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Multiplexed optimization for complex air conditioning systems

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ABSTRACT

Optimization has been considered as an efficient tool to realize energy efficiency in the operation of air conditioning (AC) systems. With the increase of complexity of AC systems, the computational complexity of real-time optimization appears to be a challenge for practical applications. In order to overcome the challenge, this paper proposes a multiplexed optimization scheme. Unlike conventional optimization that optimizes and updates all decision variables simultaneously, the proposed scheme optimizes and updates the decision variables sequentially and one decision variable at a time. The proposed scheme is compared with a conventional optimization method (in which the genetic algorithm is adopted) as regards computational load, energy performance and system stability. Case studies show that compared with the conventional optimization method, the computational burden of the proposed scheme is greatly reduced, up to 98.3%; the energy saving achieved by the proposed scheme is 6.8%, which is comparable to that achieved by the conventional method (6.7%); and the system operation stability is significantly enhanced since the average tracking errors for several monitored variables were reduced around 50%.

1. Introduction

Optimization addresses energy and cost-efficient control of AC systems while providing satisfactory indoor comfort and healthy environment under variable working conditions [1]. It is utilized to seek energy or cost-efficient control settings for local controllers or operation modes of the components of an AC system without sacrificing indoor thermal comfort. Optimization is often carried out by taking account of interactions among AC components and thermal characteristics of a building according to present or predicted weather and/or occupancy conditions. A number of optimization controls have been developed since 1980s, reviewed by ASHRAE handbook [1]. New developments since 2000 were surveyed by Wang and Ma [2]. Those review studies show that a generic framework of optimizing AC systems has been established, and the basic components are cost function, decision variable, and constraint.

A cost function is actually a mathematical model that describes the relationship between a cost and its relative variables. In AC optimization the cost function is usually a utility cost over a billing period (*e.g.* a month) or monthly/annual energy consumption [1]. The relative variables of a cost function are variables that have significant impacts on the cost, which include uncontrolled variables, continuous control variables and discrete control variables. Not all of the variables need to be optimized. The variables that are optimized are titled as decision variables. The decision variables can be separated into two categories: operation mode (*e.g.* on/off status of AC components, usually being a discrete control signal) and set-points for some local control settings.

The AC optimization is always subject to various constraints. Constraints describe feasible ranges or limitations on the operation of AC systems. There are two types of constraints: hard and soft constraints. Hard constraints (or physical operating constraints) include energy and mass conservation, mechanical limitation and environmental limitation. Soft constraints are used to describe requirements from equipment and occupants. For example, a room temperature should be limited to around 25 °C to satisfy occupants' thermal comfort requirement; and chillers should not be frequently switched on and off in order to protect the equipment. Constraints are generally described using equalities or inequalities.

Many optimization algorithms, including evolutionary algorithms [3–5], branch and bound [6,7] and simulated annealing [8,9], have been shown to be successful in minimizing energy consumption and reducing operation cost for small-scale AC systems. With the increase of system scale and complexity, optimization becomes more and more complex. For example, more

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decision variables need to be considered; and more constraints should be taken into account. Since the cost function used in a general optimization is always nonlinear to decision variables, real-time computational burden becomes an issue. Meanwhile, as multiple decision variables are optimized and updated simultaneously, system stability might be another issue because main components of an AC system are always under closed-loop control and these components interact with each other. For example, the change of chilled water temperature will affect the control of the supply air temperature of an air-handling unit. When the set-points for both the chilled water temperature and the supply air temperature are changed simultaneously, a significant disturbance might be added to the control loop of the supply air temperature, where a PI control is generally adopted [10]. If the control parameters of the controller are not well tuned (always true in practice), a large variation or even oscillations may occur in the supply air temperature [10,11].

To address the above issues, a multiplexed optimization scheme is proposed for a complex AC system when computational complexity and system stability appear to be challenges. The concept of multiplexed optimization is proposed and developed based on the observation that (i) the computational complexity of optimization will reduce if the number of decision variables is reduced; and (ii) the control stability will improve if the number of simultaneously updated decision variables is reduced. Suppose that a given dynamic optimization requires τ seconds to update all the N decision variables simultaneously. The multiplexed optimization scheme uses a faster optimization frequency or a shorter optimization period, *i.e.* τ/N seconds, to optimize and update only one decision variable at a time. All the decision variables are optimized and updated once and only once in each original optimization period (τ seconds) following a fixed sequence. Since there is only one decision variable at each optimization time, exhaustive search can be used as a tool to seek the optimal solution. It is chosen due to the nonlinearity of system models, which may lead to a non-convex optimization, and analytic solutions being difficult to find.

