Application of Tabu Search Heuristic Algorithms for the Purpose of Energy Saving in Optimal Load Distribution Strategy for Multiple Chiller Water Units

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***Abstract*—Tabu search algorithm has been applied to solve the optimal load distribution strategy problem for the cooling system constituted by multiple chiller water units, which has the characteristic such as complexity, constraint, nonlinearity, modeling difficulty, etc. The tabu search algorithms based on the neighborhood search can avoid the local optimization avoidance and has the artificial intelligence memory mechanism. In this paper, two chiller water units connected in parallel working using the tabu algorithm was observed. Compared with the conventional method, the results indicated that the tabu search algorithms has much less power consumption and is very suitable for application in air condition system operation.**

Keywords-energy consumption; energy saving; algorithm; tabu search algorithms; optimal chiller load distribution; part load; chiller water units; direct load control

I. INTRODUCTION

With the increase of the building scale, more and more chiller water unit and hot water unit was in using, and the energy consumption of the multi chiller and hot water units was depends not only on the feature of these equipment itself, but also the load distribution strategy under the part load condition., therefore, with the chiller water units was given, how to find an optimal load distribution in the running of the equipment become the critical problem in the system energy conservation.. There are some conventional and common methods put forward in some paper to obtain good load distribution for energy saving.

In this paper, the author investigate the part load feature of the chiller water units, establish the nonparametric model for the optimal load distribution regardless of the type of the equipment, use tabu search algorithms to solve the load distribution problem for energy saving.

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II. OPTIMAL LOAD DISTRIBUTION STRATEGY

A. Nonparametric Model of the Chillers Water Unit

For simplicity, we think the cold source of the air-conditioning system is composed of n chillers connected in parallel, the output cold of the number i chiller water unit is q_i, the input power of the chiller is W_i. The cold load of the building changing with the environment, the practical output cold of the chillers changing with the building cold load, the input power of the chillers changing simultaneously, so, W_i is a function of q_i ,that is :

$$W_i = f_i(q_i) \tag{1}$$

In the working process of these chillers how to distribute the cold load of each chiller to meet the user's need and to achieve the minimum input power is an optimization problem.

Taking the energy consumption as the optimization goal, when the input power of all the chillers is minimum, the load distribution is optimal. The mathematical model is

$$W_n^*(L) = \min W(Q) = \min \sum_{i=1}^{n} f_i(q_i), \qquad Q \in E^n \tag{2}$$

$$Q = (q_1, q_2, \ldots, q_n,)^{\mathrm{T}} \tag{3}$$

Where W_n^* is the optimal goal function; L is the actual cooling load.

Simultaneously, the total output cooling capacity of all the chillers must satisfy the actual cooling load of the buildings, thus the following constraints condition must be satisfied:

$$H(Q)=\sum_{i=1}^{n}q_i=L \quad (4)$$

In practice, each chiller has an appropriate load range, in which the chiller works at the most high efficiency status. Thus, the following constraints must be satisfied:

$$q_{\min}\le q_i\le q_{\max},\quad i=1,2,\ldots,n$$

Where q_i is the actual output cold of the number *i* chiller; $q_{i\min}$ is the minimum output cold of the number *i* chiller; $q_{i\max}$ is the maximum output cold of the number *i* chiller.

For the complexity, constraint, nonlinear, difficulty in modeling of the multiple chiller water units, an optimal load distribution strategy based on tabu search algorithms is presented in this paper.

B. Tabu Search Algorithms

The tabu search optimization algorithm is a meta-heuristic optimization process[1-3]. In contrast to other algorithms of its category, the most distinctive feature of the tabu search optimization algorithms is the emphatic use of memory during the optimization process.

The tabu search algorithm maintains a list of recently visited solutions and uses the information being kept in this list to prevent cycling especially when the search moves away from local optima through non-improving moves. The tabu list is an example of short term memory being used in the tabu search algorithm and the life span of a visited solution being banned through the tabu list is controlled by a predefined parameter: the tabu tenure.

