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A simulation–optimization approach for energy efficiency of chilled water system

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ABSTRACT

This study combines an energy simulation program with a hybrid optimization algorithm to identify the optimal settings and minimize the energy consumption of chilled water system. This study employed EnergyPlus, a flexible and highly accurate energy simulation program, to construct the model. To determine the optimal temperature settings for chilled and cooled water for chilled water system, this model used a hybrid optimization algorithm that combines the particle swarm optimization algorithm and the Hooke–Jeeves algorithm. We selected four days in summer and four days in winter to conduct the optimization. The results indicated that the optimized settings reduced the total energy consumed by the chilled water system by 9.4% in summer and 11.1% in winter compared to conventional settings.

1. Introduction

After an air conditioning system is selected, enabling the system to function at the optimum level is crucial. A highly-efficient system that cannot conserve energy, despite being designed to, is useless. Ensuring the system functions at the optimal level requires not only fault detection and diagnosis, but also system optimization for energy efficiency.

Numerous studies have been conducted regarding the optimization of air conditioning systems. Chang et al. [1,2] proposed a new energy conservation method called optimal chiller loading (OCL) and used the Lagrangian method for optimization. However, their study showed that this optimization method could not converge at low loads; thus, they employed a genetic algorithm (GA) to resolve the issue. Lee et al. [3,4] showed that the particle swarm optimization (PSO) algorithm and differential evolution algorithm were more effective for OCL. Lu et al. [5] used a modified GA to identify the optimal air and water loop pressure settings for heating, ventilation, and air-conditioning systems. Fong et al. [6,7] used a simulation program to construct a model for optimizing the supply air temperature set-point and supply water temperature set-point of an air-conditioning system. Evolutionary programming (EP) was then used to optimize the settings, after which a robust evolutionary algorithm was employed. The results showed that using this method facilitated a superior optimal solution and greater efficiency compared to that of EP and GA. Ma and Wang [8] used an optimal control strategy to optimize the chilled water supply temperature set-point and the critical loop differential pressure set-points for a chilled water system. Kusiak et al. [9] adopted a data mining method to establish an energy consumption model and used the PSO algorithm to optimize the supply air temperature and supply air static pressure control settings.

This study collected information on the supervisory control and data acquisition (SCADA) system for an office building, used the energy simulation program EnergyPlus [10] to establish a model, and combined optimization algorithms to optimize the supply temperature of chilled and cooling water in the chilled water system of an office building. The PSO [11] and Hooke–Jeeves [12] algorithms were combined to identify the optimal and recommended settings for various cooling loads.

2. System description

This study used a chilled water system in a traditional office building in Taipei, Taiwan, as the case for optimization analysis. The schematics of this system are shown in Fig. 1. The system consisted of two identically-sized water chillers, each with a rated capacity of 703 kW, a rated power of 143.2 kW, a rated COP of 4.91, and two cooling towers, which each had a rated capacity of 879 kW, a fan rated power of 7.46 kW, a rated water flow of 3250 l/min, a rated wind volume of 1690 m^3/min, and a constant speed fan. The chilled water loop had a primary/secondary system layout. The primary side had two chilled water pumps, each with a rated power of

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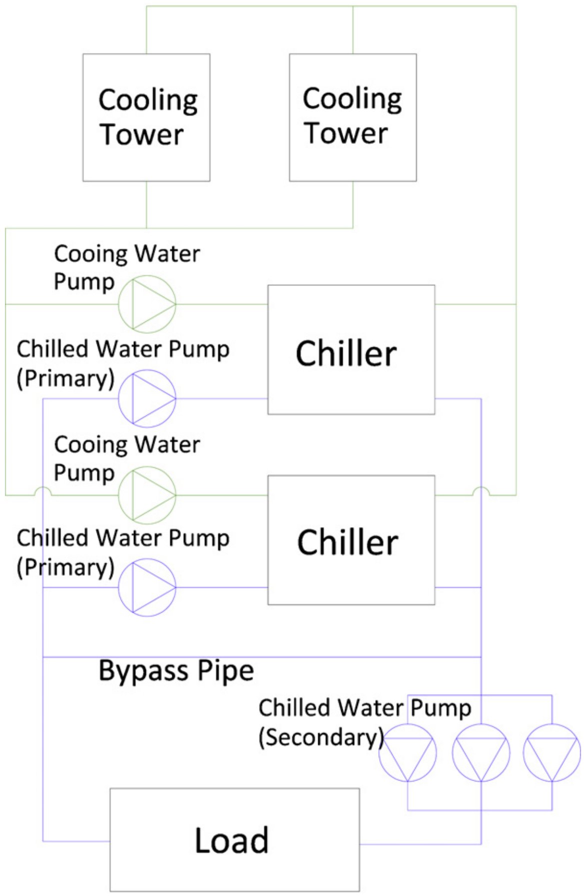

Fig. 1. Schematic diagram of chilled water system.

