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A library for the simulation of smart energy systems: the case of the Campus of the University of Parma

Agostino Gambarotta, Mirko Morini*, Michele Rossi, Matteo Stonfer

Industrial Engineering Department, University of Parma, Parco Area delle Scienze 181/a, 43125 Parma, Italy

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Abstract

Smart energy systems are complex systems (i.e. composed of windmills, PV panels, solar collectors, heat pumps, CHP systems, etc) in which synergies rise through the ICT (Information and Communications Technology) based management and control of the whole system. In the development of efficient smart energy systems, a fundamental step is the optimization of total energy conversion, transmission and utilization processes within the whole system. To this extent, mathematical models can represent very useful tools for the simulation of the behavior of the system.
In this paper, a library for the dynamic simulation of smart energy systems is presented. The library is implemented in Matlab®/Simulink® and each component (i.e. the energy conversion and distribution systems and the end-users) is developed through a modular approach. Therefore, the modules are designed by considering a standardized input/output and causality structure.
Finally, the capabilities of this approach are evaluated through the application to the district heating and cooling network of the Campus of the University of Parma. The case study is based on a branch which feeds twelve buildings with a total heating volume of about 150 000 m^3 and peak thermal power demand of about 8 MW. Results reported in the paper demonstrate the effectiveness of this approach and the capability in term of system optimization.

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Keywords: smart grid, DHC network.

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1. Introduction

The last decades have seen growing awareness and interests in environmental impacts, energy availability and costs, and providers' resilience. The development of the renewable energy sector, the concept of sustainability and efficiency in energy conversion and use became key topics that push the

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* Corresponding author. Tel.: +39 0521 905714
E-mail address: mirko.morini@unipr.it

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diffusion of distributed generation and hybrid power systems [1]. As a consequence, energy systems and networks are becoming more and more complex including renewable energy sources, fossil energy sources and storage devices. However, energy systems and grids have to be really “smart” to make the best use of available technologies through an optimal combination of energy and economic performances.

Main issues to develop efficient smart energy systems are (i) the correct sizing of each technology and (ii) the definition of optimal management strategies for each component. To this extent, following the typical approach used in automotive applications, mathematical models can be very useful tools, allowing for the simulation of systems behaviour (i.e., primary energy consumption and end-user fulfilment) over significant periods of time (typically a year). Even if nowadays dynamic simulation is becoming the main tool for electric power system analysis [2], few examples can be found with reference to heating and cooling grids [3-6]. Nevertheless, it is clear that a novel approach is needed for a proper design of smart energy systems and related management strategies [7].

To this aim, in the paper an original library implemented in Matlab®/Simulink® is presented and applied to the simulation of the district heating and cooling network of the Campus of the University of Parma.

Nomenclature

A	area [m^2]	C_b	building heat capacity [kJ/K]	c_p	specific heat [kJ/(kgK)]
M	mass [kg]	m	mass flow rate [kg/s]	P	Power [kW]
p	pressure [bar]	T	temperature [°C]	t	time [s]
U	heat tr. coeff. [kJ/(m^{2}K)]			v	velocity [m/s]

2. Model structure

Modeling district heating networks needs to handle two different domains: the hydraulic domain, which deals with the fluid distribution and considers the pressure as effort variable and the volumetric flow rate as flow variable, and the thermal domain, which deals with the heat exchange and considers the temperature and the mass flow rate as effort/flow couple.

It has to be underlined that causality is strictly defined for the hydraulic domain only, while the thermal domain follows [8]. In the following, models developed for each component of the system represented in Fig. 1 are briefly described.

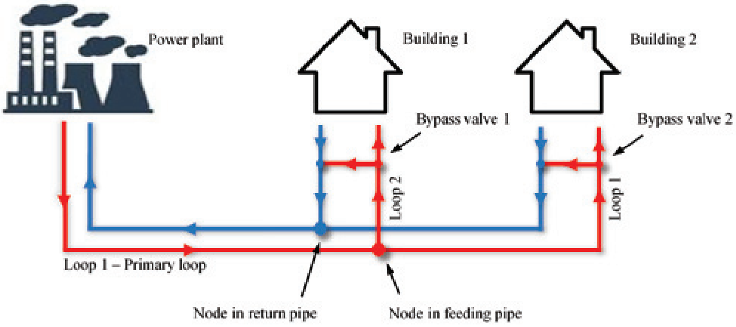

Fig. 1. Model structure and main components of a district heating/cooling network

2.1. Power plant

Power plants have been considered as composed of two main subsystems: (i) the boiler, which transfers thermal energy to the fluid, and (ii) the pumping system, which increases fluid pressure. Therefore, the power plant module takes into consideration these aspects by means of two submodels:

- the hydraulic model, which is composed of the pumps and two expansions vessels (upstream and downstream of them): pump model is based on algebraic relation between pressure head, volumetric flow rate and rotational speed (i.e., the performance maps), while expansion vessel model takes into consideration the fluid mass storage;
- the thermal model, which is composed of the boilers and two manifolds upstream and downstream the boilers: in this case, dynamics is considered both in the boiler and in the manifolds by means of the energy balance equation with the storage term.