However, some forbidden moves regarding to the tabu list and tabu tenure may be exempted if these moves satisfy some predefined aspiration criteria, which may improve the performance of the tabu search algorithm in some applications. For example, an otherwise disallowed move will be accepted if it yields a solution better than the best one obtained so far. Furthermore, the tabu search algorithm also applies two advanced searching strategic, namely the intensification strategy and the diversification strategy, to improve its performance in an optimization task. The intensification process is to encourage the optimization process to explore more thoroughly in the regions where good solutions have been discovered. The diversification process is to discourage the optimization process waste too much time in restricted regions of the state space where optimal solutions arc unlikely to be found. For example, the optimal solution is unlikely to be discovered in the regions of the state space where bad solutions are always being found.

C. Flow Chart of the Tabu Search Algorithm

Take the entire neighborhood, the objective function, the given maximum number of iterations as the candidate solution set, the fitness function, the stopping rule respectively, and set the aspiration level is better than the optimal solution in the iteration history, the flow chart of the tabu search algorithm is as follows:

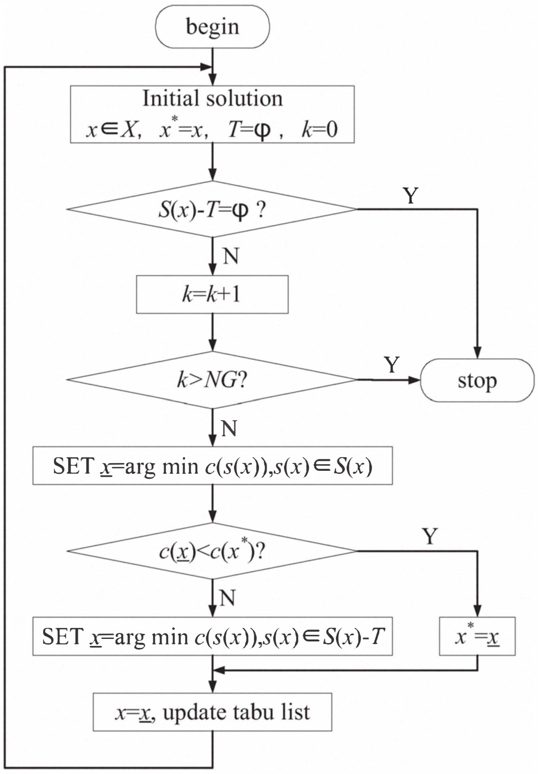

Figure 1. Flow chart of the tabu search algorithm

Where:

x is the solution,

X is the solution space,

$c(x)$ is the objective function,

$S(x)$ is the set of all the moving from the current solution,

$c(x^*)$ is the fitness function,

T is the tabu list,

NG is the maximum number of iterations,

arg is the aspiration level.

III. EXAMPLE AND RESULTS

The application of the tabu search heuristic optimization algorithm for the purpose of energy saving in optimal load distribution strategy of the cooling system constructed by multiple chiller water units has been observed in the following.

The proposed method is tested on two chillers water unit, whose part load performance parameters is shown in Table 1.

TABLE I. PART LOAD PERFORMANCE PARAMETERS

Load Ratio	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%
Input Power/kW	128	112.4	80.3	65.6	53.6	44	35	27.5	22	16.5

The two chillers are identical, running for 2400h one year in air-conditioning season. The time distribution of the different cold load ratio is shown in Table 2. The construction area is of 18000 square meters, with the total cooling load 1700Kw.

TABLE II. THE TIME DISTRBUTION WITH PART LOAD RATIO

Load Ratio	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Runtime/h	150	170	170	280	260	240	300	280	260	290

Because the facilities are operated all day long, the electric energy consumption in the chiller plant will increase immediately if the chiller load distribution is not proper.

The control of cooling water temperature and the flow rate and the supply temperature of chilled water must be taken into consideration simultaneously for executing chiller capacity control.

