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Control of Electrical/Thermal Multi-Energy Microgrid

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Abstract—Multi-energy microgrids (MEMGs) are becoming an effective way to reduce greenhouse gas emissions. Proper coordination among two or more energy vectors in this type of system can improve its efficiency and provide greater independence from large grids. This work presents a novel dynamic energy management system (EMS) for an MEMG that consists of heat and electricity vectors. The thermal network is composed of a gas boiler, an electric boiler and a heat load. On the other hand, a PV system, a battery bank, an electric load and a connection with the grid constitute the electrical network. In general, the EMS evaluates the PV power and electric demand and adjusts the temperature of the water in the electric boiler to avoid excessive dependency on the local grid. The MEMG and EMS were evaluated through a 4.5 hours-simulation and various conditions of sun irradiance, heat, water, and electric demand. The results show the suitability of the EMS for reducing the dependency on the local grid.

Keywords—Multi-energy microgrids, energy management system, PV system, battery bank, thermal vector.

I. INTRODUCTION

The drive for reducing greenhouse gas emissions is boosting the development of distributed generation based on microgrids (MGs) with renewable sources, such as solar or wind energy, associated with energy storage systems (EESs) to mitigate their fluctuations. One step further considers an MG with more than one energy vector besides electricity, such as gas or hydrogen [1]. If there is complementarity between the energy vectors to improve the MG's efficiency, this is called a multi-energy microgrid (MEMG) [2].

MEMGs can contain gas-to-power (G2P), power-to-gas (P2G), hydrogen-to-power (H2P), or power-to-hydrogen (P2H) units to supply electrical or thermal loads and store energy in hydrogen, electrical, or thermal systems. Thus, MEMGs can have different input or output energy vectors, with internal relationships between them, generation sources, and energy storage units [3].

The main development of MEMGs has occurred in small applications, such as buildings, communities, and industries,

where electricity and gas are prevalent. In these cases, the energy vectors usually originate from clean energy sources, renewable sources for electrical energy, and natural gas for thermal energy. Distributed generation with interconnected MEMGs improves the stability and efficiency of the entire system, allowing local generation of energy vectors using renewable energy technologies (RETs) with different ESSs [2]. On the other hand, one of the most important advantages of MEMGs and distributed generation is their flexibility, enabling to smooth out fluctuations in generation and consumption within the MEMGs, and with the interconnection to the distribution network.

A typical configuration of an MEMG depends on its application, but it is basically composed of several interrelated units such as: a) energy sources, typically RETs such as PV systems and/or wind turbines; b) ESSs such as electrical batteries, supercapacitors, cooling/heat storage units, or hydrogen tanks; c) energy conversion systems (ECS) such as electrolyzers, fuel cells, electrical heat pumps or chillers, or natural gas power plants (cogeneration); d) transmission systems (TS) such as electrical, natural gas, or hydrogen networks; and e) final consumption units or electrical, thermal, or hydrogen loads [4].

The modelling of MEMGs is key to the design and assessment of their control, stability, and coordinated operations between different energy vectors. MEMGs models can be considered from two perspectives: 1) ‘outside’ point of view”, and 2) ‘inside’ point of view. In the first one an MEMG works as a single unit to determine its interaction with the outside world. This enables an input-output perspective, which is useful in static applications such as power system operation and planning [4].

The ‘energy hub’ concept is one of the most remarkable steady-state modelling approaches for MEMGs, serving as an aggregation model from an economic perspective that allows multi-energy conversion, conditioning and storing energy [5]. Nevertheless, one of its main limitations is describing the internal relationships in complex systems [6]. An MEMG was modelled in [7] to characterize its internal complex energy interactions. A deterministic mixed-integer linear programming (MILP) based coordinated scheduling method was also implemented to determine the operational strategies for the MEMG. This method considered the uncertainties of the efficiency and performance of distributed energy resources, as

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well as the uncertainties of renewable power injection and energy demands in the scheduling model.

