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Nonlinear multivariable hierarchical model predictive control for boiler-turbine system

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ABSTRACT

Economic optimal control has been a major concern in modern power plant. The HMPC (hierarchical model predictive control) incorporates both the plant-wide economic process optimization and regulatory process control into a hierarchical control structure, in which the model predictive control technology has been an effective tool for solving the higher-layer economic optimization problems. Since the power plants are typically nonlinear multivariable large-scale processes, applications of the HMPC can be computationally extensive and resulting in nonlinear and non-convex optimization problems. Since the power plant dynamics changes with load, fuzzy model representing the local input–output relations of the nonlinear power plant system is incorporated to facilitate the convex QP (quadratic program) routine, and thus realize the HMPC. Detailed analysis on power plant steam-boiler generation system has been made to demonstrate the effectiveness of the proposed nonlinear HMPC.

1. Introduction

In a large-scale power system, the thermal power generation plays a leading role in producing electric power. In a thermal power plant, fossil fuel is combusted in a boiler to produce steam from water, which then rotates a turbine. Turbine drives a generator to provide three-phase a.c. power at 50 Hz (in China). Boiler operates following the thermo-dynamic Rankine steam cycle.

A major control task in a power plant is to coordinate the boiler and the turbine-generator as a single entity to achieve a fast and stable dynamic response during load tracking and disturbances, and to further realize the life extension, low emission, heat-rate improvement, etc. Therefore, optimization has been a much concerned issue in thermal power plant operation.

MPC (Model predictive control) has been developed considerably in recent years to become a high-performance control and optimization strategy. The major advantage of MPC is that a constrained multivariable optimization problem can be handled in a straightforward manner. The MPC has made a significant impact on many aspects of energy control system. For example, a constrained multivariable predictive control has been applied to an organic Rankine-cycle based waste-heat energy conversion system to achieve set-point tracking and disturbance rejection [1]. The MPC approach has also been applied for achieving economic efficiency in micro-grid operation management, while satisfying a time-varying request and operation constraints [2]. In a solid oxide fuel cell system, a neural network predictive controller is implemented for thermal stress management by controlling the cell tube temperature to avoid performance degradation by manipulating the temperature of the inlet air stream [3]. In a work on a refrigeration system, the authors describe a novel economic-optimizing MPC scheme that reduces operating costs by utilizing the thermal storage capabilities [4]. A generalized model predictive control has also been applied to control proton exchange membrane fuel cell for realizing maximum power efficiency operation [5]. Since the steam-boiler generation system is a multivariable system subject to various kinds of physical constraints, the MPC can be quite suitable for optimization. The earliest attempt was made by Hogg and El-Rabaie [6], in which a multivariable GPC (generalized predictive control) was constituted on a boiler system. They later developed a local model networks based multivariable GPC for thermal power plants [7]. The GPC has also been used for controlling boiler steam temperature by using neuro-fuzzy networks [8]. It was also applied in a waste heat recovery power plant [9]. Apart from GPC, the DMC

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(dynamic matrix control) was also applied in the drum-type boiler–turbine system [10,11]. More recently, some advanced nonlinear MPC schemes, such as the nonlinear constraint MPC on the coordinated control [12], and the model predictive iterative learning control [13], were developed for controlling the nonlinear boiler-turbine system.

These optimization schemes have been successfully implemented to regulate process variables, and improve the power plant operation. However, nowadays, the major concerns of power plant operation have been on the economic and environmental issues, which are no longer purely engineering problems. The recently developed HMPC (hierarchical model predictive control) could be a quite effective way for realizing the closed-loop economic performance improvement, and reducing the overall operational costs.

In HMPC, integrating dynamic economic optimization and the MPC for optimal operation is usually realized by a hierarchical control structure. In this framework, the higher layer is in essence the HMPC system, which computes economically optimal operating trajectories for the process by optimizing a synthesized cost function over a finite prediction horizon. The lower layer computes feedback control actions using traditional control strategy, which forces the process states to track the operating trajectories coming from the upper layer.

To realize the HMPC function, it is also convenient to define the optimization goal as the integral of the product of energy value and net power produced. In this case, the HMPC utilizes an object function directly reflecting revenue rather than the typical quadratic objective function used in traditional MPC.