Many companies still use the equal loading rate manner and lots of power energies are consumed imperceptibly. So, the optimal cold load distribution method based on the tabu search algorithms is proposed in this paper to overcome these shortcomings and reduce the power consumption and the operation costs. The presented method estimates chiller output refrigerating capacity by measuring flow, supply and return temperatures of chilled water. Then, the input power kW-part load ratio curve can be easily obtained for each chiller through regression applied to measured data coming together with the input electric power. The electric energy saving can be achieved in the condition of minimum input electric power and satisfying total cooling load demand.

The following is the results of the conventional methods and the proposed method. The potential performance of the proposed method is demonstrated by mean of two screw type water chiller systems. Compared with the conventional method, the proposed method has much less power consumption and is very suitable for application in air condition system operation.

The cooling load (Refrigeration Ton) of a chiller can be calculated by the formula (5) [4]:

$$Q = fm(T_{CHr} - T_{CHs})/3517 \tag{5}$$

where f= the flow rate of chilled water(kg • s^{-1})

m= the specific heat of chilled water(J • kg^{-1} • k^{-1})

T_{CHr}= the return temperature of chiller water(k)

T_{CHs}=the supply temperature of chiller water(k)

Because of constant chilled water flow in a chiller, its cooling load can be determined if the supplied temperature and the return temperature of chilled water are measured. The input power (kW) can be gotten by usage of a power meter and then the input power (kW)-part load ratio data can be obtained by applying regression. The load demand variation can also be determined from measuring the water flow and the temperature in the main pipe on the load side.

Three groups of data obtained by two kind of conventional methods and the proposed method are illustrated as follows:

TABLE III. OPERATION SCHEME 1 USING THE CONVENTIONAL METHOD 1

System Load Ratio	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Runtime/H	150	170	170	280	260	240	300	280	260	290
Part Energy Consumption of Chiller1/kWh	3,300.00	5,950.00	9,112.00	22,484.00	33,280.00	12,864.00	19,680.00	22,484.00	29,224.00	37,120.00
Part Energy Consumption of Chiller2/kWh	0.00	0.00	0.00	0.00	0.00	12,864.00	19,680.00	22,484.00	29,224.00	37,120.00
Total Energy Consumption of Operation Scheme 1/kWh(1 Year)				316,870.00						

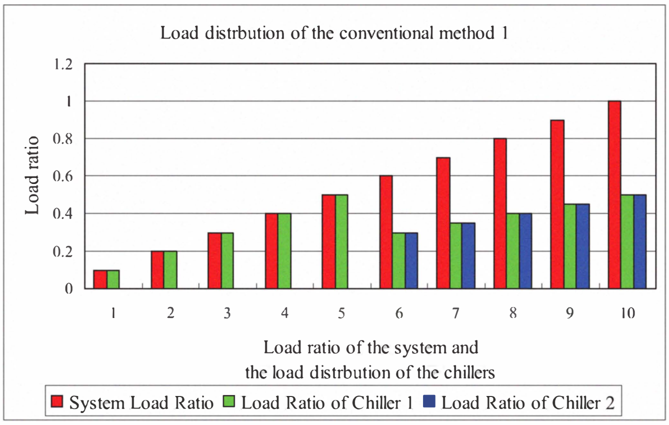

Figure 2. Load distribution of conventional method 1

Table III and Fig.2 are the energy consumption and the load distribution of the chiller water unit running at the one of the conventional methods. The total energy consumption of it is 316,870.00kWh in one year.

The conventional method 1 uses the following program:

When the actual load of the chiller water units is less than 50% of the total load of the system, one chiller water unit bears the entire load, while the other stop working.

When the actual load of the chiller water units is greater than 50%, the two chiller water units work simultaneously; each unit bears half of the entire load.

The switching point of the program of the load distribution strategy is the 50% of the entire load of the system. It is the most commonly used control method, but such widely used method may not be the best load distributed control method.

Now let's investigate another conventional method which will be described in detail in following. The program is also widely used on many occasions.