The causality of the power plant module implies that the model needs inlet and outlet volume flow rates and inlet fluid temperature to calculate pressures inside the two vessels and the outlet temperature.

2.2. Buildings

Particular attention has been paid to the development of the building module. Starting from the dynamic energy balance equation of the building, a single state grey box model described by Eq. (1) has been implemented:

$$\frac{dT_\mathrm{b}}{dt} = -c_1 \cdot (T_\mathrm{b} - T_\mathrm{e}) + c_2 \cdot P - c_3 \cdot (T_\mathrm{b} - T_\mathrm{e}) - c_4 \cdot (T_\mathrm{b} - T_\mathrm{air}) \qquad (1)$$

Differently from similar approaches presented in literature [9], the coefficients considered in Eq. (1) take into consideration the heat exchange with the environment through walls by means of the first term, the power input (from the heating system, sun radiation, etc.) by means of the second term, the air infiltrations by means of the third term and the air change rate through forced ventilation in the fourth term, i.e.,

$$c_1 = \frac{U_\mathrm{b} A_\mathrm{b}}{C_\mathrm{b}} \qquad c_2 = \frac{1}{C_\mathrm{b}} \qquad c_3 = \frac{m_\mathrm{leak} c_\mathrm{p,air}}{C_\mathrm{b}} \qquad c_4 = \frac{m_\mathrm{forc} c_\mathrm{p,air}}{C_\mathrm{b}} \qquad (2)$$

Values of the four coefficients are calculated through an identification procedure, starting from a simplified TRNSYS [10] model of the building, by enabling sequentially the four contributions.

The power from the district heating network is transmitted to the building module through the heat exchanger subsystem. This module determines a pressure drop in the fluid and a reduction of the fluid temperature according to the exchanged power.

The causality of the building module implies that the model needs external temperature, inlet volume flow rate and temperature in order to calculate the pressure drop, the outlet fluid temperature and the building temperature.

2.3. Network

The fluid distribution network has been split into loops, segments and nodes. A loop is a branch of the network that terminates in a building and it is composed by a feeding pipe and a return pipe. The primary loop starts from the power plant, while in general a loop stems from another loop. The connection between two loops is a node. Within a loop, a segment is a portion of the pipe that separates two nodes.

Hydraulic dynamics is considered in the loop by means of the momentum balance, which allows the calculation of changes in fluid velocity as

$$\frac{dv}{dt}=\frac{\left(p_{\mathrm{in}}-p_{\mathrm{out}}-\sum\Delta p_{\mathrm{seg}}\right)\cdot A_{\mathrm{p}}}{M} \tag{3}$$

Segments and nodes are algebraic elements. The segments perform the calculation of the pressure drop Δp_{seg} according to the flow velocity and the geometry of the pipe, while the nodes assure the continuity equation.

Regarding the thermal domain, the dynamics is considered at a segment level by writing the energy balance with the storage term and by considering the heat loss towards the ground. Nodes are represented by algebraic energy balance.

The causality of the loop module implies that the model needs inlet and outlet pressure and inlet temperature in order to calculate the volumetric flow rate and the outlet fluid temperature.

3. Application to the Campus of the University of Parma

The fulfilment of the heating and cooling demands of buildings in the Campus of the University of Parma is provided by a district heating and cooling network. The network is divided into four different main branches fed by natural gas boilers. The peak heating power demand of the whole Campus is equal to 16 MW. The analysis presented in this paper focuses on one of these four branches: the “Nuova Sud” branch. This branch feeds twelve different buildings (Fig. 2). The mass flow rate in each building heat exchanger is regulated by means of a bypass valve in order to maintain the temperature inside the building equal to 20 °C during working hours.

The application to a real district heating network allows to show the potential of the model, in the Smart Energy framework [11]. In order to evaluate model capability two different network management strategies have been implemented and compared.

The first one, which is the current management strategy, allows the adjustment of the flow rate inside the heat exchangers, only through the opening or closing of the bypass valves. All the loops are active at the same time.