It should be noted that the development of multiplexed optimization was motivated by the work of Ling et al. [12,13], which aimed to reduce the computational complexity of model-based predictive control (MPC). Here we want to emphasize the application of multiplexed optimization in a complex AC system and study its performance as regards computational load, energy performance and system stability. Case studies are therefore concentrated on analyzing the three aspects by comparing it with a conventional scheme in which multiple decision variables are optimized and updated simultaneously. In the rest of the paper, a complex AC system is firstly described and the general form of a conventional optimization design is introduced; the proposed multiplexed optimization scheme is illustrated as follows; and finally presented are the case studies and results analysis.

2. Optimization of complex AC system

2.1. Complex AC system

A complex AC system in this study refers to a system that consists of a cooling water loop, two chilled water loops (primary loop before heat exchangers and secondary loop after heat exchanger), and an air distribution subsystem. Fig. 1 shows the structure of a complex AC system that consists of cooling towers, chillers, heat exchangers, air-handing units and zones. The multiple-chiller plant is used to generate chilled water while the multiple-cooling-tower system is used to dissipate heat. Variable speed pumps are used to deliver chilled water from the chiller plant to the primary and secondary chilled water loops. The chilled water is conveyed to the air-handling units to condition supply air that is delivered to zones for cooling.

Fundamental controls used in this type of AC systems are described as follows.

Chiller sequencing control: this control determines which and how many chillers should be switched on or off according to current load condition. Total cooling load based sequencing control is used, in which the sequence is determined according to the instantaneous cooling load Q_{ch} measured by Eqn. (1) [14], where C_p is the specify heat of water, M_w is the water mass flow rate; and $T_{chw,rtn}$ and $T_{chw,sup}$ are the temperature of the chilled water return and supply. When the operating chillers have equivalent rated cooling capacity Q_{rate} and are allocated equivalent cooling load, the number of chillers N_{ch} that should be staged on can be simply calculated by Eqn. (2), where ceil(·) is a function to round a number to the nearest integer toward positive infinite.

$$Q_{ch} = C_p M_w \left(T_{chw,rtn} - T_{chw,\mathrm{sup}}\right) \tag{1}$$

$$N_{ch} = \mathrm{ceil}(Q_{ch}/Q_{rate}) \tag{2}$$

Cooling tower sequencing control: this control determines which and how many cooling towers should be switched on according to the amount of the heat needed to be rejected. The number of cooling towers N_{ct} is determined simply according to the

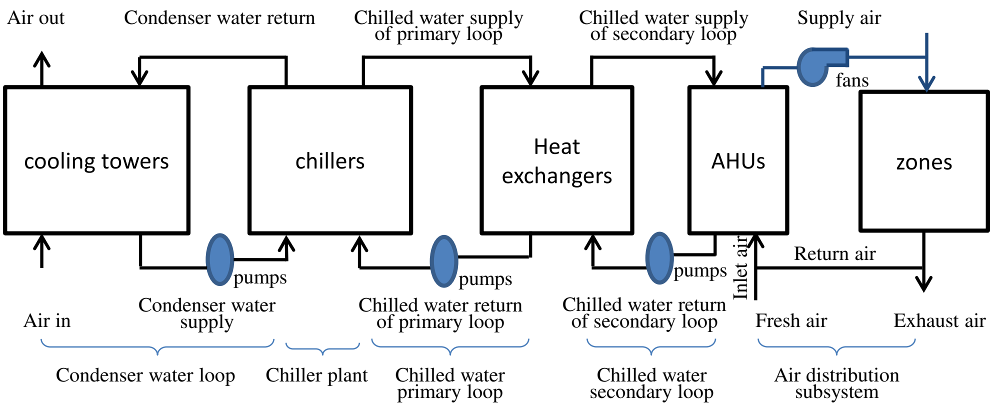

Fig. 1. Structure of a complex AC system.