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Optimal chiller loading by improved invasive weed optimization algorithm for reducing energy consumption

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ABSTRACT

In this study, an improved invasive weed optimization (*EIWO*) algorithm is investigated to solve the optimal chiller loading (*OCL*) problem for minimization of the power consumption. In the proposed algorithm, several components are developed, such as decimal-based representation, reproduction approach, spatial dispersal method, and competitive selection mechanism. Then, the local search strategy for elite weed is proposed, which can improve the searching ability of the algorithm. To verify the efficiency and effectiveness of the proposed algorithm, three well-known instances based on the *OCL* problem in air-conditioning systems are tested with the comparison with other recently published algorithms. The experimental results show that the *EIWO* algorithm can find equal or better optimal solution compared with other algorithms. The convergence ability, stability and robustness are also verified after the detailed comparisons.

1. Introduction

In many large buildings, the air-conditioning system accounts for 10–20% of the overall facilities usage [1]. The multiple chiller system is widely used in the air-conditioning system. As major components of the air-conditioning system, chillers consumed about 25–40% of the total electricity consumption in a commercial building [2]. In order to achieve the goal of energy saving of buildings, it is necessary to improve the energy efficiency of the chillers. Chillers have different performance features and capacities, which can increase flexibility of the operation, minimize energy consumption under the condition of meeting demands of different loads [3]. The optimal combination of part load ratio of each chiller can obtain minimum energy consumption of air-conditioning system. Therefore, the optimal chiller loading (*OCL*) problem becomes a valuable research problem.

In recent years, lots of optimization algorithms have been researched for the *OCL* problems. We can classify them into two categories, i.e., the exact algorithm and the *meta*-heuristic algorithm. Some exact algorithms, including Lagrangian method (*LM*) [4], branch and bound (*B&B*) method [5], gradient method (*GM*) [6] and generalized reduced gradient (*GRG*) method [7], have been used to solve the *OCL* problem. *LM* is used to find the optimal solution which consumes minimal energy consumption of chillers, but the system can't converge at low demand. The *B&B* method is employed to determine the startup of chillers while using *LM* to solve the *OCL* problem. Compared with *LM*, *GM* has the convergence ability to reach the optimal searching space at low demand. The *GRG* method has also been used to solve the *OCL* problem, which can find competitive results compared with some *meta*-heuristic approaches.

Recently, more and more researchers have utilized the *meta*-heuristic algorithms to solve the *OCL* problems, including genetic algorithm (*GA*) [8,9], simulated annealing (*SA*) [10,11], continuous genetic algorithm (*CGA*) [12], binary genetic algorithm (*BGA*) [12], particle swarm optimization (*PSO*) [12,13], evolution strategy (*ES*) [14], differential evolution (*DE*) [15], cuckoo search algorithm using differential operator (*DCSA*) [16], differential search (*DS*) [17], neural networks model with particle swarm optimization (*NNPSO*) [18], improved firefly algorithm (*IFA*) [19] and teaching-learning-based optimization (*TLBO*) [20]. It can be concluded from the presented algorithms that, the *meta*-heuristic algorithms have shown efficiency for solving the *OCL* problem.

Mimic by the process of weed colonization in the nature, the invasive weed optimization (*IWO*) algorithm was developed by Mehrabian and Lucas in 2006 [21], which is a new swarm intelligent optimization algorithm. Due to the characteristics such as robustness, adaptation, randomness and ease of implementation, *IWO* and its different variants are used to solve many combination optimal

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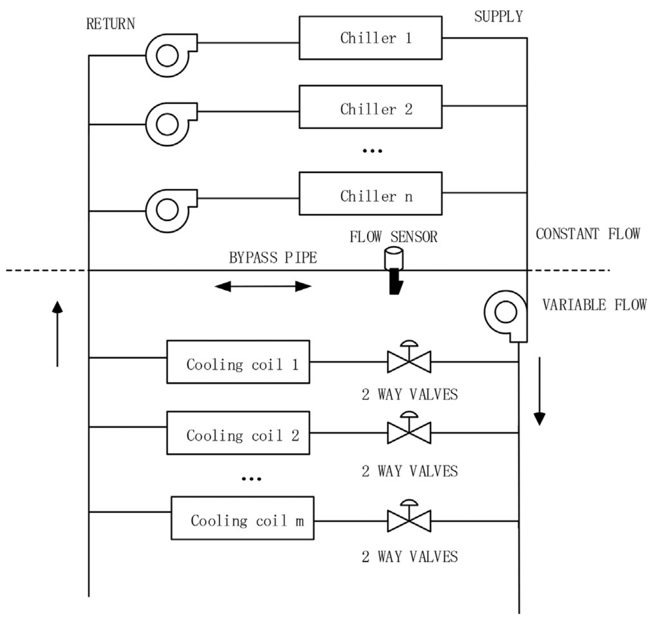