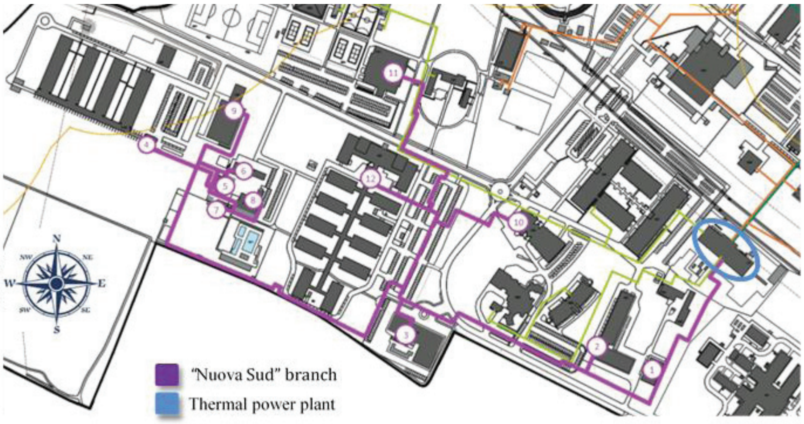

Fig. 2. “Nuova Sud” network of the Campus of the University of Parma

With the second strategy, instead, the twelve building are divided into three different groups. Firstly, the heating fluid is provided only to the buildings that request longer periods to reach the target temperature of 20 °C. Then the fluid is sent also to the buildings that belong to the second group (opening the valves on the nodes) till the achievement of the target temperature and finally to the third group of buildings. In this way, the thermal transients of buildings' temperature terminate approximately at the same time (Fig. 3b) avoiding to reach the target temperature too soon and reducing heat losses (Fig. 3a).

Thanks to the simulation, it can be seen that with the modified management strategy the boilers start-up can be postponed of 2 hours on Monday (the first day of the week after the weekend shutdown) and of one hour for all the other days (from Tuesday to Friday) (Fig. 4). Moreover, the energy used to provide the heating for all the buildings is reduced, due to the reduction of the overall time spent by the twelve buildings to reach the set point temperature (Fig. 3b). The simulation of the whole winter period (from October 15th to April 15th) shows an energy saving with the modified control strategy, with respect to the first one, equal to 104 MWh (about the 1.5% of the total energy used).

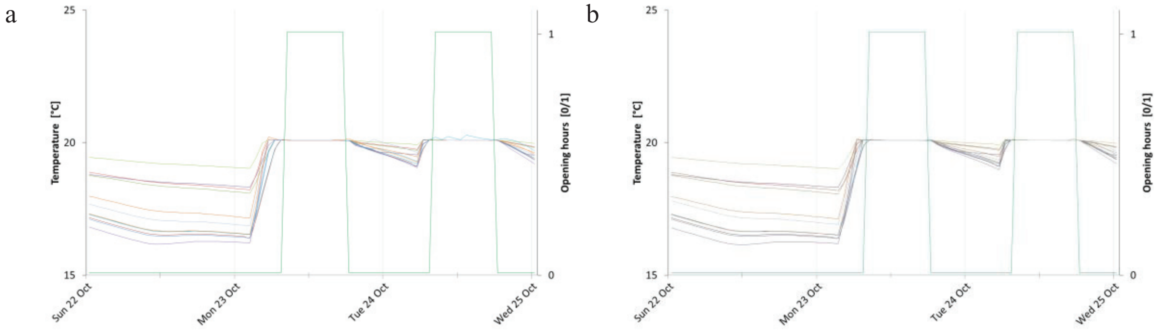

Fig. 3. Internal temperature of the 12 buildings and opening hours of the Campus (green) for a week of simulation (a) current management strategy; (b) modified management strategy

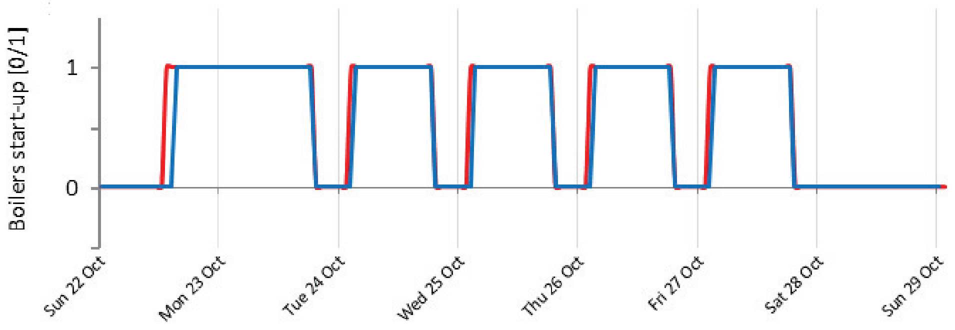

Fig. 4. Comparison between the boilers start-up according to the current (red) and modified (blue) management strategy

4. Conclusions

A dynamic model for the simulation of district heating and cooling network has been developed and applied to the case of the Campus of the University of Parma.

The model is based on a library implemented in Matlab®/Simulink® composed by modules (e.g. the power plant, the buildings, the distribution network) designed by considering a standardized input/output and causality structure. The model handles two different domains: the hydraulic domain, which deals with the fluid dynamics, and the thermal domain, which deals with heat exchange and energy storage.

The application of the model to a branch of the Campus network which feeds twelve buildings with a peak power demand of about 8 MW allowed the evaluation of a modified management strategy. This modified strategy allows for an energy saving with respect to the current management strategy of about 1.5% of the primary energy.

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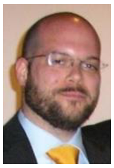

Biography

Mirko Morini received his PhD in Engineering Science in 2008 at the University of Ferrara. From 2010 to 2013 he was a researcher at the Engineering Department of the University of Ferrara and then he holds the same role at the Industrial Engineering Department at the University of Parma.