In contrast, an optimal design model was proposed in [8] for an energy community to reduce its carbon footprint. The community was modelled as a network of spatially decentralized energy hubs. The model aimed to define the optimal quasi-dynamics structure to meet energy demand. Open-source modelling tools like MESMO and FLEDGE were proposed in [9,10] to help build and simulate a MEMGs with coupled electric, thermal and gas grids. The study presented in [11] focused on the coupling of electric-thermal power flow, which poses significant challenges owing to different dynamic response times. A mixed-flow model and key equipment models for an electric-thermal coupling node were developed. An extended Newton-Raphson algorithm with a modified Sukhov cooling operator was used, which allowed for faster convergence of the algorithm during the iteration process.

An MEMGs optimization model was implemented in [12] using a MILP model for a corrective receding horizon. This study considered various types of local generation units, renewable energy sources, and consumers. By optimizing over annual and daily time horizons, the performance of different configurations in various environments was evaluated in terms of costs, emissions, and flexibility.

Some studies have attempted to consider the dynamics in MEMGs models, such as in [13], where an optimal planning method was developed with intra-hour dynamics of the heating system as constraints for energy dispatch and unit sizing. Tests were conducted on an MEMG using the proposed model and compared with the traditional steady-state approach to prove the improvement of the proposed method. A three-stage model was implemented in [14] to optimize the operation of an MEMGs, enabling proper management of the grid-connected system, a stable islanding process, and a correct dynamic behavior when transitioning to island mode. Similarly, a dispatch strategy was introduced in [15] for an MEMG connected to a grid. This work modeled the multi-energy flows among all units and proposed a multi-period optimal dispatch model to reduce the net operating costs.

The second modelling perspective of MEMGs is the ‘inside’ point of view, where the focus of the study is their control and operation, and the models must include the nonlinearities of energy conversion and transmission dynamics. In these cases, one of the main problems is the difference in the temporal response speeds of the energy vectors, in such a way that fast transients can clearly influence slower response systems. Therefore, dynamic models of MEMGs are necessary to ensure the feasibility and efficiency of computation. In this regard, some works can be found in the literature that model the dynamics of each MG module in detail and applied a control algorithm to optimize their operation under certain criteria.

An analysis of a renewable energy-based heat and power system was presented in [16], providing dynamic modelling of each module and proposing a real-time regulation method for the dynamics of the entire system to compensate for renewable energy fluctuations and stabilize energy supply. The same authors proposed in [17] a similar system using surplus renewable energy to source heat and meet heating demands. In

addition to the dynamic model of the system, a coordinated control method enhanced the operational control flexibility in the studied scenarios. A similar study was carried out in [18], where renewable sources produced electricity and heat and a two-level coordinated control strategy was implemented. The lower control level smooth out the power fluctuations and the upper control level satisfy the thermal load demands.

A static EMS operates with predetermined strategies that do not adapt to real-time changes in energy demand. Such strategies are typically based on historical data or predefined rules. A static EMS follows a fixed set of rules for achieving a specific objective. In contrast, a dynamic EMS involves real-time monitoring and control of energy usage considering transient modes. It can respond to real-time changes in demand, adjusting production based on weather conditions or the state of charge of the ESSs.

Most studies of MEMGs [8,9,10,11,12,13,15,16] have focused on static analysis over hourly or daily timescales, based on economic or power flow optimization. However, only few papers have addressed the dynamic modelling and control of MEMGs [14,17,18] and these typically considered only timescales of a few seconds or hours. This paper provides new solutions for the dynamic study and control of MEMGs, with the goal of enabling real-time control taking into account the dynamics of the elements of the MEMG. The proposed dynamic EMS allows the control of the MEMG considering different climatic scenarios and a variant thermal/electrical profile with the goal of avoiding the consumption of the main grid to feed the loads.

