Applied Energy 154 (2015) 491–499

Contents lists available at ScienceDirect

Applied Energy

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

Energy conservation improvement and ON–OFF switch times reduction for an existing VFD-fan-based cooling tower

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HIGHLIGHTS

- Achieve energy saving and reduce the ON/OFF switching frequency at the same time.
- Propose a PI feedback controller with a temperature zone setting.
- Implement hybrid operations of rule-based and equation-based feedback control.
- Introduce larger approach for the setting of the outlet cooling water temperature.

ARTICLE INFO

Article history:
Received 19 December 2014
Received in revised form 3 May 2015
Accepted 9 May 2015
Available online 29 May 2015

Keywords:
Cooling tower
Energy conservation
Variable-frequency drive
Zone control
Approach

ABSTRACT

The increasing economic advantage of replacing traditional two-speed fans with variable-frequency drive (VFD) fans has been gaining popularity in the industry. However, concerns regarding frequent ON/OFF switching and the lack of a well-devised controller have discouraged widespread adoption. In this study, a temperature zone method is proposed to replace the set-point method of fan control. Additionally, the highest output water temperature allowed in the process is set as the upper limit of a zone in order to further conserve energy. Both strategies are comprehensively analyzed for a virtual cooling tower that uses operational data from an existing VFD-fan-based cooling tower system in Taiwan. The results show energy savings of 38% for a 0.75 °C zone without increasing the ON/OFF switching frequency. The proposed strategies were further verified via an on-line field experiment. The proposed methods can be universally and easily applied to any existing cooling tower, and have significant implications for energy conservation if adopted globally.

1. Introduction

Cooling towers are a common feature of industrial plants, especially in energy-intensive sectors such as the iron, steel, or petrochemical industries. A cooling tower dissipates waste heat to the atmosphere through a combination of heat- and mass-transfer processes. When considering an individual plant, the potential energy savings for a cooling tower may not be as great as those of powered devices, such as compressors, or energy-intensive components such as boilers or distillation columns. In addition to industrial applications, cooling towers are also widely used in heating, ventilating and air-conditioning systems. Overall, any improvement in cooling tower operations would provide significant opportunity for energy conservation.

Variable-frequency drive (VFD) devices have been available for more than four decades, but were not applied to cooling tower fans until their prices fell sharply over the past decade. Recently, two-speed fans have been gradually replaced with VFD-fans. Practical concerns remain, of how to avoid frequent START/STOP fan operation, which can cause sudden increases in stress due to the large inertia moment. This drawback has limited cooling systems based on VFD-fans from fully exploiting their energy-saving potential, which is more compelling and significant in large-scale, multi-cell systems used in energy-intensive industries. This study proposes two operational strategies to take advantage of energy-saving potential represented by VFD-fan-based cooling tower systems to the greatest possibility.

Many studies on cooling towers have focused on design [1–6] and performance parameters [7–9]. Comparatively few studies

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http://dx.doi.org/10.1016/j.apenergy.2015.05.025
0306-2619/

Nomenclature

CV	controlled variable
Δt	sampling period (min)
e_k	error term at the *k*th run
f	fan operating frequency (Hz)
H	relative humidity (%)
I	total number of fans
K_C	controller gain (kW/°C)
MV	manufactured variable
p_k	power requirement of fan set (kW)
p_{min}	power requirement of fan set at the minimum operating frequency (kW)
p_{cutoff}	the cut-off value of power requirement (kW)
τ_I	integral time (min/°C)
$n_{\text{fan,k}}$	number of fans operated at *k*th run
T_{sp}	set point temperature (°C)
T_{air}	air temperature (°C)
$T_{\text{w,out,k}}$	outlet water temperature at *k*th run (°C)
$T_{\text{w,in}}$	inlet water temperature (°C)
T_{UL}	upper limit temperature in the temperature zone control (°C)
T_{LL}	lower limit temperature in the temperature zone control (°C)
y_k	measured value of the CV at the *k*th run
Y_{sp}	set point of the CV

have addressed the optimal operation of cooling towers. Castro et al. [10] simulated the operating cost of a water-cooling system considering water make-up, energy consumption, and climatic effects. Cortinovis et al. [11] minimized operating costs by optimizing the fan speed, rate of water removal, and the positions of valves at heat exchanger branches. They also suggested that economical operation would require the water outlet temperature to remain as high as possible. The findings of these studies were based on single-cell tower operations utilizing two-speed fan mode. Wang et al. [12] used statistical modeling to predict outlet water temperature and developed a discrete model-based strategy to determine optimal fan-operating mode in a multi-cell cooling tower with two-speed fans. In that work, the authors simulated a virtual plant to verify their proposed method.

