability and quality of energy supply [7–10].

The idea of a consumer, and potentially micro-producer, having an energy management device, the so-called EB (energy box), installed at his residence or small business and working under a real-time tariff was proposed in Ref. [11]. In the context of the present work, this concept is extended to the case of deploying multiple EBs integrated in a microgrid (Fig. 1), having local renewable energy sources, electricity loads and EVs (electric vehicles), while being managed by an aggregator, which exchanges information with the multiple EBs to guarantee the grid's frequency stability. Under these conditions, this platform can be considered a SmartGrid with the capability of placing bids to electricity markets. The structural characteristics of the available markets are closely related to the purpose that the production of this commodity serves, having obviously different control regimes, prices, power dispatched and contract terms.

The distinctive characteristics of the proposed EB implementation as a residential energy management tool include the consideration of the EV battery as a local storage option coupled with an improved discretization of the battery charge profile, and

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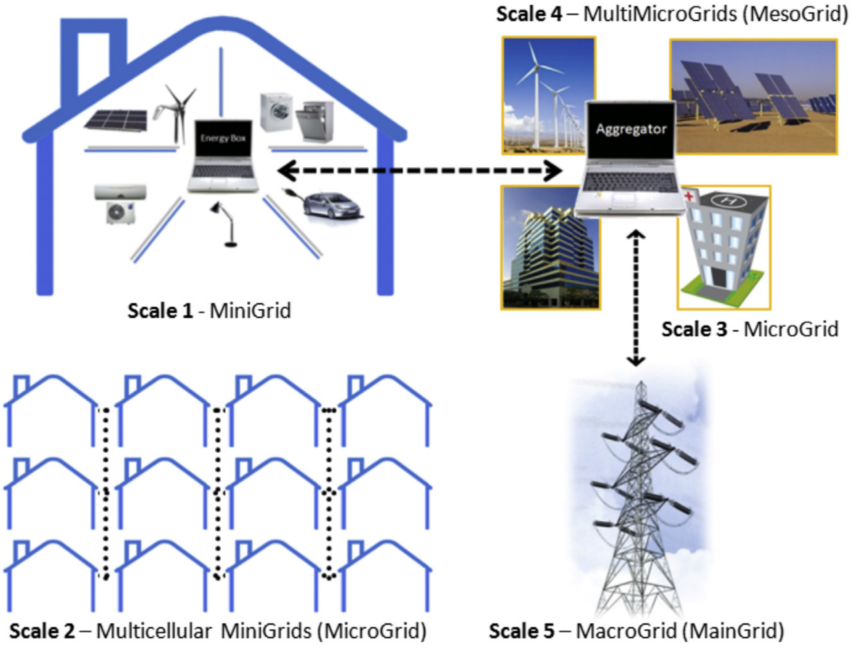

Fig. 1. Energy box paradigm (Scale 1) as a part of the SmartGrid MSP (MultiScale Programming) architecture.

its capability to participate in electricity markets. To make the optimal set of decisions for the energy management of the residence, such as charge or discharge the EV battery, control the heating/cooling system to cover the thermal needs, and even buy and/or sell electricity from/to the grid, the EB exchanges information with the aggregator and uses forecasted values of several parameters within a time window of 24 h, considering that it operates both in the peak power market and as an ancillary service. The use of the V2G (vehicle-to-grid) technology as an ancillary service is introduced and discussed by several researchers [12–14], and in this direction, the EB approach acts as a merger between V2G capacity and DR (demand response) to present a competitive solution. To this end, this work examines a number of scenarios for a typical residence in Portugal that is controlled by an EB working under a real-time tariff, and considers the case of a number of EBs integrated in a microgrid in order to supply power and compete as an ancillary service in the Portuguese tertiary electricity market.

The rest of the paper is structured as follows. Section 2 provides the general outline and theoretical framework of the EB operation. Section 3 introduces the main mathematical model of the EB and the auxiliary tool that simulates the thermal model of the building. Section 4 analyzes the inputs and algorithms for the implementation of the EB, while Section 5 describes its operation as an ancillary service. The subsequent section presents the results from a number of scenarios and cases using the EB for the energy management at residential level and as an ancillary service in the Portuguese tertiary electricity market respectively. Section 7 discusses the limitations of the proposed approach and the last section underlines the main conclusions.

2. Problem context

2.1. Infrastructure at the residence

In the frame of this work, it is considered that the physical infrastructure under the control of the proposed EB management tool includes the following components:

(i) A *micro-wind turbine* installed on a tower annex to the residence in order to avoid the potential noise and structural problems of roof mounting [15]. In this paper, two cases are examined for the power output of the turbine, having a rotor diameter of 3 m and 5 m respectively. It is further assumed that the micro-wind turbine is equipped with a small battery bank to smooth the voltage variation and prevent damaging the inverter.

(ii) A *PV (photovoltaic) panel* placed on the roof of the residence. Similarly, two cases are examined for the PV panel, with corresponding rated power output of 0.5 kW and 1 kW under a SSI (standard solar irradiation) of 1000 W/m^2.

(iii) A *plug-in EV*, e.g. a PHEV (plug-in hybrid electric vehicle) or a BEV (battery electric vehicle), similar to the Mitsubishi *i-Miev* [16], equipped with a 20 kWh battery pack providing a range of 160 km under an approximate power consumption of 125 Wh/km [17]. Given that the battery charging time depends on the available power and voltage, a slow charging option at 200 V a.c. (alternating current) is also assumed, requiring approximately 8 h (to be conservative).

(iv) A *smart meter*, that is an advanced metering device capable of recording, among other parameters, the consumption on an hourly or more frequent basis and transmitting the daily measurements via a communication network to a central collection point [18], which in this case is the EB.

(v) A *dish washing machine* as a typical example of a smart appliance that can be controlled remotely by using the EB. In this case, the instructions needed are given by the occupant of the residence and the EB schedules the operation of the device in the most beneficial instant (within a predefined time frame). It is considered that the corresponding load is 2 kW and, for simplicity, the time for a complete wash is 1 h.

(vi) An *AC (air conditioning) system*, which is also remotely controlled by the EB. The latter one determines the temperature to set for each decision point and uses the residential thermal model (refer to Subsection 3.3) to compute the power required for the AC. Without loss of generality, it is

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