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ScienceDirect

Energy Procedia 148 (2018) 352–359

Energy Procedia

www.elsevier.com/locate/procedia

73rd Conference of the Italian Thermal Machines Engineering Association (ATI 2018), 12–14 September 2018, Pisa, Italy

A Model-in-the-Loop application of a Predictive Controller to a District Heating system

Nora Cadau[a], Andrea De Lorenzi[a], Agostino Gambarotta[a,b], Mirko Morini[a,b], Costanza Saletti[b]*

[a]*Center for Energy and Environment (CIDEA), University of Parma, Parco Area delle Scienze 42, 43124 Parma, Italy*
[b]*Department of Engineering and Architecture, University of Parma, Parco Area delle Scienze 181/A, 43124 Parma, Italy*

Abstract

The high weather variability due to climate change and the need to reduce carbon emissions require innovative solutions for energy systems and grids. In particular, improvements in control strategies allow to increase efficiency without changing the system configuration. Adaptive controllers, as currently proposed, base the management of the system on its past behavior. The main drawback of these methods is the lack of flexibility required to face the mentioned scenario. This paper presents a Model Predictive Control approach which, instead, is based on the prediction of the future evolution of the controlled system. Since it allows to consider the external conditions variability, a more resilient way to manage District Heating and Cooling networks can be achieved. The novel control strategy is developed and tested through a Model-in-the-Loop application to a thermal energy network. This latter is composed by combining physics-based dynamic models from a dedicated library of energy systems components developed by the authors in the Matlab®/Simulink® environment. The network model is controlled by the MPC controller model, which shows to be flexible and reliable in the optimization and management of energy systems.

Keywords: energy network; Model Predictive Control; model-in-the-loop; District Heating and Cooling model library.

* Corresponding author.
E-mail address: costanza.saletti@unipr.it

1876-6102
10.1016/j.egypro.2018.08.088

1. Introduction

District Heating and Cooling networks (DHC) distribute thermal energy from multiple production plants to multiple utilization sites (e.g. in the service sector). This concept allows different available energy sources to be taken advantage of. Therefore, the integration of renewable energy sources and significant improvements in energy efficiency and flexibility are possible [1]. As more than 40 % of global energy consumption covers buildings air conditioning requirements [2], DHC represents a promising research field and offer opportunities for energy saving. Nonetheless, the increasing availability of alternative and aleatory energy resources introduced new challenges such as efficient allocation of the load and control of these multi-source systems [3]. Currently, the control strategies for building heating systems are based on operator experience, since the heating system is arbitrarily switched on with a specific time schedule to meet the temperature requirements. Alternative control systems can be based on rule-based or adaptive techniques which do not guarantee optimal energy distribution [4].

Hence, since conventional approaches for control and management of energy systems do not allow to exploit their full potential, smart optimization strategies and simulation tools have to be adopted [5]. For instance, the optimization of the operation of the multi-source DHC system reported in [6] allows for the minimization of the system operational cost. The network model, though, is steady state and the dynamic behavior of the system is not taken into account. On the other hand, another study proposes a library of models which permits the dynamic simulation of DHC [7]. As far as the control is concerned, other works foresee promising results in terms of flexibility by applying innovative strategies such as Model Predictive Control (MPC) to energy applications [8,9]. In particular, a recent example of MPC-controlled DHC [10] shows the benefits of this active control approach. However, a state-of-the-art methodology that includes production, distribution and utilization sides of an energy network has not been demonstrated yet and further studies seem to be required.

In this paper, a model-in-the-loop (MiL) application of MPC to a simple energy distribution network is proposed. The behavior of the system is simulated by means of a library of modular dynamic models developed in the Matlab®/Simulink® environment. The system model is controlled by a MPC controller block. This work aims to demonstrate the effectiveness of the approach and to show its further applicability to more complex situations.

Nomenclature

A_p	pipe cross sectional area [m^2]	c	specific heat [kJ/(kg K)]	M	mass [kg]
$\dot{m}$	mass flow rate [kg/s]	P	power [kW]	p	pressure [Pa]
$\dot{Q}$	heat power [kW]	T	temperature [°C]	t	time [s]
v	velocity [m/s]	ρ	density [kg/m^3]		

2. System components

The MPC algorithm has been applied to a simple energy system model, which includes the most common items of a typical district heating network. The system has been modeled using components sub-models from a library developed by the authors in Matlab®/Simulink®. In the following, an overview of the system components sub-models is given to show how the main parameters have been customized for a proper physical representation. A summary of the main features of the library is presented in Table 1.

