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Robust optimal design of chiller plants based on cooling load distribution

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Abstract

Conventional designs of chiller plants are typically based on the peak cooling loads of buildings, while only a small proportion of time in a year the cooling load of a building is at its peak level. In this paper, a robust optimal design concerning the cooling load distribution in design is proposed to select the optimal combinations of chiller plants, which have the highest probability to operate at high part load ratio (PLR) and COP. A case study on the air-conditioning system of an underground station in Hong Kong is conducted to test the robust optimal design and demonstrate the processes of determining the optimal chiller combination. The results show that the robust optimal design can ensure the selected chiller plant to operate at higher PLR and COP compared with that using a conventional design method.

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Keywords: air-conditioning system, optimal design; robust optimal design; uncertainties;

1. Introduction

The building sector has been the largest energy consumer in most countries and districts worldwide [1]. In commercial buildings, about 40-60% of the total electricity consumption is consumed by the Heating, Ventilation and Air-Conditioning (HVAC) system [2]. Among all HVAC components and equipment, chillers are usually the major energy consumers, accounting for up to 50% of the total energy consumption of the entire system [3]. It is found that a significant energy saving potential can be achieved by chillers through the optimal design and energy efficient operation [4].

The sizing and selection of chillers play the most important role in determining the overall energy performance of the HVAC system. The conventional workable design of chiller systems is usually based upon sizing the components individually to meet a peak duty of a nominal operating point. Due to the inevitable uncertainty of weather data, indoor occupants and internal heat gain, designers tend to select a

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much larger system capacity than the peak duty (e.g., multiply a safety factor) in order that the system can fulfil the cooling demand under any uncertain conditions for safety [5, 6]. This may result in significant oversizing of chiller plant systems and thus cause a large amount of energy wastes since the actual operating conditions are seldom the same as the design condition. Some measures, such as using a detailed simulation method, statistic and realistic weather data and model calibration, have been recommended to reduce the oversizing problems to a certain degree caused by uncertainties [7]. Different from previous design methods that only address the peak cooling load on the design day, few studies also has taken part-load conditions into account in order to achieve a high efficiency in most of operating time throughout the cooling seasons [8]. Nevertheless, most conventional chiller design methods are based on the predefined conditions and subject to a deterministic model-based simulation. Using such methods, it may achieve a satisfactory performance when the actual operating conditions are the same or similar as the predefined conditions. However, chiller systems are very likely to operate at a low efficiency when the actual conditions are different from predefined conditions considering large uncertainties exist in the HVAC system [9].

In order to achieve a more flexible, resilient and sustainable design of the chiller system, a robust optimal design method is proposed in this paper. It can ensure the performance of chillers selected to operate at a high level under different load conditions throughout the entire cooling season, even though the load conditions deviating from the design conditions significantly due to various uncertainties of main variables (i.e., weather conditions and number of occupants). The concept of robust optimal design and the procedure of implementing this method are introduced. A case study on the application of this method for the chiller system design of an underground station in Hong Kong is also presented.

2. Robust optimal design method of chiller plants

2.1. Concept of robust optimal design

In engineering field, the aim of *optimal design* is to improve the design so as to achieve the best way of satisfying the original demand with the available methodologies [10]. Optimal design involves the selection of a series of variables to describe the design alternatives, and the selection of an objective, expressed in terms of the design variables, which is to be minimized or maximized. The typical definition of *robust design* is described as *a product or process is said to be robust when it is insensitive to the effects of sources of uncertainties, even though the design parameters and the process variables have large tolerances for ease of manufacturing and assembly* [11]. Robust design improves the quality and reliability of a product by minimizing the negative effect of uncertainties.

Combining the advantages of optimal design and robust design, a concept of *robust optimal design* is proposed not only to ensure the performance of chiller plants at a high level when the plants operate in design conditions but also ensure the performance at a relative high level when load conditions deviate from the design conditions due to uncertainties.