TABLE IV. OPERATION SCHEME 2 USING THE CONVENTIONAL METHOD 2

System Load Ratio	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Runtime/h	150	170	170	280	260	240	300	280	260	290
Part Energy Consumption of Chiller1/kWh	3,300.00	5,950.00	9,112.00	22,484.00	33,280.00	30,720.00	38,400.00	35,840.00	33,280.00	37,120.00
Part Energy Consumption of Chiller2/kWh	0.00	0.00	0.00	0.00	0.00	5,280.00	10,500.00	15,008.00	20,878.00	37,120.00
Total Energy Consumption of Operation Scheme 1 kWh(1year)				338,272.00						

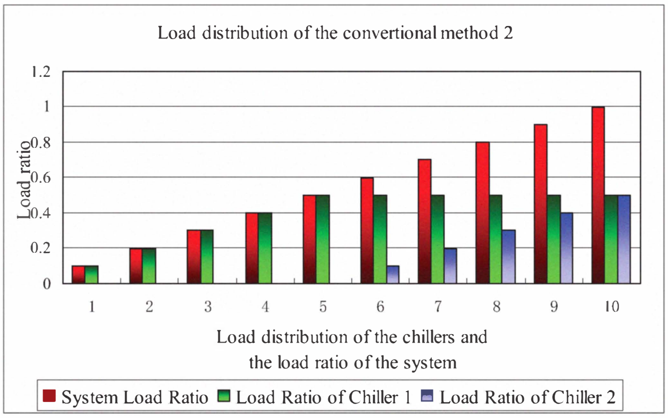

Figure 3. Load distribution of conventional method 2

Table Ⅳ and Fig.3 are the energy consumption and the load distribution of the chiller water unit running at the other one of the conventional methods. The total energy consumption of it is 338,272.00kWh in one year.

The program is another common used method for load distribution of the chiller water units which can be described as follows:

When the actual load of the system is greater than 50% of the entire system load, one chiller works in full load condition, and the other takes the rest of the load;

When the actual load is less than 50% of the entire load, one chiller takes all of the load, and the other stop working.

Moreover, the switching point of the conventional method 2 is 50%, which is also the most widely used method, but it is not necessarily the optimal load distribution method.

TABLE V. OPERATION SCHEME USING THE TABU SEARCH ALGORITHM

System Load Ratio	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Runtime/h	150	170	170	280	260	240	300	280	260	290
Total Energy Consumption of Chillerl/kWh	3,300.00	5,950.00	9,112.00	9,800.00	9,100.00	12,864.00	19,680.00	22,484.00	33,280.00	37,120.00
Total Energy Consumption of Chiller2/kWh	0.00	0.00	0.00	9,800.00	9,100.00	12,864.00	19,680.00	22,484.00	20,878.00	37,120.00
Total Energy Consumption of Operation Scheme 1 kWh(1 year)				294,616.00						

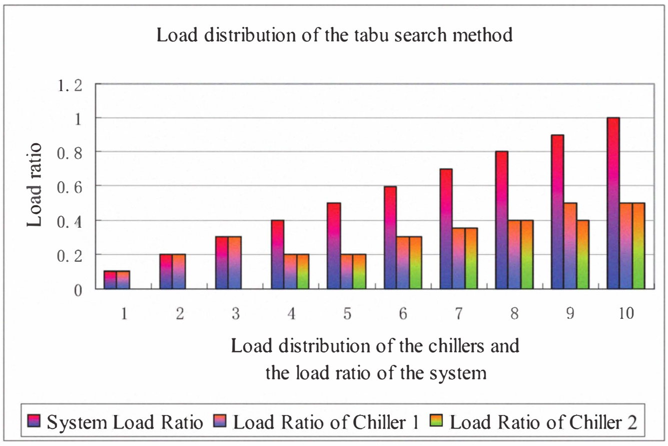

Figure 4. Load distribution of tabu search method

Based on the optimal load distribution model proposed above, using the tabu search heuristic algorithms, a new method to consume less energy is explained in the following.

