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Hybrid Adaptive Modeling to Enhance Robustness of Real-Time Optimization

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***Abstract*—**Real-time optimization has been considered an effective approach for improving energy efficient operation of heating, ventilation, and air-conditioning (HVAC) systems. In model-based real-time optimization, model mismatches cannot be avoided. When model mismatches are significant, the performance of the real-time optimization will be impaired and hence the expected energy saving will be reduced. In this paper, the model mismatches for chiller plant on real-time optimization are considered. In the real-time optimization of the chiller plant, simplified semi-physical or grey box model of chiller is always used, which should be identified using available operation data. To overcome the model mismatches associated with the chiller model, hybrid Genetic Algorithms (HGAs) method is used for online real-time training of the chiller model. HGAs combines Genetic Algorithms (GAs) method (for global search) and traditional optimization method (i.e. faster and more efficient for local search) to avoid conventional hit and trial process of GAs. The identification of model parameters is synthesized as an optimization problem; and the objective function is the Least Square Error between the output from the model and the actual output from the chiller plant. A case study is used to illustrate the implementation of the proposed method. It has been shown that the proposed approach is able to provide reliability in decision making, enhance the robustness of the real-time optimization strategy and improve on energy performance.

***Keywords*—**Energy performance, hybrid adaptive modeling, hybrid genetic algorithms, real-time optimization, heating, ventilation, and air-conditioning.

I. Introduction

THE world's energy consumption has scaled over recent years [1], making energy conservation an important issue worldwide. Building energy consumption contributes heavily to the world energy consumption. For instance, building energy consumption in U.S. was 41.1% of total energy consumption, 40 % of which was contributed by building HVAC systems [2]. This percentage is more than double for Hong Kong [3]. Therefore, there has been increasing interest in developing advanced control techniques to optimize the energy consumption of HVAC systems [4]-[6].

Previous studies have shown real-time optimization is able to capture the complex dynamic of HVAC systems and is able to provide reasonable energy saving [7], [8]. The model-based real-time optimization relies on subsystem dynamic models of HVAC system. In order, to predict the performance and expected energy consumption. In past, large number of models has been documented. The reference manual HVACSIM + building system and equipment's documented 26 dynamic models for HVAC components [9]. The ASHRAE reference guide reviewed the dynamic models for HVAC systems [10]. Due to the complexity of physical models means it requires high computational load and memory demands. Making physical models not suitable for real-time optimization. Consequently, simplified semi-physical or grey box models are preferred. The parameter identification of grey box models is done once mostly through regressing [11]. In practice under variable ambient conditions, model mismatches of performance models of HVAC systems cannot be avoided. The model mismatches in performance models of HVAC systems (used to predict the performance), can result in poor performance of the real-time optimization and consequently reducing the energy savings.

This paper presents an investigation for robustness enhancement of real-time optimization. For this study, effects of model mismatches of chiller plant performance model, i.e. difference between prediction and actual plant output, on real-time optimization have been considered. To improve the reliability of prediction of chiller plant performance model, hybrid adaptive modeling technique was developed, which incorporates the HGA methods [12] for the online real-time training of chiller plant performance model. HGA uses GA method for global search and for local search traditional optimization method is employed, which provides faster convergence in local search. Since GAs can struggle to converge and increases computationally load when it comes to local search [12]. To illustrate the implementation of proposed method, a dynamic simulation platform of a typical HVAC system is constructed using the simulation software TRNSYS and used as 'actual' system.

This paper is arranged as follows: Section II illustrates the concept of the hybrid adaptive modeling of chiller plant; Section III presents a case study to demonstrate the performance of the proposed method; Followed by the concluding remarks.

II. Methodology

A. Real-Time Optimization of HVAC Systems

Real-time optimization of HVAC systems is used to find the optimal setting or set-points for system operation. It relies on current operating condition (by means of sensors) and subsystem performance models of HVAC system to describe the relationship between set-points and power consumption. The overall system power consumption may be treated as a

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cost function or objective function for the optimization problem. Following this subsystem power models are required to formulate model based optimization task. Grey box model or simplified semi-physical models are selected for this task. That requires training or identification of parameters. But due to static nature of performance model and variable operating condition (or ambient condition) model mismatch could not be avoided. That could affect the reliability of optimization and affect the overall energy performance of the HVAC system. The adaptive model can be used to overcome this problem; that would require online re-calculation in real-time on a regular time basis, that could increase the computational load significantly. Secondly, performance of adaptive model has to be reliable. In this study HGA is synthesized to provide a reliable solution to this problem. Simplified chiller plant model will be tested with hybrid adaptive modeling technique in this study.

