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Enhancing the dispatchability of distribution networks through utility-scale batteries and flexible demand☆

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ABSTRACT

In this paper, the problem of dispatching the operation of a distribution feeder comprising a set of heterogeneous resources is investigated. The main objective is to track a power trajectory, called the *dispatch plan*, which is computed the day before the beginning of operation. In this paper, we propose a method to optimally compute the dispatch plan so as to optimize the operation of the feeder while making sure to allocate enough local reserves to absorb deviations of the realizations. Indeed, during real-time operation, due to the stochasticity of part of the resources in the feeder portfolio, tracking errors need to be absorbed in order to track the committed dispatch plan. This is achieved by modulating the power consumption of a utility-scale battery energy storage system and of the heating, ventilation and air conditioning system of a commercial controllable building. To this end, a hierarchical controller is designed to coordinate these two controllable entities while requiring a minimal communication infrastructure. Due to the inherent different response times of these systems, the power injection of the electrical battery is controlled at a sub-minute time-scale so as to absorb high-frequency tracking errors and, therefore, deliver the dispatch service. At a slower time-scale, the controllable building is controlled to maintain the state of charge for the electrical battery at a scheduled level by means of a model predictive controller. The model predictive controller is designed in order to account for both comfort and operational constraints of the controllable building, as well as power limits for the electrical storage.

The effectiveness of the proposed control framework is demonstrated by means of both an extensive simulation analysis, as well as a set of 12 full day experimental results on the 20 kV distribution feeder in the campus of the Swiss institute of technology in Lausanne, that is comprised of: 1) A set of uncontrollable resources represented by five office buildings (350 kWp) and a roof-top photovoltaic installation (90 kWp), 2) a set of controllable resources, namely, a grid-connected electrical storage (720 kVA–500 kWh), and a fully-occupied multi-zone office building (45 kWp).

1. Introduction

The electric grid is undergoing a substantial change towards a more sustainable fossil-free power generation which has motivated a rapid and significant increase of renewable generation into the energy mix [1,2]. However, renewable energy sources are inherently volatile and uncertain which poses new challenges to the classical control paradigm of the power grid [1].

In order to guarantee the proper and safe functioning of the power grid a set of power reserves are typically kept on standby and activated to compensate for both normal fluctuations and major contingencies. Historically, these reserves were provided mainly by highly-responsive power plants, *e.g.* hydro units [3]. In a scenario where both consumption and production are more

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uncertain and difficult to predict, the need for these reserves is expected to increase drastically in the near future [3]. Consequently, in recent years, both the academic and the industrial communities have shifted their attention to a more decentralized control scheme where the proper function of the entire system is achieved by controlling smaller portions of the electric grid.

In this direction, many contributions have appeared in the context of virtual power plants and grid-tied microgrids [4] which, in broad terms, consists in controlling a set of heterogeneous resources to offer grid support services. For example, in [5] Biegel et al. present a control architecture for the aggregation of multiple small-scale residential heat pumps that collectively provide services to the system operator. The control architecture was deployed in a field test showing how a set of several heat pumps can track a power reference varying between 15 kW and 35 kW. A method to directly and explicitly control the grid status of active distribution networks has been proposed in [6]. In particular, the proposed framework requires every resource in the network to communicate at each iteration an abstract view of its internal state. This is used by an aggregator entity to compute the power setpoint for the next iteration for all the resources. In [7], Costanzo et al. propose a control scheme based on distributed Model Predictive Control (MPC) to coordinate heterogeneous resources in order to reduce peak power exchange with the grid in presence of local renewable generation.

In all aforementioned contributions, the limiting factor for a large-scale deployment is the reliance on a massive deployment of ICT infrastructure for monitoring and control. This makes these solutions less compelling due to the high cost of implementation and flexibility extraction.

A different line of research is represented by plug-and-play technologies that can provide grid support services without requiring a radical change in the operational practices. One important trend in this direction concerns the integration of Battery Electric Storage Systems (BESS) to absorb the fluctuations of renewable production which is also referred to as *capacity firming*. In [8], a method to correlate the size of BESS with the uncertainty of solar production on different time-horizons, has been proposed. Moreover, a control strategy was designed and validated in a simulation analysis to operate the battery within the desired limits while absorbing the fluctuations of PV production. A similar contribution is represented by Perez et al. [9], where authors propose an MPC scheme to minimize economic imbalances in a setup comprising PV generation and a BESS system. The importance of accurate predictions for the minimization of the energy requirements of the BESS was highlighted in [9]. Due to the similar dynamics involved, the importance of predictive control [10,11] and accurate short-term predictions [12,13] has been emphasized also in the context of wind farms production.

