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Stochastic model predictive control for economic/environmental operation management of microgrids: An experimental case study ☆

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ABSTRACT

Microgrids are subsystems of the distribution grid which comprises generation capacities, storage devices and flexible loads, operating as a single controllable system either connected or isolated from the utility grid. In this work, microgrid management system is developed in a stochastic framework. It is seen as a constraint-based system that employs forecasts and stochastic techniques to manage microgrid operations. Uncertainties due to fluctuating demand and generation from renewable energy sources are taken into account and a *two-stage stochastic programming* approach is applied to efficiently optimize microgrid operations while satisfying a time-varying request and operation constraints. At the first stage, before the realizations of the random variables are known, a decision on the microgrid operations has to be made. At the second stage, after random variables outcomes become known, correction actions must be taken, which have a cost. The proposed approach aims at minimizing the expected cost of correction actions. Mathematically, the stochastic optimization problem is stated as a mixed-integer linear programming problem, which is solved in an efficient way by using commercial solvers. The stochastic problem is incorporated in a model predictive control scheme to further compensate the uncertainty through the feedback mechanism. A case study of a microgrid is employed to assess the performance of the on-line optimization-based control strategy and the simulation results are discussed. The method is applied to an experimental microgrid: experimental results show the feasibility and the effectiveness of the proposed approach.

1. Introduction

Microgrids are integrated energy systems with the possibility of bidirectional power flow, which can operate either in parallel with the grid or in an intentional island mode. A typical microgrid consists of interconnected loads and distributed energy resources (DERs), i.e., distributed generators (DGs), renewable energy resources (RESs) and storage devices [1,2]. Microgrids have also the ability of supplying thermal load with combined heat and power (CHP) capabilities; this would increase the overall system efficiency. The microgrid concept could efficiently support high penetration of RESs, storages and the integration on demand response policies in the *smart grid* [3,2]. This led to the motivation behind using microgrids, which are capable of managing and coordinating DERs and loads in a more decentralized way reducing the need for the centralized coordination and management [4]. The growing need of reducing carbon emissions makes the concept of microgrid even more attractive.

Thus, in the *smart grid* scenario, new modeling requirements are needed, e.g. storage modeling must be incorporated into the operation planning problem in order to coordinate storage use with RES generation and energy prices, and address the complexity of the charging/discharging schedule [5]. It is important to notice that there are no current modeling tools including flexible loads and energy storage modeling in a smart grid environment, which also take the inherent uncertainty sources into account [6]. The modeling capabilities and the computational advances of Mixed Integer Problem (MIP) algorithms, have led several Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) to implement MIP-based solution methods in order to find a better solution to solve day-ahead and real-time market problems [7]; however, not solving unit commitment problems to complete

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optimality can cause several issues, such as incorrect energy prices (generator payoff deviations) and surplus issues [8].

The main objectives from an energy and control prospective are to coordinate various DGs, RESs, storages and loads in order to determine the optimal energy scheduling depending on running costs, thermal and electrical energy requirements and consumers preferences; the main challenges are then represented by flexible loads, which account for consumers preferences, and uncertainties due to RESs and loads [9].

In this paper we tackle the optimal economic/environmental operation management of a microgrid under supply and load uncertainties. This problem aims at achieving the optimal trade-off between the overall microgrid operating costs and emissions to meet load demand of a certain period (typically one day) while satisfying complex operational constraints.

Literature review. Though there is already a vast literature on microgrids energy management system, there are still many research and development needs associated to microgrids, among these one of the most crucial elements is finding the best operational strategy under uncertainty.

Several models have been proposed for microgrids, some of them solving also the microgrid environmental/economic optimization problem (e.g., [10–13]).

Typically the proposed approaches either are computationally intensive and/or heuristics or decomposition techniques are applied; further either the optimization problem stays nonlinear or other important features, such as minimum up and down times and demand side programs, are neglected, e.g. see also [14–20].

In a stochastic framework, multistage stochastic programming, in particular with a two-stage form, has had several applications in energy models. Literature on optimization under uncertain conditions indicates that stochastic programming is considered as an appropriate approach for handling uncertainties (see [21,22] and references therein). Stochastic approaches have been proposed in literature for smart grids and microgrids, with the goal of minimizing running costs and/or emissions, e.g., [23–27]. Multi-objective approaches employ ε-constraint technique and lexicographic optimization to solve the microgrid scheduling problem [28,29]. Simulation results show that generally the stochastic decisions outperform the deterministic decisions.