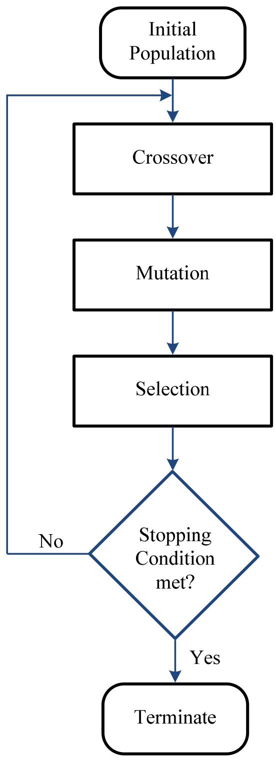

Fig. 1 Sequence of mutation, crossover and selection operation

B. GA Method

A GA is a population-based soft computing technique, generally used for optimization [13]. It is based on the process of natural evolution and Generic principles. GA method is considered to be global search method. The power of a GA comes from their ability to explore for promising solutions in the search space and at the same time exploiting the best solutions found so far.

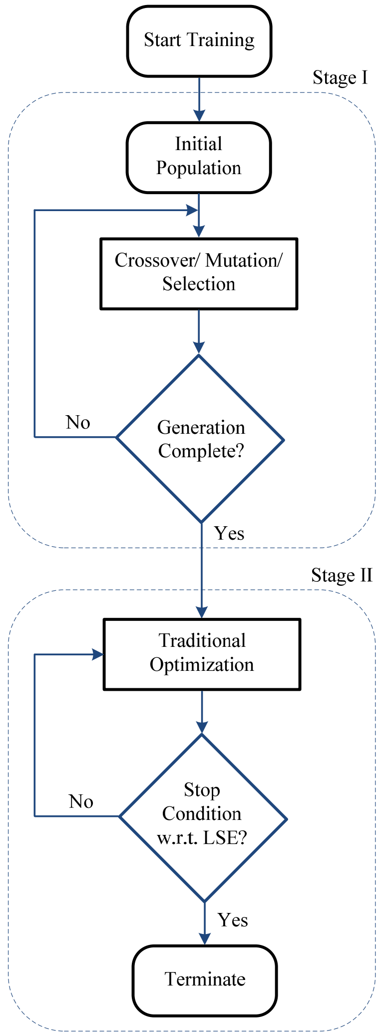

Fig. 2 Workflow mechanism of adaptive modeling with HGAs

Set of possible solutions (or individual) are input of the algorithm, with fitness value assigned to each solution to quantify goodness of a solution. The solutions in the population are represented by chromosomes. GAs method performs three basic operations: mutation, crossover, and selection, in order to generate new population from the present population, i.e. illustrated in Fig. 1. Selection operation selects chromosomes based on fitness value, from new chromosomes class generated by mutation and crossover operations.

In practice, due to the finite population size, sampling ability of GA method is impaired. Furthermore, with the finite population size GA method can produce a solution of low quality as compared to the solutions produced by traditional optimization method. GA method is considered to be global search method since they are able to search space in which global optimum exists fairly quickly. But they suffer from the rate of convergence when it comes to local optimum. This may increase the computational load as well.

C. HGAs for Adaptive Modeling

HGA adaptive modeling technique is used in this study to enhance the convergence and accuracy of the final result, without amplifying the computational load. HGA combines the GAs ability of more rapid global search and traditional optimization methods ability of faster and more effective local search [12].

The identification of chiller model parameters is synthesized as an optimization problem with HGAs. Where the Least Square Error between the actual output power of chiller plant and the estimated output power of chiller performance model is treated as a cost function. At first stage of training, GAs method is used to find initial population/ variables from given limited set of data, which is then utilized in the second stage by traditional optimization method to search for a final set of chiller plant model parameters, much faster (avoiding the long hit and trial process of GAs). Workflow mechanism of HGAs is illustrated in Fig. 2.

