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Energy reduction for a dual circuit cooling water system using advanced regulatory control ☆

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HIGHLIGHTS

- Potentially reduce energy required by a dual circuit cooling water system by 30%.
- Accomplished using an advanced regulatory control and switching strategy.
- No formal process model is required.
- Can be implemented on control system hardware commonly used in industry.

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ABSTRACT

Various process utilities are used in the petrochemical industry as auxiliary variables to facilitate the addition/removal of energy to/from the process, power process equipment and inhibit unwanted reaction. Optimisation activities usually focus on the process itself or on the utility consumption though the generation and distribution of these utilities are often overlooked in this regard. Many utilities are prepared or generated far from the process plant and have to be transported or transmitted, giving rise to more losses and potential inefficiencies. To illustrate the potential benefit of utility optimisation, this paper explores the control of a dual circuit cooling water system with focus on energy reduction subject process constraints. This is accomplished through the development of an advanced regulatory control (ARC) and switching strategy which does not require the development of a system model, only rudimentary knowledge of the behaviour of the process and system constraints. The novelty of this manuscript lies in the fact that it demonstrates that significant energy savings can be obtained by applying ARC to a process utility containing both discrete and continuous dynamics. Furthermore, the proposed ARC strategy does not require a plant model, uses only existing plant equipment, and can be implemented on control system hardware commonly used in industry. The simulation results indicate energy saving potential in the region of 30% on the system under investigation.

1. Introduction

Process utilities are used extensively in the operation of any petrochemical plant and may include steam, electricity, compressed air, cooling water, fuel gas and inerts such as nitrogen. A substantial portion of the fixed cost associated with plant operation is attributed to utilities and therefore it is common practice to optimise on the plant's consumption of these utilities [1,2]. The generation and distribution of these utilities also require energy yet these aspects do not get the deserved attention while studies have shown that the energy losses are in many cases substantial [3,4]. Furthermore, better control can reduce the variability of the utility which could improve plant stability and reduce the need to run large buffer capacities.

The optimisation of utilities can be very beneficial but usually requires additional capital expenditure which is a main deterrent for many energy efficiency improvement initiatives [5–7]. Furthermore, with steep increases in energy costs, a solution which is currently deemed infeasible could become feasible in the near future although a re-evaluation of the opportunity will seldom be done which results in missed optimisation opportunities.

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In several recent publications, model based control techniques such as optimal control and model predictive control (MPC) are used for energy optimisation which require system models to be developed and an optimisation algorithms capable of solving the optimisation problems (usually as a real-time requirement).

In [5,6], a fuel gas blending system is optimised using model predictive control and real-time optimisation. In [8], optimal control and model predictive control strategies are used for optimising power flows between the grid and a photovoltaic-battery system using time-of-use tariffs and sell back rates. In [9], occupancy and weather forecast data is used with an MPC scheme to minimise the energy consumption of a building temperature control system taking into account specified comfort requirements. In [10], an optimal control strategy is used to optimise water flow rates in a ground source heat pump system. In [11–13], optimal control is used to optimise energy consumption and costs for belt conveyor systems. In [14], MPC is used with time-of-use cost data to optimise the energy cost for a run-of-mine ore milling circuit. In [15–17], optimal control and/or MPC techniques are used to optimise energy costs in a water pumping systems.

In industrial applications, these control techniques typically imply additional software licence fees and computer hardware (or even the installation of additional plant equipment such as variable speed drives).

This paper demonstrates a novel way of obtaining significant energy savings on a process utility containing both discrete and continuous dynamics by applying advanced regulatory control (ARC) and switching logic. Furthermore, the proposed ARC and switching strategy does not require the development of a plant model, uses only existing plant equipment, and can be implemented on control system hardware commonly used in industry.

The developed solution is applied to a dual circuit cooling water system in a simulation study and compared to the unoptimised base case to illustrate the potential benefit of utility optimisation. Specific focus is on the reduction of electricity consumed by the system while still taking the process constraints into account.

