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Multiplexed real-time optimization of HVAC systems with enhanced control stability

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HIGHLIGHTS

- Multiplexed real-time optimization was developed for HVAC systems.
- Degree of freedom based reset was integrated into the multiplexed optimization.
- Around 10% energy savings was achieved by the proposed method.
- Tracking errors of the HVAC local loop controls were reduced by over 26%.

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ABSTRACT

In a central heating, ventilation, and air conditioning (HVAC) system, the set-points for several local control loops have a significant influence on the overall energy performance of the system. Real-time optimization (RtOpt) of those set-points has therefore been widely studied. However, due to the nonlinear dynamics of the HVAC system as well as the constraints associated with the system operation, real-time optimization always suffers from a heavy on-line computational load when those set-points are optimized simultaneously. To overcome this problem, multiplexed real-time optimization (MRtOpt) has been developed, which optimizes only one set-point at a time but with a faster optimization frequency. Because frequently resetting the set-points introduces artificial disturbances into the local control loops and may deteriorate the system stability, this paper presents a study to enhance the system stability of the multiplexed real-time optimization by integrating a degree of freedom (DOF) based set-point reset to renew the set-points instead of the conventional step-change set-point reset. The control performance of the integrated strategy was investigated using case studies. The results showed that around 10% of the energy saving was achieved by the proposed method compared with a method without real-time optimization. When compared with the conventional real-time optimization method, the proposed method resulted in around 70% computational load reduction, and over 26% reduction in the tracking errors of the local control loops.

1. Introduction

Climate change has created international pressure to improve building energy efficiency [1]. Because heating, ventilation, and air-conditioning (HVAC) systems are the largest primary energy consumer in buildings (generally over 40% of the total energy use in commercial buildings), it is important to improve the energy efficiency of such systems [2]. As an efficient method for improving building energy efficiency, optimal control gains growing interest nowadays [3–8]. Optimal control can be applied to the HVAC system to search the optimal set-points regarding the system energy use because the set-points for several local control loops in a typical central HVAC system have a significant influence on the system overall energy performance [4–7]. It is well-known that the optimal set-points for the local control loops will be different at different operating environment regarding the system energy use, and thus real-time optimization becomes necessary. The basic structure of the real-time optimization is shown in Fig. 1, where the real-time optimization identifies the optimal set-points for the local control loops according to current operating condition and based on the system models that can describe the relationship between the set-points (decision variables) and the energy use (the cost function).

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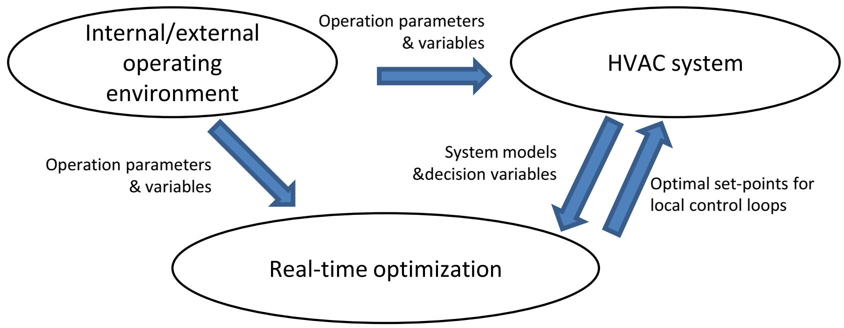

Fig. 1. Modularized real-time optimization of HVAC systems.

Previous studies have shown that the real-time optimization of HVAC systems is able to exploit complex interactions between physical variables and their dynamics to achieve substantial energy savings (up to 30%) without sacrificing air quality and thermal comfort [8–10]. However, the real-time optimization of HVAC systems is always a large-scale mathematics programming challenge due to: (i) multiple set-points being involved simultaneously, (ii) the use of a large number of equations to describe the input-output relationships of the HVAC components and the interactions among the components, and (iii) the use of many inequalities to describe operational constraints [11–13]. Thus, the online computational burden of the real-time optimization of HVAC systems is high, and the global optimizers may be difficult to find as the optimization is always non-convex [14–16].