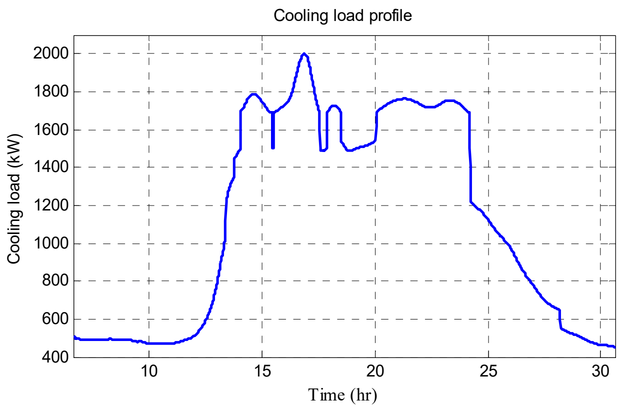

Fig. 3 Comparison of overall power consumption of two cases

III. Case Study

A case study is carried out to demonstrate the implementation of the proposed approach. Dynamic simulation platform was constructed for this purpose and real-time optimization was implemented with hybrid adaptive chiller plant model. Comparison between proposed approach and conventional approach was carried out based on two criterions energy performance of the overall system and mean square error of decision variables.

A. Simulation Platform

Simulation test bed is constructed using simulation software's TRNSYS and MATLAB. Major components used for HVAC system design are chiller, cooling tower, cooling coil, variable speed pumps, variable speed fans, flow mixer/ diverter and proportional-integral (PI) controller. The basic structure of simulation platform involves one cooling water loop, two chilled water loops (primary and secondary) and one air conditioning loop. Chiller plant supplies chilled water at desired set-point that is derived through the primary and secondary chiller loops by means of constant speed pump in primary loop and variable speed pump in the secondary loop. The heat rejection from the condenser is carried out through cooling water from the cooling tower. Chiller water is supplied to air handling units (AHUs) to condition the supply air, which is conveyed to the load. Supply air set-point is also optimized to maintain the optimal power setting. PI controllers are used as control/ compensator element in local loop control as it acts as low pass filter to minimize noise components and has the ability to eliminate steady state error. Dynamic simulation platform was in TRNSYS simulation environment and optimization of system decision variables was carried out in MATLAB.

Cooling load profile derived from real building in Hong Kong was used in this study, i.e. presented in Fig. 3.

B. Optimization Problem

Optimization is carried out on regular time bases to find the setting of the HVAC system such that overall system power consumption will be optimized. A typical objective function is presented in equation (1) that is total power consumption of chiller, cooling tower, pumps and fans at time instant k [11], [14]. The objective is to find optimal control setting or operational set-points (cooling water set-point temperature, chilled water set-point temperature and supply air set-point temperature) for local control loops. Mathematically optimization problem can be given by (2).

$$P_{sys,tot,k} = P_{ch,tot,k} + P_{ct,tot,k} + P_{pump,tot,k} + P_{fan,tot,k} \quad (1)$$

$$\left(T^*_{cwr,k}, T^*_{chws,k}, T^*_{sa,k}\right) = \arg\min_{T_{cwr,k}, T_{chws,k}, T_{sa,k}} P_{sys,tot,e} \quad (2)$$

subject to operational constraints to specify the upper and lower limits of decision variables:

$$\begin{gathered} 28^\circ C \le T_{cwr,k} \le 35^\circ C \\ 5^\circ C \le T_{chws,k} \le 8^\circ C \\ 14^\circ C \le T_{sa,k} \le 20^\circ C \end{gathered} \quad (3)$$

C. Performance Evaluation

In order, to evaluate the performance of the proposed approach, to cases were examined:

i) Real-time optimization using static chiller model
ii) Real-time optimization using hybrid adaptive chiller model

For case, (i) training of chiller model was carried out in different load condition then the test condition. The Same model was used as an initial model for (ii) case, i.e. with hybrid adaptive chiller model. The performance of static chiller plant in real-time is presented in Fig. 4. It shows static chiller model does fairly good job in low load period, but it struggles in high load period, due change in operating condition and static chiller model. The performance of adaptive chiller plant in real-time is presented in Fig. 5. It can be it does as a very good job for both low load and high load period.