Both hydraulic and thermal domains are considered in the models and, consequently, the involved variables are mass flow rate, temperature and pressure. Each physical element of the energy system has been represented by its governing equations in differential or algebraic form depending on whether the element provides or not any type of accumulation (i.e., energy, mass or momentum).

2.1. Pumping station

The pumping station consists of three elements: the pump and two expansion vessels located upstream and downstream. Summarizing, it produces the pressure head required to circulate a specific mass flow rate inside the network. The pump model is based on algebraic relations between pressure head, volumetric flow rate and rotational speed (i.e., the performance maps) [11]: for given values of head and rotational speed, the pump model provides the effective mass flow rate withdrawn from the upstream vessel and conveyed to the downstream one. The expansion vessel models are required to define the inlet and the outlet pressure of the network, which are used by the pump model to estimate the conveyed mass flow rate. Inlet and outlet pressures are indirectly obtained from the actual pressure of air inside the vessels – considered as an ideal gas – compressed during the filling and decompressed during the emptying.

2.2. Thermal power unit

The thermal power unit includes a boiler and a specific model for heat transfer process between combustion gases and heating fluid. The boiler model is based on the UNI 11300 technical standard and it evaluates the effective thermal power produced by the combustion of a defined amount of fuel, considering the actual efficiency as a linear function of the thermal load. The resultant heat is transferred to the water through a specific element, which simulates the heat exchange process. The governing equation is the energy balance, which allows for the calculation of the circulating fluid outlet temperature as follows

$$T_{\text{out}}(t) = T_0 + \int_0^t \frac{\dot{Q} + \dot{m}(c_{\text{in}} T_{\text{in}} - c_{\text{out}} T_{\text{out}})}{\rho V c_{\text{out}}} d\tau \tag{1}$$

Furthermore, the model estimates pressure losses through the boiler with the Darcy-Weisbach equation for a cylindrical pipe.

2.3. Network

The fluid distribution network is made up of two pipeline segments, one of them preceding the thermal user and the other one following it. Together, the two pipeline segments represent a basic distribution loop. Hydraulic dynamics is considered in the loop by means of the momentum balance, which allows for the calculation of changes in fluid velocity as [11]:

$$v(t) = v_0 + \int_0^t \frac{(p_{\text{in}} - p_{\text{out}} - \sum \Delta p_{\text{loss}}) A_p}{M} d\tau \tag{2}$$

Pipeline segment models are based on algebraic equations to estimate the overall pressure drop as a sum of geodetic, concentrated and distributed losses through the pipe. These contributions depend on the flow velocity and the geometry of the pipe.

As far as the thermal domain is concerned, the dynamics of each pipeline segment is considered by using the energy balance equation with the storage term (as in Eq. (1)) and by considering the heat loss towards the ground.

The causality implies that the coupled pipeline segments model requires inlet and outlet pressure and inlet temperature in order to calculate the volumetric flow rate and the outlet fluid temperature.

2.4. Building

The thermodynamics of the generic thermal user has been simplified for the purpose of the simulation. The causality of the building model implies that once fluid mass flow rate and the inlet fluid temperature are known, then the model can evaluate the fluid outlet temperature and the actual air temperature inside the building.

In particular, the building thermal behavior is characterized using four performance coefficients (i.e. a, b, c, d) which represent the contributions of heat exchanged through the walls, heating power, forced ventilation and air infiltrations respectively [11]. Hence, the internal temperature of the thermal user is defined as

$$T_{\text{int}}(t) = T_{\text{int}_0} + \int_0^t \left[-a\left(T_{\text{int}} - T_{\text{ext}}\right) + b\dot{Q} - c\left(T_{\text{int}} - T_{\text{ext}}\right) - d\left(T_{\text{int}} - T_{\text{air}}\right) \right] d\tau \tag{3}$$

The heat flow rate is calculated using the heat transfer equation for an equivalent heat exchanger.