Other studies addressed the economic gains of applying VFD to cooling tower fans. Cohen [13] indicated that variable-speed fans can significantly reduce the energy requirements of cooling tower systems by precisely assigning air flow rates to the required heat dissipation. Also in his theoretical viewpoint, in a multi-fan VFD system, i.e., multi-cell, the fan speed must be synchronized, because a marginal increase in fan speed increases the power consumption, whereas synchronized fan speed put more cells into service and maximize the total heat transfer surface while minimizing the power consumption. Muntean et al. [14,15] implemented temperature control for VFD-fan operation in a cooling tower and found that energy savings and control of out-flow water temperature are the two major advantages. They also claimed that using VFD technology to track wet-bulb temperature throughout the year resulted in annual energy savings of 83% compared to running the fans continuously at full speed. These studies addressed the advantages of VFD installations and the configurations of the simulation examples. However, as pointing out in this work, synchronizing fan speeds across the cells during low-speed stages is not practical because it may cause frequent ON–OFF switching among fans. It is the very reason that we propose temperature zone control, and hybrid operation of rule-based and equation-based feedback control in this study.

Yu and Chan [16] used a load-based method to control the speed of cooling tower fans and condenser water pumps in order to improve the energy efficiency of a cooling tower system, and highlighted the need to widen the use of such control systems. Aha and Mitchell [17] proposed optimal supervisory control strategies for the set points (exact values) of controlled variables such as supply air, chilled water, and condenser water temperatures. The fan speed was controlled via a proportional-integral-derivative (PID) feedback controller such that the water temperature reached the set point designated by the optimal supervisory control strategy. Those studies considered the integration of cooling towers and chiller systems. However, previous studies have not addressed the frequency of ON/OFF switching in VFD fans.

In traditional cooling towers, two-speed fans, i.e., OFF, low, or high speed, are the most common type. The limited choices of fan speed make feedback controllers difficult to control outlet water temperature at the desired target. As a result, feedback control is rarely used in the traditional cooling tower. With improving affordability, VFD fans have gained popularity and gradually replaced two-speed fans in cooling towers. This provides a great opportunity to fully exploit the energy-saving potential of VFD technology by applying feedback control to ensure outlet water temperatures are maintained at set points. Nevertheless, frequent ON/OFF switching of fans and the lack of a well-devised controller prevented industry from widely adopting or wholly utilizing this technology. As an alternative, rule-coded programmable logic controllers (PLC) were used instead of the feedback controller. The control of the outlet water temperature at the highest allowable temperature is then compromised, as is the energy-saving potential associated with the introduction of VFD-fans. The shortfall is more apparent in a large-scale cooling tower system comprising multiple cells. Therefore, this study proposes two operational strategies to fully exploit the energy-saving potential of VFD-fan-based multi-cell cooling towers.

2. Operational strategies

Section 2.1 describes the effects of a larger "approach value" on energy savings during fan operation. Section 2.2 details the implementation and theoretical development of zone-setting proportional-integral (PI) controllers. The rule based control strategy to avoid frequent ON–OFF switch is described in Section 2.3.

2.1. Larger approach strategy

In a cooling tower system, heat is removed from the water by sensible heat, via temperature differences; and by latent heat, via the evaporation of small amounts of water. The evaporation process accounts for 80% of total heat removal. The rate of water evaporation in a cooling tower is determined by relative humidity, ambient air temperature and airflow rate. The thermal performance of the cooling tower depends principally on the wet-bulb temperature of inflowing air. The lowest outlet water temperature is limited by ambient air wet-bulb temperatures.

Two kinds of temperature differences are indexed for the design and operation of tower systems, namely, range and approach. The temperature difference between water entering and leaving the cooling tower is called range, (or cooling tower range, or cooling range). Range is determined using a heat load and water flow rate, rather than by the thermal capability of the cooling tower. The difference between the outlet water temperature and the wet-bulb temperature of inflowing air is termed approach. At the design