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Optimal Short-Term Scheduling of Multi-Chiller Plants Considering Energy Requirement of Cooling Towers, Pumps and Chillers

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Abstract

During extremely hot summer days, air conditioning systems are known as major electricity consumers in residential, commercial and industrial sectors. Moreover, high energy requirement of multiple-chiller plants may cause an interconnected power grid be faced with annual on-peak electrical demand, load-generation mismatch, voltage collapse and catastrophic wide area blackout. Therefore, this paper presents a day-ahead economic dispatch model for water cooled multiple chiller systems aiming to minimize total power consumption of cooling towers, pumps and chillers. In addition, refrigeration capacity limit of each chiller and cooling load-generation balance criterion are considered as optimization constraints. On/off status and partial load ratio of each chiller, power consumption of pump/cooling tower/chiller, temperature of chiller outlet water, temperature of cooling tower outlet water, mass flow rate of cooled water, mass flow rate of water flowing in and out of cooling tower are considered as decision variables. Simulations are conducted on a benchmark system with two 550 refrigeration ton (RT) units, four 1000 RT chillers and different cooling load levels over a 24-hour time horizon using generalized algebraic mathematical modeling system (GAMS) software.

Keywords: Cooling tower; Energy consumption; Economic dispatch; Multi-chiller plant; pump; Water cooled chiller
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1. Introduction

In summer season, air conditioning systems such as compression chillers consume a large value of electrical energy in order to supply cooling demand of buildings. Therefore, hot and humid regions usually face with energy crises. In addition, seawater desalination plants consume electricity for producing fresh water. Meanwhile, energy crises may lead to potable water shortage in tropical areas. Therefore, annual on-peak electricity demand should be clipped by optimal operation of air conditioning systems [1].

In recent years, many fast and computationally friendly optimization techniques have been presented by researchers for minimization of total electricity consumption in multi-chiller microgrids. For example, Change et al. [2] combined a branch and bound analysis with Lagrangian method and finds optimum value of partial load ratio (PLR) of each chiller aiming to minimize total power consumption in feasible search space. Scholars of [3] demonstrated that gradient method (GM) converges to a better solution with lower computational burden and high accuracy than Lagrangian optimization algorithm. Reference [4] proved that neural networks and hybrid particle swarm optimization (PSO) algorithm achieves better solutions with 12.68% to 17.63% power savings on 55% and 70% PLRs in comparison with linear regression and equal loading distribution method. In [5], it is demonstrated that simulated annealing (SA), which is started by cooling of a metal after heating it up to melting point and reducing its defects, eliminates Lagrangian problem and discovers highly accurate results. In [6], Gaussian distribution function based firefly algorithm is employed for solving optimal chiller loading (OCL) problem. Firefly algorithm solves optimization problem by attracting mating partners according to their light intensities assuming this fact that all fireflies except one have same sex and one firefly is only attracted by others. Differential cuckoo search algorithm (DCSA) [7], evolution strategy (ES) [8], exchange market algorithm [9], differential evolution algorithm [10], basic open-source nonlinear mixed integer programming (BONMIN) solver [11], and teaching learning based optimization (TLBO) method [12] are applied on multi-chiller plants to achieve a better chiller dispatch solution than that of genetic algorithm (GA) [13, 14]. In [15], ripple bee swarm optimization (RBSO) process is presented to design multi-chiller dispatch problem economically using non-linear ripple weight factors and self-adaption repulsion index. Zheng and Li [16] proved that invasive weed optimization (IWO) procedure is equal to or better than all mentioned algorithms with short calculation time, more convergence speed and lower power consumed by chillers in three case studies.

As stated, different searching methods have been proposed for solving OCL problem and saving energy in air conditioning systems. But, energy requirement of cooling towers and pumps have not been considered in optimization process. Hence, this paper aims to solve an economic chiller dispatch problem for satisfying load-generation balance constraint and chiller refrigeration capacity limit so that total power consumption of cooling towers, pumps and chillers is less than that of recently published works with a shorter computational time and fast convergence.