2.5. Controllers

The comprehensive system is managed by three different proportional–integral–derivative controllers (PID). The first one evaluates the difference between the set-point value and the simulated value of the fluid mass flow rate circulating inside the network: the correction affects the pump rotational speed. The second PID controller evaluates the deviation between the simulated value and the set-point value of the boiler outlet temperature and then provides the correction of the fuel flow conveyed to the boiler burner. The two set-point values are determined by the MPC algorithm described in Section 3. The algorithm is executed periodically during the simulation: it collects the actual internal temperature of the building and updates the set-point values of the PIDs.

The last PID regulates the activation of the building radiators and fan coil units. It compares the actual temperature of the outgoing fluid and the set-point temperature – fixed to a design value – thus it controls the space heaters operation by increasing or decreasing the heat exchanged between the circulating fluid and the thermal user.

Table 1. System components summary.

Component	Inputs	Outputs	Parameters	Th.[1]	C.[2]	I.[3]
Pumping station						
Expansion vessel	Incoming mass flow Outgoing mass flow	Pressure	Volume	✕	✓	✕
Pump	Upstream pressure Downstream pressure	Outgoing mass flow	Rotational speed	✕	✕	✕
Thermal power unit						
Boiler	Fuel mass flow	Thermal power	Nominal and minimum load power Nominal and minimum load efficiency Fuel LHV	✕	✕	✕
Heat exchanger	Incoming mass flow Incoming pressure Incoming temperature Thermal power	Outgoing mass flow Outgoing pressure Outgoing temperature	Internal diameter Length Nominal pressure drop	✓	✕	✕
Network						
Pipeline	Supply pressure Discharge pressure Incoming temperature	Outgoing mass flow Outgoing temperature Pressure losses	Pipe external/internal diameter Insulator external diameter Sheath external diameter Pipe length External conditions Roughness and resistance coefficients	✓	✕	✓
Building						
Thermal user	Thermal power	Building temperature	Performance coefficients (a,b,c,d)	✓	✕	✕
Heat exchanger	Incoming mass flow Incoming pressure Incoming temperature	Outgoing pressure Outgoing temperature Thermal power	Heat transfer surface area Overall heat transfer control	✓	✕	✕

[1] Thermal dynamics
[2] Capacitance
[3] Inertance

3. Model Predictive Control

MPC is a family of control strategies that exploit a dynamic model of the system to predict its behavior over a future time horizon, known as prediction horizon. The prediction horizon is discretized in a certain number of time-steps. Given the prediction of the future behavior of the system and of external disturbances, an optimization algorithm calculates the sequence of control actions that minimize a determined cost function throughout the prediction horizon. However, only the first element of this control trajectory, corresponding to the first time-step, is actually returned from the controller and implemented in the system. Then the prediction horizon is moved one step forward, the system variables are updated and the whole calculation is repeated. This allows to reduce the influence of lacking knowledge of disturbances and modeling approximations by producing an implicit feedback. The many advantages such as the consideration of predicted disturbance, the possibility to handle constraints and the concomitant optimization make MPC a suitable control technique [12] for multi-source complex energy networks.

It is not common to have a thermal network available for measurements and testing. The MiL approach gives the possibility to analyze different control strategies with different boundary conditions by means of a detailed model of the real application. This allows for a comprehensive understanding of its operation which can be exploited for further applications to real systems. The detailed model built with the library DHC components described in Section 2 simulates the behavior of the real system for the desired time span and is controlled by a model of the controller.

In this paper, the MPC controller has been used as a supervisory controller. This means that the values of the system manipulated variables (i.e. inputs) returned by the MPC are given as input set-point to the PID controllers described in Section 2.5.

The MPC controller used in this work to calculate the optimal input set-points has been previously developed by the authors and presented in [13]. The two main components required for the MPC application are:

- a simplified dynamic model of the system, also called MPC-model. The MPC-model is a simplified grey-box model which allows for the on-line optimization while maintaining a physics-based description [12]. The parameters of this model have been obtained through the identification procedure described in [13];
- an optimization algorithm which solves the optimization problem to return the optimal control trajectory. In this work, the optimization is performed by a novel algorithm developed in Matlab® and based on the Dynamic Programming (DP). The cost function to minimize is the overall energy consumption that sums up the contributions of the boiler, the pump and the heat losses through the pipes. Additional information on the DP Matlab® implementation can be found in [13].