Several HMPC schemes have been well developed over the last several years. Paper [14] presents two-layer hierarchical control systems, with the high layer corresponds to a system with slow dynamics, whose control inputs must be provided by subsystems with faster dynamics placed at the low layer. Paper [15] presents integrating dynamic economic optimization and model predictive control for optimal operation of nonlinear process systems, and proves practical closed-loop stability including an explicit characterization of the closed-loop stability region. Paper [16] proposes an energy management system for smart grids with electric vehicles based on hierarchical MPC. Scattolini [17] overviews architectures for distributed and hierarchical MPC, based on over 100 papers.

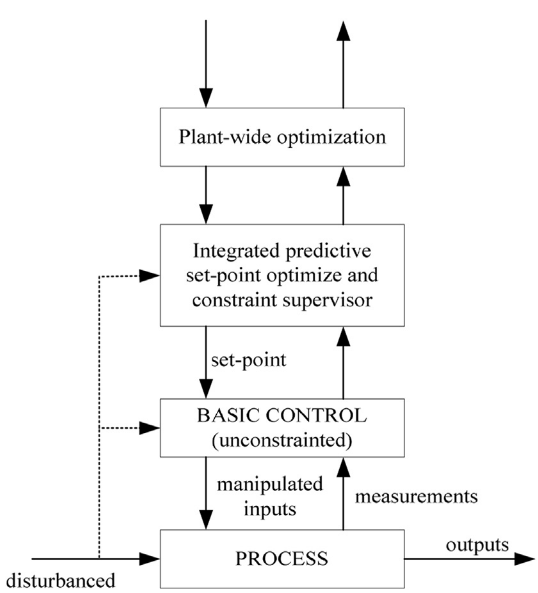

Fig. 1. Hierarchical model predictive control diagram.

Power plants are typical nonlinear multivariable systems, due to the changing operating point right across the whole operation range. In using HMPC, the big challenge is to solve large-scale, computation extensive optimization problems, usually by the SQP (sequential quadratic program). The resulting nonlinear programming problems are usually non-convex, and the online computational burden is generally large; the computing time increases exponentially with the prediction horizon.

While a general way of solving the nonlinear optimization problem is difficult to find, it is reasonable to model the plant using the knowledge of plant dynamics. This power plant dynamics can be described as load-dependent, which has motivated the development of fuzzy model to represent local input–output relationships of the nonlinear power plant. The fuzzy MPCs have been well developed for regulatory control [9,12]. Within this fuzzy modeling framework, the total optimization problem can be solved using the convex QP (quadratic program) routine, and thus the HMPC can be realized. The rest part of the paper is arranged as follows: Section 2 presents nonlinear optimization on HMPC using fuzzy model. Section 3 describes detailed application on power plant steam-boiler generation system, and Section 4 gives conclusion.

2. The HMPC framework

A very popular picture depicting the HMPC structure is shown in Fig. 1, where the regulators at the lowest layer control the actuators, while the two higher levels make reference to the plant-wide optimization problem [18].

In a practical situation, the plant-wide optimization is not always needed. Thus the control structure can be reduced as shown in Fig. 2, which has a two-level control layers. Optimization is performed at the top level, referred to as the supervisory level. It optimizes dynamically an objective function (J), the result of which generates the set-points, r, to the lower level, referred to as the regulatory level. The variables in Fig. 2 are: W, the trajectory of an external reference; y, the controlled variable; u, the manipulated variable or control; v, the measurable disturbance; and e, the non-measurable disturbance.

Obviously, the work is divided into three parts, e.g., the model, the regulatory controller and the MPC objective function. This structure closely follows [15], except that the regulator level utilizes a classical PI controller, rather than the MPC.

2.1. MIMO fuzzy model description

For the MIMO discrete-time nonlinear system, the input–output relationship can be written in the form of

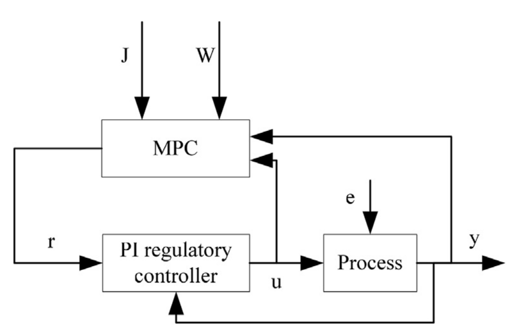

Fig. 2. A simplified HMPC diagram.