To deal with this challenge based on the understanding that '*do something sooner*' may lead to better performance than '*do the optimal thing later*', a unique optimization strategy, multiplexed real-time optimization (MRtOpt), was proposed for HVAC systems [17]. The MRtOpt strategy optimizes one set-point at a time but increases the optimization frequency (in principle all the set-points under consideration can be optimized once in one optimization cycle of the conventional strategy, which can be referred to Section 2.1). Because there is only one set-point to be optimized at each optimization time, simple search methods, such as the exhaustive search inside the feasible range of the set-points, can be adopted to seek its optimal value. The results in [17] show that the MRtOpt strategy can significantly reduce the computational burden while not sacrificing the energy performance when compared with the conventional real-time optimization.

After optimization, all the set-points need to be reset. Resetting a set-point will usually introduce artificial disturbances into the corresponding control loop because the controller needs to adjust its control output to track the new set-point. Simultaneously, the disturbance in this control loop will propagate into other interacting control loops [18]. To simplify the description, the control loop for the set-point to be reset is thereafter titled as *Type I control loop* for this set-point while all the interacting control loops are titled as *Type II control loops* for this set-point.

A traditional resetting method always follows a step change, *i.e.* the set-point is changed to its new value using one step. As the step-change reset always leads to significant disturbances in the local control loops, ASHRAE Handbook recommends a rate-limited reset [19], *i.e.* the set-point is changed to its new value using multiple steps with the same magnitude of change. However, the rate (the magnitude of change at one step) is always defined using a rule of thumb and lacks systematic study in practice. Thus, a degree of freedom (DOF) based set-point reset was proposed to systematically reduce this type of disturbances [18]. To use the DOF-based set-point reset, disturbance models should be built to describe the dynamic behavior of the local control loops activated by the set-point reset. Our previous results in [18] show that the DOF-based reset can reduce the disturbances significantly as compared to the conventional step and rate limited reset.

This paper presents a study to investigate the control stability enhancement when the DOF-based set-point reset is integrated into the MRtOpt and applied to a typical HVAC system. In the proposed integrated method, the disturbance models for each set-point that needs to be optimized will be identified to describe the transient behavior in the local control loops activated by resetting the set-point. All the disturbance models will be developed using a subspace identification method (SIM) following the canonical variant analysis approach [20–22]. Using those disturbance models, the set-point reset will be formatted as a model-based optimization problem with several DOFs to reduce the disturbances or the tracking errors in the local control loops. To illustrate the proposed method, a dynamic simulation platform of a typical HVAC system will be constructed using the software TRNSYS. This simulation test bed will be used as an 'actual' system to test the performance of the proposed method.

This paper is organized as follows. Section 2 introduces the concept of the MRtOpt and the DOF-based set-point reset and illustrates. The integration of the DOF-based set-point reset into the MRtOpt is also illustrated in this section. Section 3 presents several case studies to test the proposed method. Application issues are discussed in Section 4. Concluding remarks are given in Section 5.

2. The proposed optimization strategy

2.1. Multiplexed real-time optimization

The basic idea of the MRtOpt is shown in Fig. 2(a), where N is the total number of the set-points that will be optimized; $k\tau$ indicates the time instant; while τ is the optimization interval of a conventional strategy that optimizes all set-points simultaneously. During the interval τ, all set-points will be optimized sequentially at the time $k\tau,\ k\tau+\hat{\tau}_1,\ \cdots,\ k\tau+\hat{\tau}_{N-1}$. The intervals $\hat{\tau}_1,\ \cdots,\ \hat{\tau}_{N-1}$ may not be equivalent and they should be determined by the dynamics of the corresponding local control loops.

Compared with the conventional optimization, which is shown in Fig. 2(b), the computational load is reduced because the space for searching the optimizers is reduced from N dimensional space to 1 dimensional space although the optimization frequency is increased by times. It should be noted that the MRtOpt is only a suboptimal scheme compared with the conventional RtOpt. However, the MRtOpt offers a more rapid response to the load variation,