The controller block, at each time-step, (i) gets the actual value of the system state, (ii) updates the variables and disturbance prediction and, eventually, (iii) calls the optimization algorithm to give the values of the optimal input variables as a result.

4. Application

The MPC control strategy – described above – has been applied to a representative simple district heating network whose aim is to guarantee a determined comfort temperature inside a building (i.e., a school gym located in northern Italy). The whole energy system is schematically represented in Fig. 1.

The distribution system, supplied by a pumping station and a thermal power unit, is responsible for the water circulation and – consequently – the fulfilment of the building heating requirements. The thermal power unit is composed by a modulating boiler, fueled with natural gas, and a heat exchanger. The pumping station consists of a variable-speed impeller pump coupled with two expansion vessels. The characteristic system parameters and their related values are summarized in Table 2.

5. Results

The results of the MiL simulation for the application described in Section 4 are shown in Fig.2. The simulation covers a time span of 10 days during the winter season, starting from a Monday. The MPC supervisory controller allows to satisfy the user temperature requirements while optimizing the energy consumption. As a matter of fact, the controller calculates precisely the necessary timing advance and thermal power according to the day and the

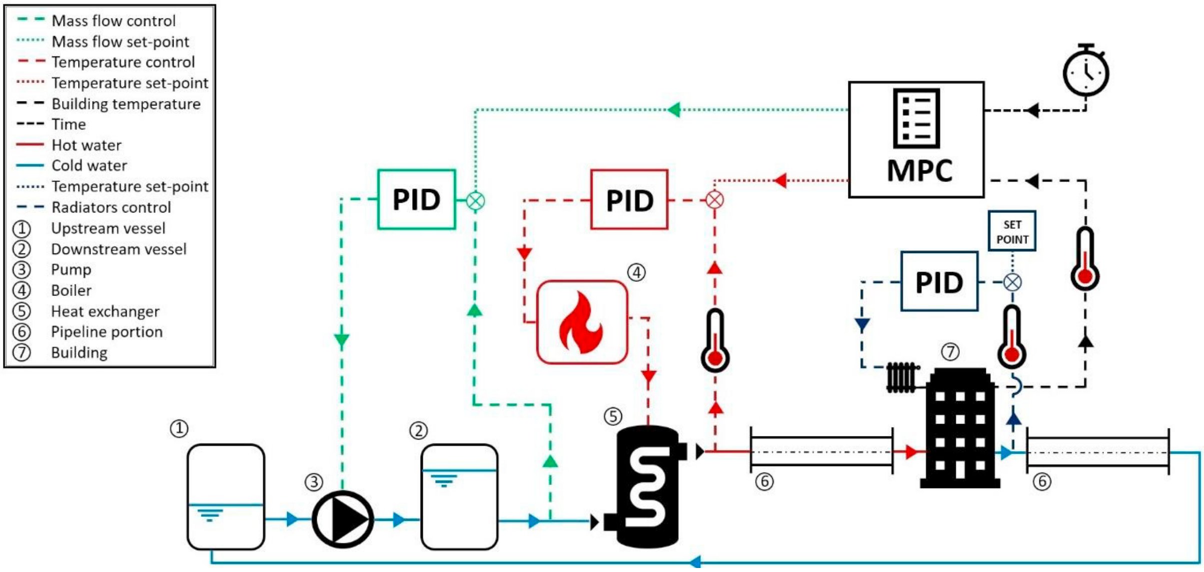

Figure 1. Modeled energy system layout.

Table 2. System parameters used for the simulation.

Component	Parameters	Value	Component	Parameters	Value
Pumping station			Network		
Vessel	Volume	0.1 m³	Pipeline	Pipe ext./int. diameter	0.135/0.125m
				Insulator ext. diameter	0.235 m
				Sheath ext. diameter	0.255 m
Pump	Nom. rotational speed	1400 rpm		Pipe length	200 m
				Roughness	0.1 mm
Thermal power unit			Building		
Boiler	Nom./min. load power	700/175 kW	Thermal user	a	0.0261 s^{-1}
	Nom./min. load eff.	91/85 %		b	$0.0077 \cdot 10^{-5}$ °C/kJ
	Fuel LHV	38.55 MJ/Nm³		c	0 s^{-1}
				d	0 s^{-1}
Heat exchanger	Internal diameter	0.125 m	Heat exchanger	Equivalent heat transfer coeff.	5000 W/·K
	Equivalent length	5 m			
	Nom. pressure drop	30000 Pa			

building occupation. It is possible to fulfill the heating demand even after the cooling down transient which takes place over the weekend as well (i.e., sixth and seventh days).