Other sections of current paper are organized as follows: Section II presents a comprehensive mathematical formulation on optimal scheduling of multi-chiller plants. Afterwards, numerical result and discussions are drawn in Section III. Finally, concluding remarks appear in Section IV.

2. Energetic Optimization of Multi-Chiller Plants

In a large-scale building, air conditioning system composes of two or more water-cooled compression chillers that are connected in parallel or series piping to a distribution feeder. A typical decoupled water-cooled multi-chiller system is depicted in Fig. 1. As obvious from this figure, temperature of water flowing in each cooling tower decreases from T_{cwr} to T_{cws}. Then, this chilled water with temperature of T_{cws} enters a chiller unit to absorb heat from water, reduce its temperature from T_{chr} to T_{chs} and supply a part of cooling load. In OCL problem, total electricity consumption of chillers, pumps and cooling towers over a *T*-hour study horizon should be minimized as formulated by equations (1)-(4) [15]:

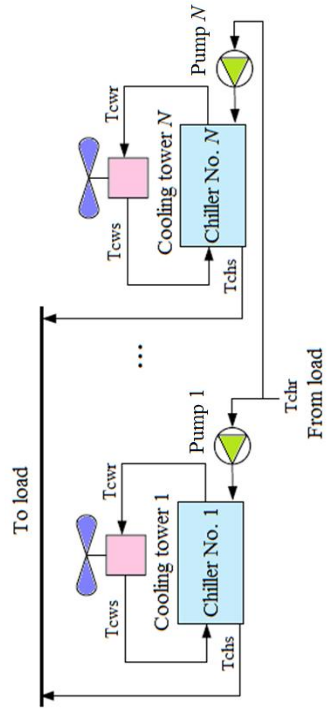

Fig. 1. A typical water-cooled multiple-chiller plant

$$\text{Objective function} = \text{Min}\sum_{t=1}^{T}\sum_{i=1}^{N} u_i^t \times \left(P_{chiller,i}^t + P_{tower,i}^t + P_{pump,i}^t\right) \tag{1}$$

$$P_{chiller,i}^t = a_i + b_i \times PLR_i^t + c_i \times \left(PLR_i^t\right)^2 + d_i \times \left(PLR_i^t\right)^3 \tag{2}$$

$$P_{tower,i}^t = m_{cw,i}^t C_w \left(T_{cwr}^t - T_{cws}^t\right) = 0.025 \times \left(P_{chiller,i}^t + Q_i^t \times 3.517^{\text{kW}/\text{RT}}\right) \tag{3}$$

$$P_{pump,i}^t = \frac{m_{cw,i}^t \times g \times h}{\eta} \tag{4}$$

u_i^t : Binary variable that equals to 1 if chiller *i* is on at time *t*; otherwise it will be 0.

$P_{chiller,i}^t$: Electrical power consumed by chiller *i* at time *t*

$P_{tower,i}^t$: Power consumption of cooling tower *i* at time *t*

$P_{pump,i}^t$: Energy requirement of pump *i* at time *t*

PLR_i^t : Partial load ratio of chiller *i* at time *t*, which belongs to interval $[0,1]$.

$m_{cw,i}^t$: Mass flow rate of water flowing in and out of cooling tower *i* at time *t*

C_w : Specific heat capacity of water

T_{cwr}^t and T_{cws}^t : Temperature of water entering and existing the cooling tower at hour *t*

h : Head of pumped water

η : Efficiency of water pump

Equation (2) indicates that if chiller *i* is on at time horizon *t*, its power consumption depends on coefficients a_i, b_i, c_i and d_i and cooling demand satisfied by this chiller, Q_i^t, as stated in relation (5).

$$Q_i^t = PLR_i^t \times Q_i^{\max} = m_{ch,i}^t C_w \left(T_{chr}^t - T_{chs}^t\right) \qquad (5)$$

In which,

Q_i^t: Cooling demand supplied by chiller unit *i* at hour *t*

$Q_i^{\max}$: Refrigeration capacity of chiller *i*

$m_{ch,i}^t$: Mass flow rate of water pumping into chiller unit *i* at hour *t*

T_{chr}^t and T_{chs}^t: Temperature of water entering and existing chiller *i* at hour *t*

