Energy and Buildings 138 (2017) 695–703

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

The analysis of the operating performance of a chiller system based on hierarchal cluster method

Manfeng Li[a,b], Yonglin Ju[a,*]

[a] School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China
[b] School of Environmental & Municipal Engineering, North China University of Water Resource and Electric Power, Zhengzhou 450011, PR China

ARTICLE INFO

Article history:
Received 6 July 2016
Received in revised form
24 December 2016
Accepted 27 December 2016
Available online 30 December 2016

Keywords:
Chiller system
Operating performance
Hierarchical cluster method
COP
*ROEE*R

ABSTRACT

A simulation model of chiller system containing four sets of chillers is built in Energyplus 7.0 simulation software. Based on the simulation data of chiller system, a data-mining tool – hierarchical cluster method is applied in chiller system to analyze the operation performance of chiller system. Using a built-in analytical tool in SPSS v17.0, hierarchical cluster method is made on the five main operating variables of chiller system over a year. There are three clusters produced by hierarchical cluster method, which represent three typical operating conditions of chiller system of a whole year. Through the analysis of the characteristics of clusters of main operating variables, the operating conditions of each chiller can be illustrated, which matches with the control strategy implemented in the chiller system. By the analysis of *COP*s of each chiller in different clusters, the potential of energy saving for the chiller system under different clusters can be illustrated. Besides, it is found that the Refrigeration Operation Energy Efficiency Ratio (*ROEER*) of one chiller over one year can be represented by the *COP*s of one chiller in different cluster centers, which demonstrates that the cluster results are reasonable.

1. Introduction

Chiller systems are commonly used to provide cooling energy for commercial and industrial facilities but with considerable electricity consumption. The operating performance of chiller systems is usually defined by the coefficient of performance (*COP*): cooling energy output divided by electric power input. As for the chiller system in actual buildings, it operates for diverse combinations of loads and weather conditions due to climatic influences, there are no straightforward means to assess the operating performance or potential energy savings, in other words, it is difficult to assess the potential energy savings resulting whether from control influences or climatic influences. The assessment would be even more complicated if a huge amount of operating data are collected at hourly or even minutely intervals from a building management system (BMS) database. In order to analyze the operating performance of chiller systems or HVAC systems based on the operating data, mass of work have been done in this field.

Chan and Yu [1] used the operating data of an air-cooled chiller system to analyze how the chiller components interact with each other and discussed how the analysis helped modelling floating condensing temperature control to improve system performance. Sun et al. [2] developed a data fusion technology to detect faults in the direct measurement of chiller system loads in order to enhance the sequencing control of the chillers. Based on a set of operating data from two experimental chillers, Swider [3] examined which modelling approach would predict more accurately the operating performance of chillers. It was shown that with sufficient amount of measured data, black-box models, because of their higher generalization abilities, may be preferred to model chiller operating performance and be used in fault detection and diagnosis with higher accuracy. The Gordon and Ng's grey-box thermodynamic model [4] was one of the generic models used for chiller diagnosis and optimization. It correlates the chiller *COP* with some temperatures monitored typically at the evaporator and condenser sides and contains some empirical parameters to account for system irreversibility associated with heat losses. The operating performance of different types of chillers can be characterized by the empirical parameters identified from regression analysis. Xu et al. [5] described a principal component analysis (PCA) model to correlate compressor power, temperatures and pressures at the evaporator and condenser sides. The PCA model was used to capture the systematic variations of chiller performance. Wavelet analysis was then applied to detect and diagnose faulty sensors and recover measurements and was capable of processing noises and dynamics.

* Corresponding author.
E-mail address: yju@sjtu.edu.cn (Y. Ju).

http://dx.doi.org/10.1016/j.enbuild.2016.12.076
0378-7788/

Nomenclature

COP	Coefficient of performance
K	Group
S	Squared deviation
BIC	Bayesian information criterion
D	Model
L	Maximized value of the likelihood function
k	Number of free parameters to be estimated
x	Sample data
$\tilde{\sigma}$	Error variance
E	Energy cost of chiller (kW)
Q	Cooling load of chiller (kW)
PLR	Part load ratio
θ	Parameters that maximize likelihood function
M	Water flow rate (kg/s)
T	Temperature (°C)
ROEER	Refrigeration operation energy efficiency ratio
I	Frequency
ε	Relative error

Subscripts and superscripts

w	Water
wl	Supply chilled water
we	Cooling water entering the condenser
ch	Chiller
cd	Condenser