In contrast to the classical management strategies, MPC allows for a fine regulation of the system input variables (i.e. water mass flow rate and boiler temperature). The evolution of their values during the second and third days, which are arbitrarily chosen as representative days, are shown in Fig. 3. The PID controllers follow satisfactorily the set-points returned by the MPC controller. Fluctuations in the actual value of the inputs are justified by the stepped variation of the set-points. In addition, it has to be underlined that, when the water mass flow rate sent to the building space heaters is equal to zero, the water temperature has no meaning and, therefore, is not plotted.

The cumulative energy in the entire time interval introduced with the fuel, the one transferred by the boiler to the water and the one effectively used to fulfill the building demand are represented in Fig. 4.

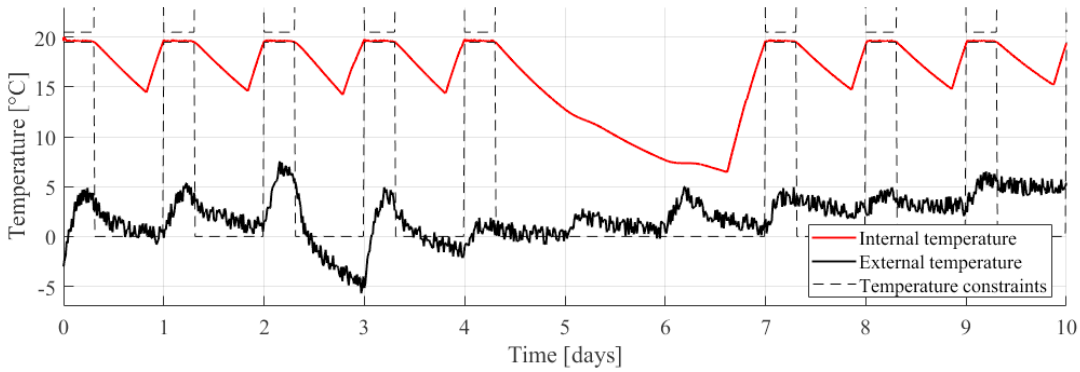

Figure 2. Results of the model-in-the-loop system operation: building internal temperature.

