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Economic hybrid non-linear model predictive control of a dual circuit induced draft cooling water system

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ABSTRACT

Petrochemical plants require the addition and removal of energy to and from the process and the movement of material to, from, and within the process piping and vessels. These fundamental mass and energy transfer requirements are typically achieved through the use of process utilities, which include electricity, steam, fuel gas, cooling water and compressed air. Utilities are responsible for a significant portion of the operating cost of a plant. Therefore, reduction in the consumption of utilities is a common process optimisation area. The situation is different when it comes to the generation and transportation of these utilities, which are often overlooked with regard to optimisation. In this paper, the potential benefits of utility optimisation are illustrated with particular focus on the generation and transportation areas. The main objectives are reductions in electrical energy consumption and cost and are illustrated for a dual circuit cooling water system. This system is non-linear and also hybrid in the sense that it contains both continuous and discrete input variables, which significantly complicates the design and implementation of control and optimisation solutions. This paper illustrates how the cost and energy consumption of a hybrid system can be reduced through the implementation of hybrid non-linear model predictive control (HNMPC) and economic HNMPC (EHNMPC). The results are compared to that of a base case and an Advanced Regulatory Control (ARC) case, showing that significant additional benefit may be achieved through the implementation of these advanced control and optimisation techniques. The paper further illustrates that additional capital is not necessarily required for the implementation of these techniques.

1. Introduction

The movement of energy and mass associated with the operation of a petrochemical plant is mainly achieved through the use of process utilities which include electricity, steam, fuel gas, cooling water and compressed air. The generation, preparation and transportation of these utilities also require energy (mostly in the form of electricity), though they are often overlooked as areas for improvement and optimisation.

The potential benefits of utility optimisation have been shown to be substantial in some cases and should therefore be explored. In [1], the losses and inefficiencies encountered in typical steam systems are analysed, revealing significant potential for improvement. In [2–5], the benefits of control improvements for cooling water systems are illustrated. In [6,7], the optimisation of an industrial fuel gas system is presented resulting in a significant reduction in operating cost. In [8], the losses encountered in compressed air systems are shown and in [9–11], the benefits in optimising pumping systems are explored.

In this paper, a dual circuit cooling water system is used to illustrate the benefit of the application of Advanced Process Control (APC) techniques on hybrid utility systems. A description of the process is first given followed by a discussion on the development of two control and optimisation schemes. The first is a hybrid non-linear model predictive control (HNMPC) configuration aimed at a reduction in energy consumption while honouring process constraints. The next is an extension of the first where Time-of-Use (TOU) electricity rates are used in an economic HNMPC (or EHNMPC) solution for the dynamic optimisation of electricity cost. The results are then discussed and the cases are compared to each other and to that of a base case and an Advanced Regulatory Control (ARC) case.

2. Process description

The system considered in this study is a dual circuit, induced draft, counter flow cooling water system as shown in Fig. 1.

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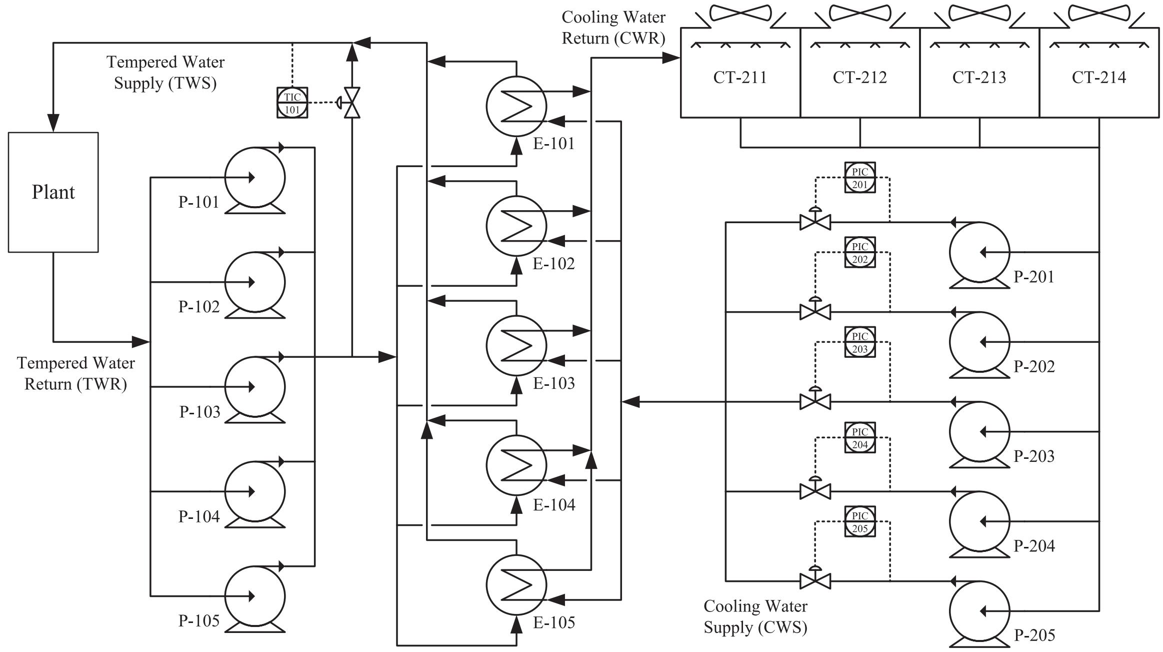

