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Low complexity energy management strategy for grid profile smoothing of a residential grid-connected microgrid using generation and demand forecasting

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HIGHLIGHTS

- Explicit power profile control scheme for a grid-connected residential microgrid.
- Concurrent power profile and battery SOC fuzzy-based control.
- Comparison of the suggested approach with other works at simulation level.
- Experimental validation of the proposed control in a real microgrid.
- The approach would foster the penetration of RES in the existing utility networks.

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ABSTRACT

This paper presents the design of an energy management strategy based on a low complexity Fuzzy Logic Control (FLC) for grid power profile smoothing of a residential grid-connected microgrid including Renewable Energy Sources (RES) and battery Energy Storage System (ESS). The proposed energy management strategy uses generation and demand forecasting to anticipate the future behavior of the microgrid. Accordingly to the microgrid power forecast error and the Battery State-of-Charge (SOC) the proposed strategy performs the suitable control of the grid power. A simulation comparison with previous energy management strategies highlights the advantages of the proposed work minimizing fluctuations and power peaks in the power profile exchanged with the grid while keeping the energy stored in the battery between secure limits. Finally, the experimental validation in a real residential microgrid implemented at Public University of Navarre (UPNa, Spain) demonstrates the proper operation of the proposed strategy achieving a smooth grid power profile and a battery SOC center close to the 75% of the rated battery capacity.

1. Introduction

The benefits that Renewable Energy Sources (RES) (e.g., photovoltaic, wind turbines…) have exhibited in the last years, such as reducing the fuel consumption and the Greenhouse Gases (GHG) emissions [1], have contributed to the development of Distributed Generation (DG) systems to become a competitive solution for future power systems (i.e., Smart Grids) [2]. They can produce electrical power with less environmental impacts, they are easy to install, and they are highly efficient with increased reliability [3,4]. However, the integration of the utility grid with DG systems in a distributed, efficient, and reliable manner without excessive investment still remains a challenge [5].

The Microgrid (MG) concept is a quite appealing alternative for overcoming the challenges to integrate Distributed Energy Resources (DER) units, including RES, into power systems [6,7], and it has emerged as an integral feature for the upcoming power systems shaped by the various Smart Grid initiatives [8–13]. In general, MGs are

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defined as low-voltage distribution network comprising loads, DG units, and Energy Storage System (ESS) (e.g., batteries, flywheels, ultra-capacitors…) that are capable of operating in both grid-connected and stand-alone modes [9,11]. The electrical connection of these elements constitute the MG power architecture which, in turn, can be connected to the mains at a single Point of Common Coupling (PCC) [10,14]. The Energy Management System (EMS) is the heart of the MG and is in charge to drive the controllable elements of the MG (i.e., those sources, loads, and storing elements which can be controlled) to reach a set of pre-defined goals depending on the MG operation mode [15].

In the case of stand-alone microgrids, where the MG is separated from the distribution network, the main goal of the EMS is keeping a reliable power supply to the customer, limiting the power output when necessary and sometimes using Demand Side Management (DSM) techniques to avoid battery depletion [16,17]. In addition, when dispatchable power units are presented in the MG, another goal is usually to reduce operating costs by optimally scheduling the different dispatchable units in the system, using different optimization routines, as seen in [18–21].

However, in the case of grid-connected mode where this work focuses on, the grid, which can act as power source or a power sink, assures the reliable power supply to consumer. In this case, the EMS has to control the power flow among the MG elements to reach a set of predefined objectives such as minimizing the MG operating costs [22,23] or maximizing the revenues according to DG bids and electricity market price [15]. The energy management strategy design should take into account the MG power architecture and, in particular, the power management capability of the elements within the MG (i.e., which sources, loads, and storage elements can be controlled). Once the power architecture and the predefined objectives are known, the energy management strategy design can be undertaken by applying different methods [4,6,8,24–28]. In this regard, there is a wide variety of works handling different scenarios in terms of power architectures, objectives, and methods.

For instance, in [29] an energy management strategy is designed using local prediction and local forecasting as well as Stochastic Dynamic Programming (SDP) to control and extend the lifetime of an ESS included in a grid-connected MG with diesel and renewable generators. In [30] a predictive control technique is applied in a grid-connected MG to manage the ESS power to compensate hourly deviations based on a forecasted energy plan. Other studies consider scenarios with more degrees of freedom where the energy management strategy drives different storage elements (e.g., batteries, fuel cells…), controllable loads (e.g., electrical load management, heat pumps…) or a combination of both, as in [31–34], to carry out Demand Side Management (DSM) and Demand Response (DR) strategies, where the control methods used in those cases are usually sophisticated as Model Predictive Control (MPC) and, include both generation and demand forecasting as in [35,36].