The MEMG investigated in this paper integrates two energy vectors: 1) heat (with a network considering a gas boiler, an electric boiler and a thermal load), and 2) electricity (with a network considering a PV system, a battery ESS (BESS), an electrical load and the grid connection). A new dynamic energy management system (EMS) based on operating modes was developed to dynamically operate the MEMG while supplying the thermal and electric loads, reducing the grid dependency, considering the PV generation and the power available in the BESS, and controlling the state of charge (SOC) of the BESS to operate it securely and extend its lifetime. In the following sections of the paper, Section II provides information about the MEMG under study. Section III discusses the control system and the energy management system (EMS) proposed in this study. Section V presents and discussed the simulation results. Finally, the conclusions are presented in Section IV and close the paper.

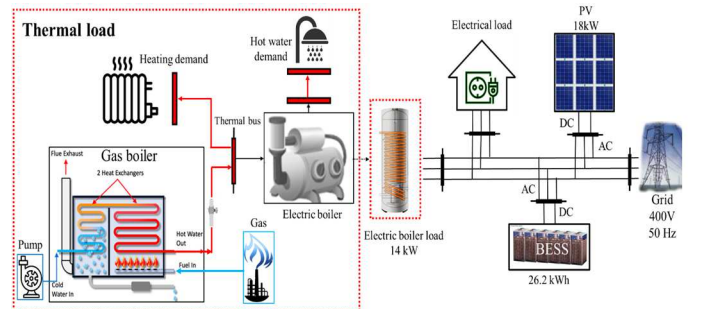


Fig. 1. Schematic diagram of the electrical-thermal MEMG.

II. MULTI-ENERGY MICROGRID

A schematic diagram of the MEMG under study is shown in Fig. 1, which consists of PV power plant, a BESS, an electrical load, and a thermal load connected to the three-phase grid. The PV power plant and battery bank feed the electrical loads as much as possible without demanding power from the grid. The 18 kW PV power plant is composed of six parallel strings and 10 series-connected modules per string, with a maximum extracted power of 300 W for each string. A ‘perturb and observe’ algorithm is applied to PV cells to maximize solar energy utilization and to satisfy the demanded power as much as possible with local RETs and not the grid.

Because the electrical and thermal load capacities are larger than the PV generation capacity, a lithium-ion BESS with a 26 kWh power capacity and 345V nominal voltage is integrated to support the RETs when energy production is not available or when more energy above the PV capacity is required. The thermal components, including the gas boiler, pump, and 300 liters electric boiler are dynamically modelled and included in the MEMG model. The electric boiler capacity is 14 kW, which feeds a varying thermal load demand. The CARNOT toolbox extension of MATLAB Simulink was used to dynamically model the thermal components of the proposed MEMG. With a focus on high-voltage AC systems, the toolbox contains thermodynamic and energy engineering models [19]. Typical components of a thermal system are provided in its library in blocksets, which are equivalent to common components. The electrothermal coordination and elements of the thermal loads are discussed below.

A. Gas Boiler

Natural gas is considered an energy source for gas boilers as a heat energy fuel. In countries with more natural gas resources, gas boilers are commonly used as a more economical method than electric boilers or heaters [20]. However, to supply heat to buildings, it is considered a major greenhouse gas emitter [21]. The gas boiler model does not consider combustion and process control constraints such as burner initialization control and delay times. In the model, the provided heat is inserted into the boiler combustion chamber. A multinode model is used on the furnace water side to consider the dependent conditions in the model [22]. Cold water is circulated through the heat exchanger to export hot water. In contrast to standard boilers that use one heat exchanger, a condensing boiler is adopted in this study to use two heating exchangers to transfer heat between the burning fuel and water. The additional heat exchanger captures moisture from the hot flue gas.

