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Combined environmental and economic dispatch of smart grids using distributed model predictive control

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ABSTRACT

This paper presents an extended distributed model predictive control (DMPC) framework and its application to a smart grid case study. Specifically, a combined environmental and economic dispatch (EED) problem is formulated and solved, which is a non-trivial multi-objective optimization problem given the high number of agents, information exchanges and constraints associated to large-scale smart grids.

In this line, the work proposed herein adopts a distributed Lagrange-based model predictive control with reduced computational demand making use of robust mixed-integer quadratic programming (MIQP) solvers. In addition, the model predictive control (MPC) nature of the framework accounts for renewable resource forecast while physical constraints are included in the formulation. The DMPC is herein extended to calculate market-based on-line energy pricing while minimizing the generation cost and emissions,and to include hard and soft constraints and ramp rate limits.

The aforementioned control framework is applied to a smart grid composed of 11 consumer centers, 6 energy storages, 11 generation systems and 31 transmission lines. Simulation results show reductions of generation costs up to 40% when predictions are included in the formulation. Furthermore, the simulation of forecast errors results in up to 8% generation overcost. These results show that DMPC can be considered as an alternative versus other heuristic methods, which do not guarantee an optimal solution to the problem.

1. Introduction

Energy generation is currently tending towards the integration of conventional fossil fuel-based power stations with other technologies such as renewable energy. However, owing to the intermittent generation associated with these renewable energy sources, the incorporation of efficient, reliable and large scale energy storage facilities is vital to their large scale deployment. Also, communication technologies are being incorporated to the electricity grids to increase the available information for the reliable and efficient management of these systems [12]. This progress moves current electricity grids towards smart grids. In this context, this work is dedicated to applying computationally efficient optimization algorithms to solve the load dispatch of smart grids.

The load dispatching problem is referred to as environmental and economic dispatch (EED) when aiming to reliably fulfill the load demand at the lowest possible cost and greenhouse gas emissions. It is well-known that EED of electricity grids is a non-trivial multi-objective optimization problem with complex constraints. In literature, many papers develop more efficient heuristic optimization algorithms to solve EED problems such as simulated annealing (SA) [23], genetic algorithm (GA) [17,11,16], particle swarm optimization [10], differential evolution [18,28,27] and bee colony [4,21] amongst others [9]. All these works have in common that the optimization algorithms are performed in a centralized system even though few works [16] present parallel programming. As a result, the main drawback of this approach is that the number of generation and customer units involved in EED exponentially increases the computational demand.

Regarding the EED of electricity grids with intermittent renewable energy, several works present algorithms for power systems with wind farms as reviewed in [7]. However, to the best of authors' knowledge, these algorithms do not conduct studies of EED with a wide renewable energy portfolio including large-scale energy storages.

In this research line, previous works have presented interesting formulations to minimize the generation costs of grids: [1] studies a stochastic energy balance analysis of a three-like distributed energy network for smart grids; [2] proposes a centralized model predictive control (MPC) controller applied to a grid composed of two residential areas without storages; [3] presents a distributed MPC controller to minimize the generation cost of a grid integrating

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three residential areas with a storage system; and [15] presents an interesting application of MPC to residential case with simulation over a solar year, real data, and linearization of the CHP unit in the model. In brief, model predictive control is an optimization strategy which accounts for system dynamics, forecasts and operational constraints explicitly by solving an optimal open-loop control problem, which is computed on-line at every sampling time in a receding horizon manner [8]. So that an optimal solution can be guaranteed, in the sense that the minimum of the cost function subject to constraints is found.

As for the work presented in this paper, the optimization algorithm is based on the control framework presented in [25], which features convenient characteristics to deal with large-scale electricity grids. The framework merges two main concepts: the energy hub modeling previously presented in [13], which represents an interface between energy inputs and outputs also including energy storage; and Lagrange-based model predictive control formulation [20]. Moreover, it handles the non-linear model of the electricity grid due to the storages as a mixed logical dynamical (MLD) model [5]. This modeling formulation allows to solve the optimization problem with mixed-integer quadratic programming (MIQP) solvers instead of non-linear programming (NLP) solvers. The main reason for using MIQP instead of NLP solvers is not related to optimality reaching (since NLP solvers would guarantee to reach global optimum when dealing with convex functions as well as MIQP solvers would) but related to the computational performance of the problem. Indeed, NLP solvers face a number of practical limitations when dealing with a high number of variables. In contrast, MIQP solvers are much more robust and computationally efficient. In fact, the use of MIQP solvers along with a structured problem statement allows to model, simulate and optimize very large networks in a computationally efficient way.

