An Equivalent Electric Circuit for the Thermal Network of the Savona Campus Smart Polygeneration Microgrid

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Abstract—The paper proposes a model for the thermal network of the Savona Campus Smart Polygeneration Microgrid (SPM) in terms of an equivalent electric circuit. Such model allows to represent in a simple but accurate way the behavior of the SPM thermal network in order to insert it into the Energy Management System (EMS) that is presently running in the SPM control room. The parameters of the thermal circuit are identified by means of an algorithm that minimizes the difference between the temperature profile as calculated with the circuit and the measured one.

Index Terms-- Energy Management, Optimization Algorithm, Parameter Identification, Smart grids, Thermal Network.

I. INTRODUCTION

One of the main focuses of microgrids research has been oriented to the development of optimal operational strategies that allow to exploit the maximum potentials of their promising features in the energy management context. Such strategies are typically implemented in the so-called Energy Management Systems (EMS).

Due to their importance, EMSs have been deeply investigated in various forms and architectures [1-2]. The most common architecture for EMSs is the multilevel hierarchical one [3], in which the higher level concerns the dispatch of active and reactive power of the programmable production units, while the lower ones account for a more detailed control of the single components. The highest level of this architecture recalls the principles of optimization of traditional electricity transmission networks, achieved by classical Optimal Power Flow (OPF) algorithms. However, the presence of dynamic components like storage devices together with the uncertainties that characterize the load request and the Renewable Energy Sources (RES) and the combined presence of electric and thermal infrastructures makes such optimization problem a very hard task from a computational point of view. To overcome this difficulty, many different papers have been published in literature with the aim of developing accurate and efficient algorithms for the microgrid

EMSs, addressing either the integration of RES rather than storage devices, or the so-called Demand Side Management (DSM), or again the satisfaction of electric network constraints [4-6].

In a recent paper [7], the attention of the authors has been concentrated on an efficient electric network modeling for optimization purpose that has reached a good compromise between accuracy and reduction in the CPU effort. However, the model of the thermal network consisted only of a pure thermal power balance equation, which is quite unrealistic as it is based on the knowledge of the thermal load request expressed in terms of a thermal power profile rather than a temperature one and does not consider the delay time between the instant in which the thermal source is switched on and the one in which the temperature reaches the desired value. The proposed paper aims at bridging this gap and basically defines an equivalent electric circuit for the SPM thermal network that is able to account for both these issues.

In literature, many studies deal with the modeling of thermal networks from different point of views, which are focused on optimization or simulation aspects. The advantages of district heating networks based on Combined Heating and Power (CHP) technologies have been shown in [8-9] and, in particular in [8], a model for the optimal daily operation of a district system with a CHP plant has been proposed.

As highlighted by Larsen et al. [10], models including a full physical representation of the thermal networks, in terms of mass flow rates, pressure drops and pipe dimensions, are computationally intensive and, as a consequence, they are not suitable to be inserted into EMSs; to this end, they propose a simplified method which permits to study a district heating network by reducing its topological complexity. On the other hand, Kuosa et al. [11] focus the attention on the differences between “Y” and “ring” networks and compare a traditional network with a ring one characterized by an innovative flow rate control method; furthermore, the same authors introduce [12] an equivalent thermal circuit to represent the heat transfer

process in a heat exchanger and apply this methodology to study a district heating system.

More simplified models of thermal networks are usually implemented within Mixed-Integer Linear Programming (MILP) tools [13, 14, 15], where district heating networks are optimally designed and operated in order to minimize different objectives, such as capital and daily operational costs. In the aforementioned models, energy balance equations, operational constraints and correlations for the calculation of heat losses and pressure drops are reported.

The equivalent electric circuit for the SPM thermal network, proposed in the present contribution, represents a general approach that can be adopted to study heat distribution systems in a simplified but effective way; moreover, the model can be inserted into models used to optimize distributed generation units.

As will be detailed in the following, the parameters of the proposed equivalent electric circuit have been identified by means of an inverse procedure that, starting from input and output measurements, has found out the optimal values of such parameters minimizing the distance between the measured parameters time profile and the calculated one.

II. THE THERMAL NETWORK OF THE SAVONA CAMPUS SMART POLYGENERATION MICROGRID

In this section, a brief description of the SPM is provided (see [7] and [16] for details), also referring to the thermal network.

