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Energy efficient control of variable speed pumps in complex building central air-conditioning systems

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ABSTRACT

This paper presents the optimal control strategies for variable speed pumps with different configurations in complex building air-conditioning systems to enhance their energy efficiencies. Through a detailed analysis of the system characteristics, the pressure drop models for different water networks in complex air-conditioning systems are developed and then used to formulate an optimal pump sequence control strategy. This sequence control strategy determines the optimal number of pumps in operation taking into account their power consumptions and maintenance costs. The variable speed pumps in complex air-conditioning systems can be classified into two groups: the pumps distributing water to terminal units and pumps distributing water to heat exchanges. The speeds of pumps distributing water to terminal units are controlled by resetting the pressure differential set-point using the online opening signals of water control valves. The speeds of pumps distributing water to heat exchanges are controlled using a water flow controller. The performances of these strategies are tested and evaluated in a simulated virtual environment representing the complex air-conditioning system in a super high-rise building by comparing with that of other reference strategies. The results showed that about 12–32% of pump energy could be saved by using these optimal control strategies.

1. Introduction

During the past several decades, the costs of variable speed devices have come down significantly due to the advances in technology, which allowed widespread applications of variable speed pumps in building air-conditioning systems. An increased issue associated with the use of variable speed pumps is the control and optimization of their operation.

In terms of enhancing the operating efficiency, improving the control robustness and prolonging the service life, many practitioners in the control engineering have paid great efforts on energy efficient control and operation of variable speed pumps during the last two decades [1–4]. A number of researchers and experts in the heating, ventilation and air-conditioning (HVAC) field have also devoted considerable efforts on developing and applying proper and optimal control algorithms for variable speed pumps to enhance their energy efficiencies [5–18].

Among the existing studies, Burke [5] pointed out that when pumps operate within ±20% of their best efficiency points, there would seldom have any operation problem. Bernier and Bourret [6] examined the cumulative effects of the deteriorating values of the motor efficiency and variable frequency driver (VFD) efficiency as the speed of a pump is reduced. The results showed that the power required at the inlet of a pump-motor-VFD set was significantly higher, especially for oversized motors, than the power predicted by using the classic pump affinity laws. The parallel operation of variable speed pumps in chilled water systems was studied by Hansen [7]. The results showed that the benefits gained from the unequal speed operation of parallel pumps were minimal, and all pumps in a given installation were not necessary to be equipped with the speed control devices.

To optimize the speeds of variable speed condenser cooling water pumps, an online optimal control strategy was proposed by Wang and Burnett [8], in which an adaptive and derivative method was used to set the pressure set-point according to the estimated derivative of the total power consumption of chillers and water pumps with respect to the pressure to control the pump speed. Rishel [9–12] and Tillack and Rishel [13] stated that pumps can be sequenced properly based on the wire-to-water efficiency or kW input to the pumping system and the pump speed can be controlled through the use of pressure differential (PD) transmitters located at the critical loops and continuous interrogation of them. In the optimization strategy for air-conditioning systems proposed by Lu et al. [14], an adaptive neuron-fuzzy inference

