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Optimal supervisory control of steam generators operating in parallel

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ABSTRACT

A supervisory control working as a ‘dynamic feedback’ is substantiated for optimally allocating demands to a group of n boilers in parallel. The set-points to each conventional controlled boiler are continuously changed while: (i) minimizing a combined cost, which is cumulative in time and takes into account the dynamics of all individual boilers, and (ii) generating a strategy that can cope with general disturbances, like changes in fuel composition and noisy measurements, i.e. with differences between the predicted and the measured values of the variables. The structure of the problem results in a 2n affine-linear model subject to a quadratic cost, and the resulting optimal control is also affine-linear with time-dependent coefficients, which do not depend on the total vapor demand. The methods are tested with a two case studies for 2 and 3 boilers. It is shown that this dynamical supervisory control leads to savings of at least 10% relative to nontrivial piecewise-constant strategies.

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1. Introduction

Most of the heating systems, although not all, employ boilers to produce hot water or steam. All of the major industrial energy users devote significant proportions of their fossil fuel consumption to steam production: food processing (57%), pulp and paper (81%), chemicals (42%), petroleum refining (23%), and primary metals (10%) [1]. Since industrial systems are very diverse, but often have major steam systems in common, boilers make a useful target for energy efficiency optimization. Also, heating systems in urban buildings consume a substantial proportion of their energy, and are responsible for about 25% of their total carbon emissions, as it is assessed by different surveys in Europe [2,3]. Despite the enormous effort made over the last decades to improve the energy efficiency of these heating systems, a huge potential for further energy saving still persists.

A boiler unit that produces steam is a critical component of the power plant system. One of the main concerns in recent years about the operation of a boiler unit has been the improving its controls as shown by the survey and consecutive experiments carried out in [2]. However, in the current literature and in the industrial environment, many control strategies have been applied to control the boiler as a process unit, ranging from standard methods like proportional integral derivative (PID) control [4] to intelligent and sophisticated methodologies as optimal control, sliding mode control, model predictive control and others, see [4–6] and their references.

Other main concerns of plant operation have been the basic start-up strategy of steam boilers [7], and the minimization of CO_2 emissions [8], where advanced techniques of optimization and adaptive monitoring schemes have been used to improve these objectives. However, the operation of groups of several boilers working in parallel has received little attention in recent technical literature.

In [9], an attempt to optimize energy losses to the environment (or equivalently to maximize the efficiency of the set of boilers), defined from theoretical relations among the many physical variables involved through a supervisory scheme control, is carried out in detail. That supervisory control assigns to each boiler its corresponding vapor production set-point by solving a static optimization problem by linear or nonlinear programming, which is difficult to adapt simultaneously to varying demands of steam generation in a real time operation.

Optimal allocation problems or supervisory control have a long tradition in engineering practice. In chemical processes, dynamic optimization frequently deals with distributing global energy demands of the plant into individual demands required by each member of a group of service equipment (boilers, heat-exchangers, pumps, and the like), while minimizing some predetermined generalized cost. Usually these individual demands translate into set-points communicated to controllers of the PID type, which commonly are well tuned and perform efficiently. In this paper two

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aspects of this routine will be revised: (i) the methodology for deciding the individual set-points after a new total load is required from a group of boilers, and (ii) the convenience of changing these orders continuously in time, by optimizing some combined cost (typically the compromise vapor versus fuel) accumulated during a fixed finite horizon.

According to [10]: ‘ … Real Time Optimizers have been implemented in order to optimize the cost of operating one or more loads. These Real Time Optimizers have detected a steady-state load requirement and then have provided control signals that optimize the cost of operating the loads based on this steady state load requirement. In order to operate in this fashion, the Real Time Optimizers have had to wait for transient process disturbances to settle out so that a steady state condition exists before such Optimizers can invoke their optimization procedures. However, for processes with slow dynamics and/or high levels of disturbances, the dependence of Real Time Optimizers on steady-state information substantially deteriorates the performance of the control system, as no optimization is performed during the transients created by disturbances such as changes in set-point and/or changes in load.’

Other standard treatments follow static optimization lines, common to research operation engineering (see for instance [11,12]). One of the patents related to the topic of this paper ([13], Fig. 1) asserts: ‘Boiler optimization is included in on-line control of parallel boilers by multiplying the total heat per unit time which must be supplied to all parallel boilers by the percentage of the total heat which should be supplied to each boiler in order to substantially maximize energy efficiency. The result of such multiplication is the heat per unit time which should be supplied to each boiler.’ Despite the ‘on-line’ qualification used in this description, it is clear that the ‘heat per unit time’ works as another set-point, and that this target is kept fixed while the total demand is constant. In other words, the resulting demand will be piecewise-constant, each time waiting for another static optimization routine to determine the new appropriate heat rate.