Alternatively to these analytically-based control methods, Fuzzy Logic Control (FLC) allows the implementation of the human's heuristic knowledge about how to control a system [37,38] and has also been applied to the EMS design. For instance, in [39] a FLC-based EMS is designed to prioritize selling the additional electricity generated by RES and to maintain the battery State of Charge (SOC) above the 50% to extend the ESS lifetime, whereas in [40,41] a rule-based controller (i.e., FLC) is used in combination with different optimization techniques to achieve an optimum energy cost and thermal comfort in grid connected microgrids.

From the literature review it can be noticed that most of the EMS designs for grid-connected mode, are focused on the MG economic profitability paying less attention on the resulting power profile exchanged between the MG and the grid. However, economic incentives and penalties set by grid operators are a reflection of technical issues such as line congestion or grid stability [42]. For this reason, this paper focuses directly on minimizing the fluctuations and power peaks of the power profile exchanged with the mains, as in [30,32,42–52]. Smoothing the grid power profile can be considered a suitable solution in a residential MG scenario, since it facilitates the grid operators control and, consequently, the penetration of RES into the distribution network. Moreover, the grid power profile control allows residential consumers to generate their own energy resulting in a decrease of the amount of energy consumed from the utility grid, thus, reducing their electricity bill [53]. In this regard, the studies developed in [32,34,42,44–51] focus on a very restrictive residential grid-connected microgrid with only a single controllable element (battery charger/inverter, see next section) and address the power profile control of the power exchanged with the mains.

The earliest approach to smooth the grid power profile was the use of the Simple Moving Average (SMA) filter with a window size of one day [44]. This filter splits the high- and low-frequency components of the net power (difference between the load and the generated power) of the MG which are respectively handled by the ESS and the mains. The main drawback of SMA filtering is the filter delay itself: for instance, if several consecutive days of high irradiance leading to a power delivery from the MG to the mains are followed by a cloudy day, the MG delivers to the grid more power than the power that would correspond to the new energy conditions. This situation would prevail until the window of the SMA filter is only filled with the values of the new conditions, which takes 24 h. As a result, the ESS falls into over discharge and the system loss the control of the grid power who takes the shape of the net power. For this reason, a second approach adds the battery SOC as an additional control loop [45] to keep the ESS between secure limits. The way of designing this control loop is based on simple analytical functions to limit the battery SOC variation, which parameters are heuristically adjusted. This way, the SOC range is preserved but at the expense of introducing high fluctuations in the grid power.

Taking advantage of the aforementioned heuristic approach, and with the aim of improving the grid power profile smoothness, several low-complexity FLC-based EMS detailed designs inspired in [45] were presented in [46,49,51] considering different input variables (i.e., control loops). Finally, an improved design of two inputs, one output low-complexity FLC of only 25 rules, experimentally validated in [47], led to a noticeable improvement in the grid power profile smoothness. The key factor of this improved design was to anticipate the MG future behavior by means of including the MG Energy Rate-of-Change (ERoC) (i.e., the derivative of SMA filter output) as an input of the FLC. This way, the grid power profile starts to be modified as soon as the MG power balance average value started to change. This enhanced behavior allowed a quick reaction of the energy management strategy against sudden MG energy changes to set the battery SOC close to the 75% of the rated battery capacity and to concurrently smooth the grid power profile. In fact, this new input mitigated the SMA delay effect.

In [42], making use of generation and demand forecast, the SMA filter is converted into a Central Moving Average (CMA). This way, the grid power profile is modified to meet the new MG energy state even before it occurs. This approach, however, is subject to the accuracy of the forecasted data. By means of using the cumulative forecasting error and the battery SOC the authors propose a control loop to limit the grid power fluctuations and to preserve the SOC within secure limits in front of forecasting errors. This strategy leads to a better grid profile with the same battery system. However, and as in [32], this control loop is based on analytical functions with parameters adjusted heuristically.

To improve the results obtained in [42], this paper proposes a FLC-based EMS including generation and demand forecasting which anticipates the MG future behavior to smooth the power profile exchanged with the grid. As in [42], the FLC-EMS uses a CMA filter instead of SMA one to avoid making decisions based on the MG power balance of the preceding 24-h. To limit the power fluctuations due to forecasting errors this work suggests a control loop based in two control blocks, namely: the first one is based on a low-complexity FLC design of two-input, one output, and 25 rules, which takes into account the power forecasting error and the battery SOC with the purpose of

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