B. Electric Boiler

The new generation of boilers consumes clean renewable energy instead of fossil coal/gas fuels, which has brought benefits not only in reducing carbon emissions but also in operating efficiently, feeding a variety of loads, and enhancing the flexibility of heat sources [19,22]. An electric boiler converts the received electricity into heat. The main components of an electric boiler are tubular heating elements, insulation layers, and exterior bodies [23]. Electric energy is injected into the electric boiler to heat the water used as the heat carrier. To heat water, a set of electrical elements is used in a spiral structure. The insulation layers are used to avoid heat dissipation and

reduce energy consumption. The introduced mass flow in the thermal bus is heated by the electrical power entered from the electrical side of the MG. The model considers the ambient thermal losses by defining a thermal node, in which the ambient temperature is the initial temperature of the node [19,24].

C. Thermal Bus

A thermal bus, which combines both gas and electric boilers, is used to meet the heat demand of consumers. Heat transfer, thermal load considerations, and water temperature control can be provided to the thermal bus. The water is in the circulation loop between the boilers and thermal loads in this bus. The hot water is utilized in the heating loop as it provides heating advantages over the other carriers, such as a large radius, high energy storage capacity, and valuable energy utilization.

D. System Operation

The operation of the heating load is described as follows. First, the water is pressurized using electrical pumps throughout the building supply pipe. Then, the water is warmed by a gas boiler. Following this, the warmed water enters a thermal bus that connects the gas and electric boilers to the thermal loads. The thermal bus water is then heated to the temperature required for the bus by an electric boiler. The temperature status must be appropriate for thermal loads that are considered to be hot water and indoor heating radiators, and the electric boiler should be fed by a MG that consumes a sufficiently high amount of electrical energy. The water flow and demanded hot water vary during the heating process, and therefore, the water temperature and consequently the requested electrical power are regulated. A proportional-integral (PI) controller is used to tune the temperature gap between the thermal bus and gas boiler. Finally, when more heated water is introduced, it returns to the thermal bus. Thus, less natural gas is consumed to warm the water.

III. CONTROL SYSTEM AND EMS

A new control system and an EMS are proposed for the MEMG presented in Section II. The objective of the EMS is to coordinate the operating modes of the gas and electric boilers according to the production of PV power plant, BESS, and the electric load demand. The MEMG acts as a self-supporting MG without needing a local grid to support the thermal and electric loads. The designed control system comprises the subsystems described next.

A. Thermal Bus Control

The thermal bus control subsystem is responsible for maintaining the temperature of the thermal bus (T_{bus}) at the required reference value ($T_{ref,bus}$). For this purpose, a gas boiler is employed to elevate the temperature of the input water and control the bus in response to the underfloor heating demand and hot water consumption. A PI controller is implemented to adjust the thermal power of the gas boiler (P_{GB}) to reach the required bus temperature.

B. Electric Boiler Temperature Control

The electric boiler temperature control subsystem regulates the output temperature of the electric boiler (T_{EB}) according to the operating mode set by the EMS. A hysteresis control cycle is adopted to regulate the temperature. In this regard, three different modes are defined: high temperature, normal