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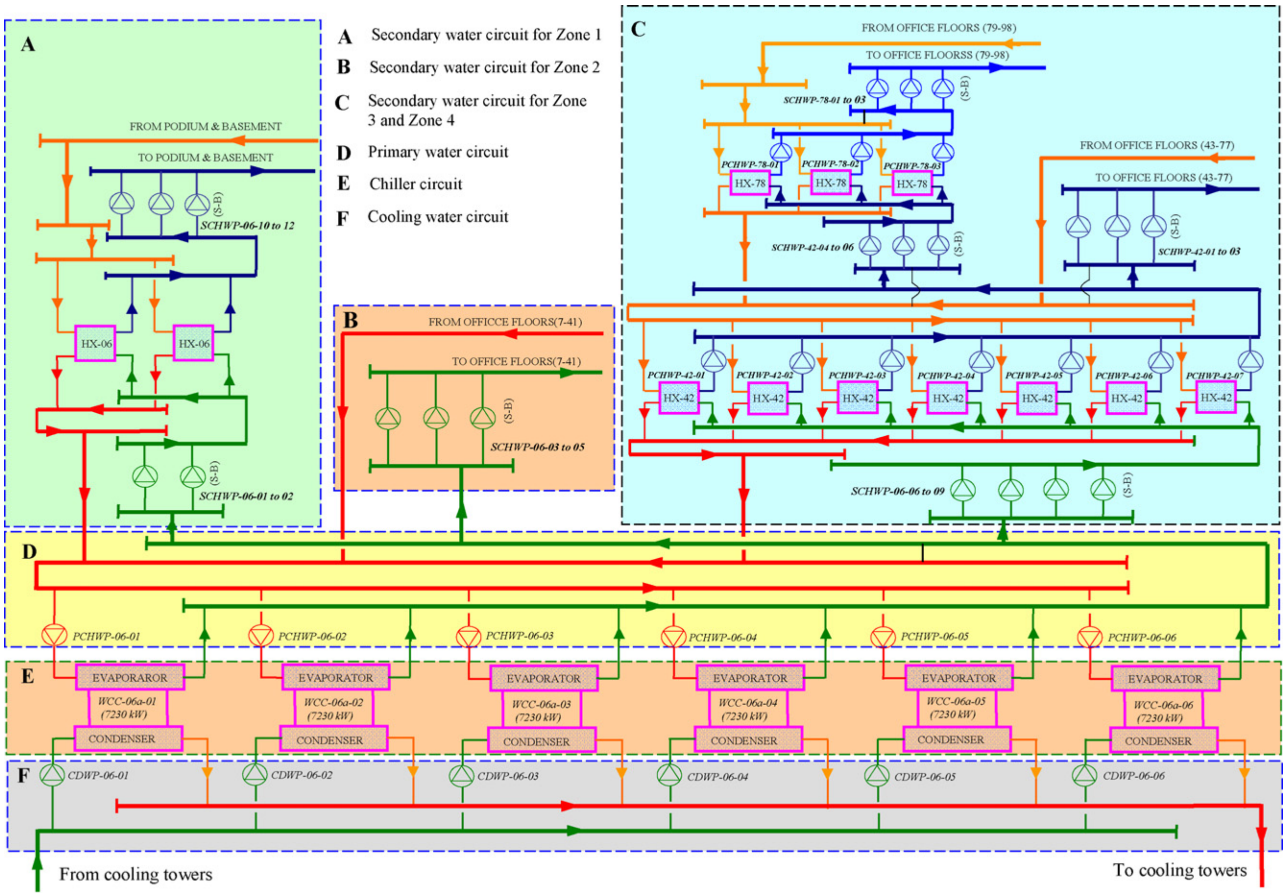

Fig. 1. Schematics of the central chilled water system.

system was used to obtain the optimal pressure differential set-point and model the duct and pipe networks based on the limited sensor information. To evaluate the energy use and economic feasibilities of alternative designs of chilled water pumping systems, a series of polynomials were used by Bahnfleth and Peyer [15,16] to model the performances of variable speed pumps.

Several studies have presented that the valve opening signal can be a valuable tool to optimize the pressure differential set-point to control the pump speed [13,17–19]. In Chapter 41 of the *2007 ASHRAE Handbook—HVAC Applications* [19], it was stated that the speed of the variable speed pump is practically controlled to maintain a constant pressure differential between the main chilled water supply and return pipelines although this approach is far from optimal. The pumps can be sequenced based on continuous monitoring of the outputs of the pump controllers.

It is noted that the pump speed control has been addressed in most of the above studies, while the studies on the pump sequence control still seem inadequate. This is probably due to one pump installation designed in many applications or simple sequence control strategies used in practice. In addition, the research associated with proper control of variable speed pumps in complex air-conditioning systems still seems missing.

This paper therefore aims at developing and addressing optimal control strategies, including the speed control strategy and the sequence control strategy, for variable speed pumps with different configurations in complex building air-conditioning systems for real-time applications. The performances of these strategies are tested and evaluated in a simulated virtual environment representing the complex air-conditioning system in a super high-rise building being constructed in Hong Kong.

2. Building and system descriptions

The building concerned in this study is a super high-rise building of approximately 490 m height and 321,000 m^2 of floor area. This building has a basement of four floors, a block building of six floors and a tower building of 98 floors. Fig. 1 is the schematic of the central chilled water system in this building, in which six identical centrifugal chillers with the capacity of 7230 kW each and the nominal power consumption of 1270 kW each at the full load condition are used to supply the chilled water at 5.5 °C. Each chiller is associated with one constant condenser water pump and one constant primary chilled water pump.

To avoid the chilled water pipelines and terminal units from suffering extremely high pressure, the secondary chilled water system is divided into four zones and only Zone 2 (indicated as B in Fig. 1) is supplied with the secondary chilled water directly. Zone 1 (indicated as A in Fig. 1) is supplied with the secondary chilled water through the heat exchangers located on the sixth floor (i.e., mechanical floor), while the chilled water from chillers serves as the cooling source of the heat exchangers. Zones 3 and 4 (indicated as C in Fig. 1) are supplied with the secondary chilled water through the first stage heat exchangers (HX-42 in Fig. 1) located on the 42nd floor (i.e., mechanical floor). Some of the chilled water after the first stage heat exchangers is delivered to Zone 3 by the secondary chilled water pumps (SCHWP-42-01 to 03) located on the 42nd floor. Some water is delivered to the second stage heat exchangers (HX-78 in Fig. 1) located on the 78th floor (i.e., mechanical floor) by the secondary chilled water pumps (SCHWP-42-04 to 06) located on the 42nd floor. The water system after the second stage heat exchangers is the conventional primary–