Proceedings of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Energy-Efficient Control of Evaporative Cooling Towers for Small Steam Power Plants

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Abstract: Forced draft evaporative cooling towers are often used for condenser cooling in small steam power plants. Conventional control strategies keep the cooling pump operating at full speed all the time, and control the cooling water temperature by modulating the tower fan speed. In this work, an energy-efficient control strategy is proposed, that minimizes the combined consumption of the tower fans and circulation pump, while also avoiding the sustained operation of the fans within some forbidden velocity range, to avoid resonance effects. The proposed strategy can be easily implemented within standard industrial control system, and is demonstrated to operate satisfactorily by a simulation study.

Keywords: Optimal operation and control of power systems; Control system design; Modeling and simulation of power systems

1. INTRODUCTION AND MOTIVATION

Many industrial processes require to cool some working fluid. For large thermal loads, like for example those encountered in power plants, a primary device used for that purpose is the evaporating cooling tower.

In a forced draft cooling tower, water is sprayed from atop against an ascending air stream, induced by fans. A small fraction of the water evaporates, whence the device name, and as a result the entire stream is cooled. Water then exits the tower at its bottom, and is collected to re-enter the process. A forced draft cooling tower thus consumes power to drive the water pumps and to drive the fans. Said consumption is often of non-negligible entity, so that its reduction yields a relevant benefit to the overall plant operation.

In this paper, we propose a control strategy for such devices, targeted at fulfilling the thermal load required by the process with a combination of water flow rate and tower outlet temperature that minimises the combined consumption of pumps and fans. We also present a validation of the strategy on an accurate dynamic model of the cooling system, subjected to realistically varying thermal loads and environmental conditions.

The paper is organised as follows. Section 2 gives a brief literature overview and further motivates the present work. In Section 3, the dynamic plant model used for the model-based control system design is described. A conventional control system for the system under consideration is described in Section 4; the proposed control strategy is illustrated in Section 5 and validated in simulation in Section 6. Concluding remarks and future work are discussed in Section 7.

2. BRIEF LITERATURE REVIEW

This section briefly reviews some related work, without any claim of being exhaustive, to better situate the present research in the overall scenario of modelling and control of cooling systems based on evaporating towers, thereby providing further motivation for it.

The literature contains many works on the design and correct sizing of cooling systems, to achieve energy savings in both the civil and the industrial field, see e.g. Kintner-Meyer and Emery (1995) or the document by the European Commission (2001). On the other hand, studies on control strategies for the same systems focus primarily on air conditioning. Schwedler (1998) argued that lowering the water temperature is not the most efficient strategy due to the high consumption of the fans, while Ahn and Mitchelly (2001) demonstrated that the exogenous variable that influences consumption in cooling towers is the wet bulb temperature, followed by the thermal load, while the dry bulb temperature has practically no influence.

The simplest and most widely used control strategy is to keep the tower outlet temperature to a constant set point, chosen as low as possible (Briley, 2003). Crowther and Furlong (2004) proposed to maintain a constant temperature difference (or *approach*) between the set point and the wet bulb, demonstrating that this choice is better than a fixed set point.

Along the same reasoning, works like Braun and Diderrich (1990), Ahn and Mitchelly (2001), Yao et al. (2004) and Sun and Reddy (2005) present strategies in which the set point is chosen as a function of the wet bulb temperature and in some cases of the thermal load, determined through multiple simulations. These strategies, however, are in general unable to determine the optimum set point for consumption minimisation, owing to model uncertainties. Also, for each operating condition, a large number of simulation runs is required.

Another research line aimed at cooling energy saving adopts optimal control strategies, as shown e,g, in Koeppel et al. (1995), Lu et al. (2004) and Ma et al. (2008), often based on genetic algorithms or neural networks, the former being considered the most promising (Ma et al., 2009).

Summarising, control-centric literature works are not primarily focused on industrial/power-generation tower-based cooling systems. In the authors' opinion, this leaves room for relevant improvements in that specific area, which motivates the present work.

