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Fault tolerant predictive control design for reliable microgrid energy management under uncertainties

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ABSTRACT

This paper presents an extension of a MPC (Model Predictive Control) approach for microgrid energy management which takes into account electricity costs, power consumption, generation profiles, power and energy constraints as well as uncertainty due to variations in the environment. The approach is based on a coherent framework of control tools, like mixed-integer programming and soft constrained MPC, for describing the microgrid components dynamics and the overall system control architecture. Fault tolerant strategies are inserted in order to ensure the proper amount of energy in the storage devices such that (together with the utility grid) the essential consumer demand is always covered. Simulation results on a particular microgrid architecture validate the proposed approach.

1. Introduction

Microgrids are increasingly considered for system solutions including distributed energy resources [6,12,14,16]. This is also because they can help both prepare for, and prevent the threat of climate change. Combating climate change necessarily involves a critical shift away from fossil fuels and towards clean energy, efficiency, and renewable energy. For this, energy resources are inherently distributed and resilient, which makes them naturally compatible with a microgrid system solution.

The flexible configuration and operation of microgrids helps avoid cascading failures and, thus, blackouts and losses of stability. Microgrids can be attached to the utility (grid-connected) and isolated (islanded) easily in case of faults or instability in the external grid. Once the disturbance in the main grid has cleared, microgrids can be connected again and system reliability is improved [1,15].

Realistic modeling and optimization for efficient, reliable and economic planning, operation and control of microgrids are very important and still open issues. Various techniques for the minimization of microgrid operating costs include robust optimization [24]; heuristics [26]; mathematical programming [8] and priority rules [27]. Only recently MPC (Model Predictive Control) has started to have a growing interest between researcher in energy filed, in particular in microgrids applications (see, for instance Ref. [25] for detailed notions on MPC). A method based on the combination of empirical mean, dynamic programming and MPC has been used in Ref. [9] for solving a power management problem within a microgrid in islanded mode operation. In Ref. [18]; a preliminary study has addressed the application of a receding horizon approach for optimizing microgrid operations while satisfying time-varying demands and operational constraints. In Ref. [19]; an approach based on MPC has been designed to manage in real-time the power production of a grid-tied photovoltaic plus energy storage power plant with a reduced energy storage system capacity. It is important to mention that all these papers do not consider explicitly the detailed modeling of the microgrid components, the constraints description and the interaction between the independent components of the micrigrid system. Instead, abstract mathematical models are used to embody the practical and functional behavior of

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the components and the focus is on the formulation of the optimization problem for minimizing costs. In Ref. [17] 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 Ref. [28]; MPC is used for energy scheduling on a hydrogen-based microgrid without batteries. In Ref. [23]; predictive control is applied for renewable energy power management with battery storage in a water desalination plant. In Ref. [13]; MPC is performed for a plug-in renewable energy source with battery storage. The electrical power transferred to the network and that stored in the battery are the control variables considered. Finally Ref. [2], presents the application of hybrid modeling control for a photovoltaic-fuel cell power plant.

In this paper a microgrid is considered for exemplification, connected to the utility grid via a distribution transformer and containing local consumers, renewable generators (wind turbines or photovoltaic panels) and electrical storage facilities (denoted as batteries). These latter represent the key control components in the microgrid energy management. The overall objective of the microgrid system is to generate suitable decisions for all the source and electrical storage components in such a way to fulfill load demands. Fig. 1 illustrates a typical smart energy management system. Based on the output of the forecasting unit, the optimization unit computes a control action such that an operation cost is minimized. Once an optimal controller is obtained, then it is sent to all the storages and sources which need to be controlled. We must precise that forecasting is out of the scope of the present paper, rather we consider real numerical data for the reference profiles as given in Ref. [7].

The overall goal of this paper is to implement a realistic and flexible control scheme where:

- costs, constraints, profiles are taken into account into a centralized constrained optimization problem (i.e., via a model predictive control design);
- depending on external events and energy costs the user may receive only its essential demand or up to the entire desired demand;
- faults at the generator output level are explicitly accounted in both robust (by managing the minimal storage requirements) and adaptive fashion (change of constraints and costs, as a function of system state – healthy, under fault, under recovery).

In particular, the present work extends the optimization-based control approach developed in Refs. [21,22]. More specifically, the original contributions are the following:

- A more realistic and complex benchmark problem replaces the one presented in Refs. [21,22]. That is, we consider more realistic dynamics for the components of the microgrid (especially the key storage component, i.e., the battery) and also we consider that the operative profiles can be affected by noise and perturbations, thus requiring a robust control design.
- The battery charge/discharge cycles are penalized in the cost function, in order to account for the battery wear and tear.
- The user load is partitioned into two components:
  - essential loads, that is, demands of power related to essential processes (e.g., electricity in an operating room, fail-safe modules in critical systems) and that one must always try to meet;
  - non-essential loads, that can be reduced or shed during supply constraints or emergency situations (e.g., standby devices, day-time lighting and the like).
- Reliable functioning of the microgrid is maintained under parameter variations, noises and fault events (e.g., generator output outages). Especially for the latter case, we provide an adaptive control which can handle fault events via subsequent control reconfiguration.
- Extensive simulation results are provided through different scenarios which validate the proposed fault tolerant predictive control scheme.

The microgrid energy control in this paper is done via a centralized scheme which assumes global state, inputs and outputs which appear in the description of the dynamics, constraints and costs. We proceed by defining and illustrating in the rest of the paper these signals and associated matrices, as needed.

The paper is organized as follows. Section 2 describes in detail the considered microgrid system. Section 3 presents the optimization-based control problem for efficient energy management and the considered strategies for fault tolerant control and battery wear and tear. Simulation results are provided in Section 4 and conclusions are drawn in Section 5.

2. Microgrid system description

Any microgrid, regardless on the particular constructive details, will contain several types of components as illustrated in Fig. 2: power generators (e.g., hydro, wind turbine, photovoltaic panels and the like) denoted as

$$\{G_i\}_{i=1\cdots N_g}, \text{ where } N_g \text{ represents the number of generators}, \tag{1}$$

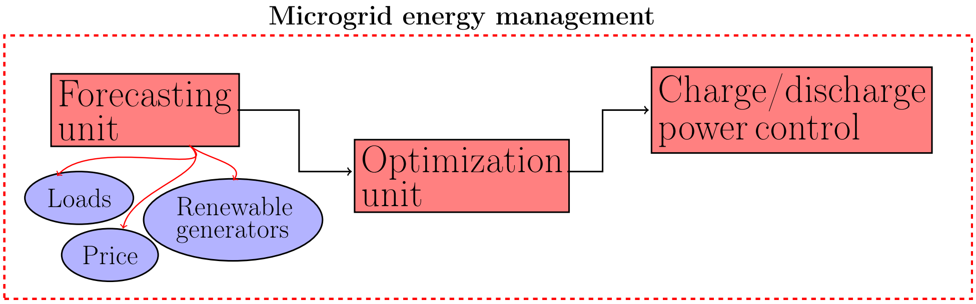

Fig. 1. Microgrid energy management.