2.2. Implementation of robust optimal design of chiller plant

In order to realize the robust optimal design of chiller plant, the most important job is to ensure the *PLR* (part load ratio) and COP (coefficient of performance) of operating chillers under various load conditions as high as possible, even though the cooling load conditions may be subject to large uncertainties. The procedures of the proposed chiller design method can be divided into three steps as follows:

Step 1: *Narrow the distribution range of cooling load through reducing the uncertainty of inputs*. There are high degrees of uncertainty in input data required to determine cooling loads. Much of this is due to the unpredictability of occupancy, human behaviour, outdoors weather variations, lack of and variation in heat gain data for equipment, and introduction of new building products and HVAC equipment with unknown characteristics. Except that the uncertainty due to the unpredictability of variables (i.e., weather conditions and number of occupants) is hard to eliminate, the impact of other uncertainty on cooling load can be reduced through some effective measures, such as using the calibrated models, using more realistic heat gain data of equipment and using the HVAC equipment with more certain characteristics. After reducing the uncertainties of inputs, the distribution of the output cooling load can consequently be narrowed to a more concentrated range.

Step 2: *Optimization of chiller number and chiller capacity to achieve high PLR*. The energy performance of chiller, usually evaluated by COP (coefficient of performance), is strongly dependent on the PLR of chiller. From the chiller performance data provided by manufactory, the highest COP usually achieves when PLR is about 70-80% rather than 100%. In other words, it seems that the relationship between the COP and PLR is not monotonic. However, more and more researchers realize that the larger PLR is, the higher COP achieves once the impact of operating conditions is separated [12, 13], as shown in Eq. (1):

$$COP = \frac{273.15 + T_{Eva}}{T_{Con} - T_{Eva}} \times \left(C_0 + C_1 \cdot PLR + C_2 \cdot PLR^2 + C_3 \cdot PLR^3\right) \tag{1}$$

where, T_{Eva} and T_{Con} are evaporating and condensing temperature (°C), respectively; C_0-C_3 are the correlation coefficients that can be identified from chiller catalogues or field measurement data. *PLR* is the part-load ratio. For engineering application, *PLR* can be simply defined as the ratio of the required cooling load (CL_R) to the available cooling capacity (CL_A) as shown in Eq. (2).

$$PLR = \frac{CL_{\mathrm{R}}}{CL_A} = \frac{CL_R}{N_{Operating} \cdot CL_{\mathrm{Nominal}}} \tag{2}$$

where, $CL_{Nominal}$ is the nominal cooling capacity of each chiller, and $N_{operating}$ is the number of operating chillers. This equation is based on the assumption that identical chillers are used in the same building, which is very common in practice. *This equation clearly shows that the PLR is not only determined by the actually cooling load but also determined by the number of operating chillers and the capacities of individual chillers*.

There are a variety of combinations of chiller number and nominal capacity to meet the maximal cooling demand (i.e., the peak duty on the design day). Different combinations result in different operating PLRs and resultant COPs. Generally, the combination of more chillers with smaller nominal cooling capacity of each chiller can provide better flexibility for achieving a high PLR than the combination of fewer chillers with larger nominal cooling capacity of each chiller. Fig.1 (a) shows the relationship between the average operating PLR throughout the entire cooling season and the selected chiller number: the more chillers are selected, the higher average PLR can be achieved. On the other hand, selecting more chillers means the nominal cooling capacity of each chiller becomes smaller. Generally, the rated COP of chiller decreases when the nominal cooling capacity of each chiller becomes smaller, as shown in Fig.1 (b). Therefore, there is an optimum selection of chiller number and nominal capacity that can make the chillers achieve the largest COP during the operating stage.

Step 3: *Achieve high COP through selecting chillers with best partial load performance*. Under the same operating PLR conditions (with the same frequency distribution), chillers with better partial load performance characteristics should be employed. Fig.2 presents the conceptual COP profile of two typical types of chillers (i.e., variable-speed chiller and constant-speed chiller). The COP of the constant-speed chiller may be even larger than that of the variable-speed chiller near the full load conditions while the variable-speed chiller performs much better under other load conditions, particularly the low PLR conditions. Considering that chillers operate under partial load conditions in most of time, a higher average COP can be achieved by selecting the variable-speed chiller than that of selecting the constant-speed chiller.

