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On the use of probabilistic forecasts in scheduling of renewable energy sources coupled to storages

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HIGHLIGHTS

- Dispatching of inflexible generation/demand using storage is discussed.
- Novel stochastic robust optimization formulation yields reliable schedules.
- Consideration of probabilistic forecasts of inflexible power and energy profiles.
- Simulations underpin achievable performance improvements.

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ABSTRACT

Electric energy generation from renewable energy sources is generally non-dispatchable due to its intrinsic volatility. Therefore, its integration into electricity markets and in power system operation is often based on volatility-compensating energy storage systems. Scheduling and control of this kind of coupled systems is usually based on hierarchical control and optimization. On the upper level, one solves an optimization problem to compute a dispatch schedule and a coherent allocation of energy reserves. On the lower level, one performs online adjustments of the dispatch schedule using, for example, model predictive control. In the present paper, we propose a formulation of the upper level optimization based on data-driven probabilistic forecasts of the power and energy output of the uncontrollable loads and generators dependent on renewable energy sources. Specifically, relying on probabilistic forecasts of both *power and energy profiles* of the uncertain demand/generation, we propose a novel framework to ensure the online feasibility of the dispatch schedule with a given security level. The efficacy of the proposed scheme is illustrated by simulations based on real household production and consumption data.

1. Introduction

Despite differences in national regulations, trading of electricity *and* operation of power systems usually require producers, consumers, and prosumers to commit a priori to some levels of production/consumption [1]. This commitment determines a schedule of power exchange with the utility grid, to which we refer in the following using the general term *Dispatch Schedule* (DiS). Unplanned deviations from the DiS, often denoted as *imbalances*, are compensated in operation using pre-allocated power and energy reserves. Maintaining and utilizing these reserves is costly. The number and severity of the imbalances that each participant is allowed to cause might therefore be subject to limitations [2]. Moreover, the cost associated with the allocation and utilization of reserves is typically distributed among the market participants who caused the imbalances [1].

This existing market and operation structure makes it difficult to integrate volatile and low-flexibility generation/demand of electricity, for which a certain level of production or consumption cannot be guaranteed a priori. Examples for such volatile and low-flexibility units are domestic loads or generation based on uncontrollable renewable energy sources such as wind or solar. Thus, the coupling of inflexible generation and/or demand to an Energy Storage System (ESS) is a topic of significant research efforts, see for example [3–9]. In fact, ESSs can act as internal capacity reserve and compensate for the volatility of the inflexible generation/demand, thus fostering and enabling dispatchability.

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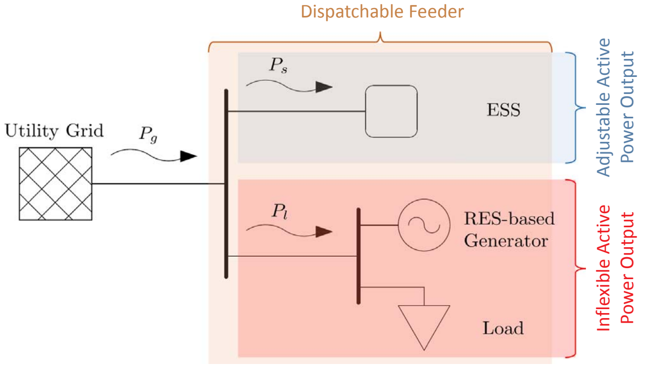

Fig. 1. Schematic diagram of a generic *dispatchable feeder*.

At the same time, as observed in [10], the flexibility provided by the ESS can be also exploited to the end of load shifting, load leveling, or peak shaving. Thus, any ESS can be used for two conflicting purposes: (i) reduction of the imbalances, by providing internal capacity reserve and (ii) reduction of the DiS cost, load leveling and peak shaving, by shifting load/production in time. Attempting to use one ESS for both purposes at the same time requires an appropriate forecast-dependent assignment of the available resources, i.e. it requires to find an acceptable trade-off between both aims. To this end, the DiS is often computed by means of optimization, including the actual state of charge of the ESS, a model of its dynamics, and available (deterministic) forecasts of the uncontrolled generation/demand, see e.g. [8,11].

However, forecasts of demand and renewable generation over a typical horizon of 24–48 h are intrinsically uncertain, cf. [12]. Moreover, the stochastic correlation between forecast errors at subsequent time instants is difficult to handle. In the literature, several techniques have been proposed to account for uncertainties in scheduling for power system operation. This includes worst-case approaches [9,13–15], scenario approaches [16–21] and methods relying on probabilistic uncertainty characterizations [22]. Yet, all these methods exhibits pitfalls. Worst-case considerations can be overly conservative. Optimization based on multiple scenarios is usually less conservative, but it either leads to scalability issues (curse of dimensionality) or requires scenario selection, which can be non-trivial [20]. Beyond these approaches, there exist techniques for direct computations with stochastic uncertainties, see [23,24]. Such methods, however, frequently consider uncertainties modeled as normal distributed independent random variables, which might not be very realistic in applications [25–27].