Total cooling load at hour *t*, CL_t, is supplied by *N* chillers, as given by constraint (6).

$$CL_t = \sum_{i=1}^{N} Q_i^t \times u_i^t \qquad (6)$$

3. Numerical Result and Discussions Inputs

In this research, a mixed integer nonlinear programming problem is solved using SBB tool of generalized algebraic mathematical modeling system (GAMS) [17] to find optimal operating point of a benchmark six-chiller plant. In addition, binary variable u_i^t, electrical power consumed by each chiller/pump/cooling tower, partial load ratio of each chiller, mass flow rate of water flowing out of cooling tower, temperature of water existing the cooling tower, cooling demand supplied by each chiller unit, mass flow rate of water pumping into chiller units and temperature of water existing chillers are considered as decision variables. Input parameters are as follows: Power consumption coefficients and cooling capacity of each chiller unit [15] are reported in Table 1. Specific heat capacity of water is considered as 4.186 kJ/kgK. Head of pumped water and efficiency of water pump are equal to 34 m and 95%, respectively. Temperature of water entering towers, T_{cwr}^t, temperature of water pumping into chillers, T_{chr}^t, and hourly cooling demand, CL_t, over a 24-h time interval are shown in Table 2.

4. Outputs

In this section, optimization problem (1)-(6) is solved using GAMS software to minimize total electricity consumption of air conditioner and determine optimum values of partial load ratios when hourly cooling load-generation balance constraint is satisfied. It is supposed that system operator desires 5 °C temperature reduction for water leaving towers. In other words, $T_{cwr}^t - T_{cws}^t = 5°\text{C}$. Hence, temperature of water existing towers, T_{cws}^t, will change as Fig. 2. In Table 3., optimal partial load ratios are presented. Hence, refrigeration capability of chillers, Q_i^t, will change as Fig. 3. Mass flow rate of water pumped into chillers and cooling towers are illustrated in Figs. 4 and 5, respectively. In addition, variations of electrical power consumed by chillers, pumps and cooling towers in different cooling load levels are presented in Figs. 6-8, respectively. It is found that hourly cooling capability of each chiller unit changes similar to its water mass flow rate, as expected from equation (5) and shown in Figs. 3 and 5. As stated in equation (5), optimum value of cooling capability provided by chiller *i* is obtained from its partial load ratio and refrigeration capacity, which are reported in Tables 3. and 1., respectively. Moreover, optimal schedules of chillers, pumps and cooling towers are found based on power consumption coefficients and partial load ratios as Figs. 6-8, respectively. Finally, daily energy requirement of test system will be equal to 265,607 kW.

Table.1.
Power Consumption Coefficients and Cooling Capacity

Chiller	a_i	b_i	c_i	d_i	$Q_i^{\max}$ (RT)
1	57.2	329.73	0.05	7.85	550
2	50.09	419.28	-123.8	76.36	550
3	-76.29	1226.94	-709.37	296.93	1000
4	-72.56	1100.42	-145.77	-137.1	1000
5	69.39	620.62	-28.24	59.33	1000
6	-186.18	1817.08	-1755.59	847.43	1000

Table.2.
Hourly Cooling Demand, Temperature of Water Entering Chiller and Tower

t	CL_t	T_{chr}^t	T_{cwr}^t
1	4043.6	12.42	29.93
2	3909.4	12.49	29
3	3809.3	12.46	27.82
4	3713.6	12.34	26.55
5	3575	12.17	25.51
6	3436.4	12	25.09
7	3298.9	11.83	25.46
8	4347.2	11.67	26.43
9	4279	11.56	27.59
10	4329.6	11.51	28.58
11	4469.3	11.69	30.07
12	4467.1	11.55	30.24
13	4601.3	11.47	30.57
14	4651.9	11.51	31.13
15	4662.9	11.72	31.94
16	4770.7	12.03	32.92
17	4686	12.33	33.83
18	4541.9	12.49	34.43
19	4544.1	12.45	34.59
20	3993	12.29	34.35
21	3917.1	12.1	33.79
22	3993	12.01	32.96
23	4103	12.06	31.85
24	4094.2	12.21	30.54

