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Robust economic model predictive control of a community micro-grid☆

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ABSTRACT

In this paper we propose a novel economic robust predictive controller for periodic operation. The proposed controller joins dynamic and economic trajectory planning and robust predictive controller for tracking in a single layer taking into account bounded disturbances, algebraic constraints and periodic operation. We study the closed-loop system properties of the proposed controller and provide a design procedure that guarantees that the perturbed closed-loop system converges asymptotically to the optimal economic reachable periodic trajectory, constraint satisfaction and recursive feasibility. The proposed controller has been applied to control a cluster of interconnected micro-grids. Each nano-grid is connected to an electric utility and has a renewable energy source, a cluster of batteries and a metal hydride based hydrogen storage system. The cluster must satisfy a periodic energy demand while maximizing the profit of the energy sold to the electric utility taking into account time varying prices.

1. Introduction

Nowadays, the increase of the energy demand is an important problem which is usually faced with limited fossil fuel sources and with environmental restrictions. A way to deal with this problem is the increase in the use of renewable energy sources. In this scenario, micro-grids have gained a relevant role. The definition of a micro-grid from the U.S. Department of Energy Micro-grid Exchange Group is the following: “A micro-grid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A micro-grid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode”. Because the main aim of a micro-grid is to satisfy an internal demand and if possible sell or store the excess of produced energy, the energy storage systems have become very important in the optimal management of this type of systems. The most widely spread storage systems are batteries, however its discharge rate has motivated the development of alternative storage system such as hydrogen based systems.

The optimal management of this type of networks is a challenging problem that has received a lot of attention from the research community. In Ref. [12] a wireless data-link based power management system for a distributed hydrogen system is proposed. In Ref. [27] the important of smart control strategies for PV-hydrogen systems is demonstrated through extensive simulations. In Ref. [18] an experimental small-scaled stand-alone power system based on hydrogen is presented. In Ref. [4] a set of wind/hydrogen energy system modelling tools were validated. Model predictive control has also been applied to this class of systems, see for example [19–22,28] and [24].

Model predictive control (MPC) has demonstrated to be an excellent choice for optimal management of complex control systems, such as multivariable constrained systems, when the main objective is to guarantee closed-loop stability and constraint satisfaction while minimizing a cost function without expert intervention [3,26]. Of particular interest for the optimal operation of micro-grids is the use of an economic cost function as stage cost

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function, that is the so-called economic MPC. This control technique allows the controller to improve its performance during the transients and take into account economic issues explicitly such as the energy and/or degradation costs. Some examples are shown in Refs. [7–9] where MPC designs based on Lyapunov theory have been developed. These approaches are capable of optimizing closed-loop performance taking into account economic considerations for a broad class of complex process systems, such as those subject to asynchronous and delayed measurements and uncertain variables. In addition, in Ref. [25]; recent results on the stabilizing design of economic MPC are summarized. Another important research is presented in Ref. [6] where the terminal constraint is taken from an economic MPC without loosing the stabilizing features of the controller. In Ref. [31]; a single-layer economic MPC has been proposed integrating the RTO into the MPC.

The previous results try to regulate the system to an optimum steady state operation point however, in certain cases, the best way to operate a system from an economic point of view is to follow a non steady trajectory, usually periodic, see Refs. [10,11,14]. In renewable energy systems non-steady state operation appears naturally because of the quasi-periodic disturbances such as exogenous periodic demands, fluctuating prices (as in the electricity for instance) and energy generation profiles. A typical solution to deal with non-steady operation is the use of a predictive control structure composed by two layer in which the optimal trajectory is calculated by a dynamic real time optimizer, that is a RTO which takes into account the dynamic model of process to control, and a predictive control to move the closed-loop system to the previous optimal trajectory, see Ref. [30]. However this approach does not take into account the economic cost function during the transient which has motivated to several authors to propose the use of the economic cost function as a stage cost. Examples of it can be found in Refs. [2,10,11].