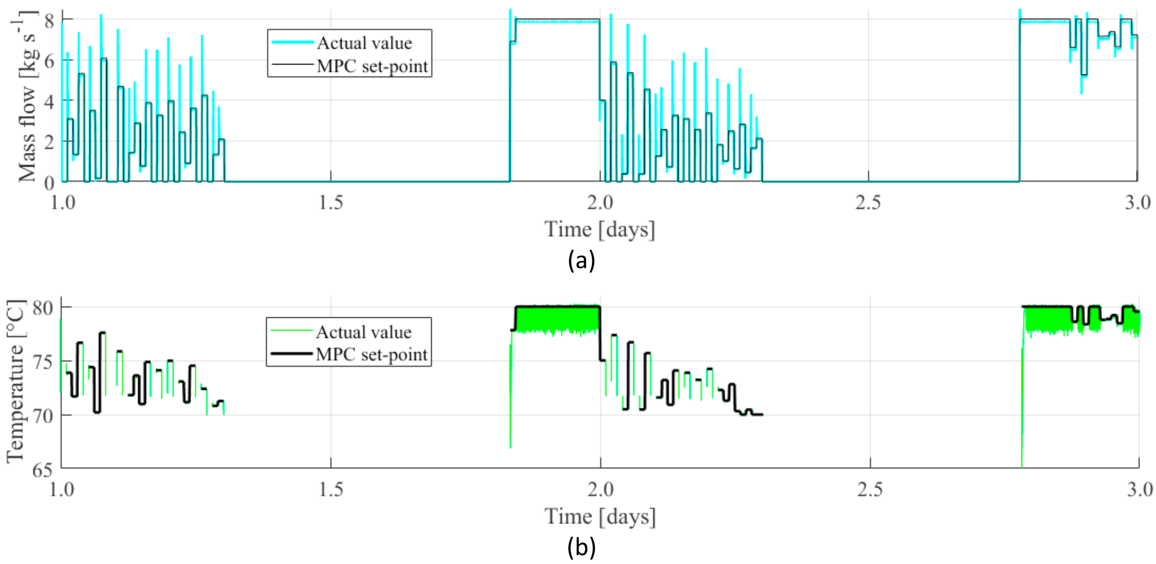

Figure 3. Actual values and set-points of the input variables: (a) water mass flow rate and (b) boiler outlet temperature.

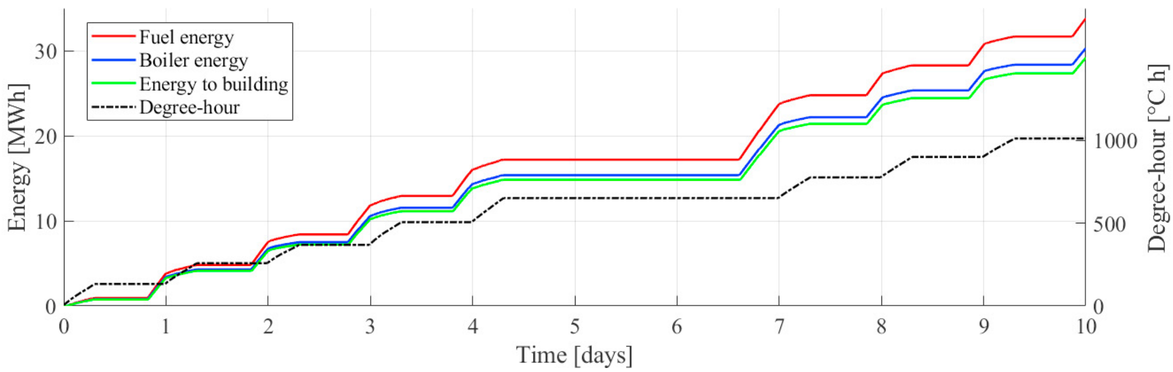

Figure 4. Energy introduced with the fuel, produced by the boiler and transferred to the building and degree-hour throughout the time span.

The total fuel energy consumption can be related to the effective user requirement by dividing it by the degree-hours resulting in 33.2 kWh/(°C h). This parameter is compared with the outcome of a standard control strategy consisting of delivery of maximum thermal power to the building five hours prior to occupation on weekdays and ten hours beforehand on Mondays. The MPC strategy allows for a reduction of 6 % in fuel energy consumption. Better results are achieved when milder external temperature are considered (e.g., savings up to 13 % in November).

Overall, this MiL-MPC application allows for the simulation of 10 days in a computational time lower than 2 hours with a standard laptop. This confirms the significant versatility of this approach in monitoring energy systems performance and developing and comparing different control strategies.

6. Conclusions

In this work, a MPC strategy has been applied to an energy distribution system model. The testing model has been developed using a components library built by the authors in Matlab®/Simulink®. The library modular approach shows its capability to easily build up dynamic models of DHC networks with several layouts and different configurations. Once the testing model has been set to match the real system features, it was possible to apply the MPC strategy for a 10-day-time horizon during the winter season. As seen in Section 5, the cause-effect relationship between disturbance evolution, set-points variations and system responses shows the effectiveness of the controller. The MPC confirmed to be promising for the optimization of the energy delivery in DHC application by satisfying the scheduled constraints without any advance or delay that would increase thermal losses. A significant reduction in fuel energy consumption compared to a classical management strategy is achieved. Further studies will be focused on more complex networks and, eventually, on application to real systems.

In conclusion, the Model-in-the-Loop approach proved to be useful to develop control strategies in DHC application since it allows the testing of these strategies without compromising the fulfilment of user thermal demands and their comparison with the same boundary conditions.

Acknowledgements

This work was supported by the "Efficity – Efficient energy systems for smart urban districts" project (CUP E38I16000130007) co-funded by Regione Emilia-Romagna through the European Regional Development Fund POR-FESR 2014-2020.

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