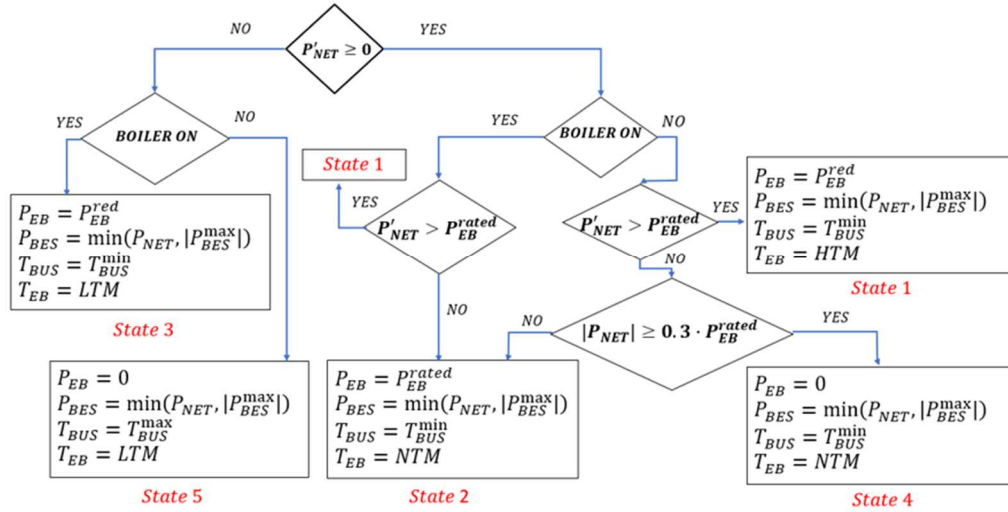


Fig. 2. Flowchart of the EMS.

temperature and low temperature. Each operating mode is limited by two thresholds. Therefore, the electric boiler is turned on until it reaches the upper threshold. At that moment, the electric boiler is turned off until it achieves the lower threshold. In this way, the temperature control is achieved without the need to constantly feed power to the electric boiler.

C. EMS

Fig. 2 represents the flowchart of the EMS. First, the SOC control provides the maximum power that the BESS can handle (P_{BES}^{max}). It is based on maintaining the SOC level in a safe operating zone, defined by upper and lower limits (SOC_{max} , SOC_{min}). The upper limit is set at 90% and the lower limit to 30%. The BESS cannot be discharged below SOC_{min} and neither charged above SOC_{max} . Furthermore, in the discharging mode, the maximum power delivered by the BESS is proportional to the SOC level when the SOC is between 30% and 50%.

The EMS consists of four inputs and two outputs. The inputs are the PV power (P_{PV}), the electric load demand ($P_{E,L}$), the electric boiler demand (P_{EB}), and the maximum BESS power available. The outputs are the reference BESS power and the operation mode for the gas and the electric boiler. The EMS uses net gross power (P'_{NET}) and net power (P_{NET}), which are defined as follows:

$$P'_{NET} = P_{PV} - P_{E,L} \quad (1)$$

$$P_{NET} = P'_{NET} - P_{EB} \quad (2)$$

On the basis of these definitions, the following five possible modes of operation are defined:

1. High-temperature mode (HTM): When $P'_{NET} > 0$ and $P'_{NET} > P_{EB}^{rated}$, the system operates with excess of renewable power. Thus, the electric boiler is set on in on a HTM and the gas boiler works in low temperature. The excess of renewable power is managed by the BESS and operates in charging mode according to its SOC.
2. Normal-temperature mode (NTM): In the case of $P'_{NET} > 0$, and $P'_{NET} < P_{EB}^{rated}$, the electric boiler is set on a NTM and the gas boiler increases its temperature. The BESS is discharged to meet the electric demand. Besides, if the electric boiler is set off and $|P_{NET}| < 0.3 \cdot P_{EB}^{rated}$, the EMS sends the order to turn on the electric boiler in this operation mode.
3. Low-temperature mode (LTM): If $P'_{NET} < 0$, the electric boiler turns on at low temperatures, while the gas boiler increases its temperature as in the NTM. If the boiler was set off, it will remain off.
4. Off mode (NTM): When $P'_{NET} > 0$, and $P'_{NET} < P_{EB}^{rated}$, the boiler will remain off in NTM if $|P_{NET}| > 0.3 \cdot P_{EB}^{rated}$.
5. Off mode (LTM): When $P'_{NET} < 0$ and the boiler is turned off, it will remain off in LTM.

IV. RESULTS AND DISCUSSION

Simulations of the MEMG and designed EMS were conducted in MATLAB/Simulink, with results presented and

Time (s)	0	500	1000	1500	2000	2500	3000	3600	4500	6000	8500	9000	9500	10000	11000	13850	14500
Water consumption (kg/s)	0.02	0.04	0.06	0.15	0.10	0.0	0.12	0.15	0.13	0.11	0.09	0.07	0.06	0.08	0.25	0.15	0.22
Irradiation (W/m ²)	1000	1000	1000	800	800	800	800	800	700	700	100	100	100	120	120	120	120
Underfloor heating (W)	4000	4000	4000	4000	0	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000

Table 1. MEMG operating parameters.