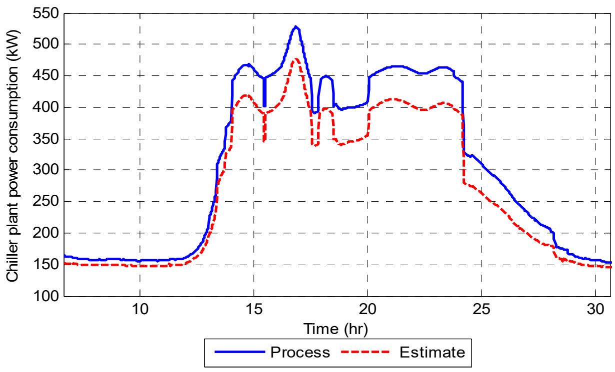

Fig. 4 Real-time performance of static chiller plant model

These performances are reflected in local loop performance of decision variables MSE. As shown in Table I, for condenser water return temperature (CWRT) there was not much difference between two cases. Chilled water supply temperature (CHST) suffers most in case (i) and about 84.21% improvement from the case (i) to case (ii) was observed. There was 38.45% improvement from the case (i) to case (ii) for supply air temperature (SAT). Following this, it can be said that proposed approach was able to enhance system stability.

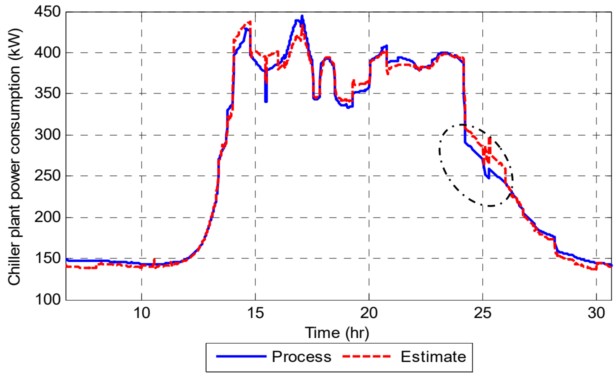

Fig. 5 Real-time performance of online trained chiller plant model

These performances are reflected in local loop performance of decision variables MSE. As shown in Table I, for condenser water return temperature (CWRT) there was not much difference between two cases. Chilled water supply temperature (CHST) suffers most in case (i) and about 84.21% improvement from the case (i) to case (ii) was observed. There was 38.45% improvement from the case (i) to case (ii) for supply air temperature (SAT). Following this, it can be said that proposed approach was able to enhance system stability.

TABLE I
LOCAL LOOP PERFORMANCE W.R.T. MSE

	MSE		
	CWRT	CHST	SAT
Case i	0.0208	0.2585	0.084
Case ii	0.0212	0.0408	0.0517

The comparison of overall system power consumption is presented in Fig. 6. It can be seen for case (ii) proposed approach performs better in high load period as compared to the case (i); which suffers due to model mismatch. Even for case (ii) it can be realized from a marked portion of Fig. 5 and Fig. 6; total power consumption swells when there is a small mismatch in power consumption of chiller plant. Energy consumption for case (i) with real-time optimization using static chiller model was 1456.8 kWh and for case (ii) with real-time optimization using hybrid adaptive chiller model was 1440.2 kWh. Overall there was 1.14% improvement in energy consumption from case (i) to case (ii).

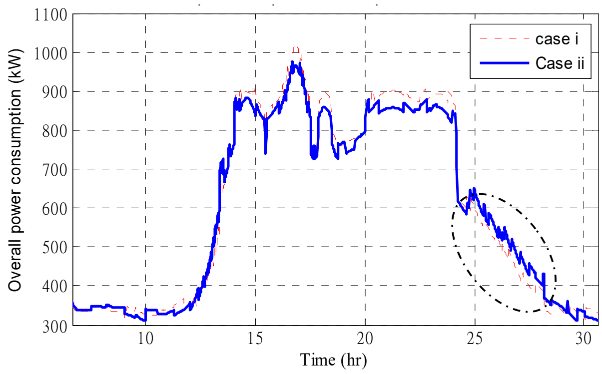

Fig. 6 Comparison of overall power consumption of two cases

IV. CONCLUSION

This paper deals with the model mismatches of performance model of chiller plant incorporated for the real-time optimization. The HGA method was used for adaptive model development of chiller plant performance model, to overcome this problem. The HGA provides faster global search through GA method and more effective local search through traditional optimization method, to provide efficient online training of the chiller performance model. Overall it provides reliable performance (as it always converges) and fast online training of chiller model. A case study was included to verify the performance of the proposed approach. It was demonstrated from results that the proposed approach is able to provide reliability in decision making by overcoming model mismatches to enhance the robustness of the real-time optimization strategy and improving on local loop performance with respect to MSE, and overall energy performance of HVAC system.

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