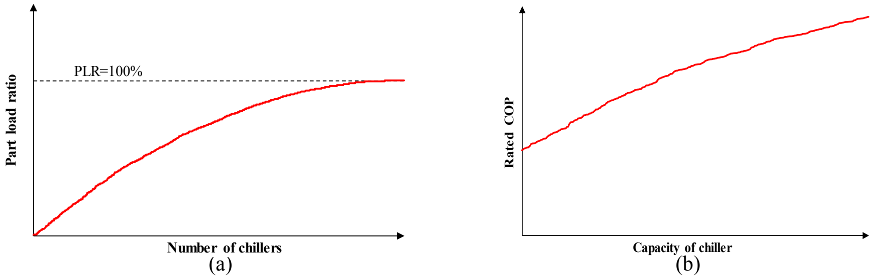


Fig.1 (a) the number of chillers vs. the operating PLR; (b) the rated COP vs. the nominal capacity

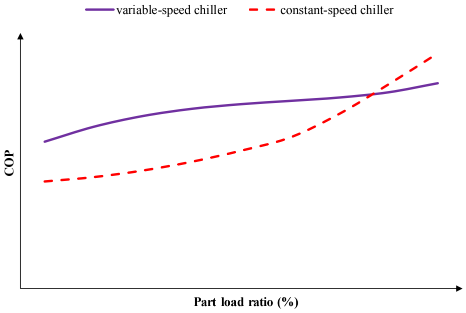


Fig.2 the COP profile of constant-speed chiller and variable-speed chiller

3. A case study in an underground station in Hong Kong

A case study is presented to demonstrate the implantation of the proposed robust optimal design method in an underground station in Hong Kong. According to the aforementioned procedures of the proposed method, the first step is to narrow the cooling load distribution by reducing the impact of uncertain factors. During this step, some measures such as using model calibration, detail characteristics of internal equipment and realistic data of occupants are utilized to estimate the building cooling load as accurately as possible. The frequency distribution of annual cooling load is obtained as shown in Fig.3. It can be observed that the cooling load has the higher frequency percentage at the point around 700 kW and 900 kW. The peak cooling load of this station is about 1800 kW.

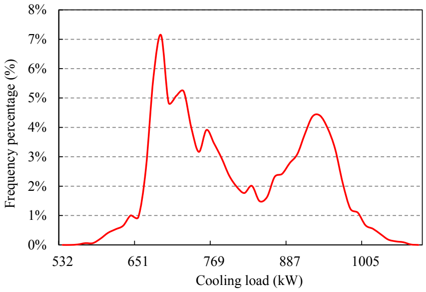


Fig. 3 Frequency distribution of cooling load throughout the entire cooling season

The second step is to achieve a higher average PLR through the optimal selection of chiller number and capacity. Eight combinations of chillers with different chiller number and nominal capacity are proposed for comparison, as listed in Table 1. Due to the limited space in underground, the chiller plant room can accommodate no more than three chillers. To achieve the flexibility and high PLR, only the combination with two chillers (at least two chillers are required for makeup) and three chillers are considered in this case study. Combinations 1-6 consist of two chillers while combinations 7 and 8 have three chillers for each combination. Combinations 3-8 are composed of the chillers with different capacities. Fig.4 presents the frequency distribution of PLR of eight combinations under the cooling load distribution. Compared with the others' combinations, combination 7 has the most centralized PLR ranging from 75% to 100%. The average PLR is summarized in Table 1. Among the eight combinations, combination 7 has the highest average operating PLR.

Followed is the third step, which is to make the chiller achieve a higher COP through selecting chillers with better partial load performance. The partial load performance of constant-speed chillers and variable-speed chillers are very different, as shown in Fig.2. Combination 1 consists of two identical constant-speed chillers and combination 3 consists of two variable-speed chillers. Under the entire cooling load distribution, the constant-speed chillers in the eight combinations are possibly maintained to operate at full load due to the high COP at peak load. Fig.5 presents the frequency distribution of COP of the eight combinations. Compared with the others' combinations, combination 8 can operate at the most centralized COP ranging from 5.0 to 6.4. The average COP of each combination is also summarized in Table 1. It can be observed that combination 8 has the highest average COP and therefore can be selected as the most robust and optimal option for the design. It means that the proposed robust optimal design method can select the available chiller plants which can operate at the high efficiency under any cooling load conditions.