3. PLANT MODEL

The presented study refers to the plant configuration shown in Figure 1. The study requires a detailed model of the cooling towers and of their thermal load, which is the steam condenser of a biomass-fired steam power plant. The boundary conditions for the system are given by the mass flow rate and specific enthalpy of the steam turbine exhaust. Most of the required components, such as the piping elements, the pump, the collecting reservoir and the condenser, were taken from the ThermoPower Modelica library (Casella and Leva, 2005, 2006), while the tower model was created on purpose for this work. Component parameters were taken from commercial datasheets. The specific application refers to an 18 MWe biomass-fired power plant, but the concepts presented here are general and applicable to a wide range of similar plants.

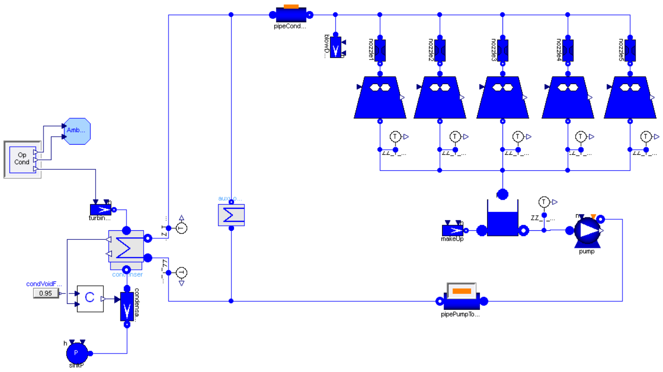

Fig. 1. The considered plant scheme as represented in Modelica.

The first component, on the left of Figure 1, is the condenser. Given the scope of the study, the steam inlet conditions are prescribed as know functions of the plant load. The condenser is a two-pass shell-and-tube heat exchanger, which is represented by two counter-current heat exchangers plus volumes to represent the energy storage in the two plena at the shell ends. The tube side heat transfer coefficient varies according to the Dittus-Boelter correlation, while the shell side (condensation) coefficient is assumed constant. A condensate extraction pump removes the condensed water from the bottom hot well in order to keep the condensate level constant; this is only needed to avoid the flooding of the condenser, but the actual way the condensate is extracted has no influence on the condenser behaviour. The condenser model has been validated successfully against design and off-design data from the manufacturer.

Continuing with Figure 1, the piping from the condenser to the towers is represented with enough detail to reproduce its dynamic effect (energy storage, transport delay) on the quantities of interest. Piping sections that are not relevant for the study, for example because they are excluded after the plant start-up, are not represented. The thermal input from auxiliary loads that are connected in parallel to the condenser is synthetically modelled by the injection of a fixed thermal load. This is justified by the fact that their heat duty is a small fraction of the condenser load, and by the lack of detailed information about them.

The cooling towers are modelled according to Merkel's theory, which is well-established in the field. The tower body is divided into N segments; within each of them, the forced air flow, travelling upwards, exchanges mass and heat with the downcoming water flow. The heat transfer is proportional to the difference between the enthalpy of saturated humid air at its wet-bulb temperature, and the enthalpy of saturated humid air at the water temperature. In order to represent the dynamic response of the temperature of the out-flowing water, energy storage in the liquid water hold-up and in the tower packaging is accounted for, while storage in the humid air is neglected. The tower fans are described by a simple model based on kinematic similarity, which states that the volume flow rate is proportional to the rotational speed, and the power consumption is proportional to the cube of the rotational speed. Ideal speed control is assumed. The heat transfer coefficient and the fan coefficients have been tuned with the tower manufacturer's design data, and the off-design performance of the has been validated against manufacturer's datasheets.

The outlet flows from the five towers mix together in a single pool, modelled as a well-mixed open tank. The pump and the piping to the condenser complete the loop. A small, fixed make-up flow rate compensates the water lost by evaporation.

The atmospheric dry bulb and wet bulb temperatures are exogenous known signals. The control signals are the pump and the fans rotational speeds, while the controlled variables are the tower outlet temperatures and the condenser steam-side pressure, i.e., the steam turbine discharge pressure. The overall plant model was calibrated in open-loop, based on steady-state design data.

4. CONVENTIONAL CONTROL SCHEME

The conventional control strategy for cooling systems like those addressed herein consists of regulating the tower outlet temperature so as to provide the condenser with the necessary cooling capacity to keep the turbine discharge pressure between convenient limits. The water pump is not controlled and always operates at full speed. The block diagram for this strategy is shown in Figure 2, that depicts only one of the five identical fan controls.

In the case under consideration, the fans could not operate within a certain speed range, in order to avoid the excitation of the first bending mode of the blades. To cope