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Multivariate diagnosis analysis for chiller system for improving energy performance

F.W. Yu*, W.T. Ho

Hong Kong Community College, The Hong Kong Polytechnic University, 8 Hung Lok Road, Hung Hom, Hong Kong

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ABSTRACT

The operating status of a large chiller system in buildings with central air-conditioning could vary at a given cooling demand and ambient condition. This study investigates the potential change of operating statuses and its influence on the system coefficient of performance (COP)—cooling energy output divided by the total electric power input. The system studied comprised four large and one small chillers. A set of primary chilled water pumps operated in different numbers to deliver the required flow rate of chilled water to the operating chillers. The actual flow rate to meet the building cooling demand was regulated by the secondary chilled water pumps. A set of evaporative cooling towers was installed to match the heat rejection required for the chillers. Comprehensive operating data were collected at 15-min intervals in 8 months. 18.46% of the total operating conditions were transitional statuses and unconventional operating statuses by switching on or off one extra cooling tower. This led to a 33.9–64.9% drop in individual system COPs. An examination of the variation of system load ratios and ambient wet bulb temperatures showed that the system COP was higher at the pair-up operation of system components even at higher wet bulb temperatures. A survival analysis indicated that the transitional statuses depended mainly on the temperature of chilled water returning to the evaporators and the temperatures of cooling water entering and leaving the condensers. Minimizing unnecessary transitional statuses and restoring the pair-up operation of system components could save electricity by 2.72%.

1. Introduction

Buildings with central air-conditioning are often equipped with chiller systems for space cooling. The operation of chiller systems depends on various controllable parameters and ambient conditions. Performance diagnosis would help examine if the system coefficient of performance (COP) complies with the expected levels and identify opportunities for improving the energy efficiency of buildings. The system COP is defined as the cooling capacity output of operating chillers divided by the total electric power input of the chillers and the associated pumps and cooling tower fans. Various modeling and statistical tools have been studied for chiller system diagnosis. Yan et al. [1] used a back-tracing sequential forward feature selection algorithm to identify most important features for system diagnosis which helped limit the number of sensors required. Wang et al. [2] proposed a Bayesian network merged distance rejection technique to remove redundant sensor features and check if supplementary features are required to enhance the probability of detecting faults. Tran et al. [3] compared the accuracy of multiple linear regression models, Kriging models, and radial basis function models. The radial basis function models coupled with the exponentially-weighted moving average residual control chart were identified to have the most sensitive fault detection. Li et al. [4] proposed a data-driven strategy with two-stage linear discriminant analysis to diagnose a chiller system. The strategy was able to identify the type of fault from the monitoring data and the seriousness of the faults. Li and Ju [5] used the hierarchal cluster method to analyze the operating performance of a simulated chiller system. The extent to which the system COP could increase was described more precisely by the simulated data at different cluster centers. Satyavada and Baldi [6] developed an integrated control-oriented model for benchmarking the aggregate performance of heating, ventilating and air-conditioning systems, taking in account interactive controls among condensing boiler, radiator, air handling unit, heat pump, chiller, fan, pump, pipe, duct, and multiple thermal zones. Yet sophisticated statistical platforms and modeling knowledge are required to replicate the aforementioned studies. Furthermore, the application of previous studies is limited to a small scale system or certain components in a system.

Abou-Ziyan and Alajmi [7] examined the effect of load-sharing operation strategy on the aggregate performance of multiple-chiller systems. The operation of chiller compressors was adjusted and uneven

* Corresponding author.
E-mail address: ccyufw@hkcc-polyu.edu.hk (F.W. Yu).

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Nomenclature

COP	coefficient of performance, given by Q_{cl}/E_{total}
c_{pw}	specific heat capacity of water (4.19 kJ/kg °C)
E_{cd}	power of condenser water pumps (kW)
E_{ch}	power of operating chillers (kW)
E_{cp}	power of primary loop chilled water pumps (kW)
E_{ct}	power of cooling tower fans (kW)
E_{sp}	power of secondary loop chilled water pumps (kW)
E_{total}	power of all system components, given by $E_{ch} + E_{cp} + E_{sp} + E_{cd} + E_{ct}$ (kW)
m_w	chilled water mass flow rate (kg/s)
Q_{cl}	cooling capacity, given by $m_w\, c_{pw}\, (T_{chwr}–T_{chws})$ (kW)
$Q_{cl,r}$	rated cooling capacity of chillers (kW)
PLR	chiller part load ratio, given by $Q_{cl}/Q_{cl,r}$
T_{cdwe}	temperature of cooling water entering the condenser (C)
T_{cdwl}	temperature of cooling water leaving the condenser (°C)
T_{chwr}	temperature of return chilled water (°C)
T_{chws}	temperature of supply chilled water (°C)
T_{db}	dry bulb temperature of outdoor air (°C)
T_{wb}	wet bulb temperature of outdoor air (°C)