Fig. 1. Dual circuit induced draft counter flow cooling water system [4,5,12].

The system consists of two water circuits. The first is the tempered water (TW) circuit which is a closed system containing treated water. The second is the cooling water (CW) circuit which contains untreated water (apart from standard dosing). Each of the circuits is equipped with its own bank of five parallel centrifugal pumps. The CW circuit also contains a bank of four cooling towers (CTs). The TW circuit runs through the plant heat exchanger network where it collects heat from the process. It then transfers the heat to the CW through an interconnecting bank of plate heat exchangers. The CW circuit then expels the heat through the cooling towers where the main mechanism for cooling is the partial evaporation of a portion of the water. On the TW side of the common heat exchangers is a bypass line with a control valve, which is used to bypass a portion of the TW to reduce total cooling. There are also control valves on the discharges of the CW pumps initially intended to prevent pumps from running beyond capacity. A detailed account of the system model is given in [4,5,12].

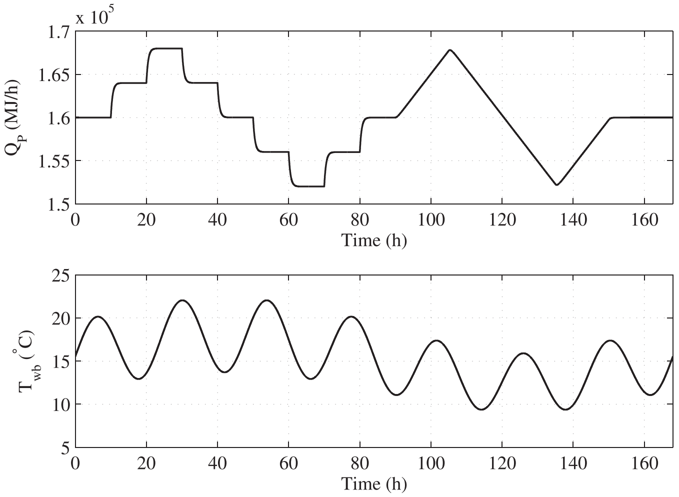

Fig. 2. Disturbance data for first simulation.

The controlled variables for the system are the TW supply temperature, T_{TWS}, the TW differential temperature, ΔT_{TW}, the total power consumption, W_T, and the total electricity cost, C_T.

The manipulated variables for the system are the number of running TW pumps, U_{TW}, the number of running CW pumps, U_{CW}, the number of running CT fans, U_{CT}, the temperature control valve opening, OP_{TV}, and the openings of the pressure control valves, OP_{PV} (the same valve opening is written to all the discharge valves of the running CW pumps). The running signals are discrete inputs whereas the valve openings are continuous handles. This combination of discrete and continuous handles classifies the cooling water system as a hybrid system, which complicates the formulation of control and optimisation solutions [13]. Furthermore, the system exhibits non-linear behaviour and is highly interactive.

The measured disturbance variables are the plant duty, Q_P, the ambient temperature, T_a, and the relative humidity, RH. The resultant model consists of 8 state equations, 14 algebraic equations, 5 inputs, and 3 measured disturbance variables together with 29 model parameters.

3. Methods

This section describes the application of various control and optimisation schemes to the cooling water system with the aim of reducing electricity consumption and/or cost while honouring process constraints.

3.1. *Simulation set-up*

Two operating scenarios are analysed. The first scenario covers a period of 7 days of artificial plant data during which step-like and ramp-like changes are made to the plant duty and sinusoidal changes are made to the ambient temperature and relative humidity (both influencing the wet-bulb temperature, T_{wb}). The second scenario uses 6 days of real plant data during a period where significant load disturbances occurred (the same data that was used for the model verification in [4,5,12]). Figs. 2 and 3 show the plant duty and wet-bulb temperature for the two scenarios. The wet-bulb temperature is calculated as proposed in [14].