Fig. 1. Structure of the decoupled system [3].

problems in varies fields [22–31]. The experimental comparisons in the present literature have shown that the *IWO* algorithm is competitive to other efficient *meta*-heuristics, such as *GA*, *PSO*, and *DE*. Based on the above analysis of the *OCL* problem and the efficiency of the *IWO* algorithm, in this study, we propose an improved *IWO* (*EIWO*) algorithm to solve the *OCL* problem. The main contributions of this study are as follows: (1) the optimal chiller loading problem by minimizing total energy consumption subject to satisfy some constraints in the multiple chiller system is investigated; (2) the strategy of local search around the elite weed is developed to enhance the local search ability of the canonical *IWO* algorithm; and (3) detailed experiments have been conducted for the parameter tuning.

The remainder of this paper is organized as follows. Section 2 describes the structure of the decoupled system of the multiple chiller system. Section 3 introduces the basic knowledge of the canonical *IWO* algorithm. The improved *IWO* algorithm which uses the strategy of local search around the elite weed is introduced in Section 4. In Section 5, the implementation of the *EIWO* algorithm on *OCL* problem is presented in detail. Section 6 lists the experiment results on three well-known instances. Parameters setting analysis of the *EIWO* algorithm is reported in Section 7, followed by conclusion and future work in Section 8.

2. System structure

In many massive public buildings, the air-conditioning system is a multiple chiller system, which is a typical decoupled system. The structure of the decoupled system is shown in Fig. 1. The multiple chiller system has two or more chillers connected by parallel or series piping to a common distribution system [3]. Each chiller has different capacity and energy consumption. The system cooling load can be allocated to two or more chillers by controlling the flow of supply water and return water. Meanwhile, the supply water and return water can flow to each other through the bypass pipe. When the chiller load distribution is properly controlled, the multiple chiller system can provide operational flexibility, standby capacity and less disruption maintenance [3].

In a multiple chiller system with all-electric cooling, the sum of power energy consumption of the chillers can be expressed as Eq. (1).

$$Sp = \sum_{i=1}^{n} P_i \tag{1}$$

Where $P_i$represents power consumption of the ith chiller, n is the total number of chillers. Sp is the total power energy consumption.

The objective function of the optimum chiller loading problem is to minimize the total power energy consumption, as shown in Eq. (2).

$$Obj = \min\left(\sum_{i=1}^{n} P_i\right) \tag{2}$$

Each chiller can be opened up or shut down, the value of S_i represents the on-off state of the ith chiller, as shown in Eq. (3).

$$S_i = \begin{cases} 1 & \text{if the chiller is on state} \\ 0 & \text{if the chiller is off state} \end{cases} \tag{3}$$

The partial load ratio (*PLR*) is the ratio of the chiller cooling load and design capacity. When the ith chiller is opened up, PLR_i must be between 0.3 and 1, when it is shut down, PLR_i is set to zero, as shown in Eq. (4).

$$PLR_i = \begin{cases} Rand\,(0.3, 1) & \text{if } S_i = 1 \\ 0 & \text{if } S_i = 0 \end{cases} \tag{4}$$

The power consumption of a centrifugal chiller (P) is a convex function of its *PLR* at a given wet-bulb temperature [9]. The calculation formula can be expressed as three forms, as shown in Eq. (5). Due to the power consumption of chillers can't be negative, P_i must be a nonnegative value.

$$P_i = \begin{cases} a_i + b_i \cdot PLR_i + c_i \cdot PLR_i^2 & \text{if } S_i = 1 \quad \text{(used by case1)} \\ a_i + b_i \cdot PLR_i + c_i \cdot PLR_i^2 + d_i \cdot PLR_i^3 & \text{if } S_i = 1 \quad \text{(used by case2 and case3)} \\ 0 & \text{if } S_i = 0 \end{cases} \tag{5}$$

Where a_i, b_i, c_i, d_i are coefficients of *KW-PLR* curve of the ith chiller with pre-defined values.

The multiple chiller system should supply enough cooling load to satisfy the system cooling load demand, and the sum of cooling load of the chillers should equal to the system cooling load, as shown in Eq. (6).

$$\sum_{i=1}^{n} PLR_i \cdot RT_i = CL \tag{6}$$

Where RT_i is the capacity of the ith chiller, CL is the system cooling load.

In a multiple chiller system, the best performance occurs when the sum of energy consumption of each chiller is minimized while the cooling load demand is satisfied [19]. The optimal chiller loading problem is to find the on-off state and the value of *PLR* for each chiller, while the objective function given by Eq. (2) is minimized and the *PLR*s of all the chillers satisfy the constraints given by Eq. (4) and Eq. (6).

3. *IWO* algorithm

The *IWO* algorithm is a numerical stochastic search algorithm mimicking the natural behavior of weed colonizing in opportunity