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Non-linear economic model predictive control of water distribution networks

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ABSTRACT

This paper addresses a non-linear economic model predictive control (EMPC) strategy for water distribution networks (WDNs). A WDN could be considered as a non-linear system described by differential-algebraic equations (DAEs) when flow and hydraulic head equations are considered. As in other process industries, the main operational goal of WDNs is the minimisation of the economic costs associated to pumping and water treatment, while guaranteeing water supply with required flows and pressures at all the control/demand nodes in the network. Other operational goals related to safety and reliability are usually sought. From a control point of view, EMPC is a suitable control strategy for WDNs since the optimal operation of the network cannot be established a priori by fixing reference volumes in the tanks. Alternatively, the EMPC strategy should determine the optimal filling/emptying sequence of the tanks taking into account that electricity price varies between day and night and that the demand also follows a 24-hour repetitive pattern. On the other hand, as a result of the ON/OFF operation of parallel pumps in pumping stations, a two-layer control scheme has been used: a non-linear EMPC strategy with hourly control interval is chosen in the upper layer and a pump scheduling approach with one-minute sampling time in the lower layer. Finally, closed-loop simulation results of applying the proposed control strategy to the D-Town water network are shown.

1. Introduction

Water distribution networks (WDNs) are critical infrastructures in urban areas. Their operational management is a subject of increasing interest, taking into account the economic and environmental factors. WDNs are also of vital importance for supporting all kinds of social activities. For the individuals living in a modern city, requiring sustainable water supply service is one of basic necessities. Besides, as the progress of society and the evolution of human civilisations, a growing number of people migrate into cities. Therefore, the increasing complexity of the WDN would cause some difficulties for the management under multiple objectives, such as economic operations, guaranteeing the whole system safe and stable.

Model predictive control (MPC) has attracted much attention of the research community all over the world throughout the past decades and has been applied to many different applications of the process industry [1,2]. Compared with the other classical control theories, the success is due to the fact that MPC is able to handle multi-input and multi-output (MIMO) control systems with hard and soft constraints for the system inputs and states, and meanwhile, having the ability to directly reach some certain system performances and operational objectives. In general, the MPC strategy (also regarded as receding horizon strategy) is based on finding the optimal control action from a sequence of open-loop control actions along the prediction horizon minimising a set of control objectives and satisfying a set of constraints including the system dynamic model and physical/operational limitations.

By investigating optimal control strategies for the management of water systems, MPC is not used in a classical way since there is no reference to be tracked. In applications of conventional MPC, the control objective is mainly focused on tracking a given reference or a family of trajectories in order to operate the plant to reach its steady state. Unlike conventional MPC, the common operational goal of many process industries, as WDNs, is the minimisation of economic costs of the energy consumptions. This lead to the so-called economic MPC (EMPC). The optimisation

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problem behind the EMPC strategy is in charge of finding a family of the optimal set-points taking into account economic benefits instead of driving the controlled system to a given set-point. The stability and cost improvement of EMPC have been investigated for non-linear processes in [3,4], where Lyapunov-based technique has been employed over the conventional MPC. In order to reduce the computational complexity, the general EMPC is divided into two layers [5], where EMPC is set in the upper layer and a lower feedback control layer is used.

Related research for WDNs has been carried out in the past several years [6–15]. These research works are focused on finding the optimal operation on the WDN in order to achieve the desired control objectives. For this purpose, some optimal control problems are posed and solved to minimise the total operational costs of WDNs, for instance in [6,16] the genetic algorithm (GA) is chosen. In [7,8,10,13], authors have successfully applied the MPC strategy in the WDN using a control-oriented model that considers only flows, i.e., the pressure/head model of each element in the WDN including water storage tanks/reservoirs, water demand sectors, pressurised pipes, booster pumps and pressure/flow-controlled valves, are not considered explicitly. For a certain WDN, in addition to satisfy water demands, it is also necessary to meet the required pressure/head at each water demand sector and particular control points. A first attempt to consider the pressure/head model in the flow-based MPC is presented in [17], where the non-linear constraints coming from the flow-head equations are used to update the operational constraints of tanks and actuators by solving a constraint satisfaction problem before the flow-based linear MPC problem is solved. Later on, an explicit iterative approach to implement non-linear constraint relaxation is proposed in [15]. The non-linear hydraulic equations in the WDN model are relaxed to be a sequence of linear approximating constraints. The underlying linear optimisation problem with the relaxed constraints can produce similar performance.

