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Definition and on-field validation of a microgrid energy management system to manage load and renewables uncertainties and system operator requirements

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ABSTRACT

The present paper proposes an Energy Management System (EMS) to be used in grid connected microgrids. To do this, first a suitable model (for optimization purposes) of all the components that typically appear in a microgrid is presented, then, four possible electric network models are detailed and finally the overall architecture of the optimization problem of the EMS is set up. Moreover, as the optimization of the energy production/consumption of a microgrid relies on the thermal and electric load and on the renewables forecasting, an online empirical correction of forecasted data is proposed, highlighting its positive impact on the overall operational cost of the microgrid. Another aspect which is accounted regards the possibility of allowing the EMS to act as a power plant controller in compliance with the Distribution System Operator (DSO) requirements in terms of reactive power management and voltage control (as requested by the majority of grid codes and national regulations). So, the proposed algorithm structure splits the optimization problem into two sub problems: the first one basically dictates the active power production of the dispatchable units minimizing an economic objective function, while the second accounts for the satisfaction of the DSO requirements. The experimental validation of the proposed EMS is performed on the University of Genoa Smart Polygeneration Microgrid (SPM), where the proposed EMS is currently running. The considered test cases highlight the effectiveness of the proposed EMS in economically operating the microgrid (compared to simpler EMS previously installed in the SPM) and in satisfying the reactive power or voltage regulation requirements provided by the Italian technical requirements.

1. Introduction

One of the key factors for the design and effective operation of a Microgrid (MG) is related to the definition of an adequate control system able to manage both the resources and infrastructures present in the network. For this reason, in recent years, the attention of researchers has been devoted to defining suitable control schemes to be integrated in the MG 'brain', called Energy Management System (EMS) [1–4].

In grid connected Microgrids, the EMS typically recalls the principles of optimization of traditional electricity transmission networks, achieved by classical Optimal Power Flow (OPF) algorithms [5–7]. However, one of the most significant differences between the traditional unit commitment and the MG energy management lays in the presence of dynamic components (like storage devices) that require the setting up of an overall optimization for the whole period of investigation. This aspect, in combination with the nonlinearities introduced by the electric load flow equations, makes the resolution of the optimization problem computationally hard. In order to face this difficulty, many different aspects of the problem have been studied in literature: from an algorithmic point of view, in Ref. [8] the optimization problem is dealt in a completely non-linear way, but the electrical storage is constrained to charge during the night period and discharge in the daytime hours; in Ref. [9] the dynamical components are not involved, hence each time sample can be treated as a single OPF problem, which lowers the computational complexity. Moreover, the approaches of Refs. [8–10] do not involve the thermal demand, with a consequent

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reduction in the number of constraints. Another possibility that has been explored consists of analyzing in details some aspects of the problem. For example, the integration of Renewable Energy Sources (RES), studied in Refs. [11–14], represents a first step to approach the optimization problem with a reduced degree of complexity. Other aspects have been investigated like the optimal integration of RES and storage devices from an economical point of view (e.g. Refs. [15–17]) and the problem of Demand Side Management (DSM), studied in Refs. [18–20], where the concept of real time operation and some real time updating strategies are proposed based on the actual energy price and load. OPF based algorithms have also been employed to face contingency issues in distribution networks characterized by high penetration of Distributed Energy Resources (DER), in order to define the best asset of generation to be disconnected from the grid to avoid distribution lines thermal overloading [21]. However, such formulation does not account for storage units, which would make the solution of the OPF problem computationally more complicated.