The cooling water system is an example of a hybrid system where both continuous and discrete handles are present in the same system which complicates the formulation of control and optimisation strategies [18–20]. Typically, the discrete and continuous portions are treated separately and several studies have been performed recently concerning the former [11,15,16]. Therefore, this strategy is particularly useful for these system where the bulk of the possible benefit may be realised without the use of the more advanced control techniques. A systematic approach is also described to allow the control and switching techniques used in this paper to be extended to other discrete or hybrid systems.

The paper is structured as follows: In Section 2, a brief process description of the cooling water system is given where-after the process model is discussed in Section 3. In Section 4, the control and switching algorithms are described and the simulation schemes for the base case and the ARC are presented. Thereafter, the simulation results are analysed and discussed in Section 5 followed by the concluding statements in Section 6.

2. Process description

An example of a utility process is that of a dual circuit cooling water system as shown in Fig. 1. The tempered water (TW) circuit is a closed treated water loop that runs through the plant heat exchanger network where it absorbs energy from the plant. The tempered water is impelled by a bank of parallel pumps. It transfers the collected energy to the second circuit, the cooling water (CW) circuit, via a bank of plate heat exchangers. The cooling water circuit is also driven by its own bank of parallel pumps. The energy is then expelled from the cooling water through the cooling towers (CTs) where the main mechanism for cooling is the partial evaporation of a portion of the cooling water as it comes into contact with the unsaturated air stream that is induced by the cooling tower fans [21,22].

This process is an example of a hybrid system where a combination of continuous and discrete process input variables are present. The continuous inputs are for example the valve openings of the control valves whereas the discrete inputs are the pump and fan running signals. In cases where the discrete and the continuous portions can reasonably be treated separately, a discrete optimiser may be used for the discrete variables whereas an independent continuous optimiser may be used for the continuous part. In cases where these layers are integrated to a great extent (as is the case for the cooling water system), it is desirable to combine the continuous and discrete aspects into a single control and optimisation solution which complicates the optimisation problem [18,19,23].

3. Process model

The model developed by Muller and Craig [20] was extended to include the valves on the discharges of the cooling water pumps (as indicated in Fig. 1) with the simplifying assumption that the same value is written to all valves for which the pumps are running. The model is used as a representation of the actual process in the simulation study that follows and is not required for the formulation of the control and switching solution discussed in Section 4. The model was re-verified using the same verification data used in [20] and the parameters updated by performing the parameter estimation exercise described in [20].

The process inputs are:

- the temperature control valve (TV) opening (OP_{TV}) (which has a linear characteristic),
- the cooling water pump discharge pressure control valve (PV) openings (OP_{PV}) (which have equal percentage characteristics – the simplifying assumption is that the same valve opening is sent to the discharge valves of all the running cooling water pumps), and
- the tempered water and cooling water pump and cooling tower fan running signals, $u_i^{TW}(t) \in \{0,1\}$, $u_j^{CW}(t) \in \{0,1\}$, and $u_k^{CT}(t) \in \{0,1\}$,

with $i = 1 \ldots n_{TW}$, $j = 1 \ldots n_{CW}$, and $k = 1 \ldots n_{CT}$ where n_{TW}, n_{CW} and n_{CT} are the numbers of tempered water pumps, cooling water pumps and cooling tower fans. The binary running signals are grouped together into discrete integer signals representing the number of pumps or fans running to give $U_{TW}(t) = \sum_{i=1}^{n_{TW}} u_i^{TW}(t)$, $U_{CW}(t) = \sum_{j=1}^{n_{CW}} u_j^{CW}(t)$ and $U_{CT}(t) = \sum_{k=1}^{n_{CT}} u_k^{CT}(t)$.

The process disturbances are.

- the plant duty, $Q_P(t)$ (MJ/h),
- the air wet-bulb temperature, $T_{wb}(t)$ (°C),
- the make-up water flow to the cooling towers, $f_{mu}(t)$ (t/h), and
- the availability of the pumps, fans, and heat exchangers.

The variables to be regulated are.

- the tempered water supply temperature, T_{TWS},
- the tempered water differential temperature ($\Delta T_{TW} = T_{TWR} - T_{TWS}$ where T_{TWR} is the tempered return temperature), and
- the power consumption of the system (W_T).