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Hierarchical economic MPC for systems with storage states☆

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ABSTRACT

Economic model predictive control (EMPC) differs from conventional tracking model predictive control by explicitly incorporating the plant economic cost into the stage cost. One particular class of systems of interest in the deployment of economic MPC are those containing storage devices such as microgrids and hybrid electric vehicles. Such systems may benefit from a two layer control architecture due to the wide range of time-scales that can be exhibited, with the first and second layers comprising a scheduling controller and the EMPC controller respectively. This, in turn, requires an alternative control system formulation since its structure differs from standard economic MPC.

This paper proposes an EMPC control algorithm that is suitable for this particular two-layer problem. The proposed control algorithm ensures that feasibility is always maintained, even in the presence of a changing cost function. Existing EMPC theory is extended in order to prove stability of a set of economically optimal steady states, in a finite time setting. The proposed controller is then used in a simulation of a network connected, hybrid solar photovoltaic (PV) / battery system, and demonstrated to provide superior performance to standard EMPC.

1. Introduction

Economic model predictive control (EMPC) has recently attracted attention within the process control community due to its ability to dynamically optimize the economic cost of system operation (Ellis, Durand, & Christofides, 2014; Rawlings, Angeli, & Bates, 2012). This can yield significant performance improvements compared to regulation based control approaches (Amrit, Rawlings, & Angeli, 2011). In addition to the process industry, EMPC has the potential to improve performance in other applications such as the control of microgrids and hybrid electric vehicles (HEVs). Microgrids and HEVs are examples of systems which contain storage devices whose storage level can vary on a relatively slow time scale compared with the other dynamics exhibited by the system. As a result of the range of time scales present, systems of this nature can benefit from the use of a hierarchical control structure in which the top layer is responsible for scheduling the storage levels on a slow time scale and the second layer is responsible for controlling the fast dynamics (Clarke, Manzie, & Brear, 2016; Olivares, Cañizares, & Kazerani, 2014; Parisio, Rikos, & Glielmo, 2014; Pereira, Muñoz de la Peña, & Limon, 2016). In order to achieve efficient transient performance an EMPC controller can be employed in the second layer as illustrated in Fig. 1.

We consider the problem of designing the EMPC layer of the control structure in Fig. 1 for a class of systems containing storage with dynamics and constraints of the following form

$$x^A_{i+1} = f(x^A_i, u_i), \qquad x^B_{i+1} = x^B_i + h(x^A_i, u_i) \tag{1}$$

$$(x^A_i, u_i) \in \mathbb{Z}, \tag{2}$$

for all $i \in \mathbb{I}$, where $x^A \in \mathbb{R}^{n-p}$ is the *non-storage* state, $x^B \in \mathbb{R}^p$ is the *storage* state and $u \in \mathbb{R}^m$ is the control input. For the case of microgrid and HEV systems the storage state x^B can represent the state of charge (SOC) of energy storage devices. The term x^B can also represent the accumulation of an intermediate or final product of a process. The omission of constraints on x^B in this formulation is justifiable in the context of the motivating applications, such as microgrids and HEVs, and is discussed further in Section 2.2.

In this hierarchical framework, the top level controller periodically provides updated storage state target set-points $\bar{x}^B$ to the EMPC control layer every T samples. This allows information regarding the value of the storage state x^B beyond the next T samples to be communicated to the EMPC controller. The objective of the EMPC controller is to minimize the system cost over the finite time period between updates from the top level controller, taking into account the *value* associated with the storage state x^B. Since the

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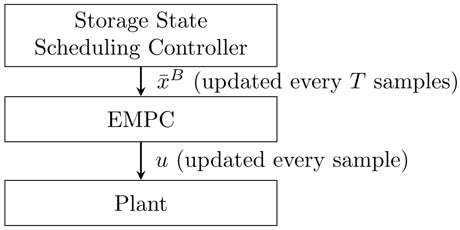

Fig. 1. A hierarchical control structure suitable for systems containing storage. $\bar{x}^B$ is the storage state target set-point and u is the control input.

economic cost is not directly dependent on x^B, the EMPC controller is only concerned with x^B at the end of the current update period. This objective can be expressed mathematically as minimizing the following cost, which is defined for $k \in \mathbb{I}_{\leq T-1}$

$$V_O(x_k^A, x_k^B, \boldsymbol{u}_O, k) = \sum_{i=k}^{T-1} l(x_i^A, u_i) + V_T(x_T^B - \bar{x}^B), \tag{3}$$

where $V_T(.)$ captures the value associated with x_T^B relative to $\bar{x}^B$, $l(.)$ is the economic stage cost, $\boldsymbol{u}_O = \{u_k, u_{k+1}, \dots, u_{T-1}\}$ is the input sequence and k is the current time index. k is incremented at every sample instant and reset when $\bar{x}^B$ is updated every T samples.