Finally, more recent works dealt with both storage and power flows constraints [22–25], but no explanation about how power flow equations are integrated in the optimization algorithm is provided. An interesting way of combining these two aspects is provided by Ref. [26] where the EMS is divided in two distinct steps. The first step is as an allocation problem that accounts for the management of the storage production profile all over the optimization horizon; then, iterative decoupled traditional OPF problems are solved to dispatch the remaining dispatchable units. Another interesting application of such a decoupled procedure is proposed in Ref. [27], also accounting for an unbalanced formulation of electric power flows equations, but without providing detailed information on the actual implementation of the proposed algorithm and focusing only on islanded MGs. The stochastic behavior of the RES power production and the thermal and electric load request is also analyzed in Ref. [27]. As the EMS basically implements a dynamic optimization problem over a well-defined time horizon, it has to rely on the forecast of the aforementioned quantities. As a consequence, an important research line is related to the definition of an efficient forecasting strategy that improves the optimization result (e.g., see Refs. [28,29]). In particular, the EMS proposed in Ref. [29] is defined over a rolling horizon and, for every time step, the load and RES forecast are updated according to a simple but effective strategy. However the electric network model assumes that all the generations and loads are connected to the same bus, thus neglecting all the voltage/current/device capability constraints.

Another interesting treatment of the stochastic behavior of the RES power production is presented in Ref. [30], where a real time control allows an optimal management of the forecast error in terms of costs to be obtained. The method is applied to a system consisting of a PV unit and a storage device connected to the public grid. This means that if, for example, the power production of the photovoltaic component is lower than the power demand, the logic chooses whether to retrieve the missing power by the battery discharge rather than by the external network according to a minimal cost evaluation. However, an extension to a more complex case in which many different generators are present in the MG does not appear so straightforward.

Moreover, the majority of grid codes and technical operation requirements pose some conditions for the connection of active users to the HV/MV public network [31–35]. In particular, at steady-state, they require producers to provide some ancillary services such as the voltage support/regulation or power factor correction. For this reason, suitable functions should be embedded in the MG EMS to make it able to match the requirements of the local Distribution System Operator (DSO), according to national standards as well as the specific grid interconnection codes. Several papers have been published on this topic (see e.g. Refs. [36,37]), focusing their attention on a specific production units (e.g. PV plants or wind turbines), but there is not much literature concerning a suitable controller for MGs compliant with the DSO requirements.

Starting from this state of the art, in the present paper, an EMS for grid connected MGs is presented, accounting for dynamic components, detailed network representations and forecasting uncertainties management. The paper is structured in the following way: in Section 3 suitable models for the devices (generators and loads) that normally compose a MG are defined, then, in Section 4, alternative representations of the electric infrastructure are analysed, highlighting their effectiveness in terms of accuracy and computational effort. Section 5 is dedicated to the definition of the optimization problem, providing four different optimization algorithms according to the described electric network models while in Section 6 the update logic for forecasted data is described. Finally, in Section 7, the proposed EMS architecture performances are evaluated by means of experimental validations, performed on the University of Genoa Smart Polygeneration Microgrid (SPM) [38,39] located in the Savona Campus. In the EMS validation the attention is paid to the fourth problem comparing its results achieved by the proposed EMS with the ones provided by the Distributed Energy Management System (DEMS [40]) developed by Siemens and originally implemented in the SPM. Section 8 is dedicated to conclusive remarks and comments about the achieved results.

2. List of symbols

In this section a list of all the variables and symbols involved in the problem formulation is presented.

2.1. General data

- j is the imaginary unit
- N_t are the time intervals in the considered horizon (t denotes the generic time instant and Δt is the length of each time interval)
- N_{DU} is the number of the Dispatchable Units (DU)
- N_{HG} is the number of the Heat Generators (HG) units
- N_{ST} is the number of the Electrical Storage (ST) units
- N_{RES} is the number of the RES units
- N_{EL} is the number of the Electric Loads (EL)
- N_b is the number of buses in the electric network
- N_L is the number of branches in the electric network

2.2. Technical data

2.2.1. DU units

The values of all the following quantities are typically present in the DU datasheets:

- $P_{DU,i}^{el,max}$ is the full load maximum electric power
- $S_{DU,i}$ is the inverter rating, if the i^{th} DU is connected to the grid by means of a power electronics converter

2.2.2. HG units

The values of all the following quantities are typically present in the BO datasheets:

- $P_{HG,i}^{th,max}$ is the maximum thermal power

2.2.3. ST units

The values of all the following quantities are typically present in the ST datasheets:

- $\eta_{\mathrm{ST},i}^{in}$ and $\eta_{\mathrm{ST},i}^{out}$ represent the efficiency values for the charging and discharging of the battery