A relevant issue that the control system should deal with is the dependence of the economic cost function on exogenous parameters that may be changed along the system evolution, such as energy prices, expected energy demand or unitary operation costs. These changes in the economic cost function may lead to a redesign of the predictive controller, including the constraints of the optimization problem, and the loss of feasibility [5,15]. Recently, a novel MPC formulation that addresses these problems was presented in Ref. [17]. This controller steers the closed-loop system to the best economically optimal periodic trajectory that the system can reach guaranteeing the constraint satisfaction and asymptotic stability even in the case of changes on the economic cost function. This controller was applied to a micro-grid in Ref. [23]. In this work, the control of a non-isolated micro-grid was considered assuming that periodic predictions of the demand and generation profiles of the photovoltaic system were available. The proposed controller did not take into account disturbances in the model or in the predictions and in spite of the inherent robustness of the predictive controllers, certain properties, such as constraint satisfaction, may be lost if the uncertainty is large enough.

On the other hand, energy distribution networks are modeled by algebraic-differential equations, where the algebraic equations typically describe energy balances in the nodes of the grid that may depend on (possibly varying) energy demand. The control system must be designed to ensure the fulfilment of these algebraic constraints along the time together with stability and recursive feasibility of the grid in presence of uncertainty. Motivated by these issues, a robust economic model predictive controller for energy systems subject to constraints on the operation limits and energy balances under random variations of the expected demands and the economic cost function is presented. This controller extends the control scheme presented in Ref. [17] to deal with the robust case following the constraint tightening method proposed in Ref. [1] and taking into account linear differential-algebraic systems. This controller considers additional decision variables introducing an artificial periodic reference and minimizes a cost function that accounts for the economic cost of the artificial variables and the deviation of the nominal predictions from artificial trajectory. The state and input constraints are tightened taking into account a semi-feedback scheme. Due to this linear feedback, the effect of the perturbations is rejected and the controller guarantees robust satisfaction. The complexity of the resulting optimization problem to be solved on line is similar to the one of the nominal controller. The resulting control law guarantees the convergence to a neighborhood of a robust optimal trajectory that minimizes the cost function and satisfies the constraints for all possible uncertainties. Equality constraints for the uncertain system are satisfied thanks to a feed-forward policy.

The proposed controller has been used for the economic operation of a cluster of interconnected micro-grids. Each nanogrid has a renewable energy source, a cluster of batteries and a metal hydride based hydrogen storage system and its connected to an electric utility. The micro-grid system must satisfy an energy load at each sampling time and maximize the profit of the energy sold to the electric utility. It is assumed that expected profiles of the renewable energy generators and of the load are available, although there may exist mismatches between the real and the expected profiles. The mismatches are modeled with a bounded additive uncertainty. The proposed control system operates the energy system minimizing a given operation economic cost and satisfying the load and the operational constraints in spite of the variations on the produced energy, the load and the unitary prices of the cost function.

1.1. Notation

Bold letters are used to denote a sequence of T values of a trajectory, i.e. $\mathbf{z} = \{z(0), \cdots, z(T-1)\}$. $\mathbf{z}(\theta)$ denotes the sequence $\mathbf{z}(\theta) = \{z(0;\theta), \cdots, z(T-1;\theta)\}$. If the cardinality of a sequence is not T, then the sequence is denoted as $\mathbf{z}_N(\theta)$ where N is the cardinal. $\mathbb{I}_{[a,b]}$ denotes the set of integer numbers contained in the interval $[a,b]$ and $\mathbb{I}_a$ denotes the set of positive integer numbers including the origin, that is $\{0, 1, \cdots, a\}$. The notation $(i|k)$ denotes the time step to which a given variable is referred.

2. Problem formulation

In this work we consider the optimal operation of systems defined by the following set of linear differential-algebraic equations subject to both measurable and unknown disturbances:

$$x(k+1) = Ax(k) + B_u u(k) + B_d d(k) + B_w w(k) \quad (1)$$

$$0 = E_x x(k) + E_u u(k) + E_d d(k) + E_w w(k) \quad (2)$$

where $x(k) \in \mathbb{R}^n$, $u(k) \in \mathbb{R}^m$, $d(k) \in \mathbb{R}^s$ and $w(k) \in \mathbb{R}^q$ are the state, input, measurable and unknown disturbance vectors of the system at time step k respectively. The evolution of the measurable disturbance signal $d(k) \in \mathbb{R}^s$ is assumed periodic with period T and known, i.e. $d(k) = d(k+T)$. The disturbance signal $w(k) \in \mathbb{R}^q$ is considered unknown but bounded. It is assumed that the equality constraints (2) have a solution, that is, they are linearly independent and the number of equations is less than the number of inputs.

This class of systems can be used to model distribution networks that must satisfy a demand for which an uncertain prediction is