From the electric point of view, the microgrid is fed by a secondary substation 15kV/400V; from this substation two feeders supply the loads of the Campus and the other two connect the main four SPM switchboards. As shown in Fig. 1, the main technologies connected within the SPM network are:

- three CSP (Concentrating Solar Power) units (electrical power 1 kW, thermal power 3 kW each), coupled with Stirling engines;
- an H₂O/LiBr absorption chiller having a cooling rated power of 70 kW;
- an electrical storage (SoNick batteries by FIAMM S.p.A) characterized by a rated capacity of 141 kWh;
- a roof mounted photovoltaic field (80 kW of peak);
- two recharging stations for electric vehicles;
- three CHP (Combined Heat and Power) units (2 Capstone C65 and 1 Capstone C30 gas turbines);
- two gas boilers (total rated thermal power of about 1000 kW).

The aforementioned systems are controlled and monitored from a control room, where the servers running the EMS are installed, together with clients for operators. A double fiber optic ring connects the servers in the control room with the

switches located in each switchboard, where TM 1703 ACP Remote Terminal Units (RTU) and I/O modules are installed.

Figure 1. The SPM layout.

In Fig. 1 the SPM thermal network is sketched by red and blue lines, respectively corresponding to the supply lines, driving the hot water from the heating station to the users, and to the return lines, driving back the cold water from the users to the heating plants. The thermal network is fed by the three cogeneration gas turbines and the two gas boilers. The pipes are installed underground and are properly insulated in order to minimize heat losses; the pipe diameters are in the range between DN80 and DN125. The Fig. 1 does not show the pipes that distribute heat inside each building, where hot water is moved by on/off centrifugal pumps and heat is transferred to the indoor air by means of radiators or fan coils.

The heating network is real-time monitored from the control room by means of on-field sensors that allow measuring the following variables: the water mass flow rate, the supply and return lines temperatures, the thermal power output of each gas turbine and boiler and the outdoor temperature; at present, the buildings are not equipped with any sensor measuring the indoor conditions as well as the water temperature and flow rate, so that it is possible to evaluate only the whole thermal load of the Campus and not at a single building scale. In the next future, each building will

be equipped with sensors in order to develop more accurate analyses and to highlight criticalities of the thermal network. In coldest winter days, the Campus thermal load can reach 900 kW of peak request and the thermal energy consumption is about 1300 MWh per year.

III. EQUIVALENT ELECTRIC CIRCUIT

The aim of the paper is to develop a model for the Campus thermal network with the following features:

1. it has to be sufficiently simple in order to be put into the EMS without increasing too much the computational complexity;
2. it has to realistically model the delay time between the instant in which the thermal source is switched on and the one in which the temperature reaches the desired value;
3. it has to provide a relationship between the desired temperature time profiles and the corresponding thermal power that has to be produced by the three cogeneration gas turbines and the two gas boilers.

To do this, an equivalent electric circuit has been developed (Fig. 2) that contains resistors to model the thermal losses, capacitors that account for the thermal inertias, current sources that model the power generation and voltage sources that account for the external temperatures (ground and outdoor). Moreover, in order to accomplish feature 1), the circuit consists of only one thermal load representing the whole Campus (from here on denoted by “user”). In particular, referring to Fig. 2, one has that:

- the current source I_0 represents the thermal power generation (that can be produced either by the CHP units and/or by the boilers);
- the capacitance C_0 accounts for the thermal inertia responsible for the time delay necessary to obtain the desired temperature in the thermal circuit;
- the resistance R_0 models the thermal circuit losses;
- the voltage source V_0 models the fact that, without any thermal source, the thermal network temperature approaches the ground one;
- the switch B_1 models the possible disconnection between the thermal network and the load (encoded in a Boolean variable S , true when B_1 is open);
- the diode D_1 models the fact that the user cannot transfer heat to the water in the thermal circuit;
- the resistance R_{11} accounts for the pipe thermal losses in the thermal circuits of the buildings;
- the capacitance C_1 accounts for the thermal inertia responsible for the time delay necessary to obtain the desired temperature of the user;
- the resistance R_1 represents the thermal losses, that depends on the user insulation;
- the voltage V_1 mimics the fact that, without any thermal source, the user temperature approaches the outdoor ambient one.

In the proposed model, V_{C0} is the voltage between terminals A and B and represents the thermal network temperature, while V_{C1} , which is the voltage between terminals A_1 and B_1 , represents the user mean temperature.