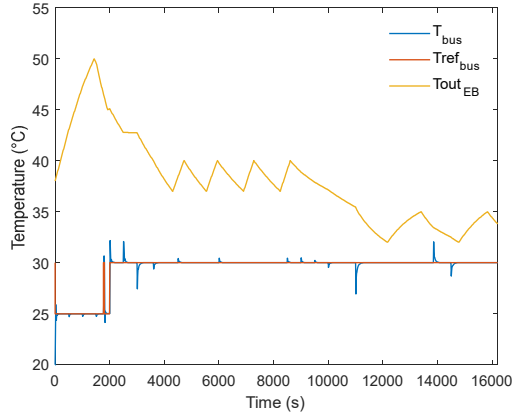


Fig. 3. Measured temperature of thermal bus, reference temperature of thermal bus and output temperature of electric boiler.

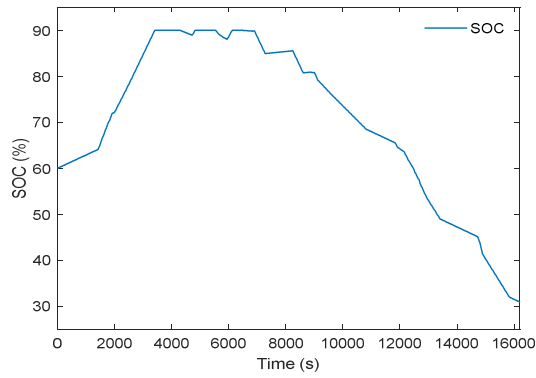


Fig. 4. State of charge (SOC) of the BES

discussed in this section. The conditions of the PV power plant, water consumption, and underfloor heating demand are defined in Table 1. The initial output temperature of the electric boiler (T_{EB}) was set at 37°C. The control temperature of the thermal bus (T_{bus}) and the output temperature of the electric boiler are shown in Fig. 3.

From 0 to 2000 s, $P'_{NET} \geq P_{BOILER}^{rated}$, and the electric boiler operates in HTM. The output temperature of the gas boiler (T_{bus}) is set at 25°C. The output temperature of the electric boiler is increased until it reaches the upper limit for the high temperature mode (50°C). At that moment, the electric boiler is set off, and the temperature decreases until it reaches the lower limit for HTM (45 °C). At 2000 s, the electric boiler is set off, $P'_{NET} < P_{EB}^{rated}$ and $|P_{NET}| \geq 0.3 \cdot P_{EB}^{rated}$, and thus, the electric boiler operates in NTM, between 37°C and 40°C, and the gas boiler elevates T_{bus} to 30°C. At 4306 s, the output temperature is 37°C, and the hysteresis control cycle sets the order to turn on the electric boiler. At 4721 s, the output temperature achieves 40°C, and the electric boiler is set off. This operating condition is maintained until 9000 s, when $P'_{NET} < 0$ and then, the electric boiler is turned off. This implies that the operation mode is changed to LTM, between 32 °C and 35 °C, and the electric boiler sets its power to half the rated power (7000 W). At 12,131 s, the electric boiler reaches 32°C and the hysteresis control cycle set the order to turn on the electric boiler. At 13,401 s, the temperature is 35°C and the electric boiler is turned off. This

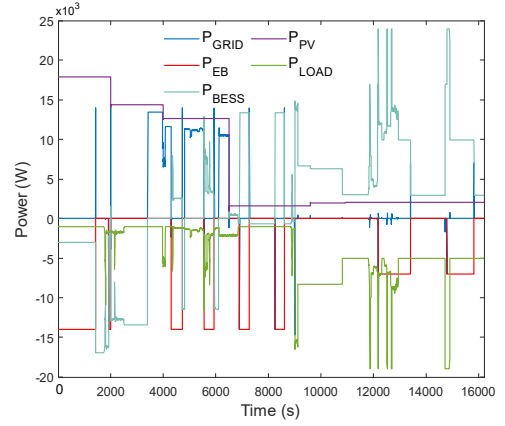


Fig. 5. Electric power balance for the MEMG.