From this point, this work extends the aforementioned control framework to include hard and soft constraints and ramp rate limits that account for the mechanical limitations of the non-renewable power plants. As presented in [4], these constraints differentiate dynamic EED from static EED. Dealing with hard and soft constraints is very important for this kind of problem since it is necessary to guarantee the satisfaction of the power demand. Then, the power demand satisfaction is defined as a hard constraint while other operation constraints can be violated in some circumstances in order to meet the demand which are defined as soft constraints. Furthermore, this paper extends EED to calculate market-based on-line energy pricing in contrast to the reviewed bibliography, where for the best of this author's knowledge, the resulting electricity prices are fixed in advance.

Given that the work presented in [25] is mostly devoted to the description of the mathematics behind the control algorithm obtention and to the extensive discussion of the stability and optimality proofs which supports this methodology, this work follows a much more practical approach. Specifically, a grid case study is modeled and the implementation of the control problem as well as the procedure to solve it are presented. In addition, a comprehensive analysis of the results is performed and extensively discussed.

While previous works simulated residential areas divided in two energy hubs [2] and three energy hubs [3], this smart grid is composed of 11 generation systems, 6 storages, 11 consumptions and 31 transmission lines divided in 6 energy hubs, which further supports the contribution of this work to the existing literature. Also, the EED is formulated with prediction and control horizons equal to 10 time steps which is more convenient than prediction horizons of 3 time steps simulated in [2,3] when optimizing energy storages.

The remainder of this paper is presented as follows: the electricity grid under study is described in Section 2 while the model is detailed in Section 3. The EED algorithm is developed in Section 4 and the simulations results are discussed in Section 5. Finally, conclusions and future works are presented in Section 6.

2. Electricity grid under study

The smart grid under study presents a high penetration of renewable energy systems with the 76% of the electricity grid generation capacity. This electricity grid can be considered a good benchmark EED since it comprises 11 generation systems: 2 coal-fired power plants, 1 nuclear power plant, 2 concentrated solar-thermal plants, 4 wind farms and 2 external electricity grid interconnections; 6 storages systems: 4 hydrogen-based energy (H2) storages and 2 molten salt thermal energy (MS) storages; 9 consumers: 6 cities and 3 factory centers. Fig. 1 sketches the geographic distribution of the grid components and the 31 transmission lines.

3. Electricity grid model

The electricity grid shown in Fig. 1 is modeled in this work following the "Energy Hub" methodology initially developed in [13]. This modeling enables integration of an arbitrary number of energy carriers and any technology for transmission, conversion and energy storage can be considered. Moreover, the general formulation ensures high flexibility in terms of modeling detail and accuracy, where simplified flow models can be used as well as detailed steady-state power flow equations. This methodology permits to model electricity grids of large size by network partitioning. Each network partition is referred to as "Energy Hub" and is interconnected with other neighbor partitions. This work adopts the energy hub modeling with the following improvements introduced in [25]: the modeling framework is reformulated as MLD in order to eliminate quadratic terms; information regarding network topology is reorganized in a defined set of matrices, which simplifies the modeling process enabling an easier construction of network models; interconnections among hubs are explicitly included in each hub model, which results in simple and standard formulations of network optimization problems.

In this section a brief explanation of the modeling methodology is included. The basis of the modeling is the application of energy balances for the different energy hubs of the electricity grid. Therefore, given a generic energy hub i shown in Fig. 2, the inputs of the

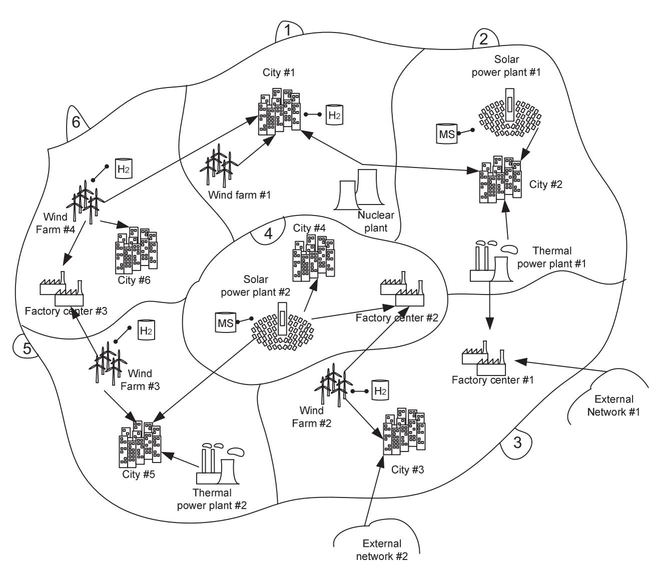

Fig. 1. Electrical grid under study.