load sharing among the compressors would improve the aggregate COP by 22–33%. Factors affecting the aggregate COP included the piping arrangement, the performance of evaporators and condensers and the heat loss from chilled water piping. Sohrabi et al. [8] ascertained that the exchange market algorithm was an effective means to solve the optimal chiller loading problem. The chiller performance curves were modeled in terms of the chiller load ratio only in their study. Lee et al. [9] examined the differential evolution algorithm for optimal chiller loading and identified its superior performance to minimize the electricity consumption of multiple chiller systems compared with the genetic algorithm and the Lagrangian method. Yet the COP variations due to the performance of heat rejection devices and the temperature of heat rejection medium remain untouched. Chen et al. [10] incorporated the temperature difference across the condenser and the chiller part load ratio into the chiller models and applied the neural network plus particle swarm optimization algorithm to optimize chiller loading. The proposed algorithm had fast convergence and highly accurate results. Liu et al [11] considered the chiller and cooling tower models to examine the maximum cooling capacity of chillers at different outlet temperatures of cooling towers. The adjusted chiller part load ratio from the maximum capacity was used to optimize the switch points of chillers to achieve the minimum aggregate power of chillers, dedicated water pumps and cooling towers.

Data-driven optimization techniques are increasingly used to improve the energy performance of existing chiller systems. Wang et al. [12] developed the event-driven optimal control for central air-conditioning systems. Yet there is a lack of research work to facilitate chiller operators to examine the system COP based purely on a large set of operating data covering all system components. The aim of this study is to illustrate how the potential change of operating statuses influences the COP of a multiple-chiller system. The configuration of the system will be described and its various operating statuses will be examined. Results will be presented on the variation of the system COP under each operating status and how the transitional and unconventional statuses caused the system COP to drop in various degrees. An investigation will be made on how the transitional and unconventional statuses resulted from the variation of chiller loads and wet bulb temperatures. Factors influencing the period of transitional statuses will be examined by survival analysis. The significances of the study are to demonstrate a systematic approach for chiller operators to analyze the change of system COP in response to different operating patterns of system components and to illustrate how survival analysis helps investigate the probability of extending the time between transitional statuses due to a variation of operating variables.

2. System description and operating status evaluation

The configuration of the system studied is shown in Fig. 1. It contains 4 chillers with a rated cooling capacity of 1758 kW each and one chiller with a rated cooling capacity of 1055 kW. Three chillers rated at 1758 kW are required to meet the peak cooling demand of 5274 kW for a building. The small chiller operated only for light duty loads outside normal operating hours in cold winter months. A set of primary loop chilled water pumps at constant speed was connected in parallel and operated in different numbers to deliver the required flow rate of chilled water to the operating chillers. The actual flow rate to meet the building cooling demand was regulated by the secondary chilled water pumps. The decoupling bypass pipe was used to balance a difference in the flow rate between the primary loop and secondary loop for building cooling coils. A set of evaporative cooling towers was installed to match the heat rejection rate of the chillers. A sophisticated central control and monitoring system was installed to automatically switch on and off the system components based on the measured building cooling demand and the temperature set point of cooling water for heat rejection. Comprehensive operating data were collected at 15-min intervals over the period of January and August in the year. The interval is fine enough to capture a change in the number of system components operating and hence the system COP. Indeed, each operating status was kept unchanged for at least 15 min and the operating variables did not have significant variations at 15-min intervals due to the thermal stability of the chilled water and condenser water circuits. The system cooling capacity was calculated based on the measured flow rate and temperatures of chilled water passing through the operating chillers. Power analyzers were used to measure the electric power consumed by the operating chillers, pumps and cooling tower fans. The system COP was evaluated by the system cooling capacity divided by the total electric

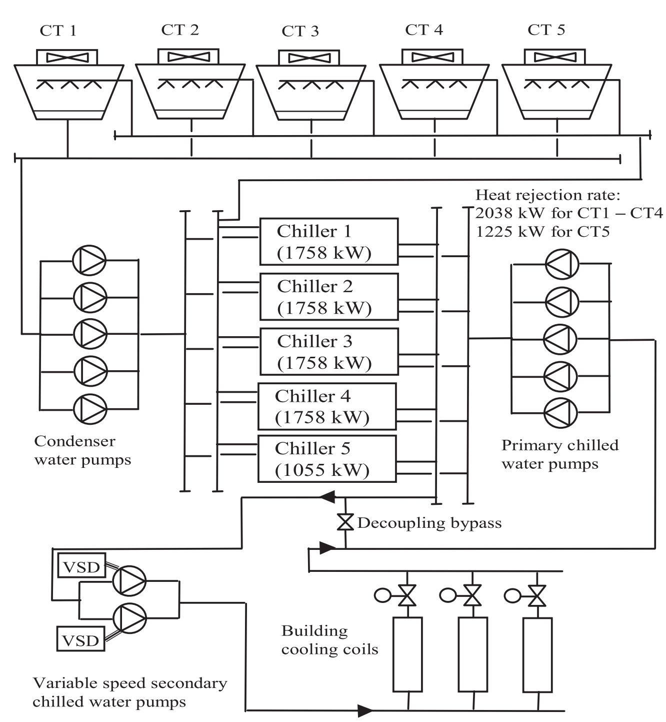

Fig. 1. Chiller system configuration.