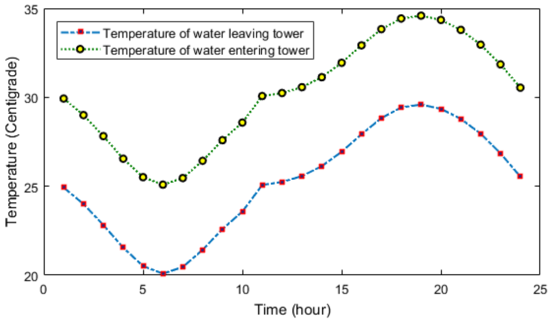

Fig. 2. Temperature of water leaving tower, T^{t}_{cws}

Table.3.
Partial Load Ratio of Chillers

t	PLR^t_1	PLR^t_2	PLR^t_3	PLR^t_4	PLR^t_5	PLR^t_6
1	0	0.8540	0.9440	1.0000	0.7650	0.8640
2	1	0.8780	0.9670	1.0000	0.7950	0.1140
3	1	0.9030	0.9900	0.0670	0.8260	0.8790
4	1	0.8710	0.9610	0.0670	0.7870	0.8700
5	0	0.9770	1.0000	1.0000	0.9230	0.1140
6	1	1.0000	1.0000	0.2220	1.0000	0.1140
7	1	1.0000	1.0000	0.0840	1.0000	0.1140
8	1	1.0000	0.2470	1.0000	1.0000	1.0000
9	1	1.0000	0.1790	1.0000	1.0000	1.0000
10	1	1.0000	0.2300	1.0000	1.0000	1.0000
11	1	0.8140	0.9010	1.0000	0.7180	0.8530
12	1	0.8130	0.9000	1.0000	0.7170	0.8530
13	1	0.8560	0.9470	1	0.7680	0.8650
14	1	0.8730	0.9630	1	0.7890	0.8700
15	1	0.8770	0.9660	1	0.7930	0.8710
16	1	0.9120	0.9980	1	0.8380	0.8820
17	1	0.8840	0.9730	1	0.8030	0.8740
18	1	0.8370	0.9270	1	0.7450	0.8590
19	1	0.8380	0.9280	1	0.7460	0.8600
20	0	0.8370	0.9280	1	0.7450	0.8600
21	1	0.8810	0.9700	1	0.7980	0.1140
22	1	0.9680	1.0000	1	0.9110	0
23	1	1.0000	0.0650	1	1.0000	0.9380
24	1	0.9610	1.0000	1	0.9010	0.1140

