Journal of Process Control 47 (2016) 191–200

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

Robustness analysis of a hybrid ground coupled heat pump system with model predictive control

S. Antonov [a,*], L. Helsen [a,b]

[a] KU Leuven – University of Leuven, Department of Mechanical Engineering, Leuven, Belgium
[b] EnergyVille, Thor Park, Genk, Belgium

ARTICLE INFO

Article history:
Received 23 February 2016
Received in revised form 18 July 2016
Accepted 26 August 2016

Keywords:
Robustness analysis
MPC
Ground coupled heat pump

ABSTRACT

MPC of thermal systems usually results in robust operation with respect to uncertainties thanks to some key characteristics of the controller. However, the true limit until which these systems will actually be robust is rarely known explicitly. In this study a Hybrid Ground Coupled Heat Pump (HyGCHP) system with MPC is investigated, for which state estimation and disturbance prediction are highly uncertain, moreover, the system performance is highly sensitive to errors at these points. It has become popular to design control systems which perform explicit computations to assure robustness (e.g. min–max Robust MPC) but this framework is computationally demanding, therefore, not widely applied. An alternative is to perform robustness analysis of an MPC controlled system which is though generally avoided due to complicated theoretical formulations, implicitness and conservativeness of the approach. To tackle these issues an existing framework for robustness analysis is extended and applied to the case of a HyGCHP system with MPC to analyze robustness with respect to state estimation uncertainty. This paper presents an approach to use the original formulation, suggested for regulation/stabilization in order to analyze robustness for the case of set point tracking. The results show that the maximum allowed state estimation uncertainty found by robustness analysis of the regulation problem is confirmed by the simulated HyGCHP system with MPC, which performs set point tracking. In conclusion, the method gives a reliable guarantee for the degree of state estimation uncertainty, up to which the HyGCHP system investigated remains robust. Future research can extend the robustness analysis method towards disturbance prediction uncertainty.

1. Introduction

Robustness to uncertainties is a key quality of MPC controlled systems and one of the methods to achieve it is to determine the level of uncertainty which will be tolerated while retaining the desired control performance. In many cases robustness of control systems to uncertainties is naturally achieved to some extent by means of incorporating feedback. If this approach is insufficient additional actions should be taken at controller side in order to achieve robustness. Maciejowski [1] formulated that the only purpose of applying feedback is to reduce the effect of uncertainties. When it comes to MPC, though, what Doyle [2] stated can be translated as that the simple MPC strategy can never guarantee robustness. Contradictory to that, Heath and Wills [3] observed the inherent robustness qualities of the MPC framework and defined the conditions which have to be satisfied in order to guarantee robustness. Research on related topics is already being developed for the past three decades, as reviewed by Bemporad and Morari [4], Mayne et al. [5], Jalali and Nadimi [6], Al-Gherwi et al. [7].

In this paper the robustness of a HyGCHP system with MPC is investigated, the performance of which is strongly dependent on both state estimation uncertainty and disturbance prediction uncertainty. The system consists of an office building, heating and cooling devices and a borehole heat exchanger as in [8]. The building is equipped with concrete core activation as heat emission system. The concrete core temperature is a state of the state space model of the building. Sourbron et al. [9] concluded that the performance of such a system is highly sensitive to concrete core

Abbreviations: HyGCHP, hybrid ground coupled heat pump; BD, building; BHE, borehole heat exchanger; COP, coefficient of performance; EER, energy efficiency ratio; HP, heat pump; PC, passive cooling; GB, gas boiler; CH, chiller.

* Corresponding author.
E-mail address: stefan.antonov@gmail.com (S. Antonov).

http://dx.doi.org/10.1016/j.jprocont.2016.08.009
0959-1524/

temperature estimation uncertainty as well as disturbance prediction uncertainty. In this study the focus is on system robustness to state estimation uncertainty.

In the context of MPC there exist two main directions to deal with robustness to uncertainties, both having advantages as well as difficulties to implement. The first direction is known as Robust Model Predictive Control (RMPC), in which, at system design stage, information about the uncertainties is explicitly incorporated within the optimization problem of the predictive controller. This way robustness is achieved by computing particular control actions according to the expected uncertainties. This strategy, though, implies substantially more computations at each time step, which hampers the implementation. The other direction relies on robustness analysis of an existing system design. In this case the robustness to uncertainties is translated into particular conditions which are then checked only once based on the controller model and the optimization problem of the MPC formulation. The goal is either to give guarantee that the controlled system will be robust given particular parameters of the MPC formulation, or to compute the maximum allowed degree of uncertainty, for which robust performance is still guaranteed. The computation time does not drastically increase but the challenge is often related to deeper theoretical considerations. However, this approach is characterized by conservativeness in calculating the maximum allowed degree of uncertainty, for which system robustness is still guaranteed.

