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A model predictive control framework for reliable microgrid energy management

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ABSTRACT

This paper proposes a framework for reliable microgrid energy management based on receding horizon control. A microgrid is considered for exemplification, connected to an external grid via a transformer and containing a local consumer, a renewable generator (wind turbine) and a storage facility (battery). Optimal scheduling of battery is sought for minimizing costs. To this aim, a predictive control framework is proposed, which allows taking into consideration cost values, power consumption and generation profiles, and specific constraints. Uncertainty due to variations in the generator model parameters is taken into account. The efficiency of the proposed approach is validated through simulation results and comparisons using real numerical data for a test system often considered in bulk power system reliability evaluation studies. The obtained results show that predictive control is a viable approach for providing optimal energy management solutions accounting for costs, profiles and constraints.

Introduction

Intelligent electrical grids with renewable energy sources have attracted increasing public attention in recent years. Green (solar and wind in particular) energy production is supposed to increase significantly in the coming years, since the traditional energy supplies of Earth are finite and suffer from a ‘‘diminishing returns’’ curse. This requires a ‘‘smartgrid’’ system capable of dealing with distributed production/intermittent variations of output and optimal scheduling of demand [1,24,40,35].

Microgrids can be key solutions for integrating renewable and distributed energy resources, as well as distributed energy-storage systems [19,3,7].

The present paper introduces a model predictive control framework for optimal management of energy production in a microgrid system with renewable and distributed supply sources. For this type of system, it is no longer possible to control each subsystem in isolation, because of the functional dynamic interactions among all subsystems [27,23,4]. Moreover, it is necessary to take into account not only exogenous factors (e.g. change in consumer load, wind speed, price profile, etc.) but also the internal (state) dynamics and the structural properties of the individual components (as wind or solar energy equipment, on-site storage, etc.), which may change (stochastically) due to degradation, failure, aging and so on.

Various approaches for microgrid energy management are reported in the literature. Proposed solution techniques include heuristics [9,26], mathematical programming [11,5] and priority rules [36]. The authors in [15,21,20,37] propose agent-based modeling and simulation to analyze the interactions between individual intelligent decision-makers in microgrid management. Energy management solutions for hybrid renewable energy generation has been proposed in [4,16]. In these works, the long-term goals are focused on the efficient use of electricity within microgrids, e.g., the planning of battery scheduling to store the electricity locally generated from renewable sources and reuse it during periods of high electricity demand. It is important to mention that in these works the decision framework is developed under deterministic conditions, e.g., those of a typical day in summer, and without taking into account explicitly the dynamics of the individual components of the microgrids.

To overcome these limitations and extend the above frameworks, we propose here to use Model Predictive Control (MPC) for handling control and state constraints while offering good performance specifications (see, for instance, [33,34] for basic notions about MPC). Typically, in MPC, the objective (or cost) function to be optimized penalizes deviations of the states and inputs from their reference values, while explicitly enforcing the constraints. Due to

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its versatility, MPC has had a successful record in industrial applications; to mention just a few recent ones: refrigeration systems [14], power production plants [8], transportation networks [27], and microgrid networks [12]. The authors in [38] propose a look-ahead predictive control algorithm to solve the economic dispatch problem with large presence of intermittent resources. In [28] a model predictive controller is applied for controlling the energy flows inside a household system equipped with a "micro" combined heat and power unit. In addition, the household can buy and sell electricity from/to the energy supplier; heat and electricity can be stored in specific storage devices. In [39], MPC is used for energy scheduling on a hydrogen-based microgrid without batteries.

In the present paper, we propose a solution approach for the reliable energy management of a microgrid system based on a predictive control framework. To the best of the authors' knowledge, there does not exist a similar work in the literature. For exemplification purposes, we consider a microgrid scheme taken from [22], which is connected to an external grid via a transformer and contains a local consumer, a renewable generator (wind turbine) and a storage facility (battery). The underlying management setting is one of multi-criteria decision-making for battery scheduling, with the objectives of:

- increasing the utilization rate of the battery during high electricity demand (i.e., decrease of the electricity purchase from the external grid) and
- increasing the utilization rate of the wind turbine for local use (with a consequence increase of the consumer independence from the external grid).

The consumers' load, wind generator and price profiles are provided. Then, a constrained multi-objective optimization problem is defined and solved in an optimal way to follow the predicted profiles, for reliable energy management.