Uncertainties in load forecasts and RES generation are generally taken into account; typically the microgrid optimization problem is formulated as a mixed integer nonlinear problem and decomposition techniques or heuristic-based approaches such as evolution algorithms and particles swarm optimization are proposed [30,28,31–39]. In particular, in [38] a robust agent-based microgrid energy management framework is proposed, which takes the probability of occurrence of some specific uncertain events, e.g., failures of electrical lines and electricity demand and price peaks, into account.

Recently, Model Predictive Control (MPC) has drawn the attention of the power system community [40]. In power system literature, an MPC method, called *rolling horizon*, has been commonly proposed to solve the unit commitment problem with wind power generation (e.g., see [41]).

Several works can be found in the literature that addresses MPC for optimal dispatch in power systems, e.g., [42–47]. Several authors showed the advantages of applying MPC to dynamic economic dispatch in a stochastic or in an environmental framework [48,49]. Some authors have shown that a stochastic MPC is a promising approach [50,49].

As before, in the solution methods proposed above, the optimization problem stays nonlinear and/or heuristics or decomposition techniques are applied; important microgrid features are in general neglected such as storage dynamics, grid interaction, generators operative constraints.

An integrated optimization-based framework for microgrid operational planning has not yet been proposed, which considers the inherent uncertainty sources, all kinds of distributed energy resources technologies (DGs, RESs, energy storages and flexible loads), as well as detailed system features and operating constraints, from both an economic and environmental viewpoint.

We would like to remark that, when storage elements are considered, generally the proposed storage modeling does not rule out the possibility that the optimal mathematical solution contemplates simultaneous charging and discharging of the storage, a physically unrealizable policy. Such outcome may occur as the mathematical consequence of unpredicted RES-generated power surplus, bounds on the exchanged power with the utility grid, and costs of the storage level. This issue has been never discussed in the corresponding studies. Similarly the interaction with the utility grid should be modeled so as to prevent solutions contemplating simultaneous selling and purchasing under certain market circumstances.

Main assumptions and contributions. Since microgrid control requirements involve different control approaches and different time scales, the typical control hierarchy of a microgrid (e.g., IEC/ISO62264 standard) requires a centralized, high level controller on the top of the hierarchy and local controllers associated with each DER and load unit [9,51]. The high level controller deals with longer time scales and aims at generating suitable set-points for DERs and flexible load units so that optimized power dispatch will be performed and a given demand is met. The local controller embedded in a DER is mainly responsible for voltage/frequency and active/reactive power control in order to ensure that the power reference values are tracked, keeping voltage stability and power quality (which has higher priority) [9].

The high level controller is very weakly dependent on the transient behavior of the fast dynamics. Then a steady state assumption for microgrid components can be safely made without much loss of accuracy. A further assumption of our approach is that the *Microgrid Operator* is the unique centralized entity in charge of microgrid management.

In this paper we develop an integrated optimization-based framework for microgrid economical/environmental operational planning in a stochastic framework, considering both thermal and electrical energy demand. We propose the use of MPC in combination with Mixed Integer Linear Programming (MILP) [52,53] and two-stage stochastic programming [54]; we will refer the proposed novel control scheme for microgrid management as MG-SMPC.

By taking the environmental concern into account, the microgrid operation optimization problem can be formulated as a multi-objective optimization (MOO) problem with conflicting objectives (operative costs and emissions), for which a set of optimal solutions (Pareto-optimal set) and the corresponding objective function values (Pareto curve) are computed. In this paper, the *weighted min–max method* is applied to compute Pareto optimal points; this approach provides both necessary and sufficient conditions for Pareto optimality [55]. The desired number of Pareto-optimal (non-dominated) solutions can be obtained by varying the weights on the objective functions.

In our problem formulation, we strove to include as many details as possible and maintain the microgrid stochastic optimization problem solvable by standard algorithms without resorting to any decomposition techniques or heuristics; this leads to improvements in solution quality and computational burden [56,57].

To guarantee a correct behavior for storage and grid interaction (e.g., non-simultaneous charging and discharging), we utilize the approach described in [58] and use the Mixed Logical Dynamical (MLD) framework. We would like to remark that, in the proposed problem formulation, only generators fuel consumption and emission functions are approximated in case they must be expressed