Table Ⅴ and Fig.4 are the energy consumption and the load distribution of the chiller water unit running at the tabu search algorithm methods. The total energy consumption of it is 294,616.00kWh in one year.

From Table Ⅴ and Fig.4 we can see when the load ratio of the system is less than 30%, only one chiller water unit bears the entire load; when the load ratio of the system is between 30%-80%, two chillers water unit share the system load average; when the load ratio of the system is greater than 80%, one chiller water unit runs in full load working condition, the other takes the rest of the system load.

Table Ⅲ,table Ⅳ and table Ⅴ show that the proposed method has much larger saved powers than those conventional methods.

Consequently, the tabu search method is better than the conventional method. The energy consumption comparison for these two systems is shown in Fig.5, where "1" and "2" is the conventional method, "3" is the tabu search method.

It is obvious that the tabu search method has larger saved energy compared to the conventional method. The execution of program is so fast that the CPU times can't be found out in these two methods.

In the actual operation of chillers, operation conditions may be different from the standard conditions, thus the performance of the chillers may change, so the above load distribution strategy will be change.

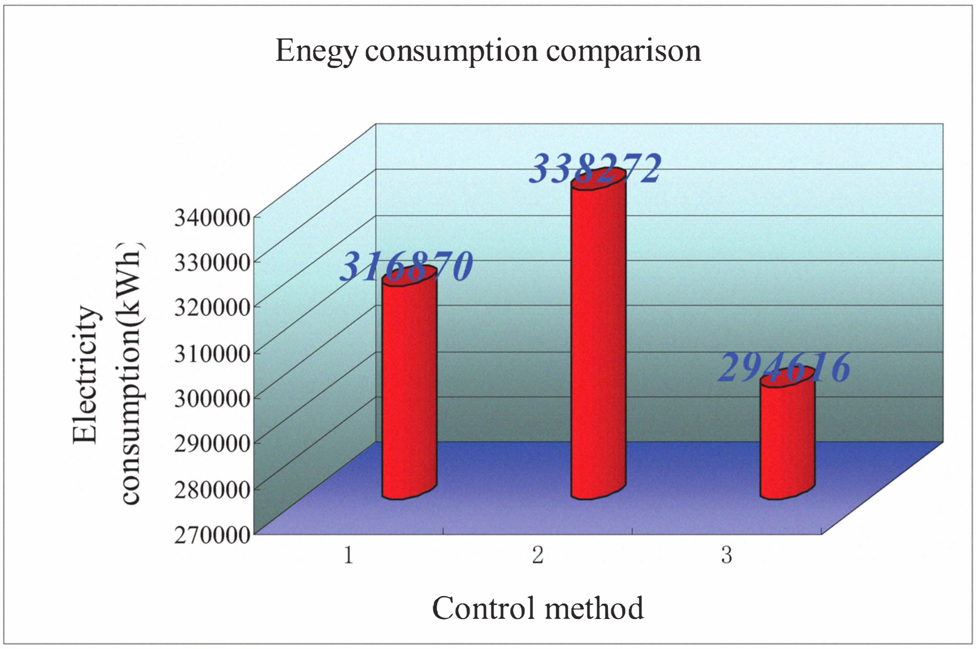

Figure 5. Energy consumption comparision between the conventional methods and the tabu search algorithms method

IV. Conclusion

The cooling load has increased enormously during recent years along with the development of Economy. We have to pay much attention to the optimal load cold distribution problem for the sake of reducing power consumption by way of operating chiller in the best effect according to different feature. In this paper, the nonparametric model of the optimal load cold distribution problem has been derived. The optimal problem is solved by usage of tabu search algorithm method. The proposed method has been tested on two example systems and compared with the conventional method. Test results show that the proposed method reduces large energy consumption and is superior to the conventional method.

The proposed method is mainly uses the load characteristic, nothing to do with the other performance parameters and chiller model, thus, this approach is universal.

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