The control-oriented model of a WDN may be built by a series of linear and non-linear differential-algebraic equations (DAEs). Subsequently, the non-linear DAE model of a WDN is used as the prediction model in the EMPC controller design. The application of EMPC to WDNs present some difficulties because of the non-linear nature of the DAE model and the ON/OFF operation of the pumps. Because of these features, the MPC problem for WDNs leads to solve a non-linear mixed-integer problem [7]. In order to avoid solving such a complex optimisation problem, a two-layer optimal control scheme is proposed in this paper as shown in Fig. 1. The upper layer is in charge of finding the optimal hourly flow set-points for actuators (pumps and valves) using a non-linear EMPC (NEMPC) strategy

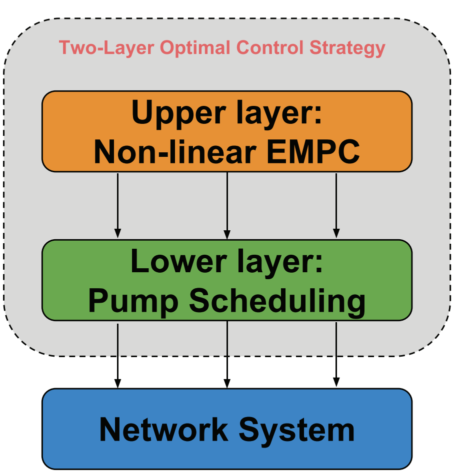

Fig. 1. Two-layer optimal control strategy of WDNs.

and the demand 24-hour forecasts using an appropriate forecasting algorithm, such as [18,19]. So far, the conventional non-linear MPC has been applied to water systems but the use of NEMPC has still not been proposed [20,21]. The lower layer is in charge of the pump scheduling, i.e., the translation of the continuous flow set-points determined in the upper layer into ON/OFF set-points for pump operation. Pumps are typically operated in ON/OFF discrete way to produce at each hourly time-step, the same water volume as the optimal strategy computed by the first layer within an hour corresponding to each MPC step. By means of the two-layer scheme, the non-linear and integer features of the EMPC optimisation problem is decoupled in two problems: one dealing with the non-linear behaviours of WDNs and the other with discrete operations of the pumps.

The main contribution of this paper is to propose a two-layer control scheme that combines the NEMPC strategy in the upper layer, and the pump scheduling approach in the lower layer. The NEMPC strategy is implemented by using the non-linear programming technique and the pump scheduling approach is realised by solving a local optimisation problem. The proposed two-layer control strategy is validated using a hydraulic simulator that emulates the real WDN behaviour. The D-Town water network, a well known benchmark, is used as the case study. The closed-loop simulation is implemented using a simulation platform with a virtual-reality hydraulic simulator that emulates the on-line operation.

The remainder of this paper is structured as follows: The control-oriented model of WDNs including the flow and pressure/head variables is presented in Section 2. The NEMPC strategy of the WDN in the upper layer is introduced in Section 3. A pump scheduling approach in the lower layer is provided in Section 4. The description and introduction of the case study of the D-Town water network is presented in Section 5. In Section 6, results of applying the proposed control strategy to the D-Town water network are summarised. Finally, some conclusions are drawn in Section 7.

2. Control-oriented modelling water distribution networks

This section briefly introduces the control-oriented mathematical modelling methodology of the WDN including the flow and hydraulic head relations for the different network components. As result of the application of this methodology to a particular WDN, a set of dynamic and static relationships that lead to a system of DAEs in discrete-time ready to be used in the implementation of the MPC is obtained. A WDN can be decomposed by a set of constitutive elements: *reservoirs/tanks, control valves, pump stations, nodes* and *water demand sectors*, each being characterised by means of flow-head relations [8,16,22,23].

2.1. Tanks

Water tanks supply and provide the entire WDN with the storage capacity of drinking water to consumers guaranteeing adequate water pressure service. The mass balance expression relating the stored volume v in the mth tank can be written as the discrete-time difference equation which describes the tank dynamical evolution as

$$v_m(k+1) = v_m(k) + \Delta t \left(\sum_i q^{\text{in}}_{i,m}(k) - \sum_j q^{\text{out}}_{m,j}(k) \right), \qquad (1)$$

where $q^{\text{in}}_{i,m}(k)$ denotes the inflows from the ith element to the mth tank and $q^{\text{out}}_{m,j}(k)$ denotes the outflows from the mth tank to the jth element. Δt is the sampling time and k is the discrete-time instant.