Another paradigm that aims at merging the two aforementioned concepts is the so-called *dispatchability of distribution feeders* that was firstly introduced by Sossan et al. in [14]. The main idea is to achieve virtually perfect dispatchability of a set of heterogeneous devices consisting of both uncontrollable loads and distributed generation (*prosumers*). The proposed framework requires computing one day in advance a forecast power profile for the aggregated prosumers. During real-time operation, in order to track the committed profile, a BESS is operated by controlling its power injection in order to absorb any errors in the forecasts. As in the context of capacity firming, the success of such a control scheme relies on two factors: 1) An accurate forecasting tool for predicting the power profile of the prosumers one day in advance; 2) an appropriate energy/power sizing of the BESS. For a given maximum prosumer power, it is desirable to achieve dispatchability with the smallest possible battery, as BESSs remain expensive devices. In all aforementioned contributions, the required specifications for the battery are dictated by the quality of the forecasting tool. However, achieving high-forecasting accuracy can prove quite challenging at a local scale where the effect of environmental factors and human behavior is not smoothed out as happens at higher levels of aggregation.

In this paper, we extend the concept proposed in [14] by considering an additional degree of freedom during real-time operation. In particular, the benefit of having a Controllable Building (CB) within the prosumer portfolio is investigated. The main reasons for considering commercial buildings over other types of loads is dictated by the following considerations: 1) Commercial buildings are typically characterized by a large thermal inertia that can be naturally exploited to defer their power consumption without affecting occupant comfort [15]; 2) most commercial buildings are already equipped with energy management systems that facilitate communication and allow a simpler variation of their energy consumption [15].

The potential of demand side resources for offering different services to the grid at different time-scales has also been extensively studied in the literature. Thus, different control strategy appeared that are typically tailored to the particular application at hand such as frequency reserves [16–18], load shedding [19], peak reduction [20,21], etc. For a comprehensive overview, we refer the reader to [22].

However, to the best of the authors knowledge, the combination and coordination of BESSs and controllable demand to dispatch the active power flows of stochastic resources has not been previously investigated in the literature.

The main contributions of the present manuscript are: 1) Propose a general optimization-based method which centrally computes the aggregated dispatch plan so as to optimize the operation of the feeder while making sure to allocate enough local reserves to absorb real-time deviations; 2) introduce a practical, completely decentralized, reformulation of the day-ahead commitment problem which still guarantees the computation of an adequate dispatch plan; 3) design a hierarchical multi-time-scale Model Predictive Controller (MPC) to accurately track the committed dispatch plan by coordinating the BESS and the CB; 4) conduct an extensive simulation study to analyze and compare the different configurations of the proposed controller; 5) experimentally validate the effectiveness of the method on a real-scale 20 kV medium voltage distribution network which is comprised of a utility-scale electric battery, a fully-occupied smart office building, conventional uncontrollable loads, and a roof-top photovoltaic (PV) generator.

The rest of the paper is structured as follows. In Section 2 we present the formulation of the dispatchability problem. In Section 3 an accurate mathematical description of all involved elements is provided. Section 4 and Section 5 describe the day-ahead and real-time operation, respectively. In Section 6 a simulation analysis of the proposed algorithm is presented. In Section 7 the control architecture is experimentally validated on a 20 kV medium voltage active distribution network. Finally, Section 8 summarizes the contribution of the paper and proposes future improvements and directions.

Notation: Throughout the article, $\mathbb{R}^n$ denotes the n-dimensional real space, uppercase letters are used for matrices and lower case for vectors. a_k represents the value of vector a at time k, whereas bold letters are used to denote sequences over time, *e.g.*, $\mathbf{a} = [a_0^T, a_1^T, \ldots, a_{N-1}^T]^T$. The notation $\mathbf{P}^{\text{res}}$ indicates the real power flow of the particular resource, res, whereas the bracket subscript notation, $\mathbf{P}_{(j)}$ stands for the power trajectory corresponding the j-th scenario. Finally, the expected value operator over the probability distribution, ϵ, is denoted by $\mathbb{E}_\epsilon\{\cdot\}$. Please refer to Tables 1 and 2 for the list of all acronyms and mathematical symbols used in the manuscript.