Data mining (DM) is an emerging powerful technology with great potential to discover hidden knowledge in large data sets. In recent years, DM has been gaining increasing interest in various industries, such as banking and financial services, retails, healthcare, telecommunication and counter-terrorism [6]. In the building field, DM is mainly used for energy prediction and operating performance analysis. In terms of energy prediction, Yu et al. [7] established a decision tree model to predict the building energy use intensity. Dong et al. [8] used support vector regression models to predict the monthly building energy bills. Zeng al. [9] applied DM tool to construct the predictive models of HVAC energy consumption, to investigate the energy savings of HVAC system. In terms of operating performance analysis, Ahmed et al. [10] investigated the impacts of building characteristics and climate conditions using classification techniques on indoor thermal comforts and indoor luminance level. Ren et al. [11] applied data mining methods, including clustering approach and decision trees to investigate the behavior of occupants adjusting their thermostat settings and heating system operations in a 62-unit affordable housing complex. Lam et al. [12] applied principal component analysis to study the influence of climatic parameters (dry-bulb temperature, wet-bulb temperature, global solar radiation, clearness index and wind speed) on the chiller plant electricity consumption.

A number of DM techniques are available nowadays and more are emerging with the development of technology. Different from model-based methods, DM technique is a statistical method with great potential to discover hidden knowledge in large data sets, which doesn't need sophisticated knowledge of the operating and control of system. For the chiller system, it is quite difficult to simulate the trade-off between the power of system components when a chiller system has various operating modes for many sets of chillers, pumps and cooling towers. Furthermore, it may be impossible to draw only on system simulation skills to explain the change of system *COP* under various combinations of load conditions and controls with climatic influences, considering that chiller systems have various designs and configurations. Therefore, it is preferable to apply DM techniques to assess the operating performance of chiller system based on operating data sets. Clustering analysis is one of the major DM techniques to identify groups of individuals similar to each other but different from individuals in other groups, which now has been applied in classifying the operating conditions of building and HVAC system. However, the studies on the analysis of operating performance of chiller system using clustering analysis are few, and the selection of cluster number still lacks reasonable explanations. This paper, therefore, applies hierarchal cluster method to assess the operating performance of a chiller system, and use the index of Bayesian Information Criterion (BIC) to select the cluster number. Through the clustering analysis of chiller system, it is found that the *ROEER* (Operation Energy Efficiency Ratio) of chiller can be represented by the *COP*s of the chiller in different cluster centers.

A simulation model of chiller system with 4 sets of chillers is firstly built in Energyplus software. Statistical software and clustering techniques will be presented to illustrate how to perform clustering analysis on the huge set of operating data. Based on the three clusters developed, the operating conditions of each chiller can be distinguished, which matches with the control strategy implemented in the chiller system. And by the analysis on the *COP*s of each chiller in different clusters, the potential of energy saving for chiller system under different clusters can be illustrated.

2. Description of chiller system

A chiller system serving an office building in Guangzhou is studied, as shown in Fig. 1. Four centrifugal chillers are designed to cater for the peak building cooling load of 12000 kW. Among all chillers, three of them are equal-sized, the rated cooling capacity is 2500 kW. For the other chiller, its rated cooling capacity is 4500 kW. The chillers are connected in parallel and operate with their constant speed pumps to deliver the amount of chilled water required to meet the changing building cooling load. With a fixed flow rate of chilled water passing through each chiller, the temperature difference of chilled water is kept at 5 °C at full load and decreases from 5 °C when the chiller load drops. The chilled water distribution system contains a decoupling bypass pipe linking the primary and secondary chilled water loops to balance the flow under part load conditions. The secondary loop chilled water pumps operate in different numbers and speed to deliver the required flow rate of chilled water for the airside system. Heat rejection of the chillers is done by four water evaporative cooling towers, each of which provides sufficient heat rejection capacity required for each of the chillers and they are linked together by a common cooling water circuit. For four cooling towers, the rated heat rejection rate of small cooling tower is 3050 kW, and rated heat rejection rate of large cooling tower is 5100 kW. The temperatures of the cooling water entering the condenser and leaving from the condenser are designed to be 33 °C and 38 °C, respectively, under the full load conditions. The cooling tower fans are cycled on with high/low speed to control the cooling water entering the condensers at around 33 °C under various operating conditions. Constant speed condenser water pumps are used to provide a fixed cooling water flow rate of 315 m^3/h for the large chiller and 148 m^3/h for each small chiller. The operating of chillers applies a sequence control strategy [13], which operates chiller in fixed sequence according to the cooling load of building. For example, when the building cooling load is smaller than the rated cooling capacity of one chiller, only one chiller operates. When the building cooling load is larger than the rated cooling capacity of one chiller and smaller than rated cooling capacity of two chillers, another chiller operates. The simulation model was built in simulation software- Energyplus 7.0 [14]. The control strategies of the chiller system are implemented in the "schedule" of Energyplus