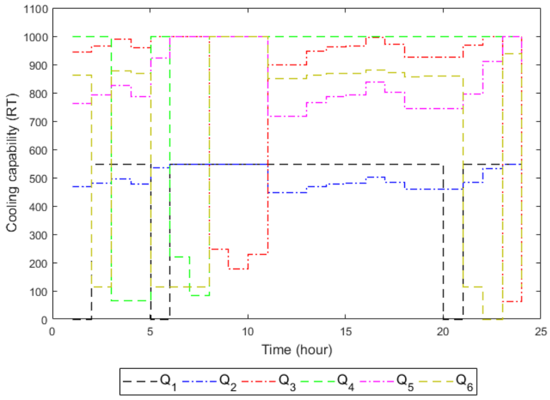

Fig. 3. Cooling capability provided by chillers

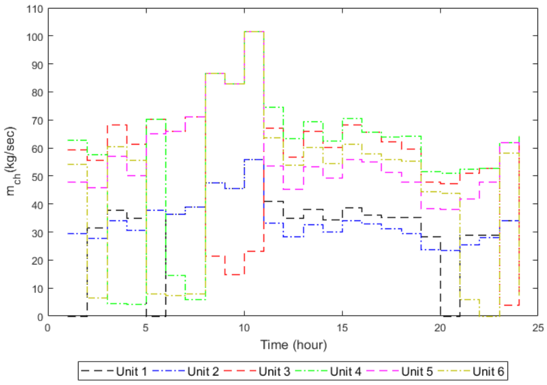

Fig. 4. Mass flow rate of water pumped into chillers, $m^{t}_{ch,i}$

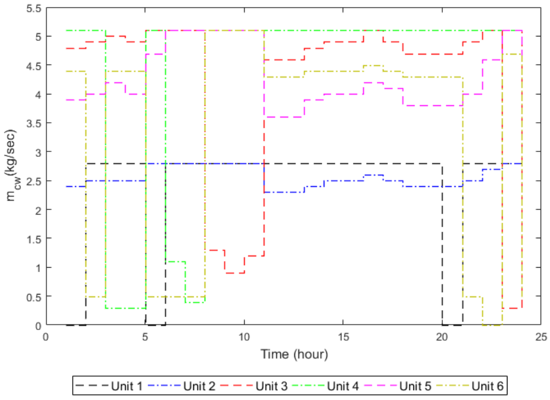

Fig. 5. Mass flow rate of water inletting to cooling towers, $m^{t}_{cw,i}$

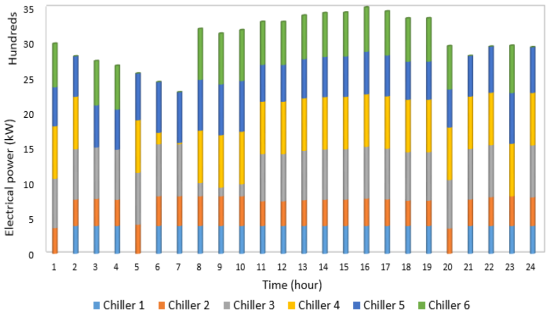

Fig. 6. Hourly energy requirement of chillers

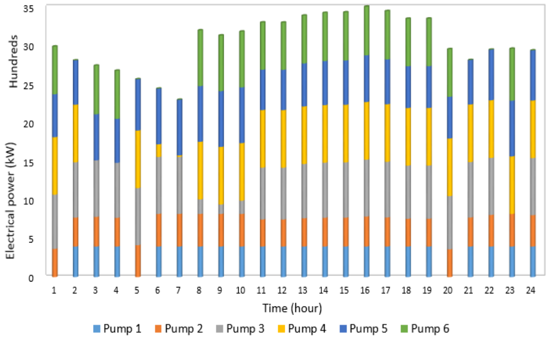

Fig. 7. Electrical power consumed by pumps

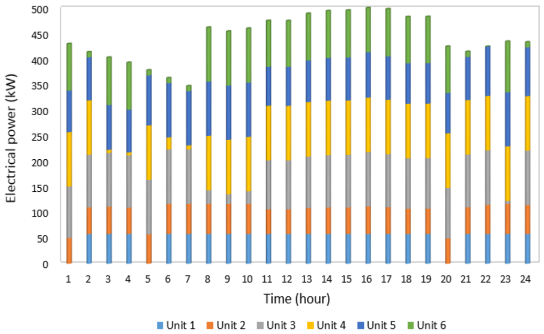

Fig. 8. Energy consumption of cooling towers

5. Conclusion

In tropical regions, large-scale buildings consume more electricity to supply their cooling load. In addition, annual on-peak energy demand of interconnected power networks usually occurs in afternoon hours of extremely-hot summer days. If performance optimization methods are not implemented on air conditioning systems, load-generation mismatch will occur in power distribution grids and may led to wide spread blackouts. Therefore, optimal short-term scheduling of multiple-chiller plants can reduce their energy consumption and overcome this issue. Hence, a novel methodology for calculation of electricity consumption in different sections of multi-chiller plants was presented in current paper. Partial load ratio of each chiller, power consumption of pump-chiller-cooling tower, temperature of cooled water, temperature of water existing from cooling tower, mass flow rate of water pumped into chiller and cooling tower are selected as decision variables to minimize total energy requirement of pumps, chillers and cooling towers in a 24-hour study horizon. It is proved that electrical power not only is consumed by chiller units but also is required in cooling towers and pumps, which has not been considered in other published works. Moreover, temperature and mass flow rate of water flowing in and out of chillers and cooling towers are important and affect total power consumption of chiller-cooling tower units. Hence, if system operator does not consider them in optimization process, partial load ratio and power consumption of chillers-cooling towers-pumps may increase, significantly.

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