With respect to previous works [21,32,22], we propose also a more realistic model of the battery. In particular, we consider leakage current and a switched model with "charge" and "discharge" functioning modes.

The remainder of the paper is organized as follows. Section 'System and model description' presents the components of the microgrid system and Section 'Optimization-based control for battery scheduling' describes the predictive control model for battery scheduling within the microgrid. Further remarks on the inclusion of a cost function with time-varying weights for better dealing with uncertainties are presented in Section 'Further remarks and results' together with a fault tolerance scheme. Simulation results are given in Section 'Simulation results and comparison' and some conclusions are finally drawn in Section 'Conclusions'.

Notation

The following notations will be used throughout the paper:

– Let $x(t+s \mid t)$ denote the value of x at discrete time instant $t+s$, predicted upon the information available at time instant $t \in \mathbb{N}$ with $s > 0$.
– The length of the prediction horizon is denoted by N_p and the time step is denoted by s.
– Throught the paper, $g(t)$ [W], $g_b(t)$ [W], $b_b(t)$ [W], $b_e(t)$ [W], $b_c(t)$ [W], $p(t)$ [W], are electrical power quantities, $b(t)$ [W h] denotes the amount of energy stored at time step t, $d(t)$ [W] denotes the consumer load, $e(t)$ [Euro/kW h] the market price per hour and $v(t)$ [m/s] denotes the wind speed.
– Let s_{max} denote the maximum number of steps for which the optimization problem is solved.

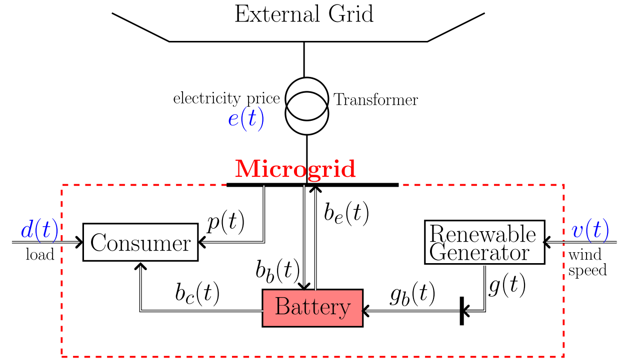

Fig. 1. Microgrid architecture.

System and model description

This section presents the microgrid system, the dynamic models which describe its components, the profiles considered for the constrained optimization problem and the cost function formulation.

Consider the microgrid of Fig. 1, which includes a local consumer (e.g., large cooling houses), a renewable generator (e.g., wind turbine) and a storage facility (e.g., battery). The microgrid is connected to the external grid via a transformer. The goal is to plan the battery schedule in order to achieve the consumer objectives of increasing the utilization rate of the battery during high electricity demand (i.e., decrease the electricity purchase from the external grid) and the utilization rate of the generator for local use (i.e., increase the consumer independence from the external grid).

The interactions between the independent components of the microgrid are most important for accomplishing the consumer objectives. As shown in Fig. 1 there are various links between the components of the microgrid, which determine the energy flow:

- The electrical power transmitted by the renewable generator to the battery at time step t is represented by $g(t) \in \mathbb{R}$ (note that the electrical power actually taken by the battery from the renewable generator can be less and is denoted by $g_b(t) \in \mathbb{R}$)[1].
- The electrical power transmitted by the battery to the consumer at time step t is represented by $b_c(t) \in \mathbb{R}$.
- In order to maximize the utilization of the battery within the microgrid, the consumer takes electrical power from the local renewable generator through the battery. The battery can be charged from the external grid but can also discharge electricity to the external grid: the electrical power transmitted by the battery to the external grid at time step t is denoted by $b_e(t) \in \mathbb{R}$.
- It is possible to sell electricity to the external grid when the level of charge in the battery is deemed sufficient for covering local needs. The electrical power transmitted by the external grid to the battery at time step t is $b_b(t) \in \mathbb{R}$ and the electrical power transmitted by the external grid to the consumer at time t is represented by $p(t) \in \mathbb{R}$. Here, the transformer provides electrical power from the external grid as well as information about the electrical market price, which plays an important role as the consumer can decide to take energy when the price is low. Therefore, the consumer has also the possibility to take electrical power from the external grid when the renewable resource is not available (or sufficient).

[1] By adding this power signal we take into account the possibility for the battery to accept less power than the maximal electrical power given by the generator, as it is the case in realistic implementations.