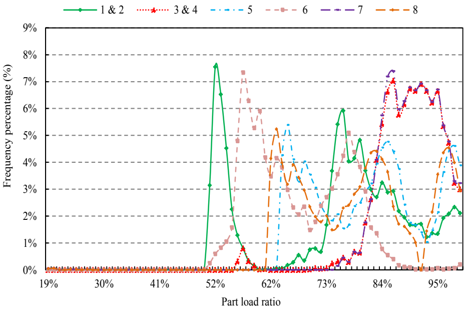


Fig. 4 Distribution of PLR

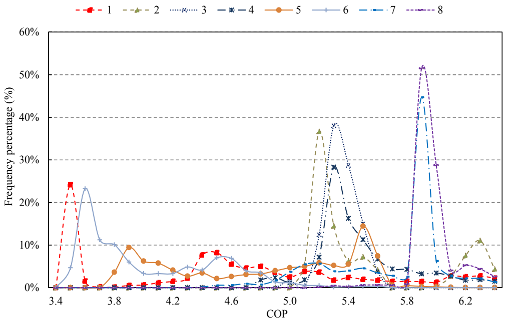


Fig. 5 Distribution of COP

Table 1. The operating performance of eight proposed combinations of chillers

No.	Combination (kW)	Average PLR (%)	Average COP
1	900 (CSD), 900 (CSD)	74.8%	4.64
2	900 (CSD), 900 (VSD)	74.8%	5.40
3	1000 (VSD), 800 (VSD)	89.1%	5.35
4	1000 (CSD), 800 (VSD)	89.1%	5.50
5	1100 (CSD), 700 (VSD)	81.2%	4.82
6	1200 (CSD), 600 (VSD)	67.3%	4.04
7	400 (VSD), 600 (CSD), 800 (CSD)	89.6%	5.71
8	500 (VSD), 600 (CSD), 700 (CSD)	81.1%	5.97

4. Conclusion

A robust optimal design method is proposed to select the optimal combination of chiller plants under various possible cooling load conditions. This method can be implemented by three steps, including narrow the cooling load distribution by reducing uncertainties, optimization of chiller number and chiller capacity to achieve high PLR, and select the chiller with best load performance. The result of a case study of an underground station shows that using the proposed method can drive the selected chiller plants operate at a high COP under any cooling load conditions.

5. Copyright

References

[1] *Hong Kong energy end-use data 2012*, Hong Kong Electrical & Mechanical Services Department; 2012.

[2] Wang S, Ma Z. Supervisory and optimal control of building HVAC systems: A review [J]. *HVAC&R Research*, 2008, 14(1): 3-32.

[3] Sun Y, Wang S, Xiao F. In situ performance comparison and evaluation of three chiller sequencing control strategies in a super high-rise building [J]. *Energy and Buildings*, 2013, 61: 333-343.

[4] Lee W L, Yik F W H, Jones P, et al. Energy saving by realistic design data for commercial buildings in Hong Kong [J]. *Applied Energy*, 2001, 70(1): 59-75.

[5] Domínguez-Muñoz F, Cejudo-López J M, Carrillo-Andrés A. Uncertainty in peak cooling load calculations [J]. *Energy and Buildings*, 2010, 42(7): 1010-1018.

[6] Sun Y, Gu L, Wu C F, et al. Exploring HVAC system sizing under uncertainty [J]. *Energy and Buildings*, 2014, 81: 243-252.

[7] Yik F W H, Lee W L, Burnett J, et al. Chiller plant sizing by cooling load simulation as a means to avoid oversized plant [J]. *HKIE Transactions*, 1999, 6(2): 19-25.

[8] Shiming D. Sizing replacement chiller plants [J]. *ASHRAE journal*, 2002, 44(6): 47-49.

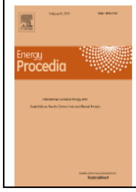
[9] Ashouri A, Petrini F, Bornatico R, et al. Sensitivity analysis for robust design of building energy systems[J]. *Energy*, 2014.

[10] Papalambros P Y. *Principles of optimal design: modeling and computation* [M]. Cambridge university press, 2000.

[11] Zang C, Friswell M I, Mottershead J E. A review of robust optimal design and its application in dynamics [J]. *Computers & structures*, 2005, 83(4): 315-326.

[12] Hong T, Yang L, Hill D, et al. Data and analytics to inform energy retrofit of high performance buildings[J]. *Applied Energy*, 2014, 126: 90-106.

[13] Wang S, Yan C, Xiao F. Quantitative energy performance assessment methods for existing buildings[J]. *Energy and Buildings*, 2012, 55: 873-888.



Biography

Qi Cheng is a PhD student, Chengchu Yan is a post-doctoral fellow, Shengwei Wang is a chair professor in the Department of Building Services Engineering, The Hong Kong Polytechnic University. Building energy efficiency and diagnosis, optimal control and optimal design of HVAC systems are among the research interests of the authors.