Figure 2. The SPM thermal network equivalent circuit.

Applying the Kirchoff's laws to the circuit of Fig. 2, one obtains the following set of two ordinary differential equations in the state variables V_{C0} and V_{C1} :

$$\frac{dV_{C0}(t)}{dt} = -\frac{1}{C_0} \left(\frac{1}{R_0} + \frac{1}{R_{11}} \right) V_{C0}(t) + \frac{1}{C_0 R_{11}} V_{C1}(t) + \frac{1}{C_0} I_0(t) + \frac{1}{C_0 R_{11}} V_{B1}(t) + \frac{1}{C_0 R_0} V_0(t), \quad (1)$$

$$\frac{dV_{C1}(t)}{dt} = \frac{1}{C_1 R_{11}} V_{C0}(t) - \frac{1}{C_1} \left(\frac{1}{R_1} + \frac{1}{R_{11}} \right) V_{C1}(t) - \frac{1}{C_1 R_{11}} V_{B1}(t) + \frac{1}{C_1 R_1} V_1(t), \quad (2)$$

with the initial conditions

$$V_{C0}(t) = V_{C0}^*, \quad (3)$$

$$V_{C1}(t) = V_{C1}^*. \quad (4)$$

Here the voltage V_{B1} at the switch B_1 is given by:

$$V_{B1}(t) = \begin{cases} V_{C0}(t) - V_{C1}(t) & \text{if } S(t)=\text{true} \\ 0 & \text{if } S(t)=\text{false} \end{cases}. \quad (5)$$

The numerical solution of (1)-(2) allows to find out the time profile of both the thermal ring and the user temperatures.

IV. PARAMETER IDENTIFICATION

Due to the complexity of the Campus thermal network, the numerical evaluation of the parameters appearing in the equivalent circuit starting from the physical properties of the network doesn't seem to be feasible. So, an identification procedure has been set up in order to find out the best values of such parameters that allow the proposed model to

reproduce the time profile of the measured quantities with the highest accuracy. More precisely, once at disposal the measures I_0 , V_0 and V_1 of in the time interval $[0, T]$, the optimal value of the parameters can be obtained by minimizing a weighted sum of the relative errors between the V_{C0} and its measure $V_{C0, meas}$, and the relative error between V_{C1} and its measure $V_{C1, meas}$: i.e.

$$\min \left[p_1 \frac{\int_{t=0}^T |V_{C0}(t) - V_{C0, meas}(t)| dt}{\int_{t=0}^T |V_{C0, meas}(t)| dt} + p_2 \frac{\int_{t=0}^T |V_{C1}(t) - V_{C1, meas}(t)| dt}{\int_{t=0}^T |V_{C1, meas}(t)| dt} \right], \quad (6)$$

subject to the obvious physical constraints that state that all the resistances and the capacitances must be positive. In (6) p_1 and p_2 represent two positive weights, such that

$$p_1 + p_2 = 1. \quad (7)$$

A numerical experiment has been conducted at the beginning of February at the Savona Campus, during a day when the thermal power was provided by the CHP units and the boilers. Moreover, three different timeslots can be defined as:

- the building pumping system works from 7 a.m. to the 5 p.m.;
- at 5 p.m. some loads are disconnected from the thermal network;
- the overall thermal ring stops working at 10 p.m. and switches on again at 6 a.m.

This suggests the fact that the circuit topology changes during a typical day; as a consequence a time dependent behavior of R_0 and C_0 can be supposed: in a first approximation, piecewise constant functions are considered. More precisely,

$$R_0(t) = \begin{cases} R_{01} & \text{if } 7 \text{ am} \leq t < 5 \text{ pm} \\ R_{02} & \text{if } 6 \text{ am} \leq t < 7 \text{ am or } 5 \text{ pm} \leq t < 10 \text{ pm} \\ R_{03} & \text{if } 0 \text{ am} \leq t < 6 \text{ am or } 10 \text{ pm} \leq t \leq 12 \text{ pm} \end{cases}, \quad (8)$$

$$C_0(t) = \begin{cases} C_{01} & \text{if } 7 \text{ am} \leq t < 5 \text{ pm} \\ C_{02} & \text{if } 6 \text{ am} \leq t < 7 \text{ am or } 5 \text{ pm} \leq t < 10 \text{ pm} \\ C_{03} & \text{if } 0 \text{ am} \leq t < 6 \text{ am or } 10 \text{ pm} \leq t \leq 12 \text{ pm} \end{cases}. \quad (9)$$