5.6 kW and a constant speed. The secondary side had three pumps, each with a rated power of 14.9 kW and a variable speed. Two cool water pumps were also included, each with a rated power of 18.7 kW and a variable speed.

3. Model validation

EnergyPlus was used for model validation. EnergyPlus is a flexible and highly accurate energy simulation program [13] that can customize numerous simulation time steps, air conditioning system layouts, and output results. The simulation program uses integrated solution technique to simultaneously interact the air conditioning load and the air conditioning system during simulations, creating more accurate predictions. EnergyPlus has been used in numerous studies, such as those regarding variable refrigerant volume, variable air volume air conditioning system measurements, and simulation validation [14,15]. EnergyPlus has also been used to construct an architectural and air conditioning system model, to evaluate the effect of various energy conservation measures [16], and an ice rink floor system, to evaluate the design and operational system improvements [17]. New integrated air conditioning systems created with EnergyPlus can assess the energy conservation potential compared to normal systems [18].

Because equalizing the simulated and measured cooling loads is difficult, a gap between the two is often set; thus, the model must be calibrated until it reaches an acceptable degree of accuracy. The validated model is then approaching reality and can be used for analysis in subsequent research. However, the scope of the study must be validated to obtain accurate simulation results. Therefore, this study validated the entire chilled water system.

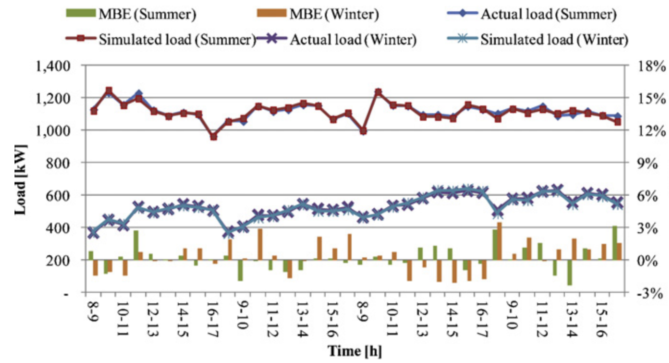

Fig. 2. Actual and simulated cooling load.

The mean bias error (MBE) [19] was used to calculate the error between the simulation and reality, determining the degree of proximity for each validation item. The formula is as follows:

$$\mathrm{MBE} = \frac{M_i - S_i}{M_i} \quad (1)$$

where M_i is the data obtained from actual measurements at time i and S_i is the data obtained from simulations at time i. The validation period was the standard office working hours (8:00 a.m.–5:00 p.m.) for four days in summer and four days in winter, where the simulation was similar to the actual hourly circumstances. Because this study optimizes an entire chilled water system, the chiller cooling load was the primary validation objective. Fig. 2 shows the chiller cooling load validation results. As shown in the figure, the actual and simulated cooling loads are extremely similar, with no hourly MBE exceeding ±4%. Fig. 3 shows the hourly validation of the chilled water supply temperature, with no hourly MBE exceeding ±2%. Fig. 4 shows the hourly validation of the cooling water supply temperature, with no hourly MBE exceeding ±4%. Fig. 5 shows the hourly validation of the total energy consumed by the chilled water system (including the water chillers, pumps, and cooling towers), with no hourly MBE exceeding ±10%. The validation showed that this completed model possesses adequate accuracy and can be used to predict the energy consumption at different cooling loads and system settings on the validation days.

4. Optimization method

Setting the system to the highest level of energy conservation is vital to optimize the function of current chilled water system. The objective function is the total energy consumption of an entire chilled water system (including the chillers, pumps, and cooling towers). The optimization variable is the temperature set-points of the chilled and cooling water supplied, where the chilled water

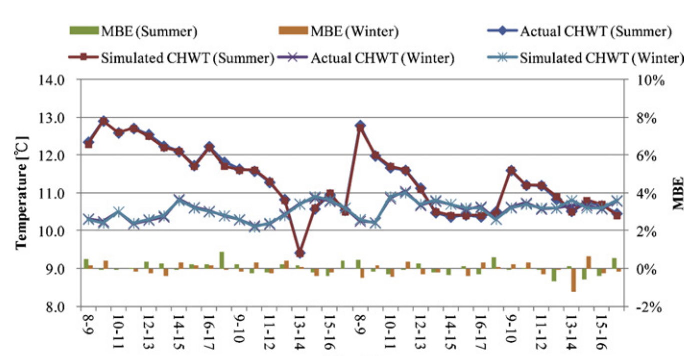

Fig. 3. Actual and simulated chilled water temperature.