It is desired the conservativeness of the robustness analysis method to be the lowest possible. This way the full range of uncertainties will be determined for which the controlled system will have robust performance. The higher the conservativeness of the method, the lower the estimated maximum allowed degree of uncertainty. This means that if the method is conservative a margin will be created between the estimated allowed uncertainty and the real degree of uncertainty, which will trigger non-robust performance. The literature related to robustness analysis methods is shortly reviewed in the following paragraph.

Robustness analysis of MPC is a research topic which has mostly been developed in the '90s suggesting different theoretical methods to guarantee robustness to model mismatch and state estimation uncertainty. A few more publications appeared later but then the research in the field has been gradually redirected towards the explicit RMPC design which recently evolves towards nonlinear systems and distributed controllers. Zafiriou [10] derived a sufficient condition for robustness to model mismatch based on contraction mapping. Due to nonlinearities the condition is difficult to check; therefore he also derived easier to check necessary conditions. Megretski [11] derived sufficient and necessary conditions in the frequency domain. He investigated robustness to feedback uncertainty with conic nonlinearities. Genceli and Nikolaou [12] investigated robustness to model mismatch for the case of an impulse response model. They derived sufficient and necessary conditions for Single Input Single Output (SISO) plants, however, for the case of Multiple Input Multiple Output (MIMO) their formulations become difficult to use. Santos and Biegler [13] used a sensitivity analysis approach to derive sufficient and necessary conditions for robustness to model mismatch for the SISO case. Heath and Wills [3] reported the inherent robustness properties of MPC designs with model mismatch. Under the conditions of stable plant and model and feasibility of the optimization for zero input the authors related the robustness guarantee to sufficiently high inputs weighting factors. The majority of the most recent contributions to the robustness analysis research are related to nonlinear discrete time systems and Nonlinear Model Predictive Control (NMPC). Scokaert et al. [14] investigated exponential and asymptotic stability for decaying perturbations. Scokaert et al. [15] showed that for NMPC the feasibility is an important factor for stability and that a suboptimal solution is sufficient for stabilizing. Pannocchia et al. [16] reported how suboptimal NMPC leads to robust exponential stability.

Despite the strong sides of the reviewed research on robustness analysis the cited studies have still characteristics, which do not fit the needs in the current study. Mostly, model mismatch is considered as the source of uncertainty. The majority of the studies are also focused on the SISO case and the strength or the applicability of the approaches decreases when extended to the MIMO case. The research on nonlinear systems and NMPC reflects the development of the control systems, however the investigated representation is still linear. The derived methods for estimation of the allowed uncertainties are difficult to compute or robustness to uncertainties is indirectly dealt with, by e.g. increasing the weighting factors within the MPC formulation.

Primbs and Nevistić [17] presented a robustness analysis framework based on checking when the cost function of the MPC formulation is a Lyapunov function and will be decreasing in consecutive time steps, which is a sufficient condition for robust stability. The condition is checked by finding a feasible solution of the resulting Linear Matrix Inequality (LMI) problem. After a successful LMI feasibility check the robust stability is guaranteed for a precise degree of uncertainty. The method can be used both for model mismatch and state estimation uncertainty. MIMO systems fit in the method and the original MPC formulation remains unaltered.

For the investigated case of a HyGCHP system in order to retain the original MPC design, to guarantee its robust performance, and to obtain new insights into the system the current study is focused on the Robustness analysis approach and based particularly on the framework of Primbs and Nevistić [17]. This approach differs from the explicit RMPC by design, although the research in that direction has progressed more during the past two decades and it is more popular now [4–7]. The aim in this paper is to find a precise range of allowed state estimation uncertainty, particularly for the concrete core temperature at the building side, for which system robust performance is guaranteed.

In this paper the method of Primbs and Nevistić is extended and applied for robustness analysis of a HyGCHP system with state estimation uncertainty in the MPC formulation. The presented work makes use of the original framework of Primbs and Nevistić [17] together with relevant clarifications, corrections and additions for easier implementation, described in details by Antonov [18, Chapter 7]. Since Primbs' method is designed for regulation problems we reason based on the state space coordinate transformation technique in order to apply the method to the set-point tracking case investigated. The composed robustness analysis LMI problem is solved and the maximal allowed state estimation uncertainty is found. The results are validated with simulations of the investigated HyGCHP system with MPC.

In Section 2 first a description of the simulated thermal system is provided and the theoretical background needed in the study is summarized. Then the specific steps taken in order to implement Primbs' method and validate the results are structured. In Section 3 the results are presented. The paper is finalized with discussion, conclusions and considerations about future research.

2. Method

This section starts with a description of the investigated HyGCHP system with MPC. Then theoretical background on key techniques is provided, on which the current study is based. Further explanation is placed about how the method of Primbs and Nevistić [17] is used for the investigated HyGCHP system with MPC and how the