Moreover, condition S(t) becomes true if

- $0 \text{ am} \leq t \leq 6 \text{ am}$ or $10 \text{ pm} \leq t \leq 12 \text{ pm}$, in order to encode condition c);
- $V_{C0}(t) > V_{C1}(t)$, in order to encode the presence of the diode D_1 ;
- $V_{C1}(t) \leq V_{C1, \max}(t)$, where $V_{C1, \max}(t)$ is the user maximum temperature allowed at the instant time t .

In this framework, nine parameters have to be selected. It is possible to observe that in the time interval identified in c) the two networks (thermal circuit and user) are independent; moreover, since $I_0(t)=0$ in the same time period, the Cauchy problem can be solved analytically and in particular the solution depends only on the product $R_{03}C_{03}$. For this reason, the number of parameters to be estimated can be reduced to eight, by fixing $C_{03}=10^8 \text{ J}^\circ\text{C}$, without losing in generality.

In the here presented test a period of 22 hours (from 11 am to 9 am of the day after), has been considered, during which the trend of I_0 , V_0 and V_1 are reported in Fig. 3.

Figure 3. Time profile of the measured thermal power I_0 (panel a), the external temperature V_1 (panel b) and the ground temperature V_0 (panel c).

The parameter identification is carried out with an optimization method according to stochastic approach: the Ant Colony Optimization (ACO) algorithm [17]. The minimum value of the cost function (6), which is 0.03, has been found for the value of the parameters reported in Table I. Moreover, by using those values of the parameters, the obtained trends of

V_{C0} and V_{C1} have been superimposed to the measured ones (Fig. 4) showing a satisfactory agreement.

TABLE I. OPTIMAL PARAMETERS VALUES

Parameter	Value	Units
R_{01}	$6.86 \cdot 10^{-5}$	$^{\circ}\text{C} / \text{W}$
R_{02}	$1.19 \cdot 10^{-3}$	$^{\circ}\text{C} / \text{W}$
R_{03}	$6.05 \cdot 10^{-4}$	$^{\circ}\text{C} / \text{W}$
C_{01}	$4.37 \cdot 10^8$	$\text{J} / ^{\circ}\text{C}$
C_{02}	$2.77 \cdot 10^8$	$\text{J} / ^{\circ}\text{C}$
C_{03}	$1.00 \cdot 10^8$	$\text{J} / ^{\circ}\text{C}$
R_1	$7.97 \cdot 10^{-4}$	$^{\circ}\text{C} / \text{W}$
C_1	$1.16 \cdot 10^8$	$\text{J} / ^{\circ}\text{C}$
R_{11}	$4.65 \cdot 10^{-4}$	$^{\circ}\text{C} / \text{W}$

Figure 4. Result of the fitting. User temperature (panel a) and thermal network temperature (panel b).

In order to test the robustness of the procedure, the obtained values for the resistances and the capacitances have been used to reproduce the temperatures trend from the measurements of the thermal power in another day. Again, a period of 22 hours has been considered, and the trends of I_0 , V_0 and V_1 as recorded during the further experimental acquisition are shown in Fig. 5. Once more, the obtained profiles are in accordance with the two measured temperatures (Fig. 6). Here, in fact, the value of the cost function resulted 0.06.

V. CONCLUSIONS

The aim of this contribution has been to model the thermal network of the Savona Campus Smart Polygeneration Microgrid (SPM) in terms of an equivalent electric circuit that

flexes its behavior. The values of the parameters involved in this model have been computed by means of an optimization procedure that minimizes the difference between the temperature profiles of the thermal circuit and the user as calculated with the proposed model and the measured ones.

The obtained numerical results show that the model describes in a very accurate way the set of measured temperatures, with an error of the order of three percent. Moreover, the robustness test highlighted a good fitting between the two profiles with a gap of only six percent.

Figure 5. Time profile of the measured thermal power I_0 (panel a), the external temperature V_1 (panel b) and the ground temperature V_0 (panel c) in the consistency test.

Figure 6. Results of the fitting in the consistency test. User temperature (panel a) and thermal network temperature (panel b).

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