The main scope of the present paper is scheduling and control of grid-connected systems, which couple inflexible generation and demand with an ESS (Fig. 1). The aim is to achieve reliable dispatchability of the active power output to the grid. In the absence of a commonly accepted terminology for this kind of coupled systems, we follow [6] denoting them as *Dispatchable Feeders* (DF).[1] Specifically, we investigate a hierarchical scheme for scheduling and control of DFs subject to forecast uncertainty, intended to be implemented directly on the side of the prosumer, respectively, on the side of the DF. The proposed scheme allows computing DiS that can be tracked by the DF with a given probability of avoiding imbalances, to which we refer to as *security level*.

The contributions of the present paper are as follows: We propose to compute the dispatch schedule using data-driven probabilistic forecasts of the power *and* energy profiles of the aggregated inflexible load/generation, exploiting probabilistic forecasts in combination with concepts of stochastic robust optimization, see [28–30] for the former, and [31] for the latter. Specifically, we work with the probabilistic quantile forecasts of the *energy profile*, which implicitly models the interdependence/correlation of forecast errors at subsequent time instants. This way, we avoid hard to verify assumptions on their distributions, neither do we require an explicit description of correlations. To the best of the authors knowledge, such a use of probabilistic power and energy forecasts has not been previously investigated in the literature. Indeed, the proposed approach differs from the majority of previous works on this topic, as existing methods focus either on robust worst case scheduling, e.g. [6], or on scenario-based optimization, e.g. [20]. Furthermore, we comment on implementation issues arising from the non-convexity of the proposed problem and from the necessity of computing the schedule far before its actual application. Finally, we draw upon simulations to demonstrate that the proposed scheduling scheme can be solved efficiently, i.e. with numerical effort comparable to deterministic scheduling schemes, while leading to less conservative results than worst-case approaches. Our results underpin that single prosumers (or clusters of prosumers)—assuming they are equipped with inflexible load/generation and an ESS—can efficiently be operated as a DF.

The remainder of the paper is organized as follows: Section 2 introduces the problem; Section 3 entails the main contribution of the paper, i.e. it presents the proposed methodology to tackle the stochastic scheduling problem; Section 4 describes how the DiS can be adjusted online within the scheduling horizon; Section 5 reports simulation results.

2. Problem statement

Consider a DF as sketched in Fig. 1. Assuming lossless connection, the aggregated active power output of the DF, P_g, is equal to

$$P_g = P_s + P_l, \tag{1}$$

where P_l and P_s are the aggregated active power output of the inflexible elements and the active power output of the ESS respectively, with positive power flows directed according to Fig. 1. For sake of simplicity, we do not consider any constraint on the value of P_g.

The power outputs of the inflexible devices (whether they are loads or generators) is either not adjustable or regulated according to independent, device-specific settings. This is often the case, for example, with wind turbines or PV generators, as well as the majority of domestic loads. Therefore, P_l indicates the aggregated inflexible active power output, regardless of the number and nature of devices contributing to it. A negative value for P_l represents power injection.

With respect to the ESS, we utilize a generic model, similar to [8]. Specifically, we denote the power output of the ESS with P_s, and the amount of energy stored in it with E_s. Adopting a discrete-time setting, E_s evolves according to

$$E_s(k+1) = E_s(k) + (1-\mu_n)P_s^+(k)\Delta t + (1+\mu_n)P_s^-(k)\Delta t, \tag{2}$$

with Δt denoting the length of each time step. The conversion losses are modeled by $\mu_n \in (0,1)$, together with a discrimination between the different directions of $P_s(k)$,

$$P_s(k) = P_s^+(k) + P_s^-(k), \tag{3a}$$

$$0 \le P_s^+(k), \quad 0 \le -P_s^-(k), \tag{3b}$$

$$0 = P_s^+(k) \cdot P_s^-(k). \tag{3c}$$

The power and capacity constraints of the ESS are

$$\underline{P}_s \le P_s(k) \le \overline{P}_s, \tag{4a}$$

$$\underline{E}_s \le E_s(k) \le \overline{E}_s, \tag{4b}$$

where $\underline{P}_s$ and $\overline{P}_s$ denote the minimum and maximum power output, and $\underline{E}_s$ and $\overline{E}_s$ denote the minimum and maximum storage capacity. We

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[1] Note that the concept of dispatchable feeders is similar yet not equivalent to virtual power plants. In fact, contrary to virtual power plants, the system considered in the present paper does not provide any capacity reserve *to the grid*. We also remark that other terms—such as intelligent power plant [5] or integrated storage and generation [8]—appear in the literature.