For this control problem, the cost in (3) is analogous to the infinite horizon cost considered in standard EMPC formulations. Hence, this problem has a fundamentally different structure compared with the standard EMPC problem e.g. Rawlings et al. (2012). As a result an alternative formulation is required to incorporate the objective in (3) into the cost function of an EMPC controller.

We therefore propose an EMPC control algorithm for systems of the form (1) with constraints of the form (2), which can incorporate the objective in (3) into the cost function and is suitable for implementation as part of a hierarchical control structure as outlined in Fig. 1.

1.1. Review of economic MPC stability theory

Unlike tracking MPC, the objective of EMPC is not to regulate the state to some reference set-point, but rather to minimize the economic cost of system operation. As a result EMPC is concerned with the stability of the economic optimal steady state or periodic orbit, as opposed to a reference set-point or trajectory. Early stability results for EMPC used a terminal point constraint in combination with an assumption of strong duality of the steady state problem to guarantee stability of the economic optimal steady-state (Diehl, Amrit, & Rawlings, 2011). In Diehl et al. (2011) the authors introduced a rotated cost function based on the strong duality assumption which allowed a Lyapunov function to be constructed. In Angeli, Amrit, and Rawlings (2012) and Zanon and Diehl (2013) this approach was extended to allow periodic cost functions and systems. It was also shown in Angeli et al. (2012) that the strong duality assumption can be relaxed to an assumption of strict dissipativity.

Stability of EMPC has also been studied without the use of a terminal point constraint. In Grüne (2013) the author showed that under the assumption of suitable controllability and turnpike properties near optimal performance and convergence to the neighbourhood of the optimal steady state solution can be obtained for a sufficiently large horizon length. This study was extended in Grüne and Stieler (2014) to demonstrate practical asymptotic stability under a relaxed set of assumptions that does not incorporate a turnpike property. Although this formulation possesses desirable performance properties and maximizes the region of attraction, in practice computational limitations can restrict the horizon length. Hence, stability and recursive feasibility cannot always be guaranteed via this approach.

An alternative approach with provable stability properties is to use a terminal constraint set and corresponding terminal cost in place of the terminal point constraint (Amrit et al., 2011). Although this approach can increase the region of attraction of the controller, one of the challenges is the selection of a suitable terminal cost and terminal constraint set that satisfy the sufficient conditions required to guarantee asymptotic stability. In Alessandretti, Pedro Aguiar, and Jones (2016) the authors address this problem by proposing three systematic methods for designing the terminal cost and terminal constraint set in order to guarantee stability of the economic optimal steady state.

In addition to modifying the cost function by adding a terminal cost, the stage cost can also be modified in order to guarantee convergence to the optimal steady state. In Angeli et al. (2012) the authors showed that strict dissipativity can be achieved by adding a convex regulatory term to the stage cost, while in Maree and Imsland (2014, 2016) the authors propose a combined economic and regulatory MPC algorithm. The dual-objective MPC controller proposed in Maree and Imsland (2014, 2016) consists of both economic and regulatory stage costs, which are dynamically weighted to ensure economically efficient transient performance, whilst also ensuring asymptotic stability of the economic optimal steady state. A similar approach is utilized in this work where an additional term is introduced into the stage cost which penalizes any state not at a steady state. However it is shown that the weighting on this term can be made arbitrarily small without sacrificing the stability guarantee. This is in contrast to the multi-objective approaches proposed in Angeli et al. (2012) and Maree and Imsland (2014, 2016) which can require non-negligible weightings on the regulatory component of the stage cost.

Another approach that provides an increase in the region of attraction compared with the terminal point constraint formulations is to utilize a generalized terminal constraint set (Fagiano & Teel, 2013; Ferramosca, Limon, & Camacho, 2014) which constrains the terminal state to be any admissible steady state. In Ferramosca et al. (2014) the authors used this approach to propose an EMPC controller for which recursive feasibility is guaranteed, even in the presence of a changing cost function. This approach was extended in Broomhead, Manzie, Shekhar, and Hield (2015) for the case of an imperfect model with a potentially periodic cost.

The EMPC problem which is the focus of this paper possesses a few key differences compared with the existing EMPC formulations for which stability results have already been developed. Unlike previously studied EMPC control algorithms we are not interested in the stability of an economic optimal steady state or periodic orbit. Instead we are interested in the stability of a set which will be referred to as the optimal pseudo steady state manifold, which is defined in Section 2.1. In addition, this EMPC problem is defined over a finite time interval T, hence we cannot conclude asymptotic stability as is often desired for infinite time problems. Instead the stability result presented in this paper ensures that, under certain conditions, the proximity of the state trajectory to the optimal pseudo steady state manifold is bounded by a class $\mathcal{KL}$ function during the finite time interval and the optimal pseudo steady state manifold is stable. This stability result utilizes an auxiliary cost function as a candidate Lyapunov function (Diehl et al., 2011) and includes a terminal constraint as in Ferramosca et al. (2014) to ensure feasibility is maintained, even in the presence of a changing cost function.

1.2. Preliminaries

Throughout this paper the symbol V is used to represent the various cost functions summarized in Table 1.