To the authors' knowledge, a thoroughly dynamic point-of-view has only been applied to particular situations, like redundant control and related problems [14]. Here an original ‘dynamic feedback’ strategy will be sought, in the sense that the set-points to each boiler will be allowed to be continuously changed while: (i) minimizing a combined cost, which is cumulative in time and takes into account the dynamics of all the individual boilers, and (ii) generating an optimal control that can cope with general disturbances, like changes in fuel composition, noisy measurements, etc., i.e. with differences between the predicted and the measured values of the variables. With these objectives in mind, a dynamics for the responses of each boiler to a new set-point indication will be assessed, directly from experimental data. Then the whole group of n boilers will be assembled into a general model with an $(n-1)$-dimensional control vector associated with heat demands, the remaining one determined by the residue with respect to the global demand, which is known during each optimization time horizon. This new ‘big’ system, together with a typical quadratic cost functional, conform an optimal control problem that has a nice mathematical solution, namely an affine-linear feedback law with time-variant coefficients. Both the proportional coefficient and the feed-through term in the control law can be calculated only once for a unitary global demand, and stored in memory, the updating for another demand being straightforward. The nature of the modeling also admits a stochastically optimal handling of noisy and systemic perturbations, and eventually a suboptimal online correction [15] of the feedback law due to hard restrictions on control values [9]. In summary, previous papers mostly want to improve the servo control of just a single boiler in different environments, or to allocate steady targets to several boilers. In the first case, they attempt to increase the speed in reaching the set-points provided by the supervisory control. In the second one, they assume that the values of the set-points will be kept constant during a certain period of time (as far as the total vapor demand does not change). The main contribution of our work, by allowing the set-points to be time-varying for all members of the group, even when the total vapor demand remains constant, is then to find their optimal evolution with respect to a quadratic cost criterion.

The rest of the article will be organized as follows: in Section 2 the theoretical setup of the problem is posed and the methods to

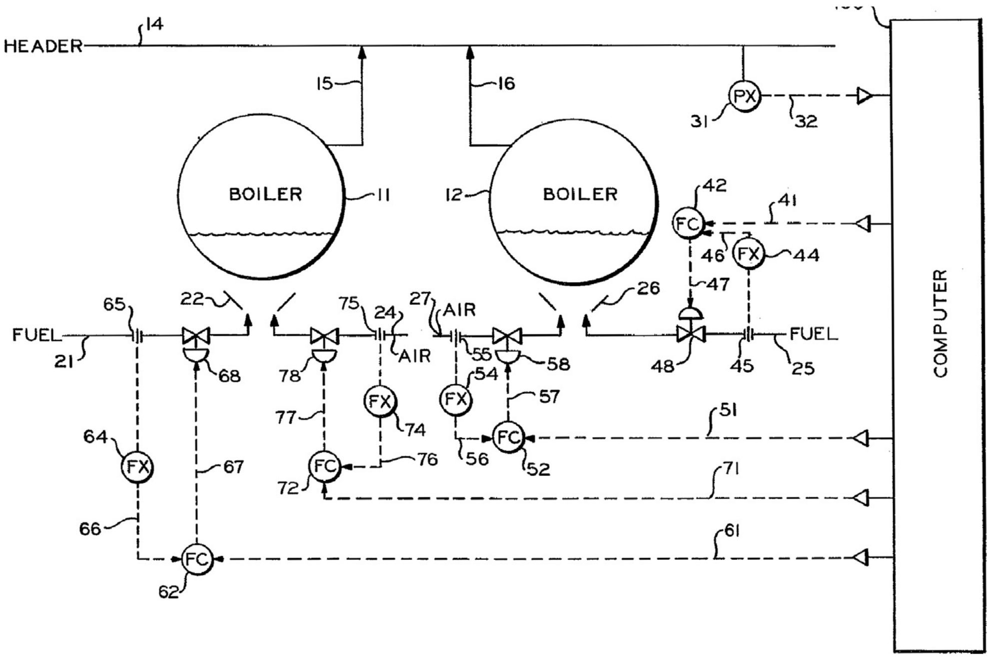

Fig. 1. Scheme showing the control instrumentation for two boilers in parallel, feeding a unique header. Details are given in [13].

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