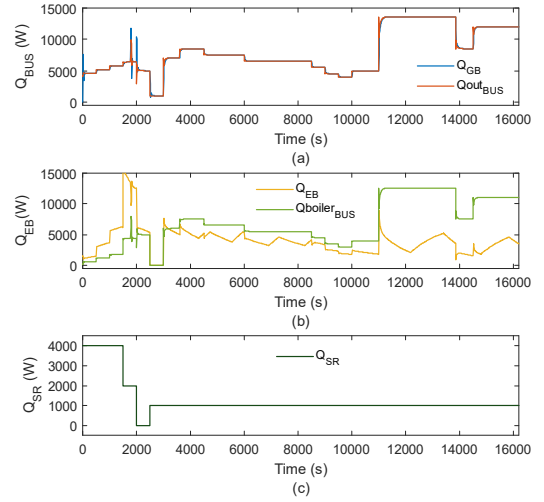


Fig. 6. (a) Thermal power injected by the gas boiler (Q_{GB}), (b) thermal power supplied by the electric boiler ($Q_{boiler,bus}$) and (c) thermal underfloor heating demand (Q_{SR}).

operating mode is maintained for the remaining of the simulation.

Fig. 4 depicts the SOC level of the BESS. From 0 to 3410 s, the BESS operates in charging mode, owing to $P_{NET} > 0$. At 3410 s, the SOC achieves the upper limit set (90%), and thus, it cannot be charged further. Therefore, the excess power is delivered to the local grid. At 6900 s, the electric load increases, $P_{NET} < 0$, and the BESS is discharged to avoid consuming energy from the grid. This is consistent with the main target of the proposed EMS discussed previously, which is to avoid the use of the local grid to meet the demand.

Fig. 5 represents the electric power balance for the PV power plant, BESS, electric load, electric boiler and local grid. It can be seen that no energy is consumed from the grid. From 0 to 2000 s, the electric boiler operates in HTM and the BESS is charged. When the PV power decreases from 18 kW to 14.4 kW, the electric boiler changes its operation mode to NTM, the SOC reaches the upper limit and cannot be charged further (90%), and the excess power is injected into the local grid. This condition is kept from 2000 s to 6500 s. At 6500 s, the PV power decreases to 1650 W, and the BESS is discharged to fulfill the

rated power of the electric boiler. At 9000 s, the electric load rises ($P_{E,L}$), $P_{NET} < 0$, and the BESS is discharged further to fulfill the electric demand.

Fig. 6 shows the thermal power balance. Fig. 6a shows the thermal power injected to the thermal bus by the gas boiler (Q_{GB}). This coincides with the thermal power extracted from the bus ($Q_{out,bus}$), which is the sum of the underfloor heating power (Q_{SR}) and the output heating from the thermal bus ($Q_{boiler,bus}$). Fig 6b denotes the heating power supplied by the electric boiler (Q_{EB}) to heat the water according to the operating conditions, and the output boiler heating from the thermal bus. Finally, Fig 6c represents the underfloor heating demand (Q_{SR}). The results show an adequate response of the EMS proposed and the high-level performance of the MEMG, adapting the operating conditions of the electric and gas boilers for high, normal and low temperature conditions.

V. CONCLUSION

The traditional approach to the study of MEMGs has been carried out from a static point of view, usually optimising an objective function to control the MEMG by considering hourly or daily simulations. Few studies have addressed the dynamic control and energy management of MEMGs. Instead, this work developed a new dynamic EMS for a MEMG composed of heat and electricity as energy vectors. The heat network consisted of a gas boiler, an electric boiler, and heat demand. Meanwhile, the electricity network included a PV system, BESS, electric demand and connection with the local grid.

The main target of the EMS was to avoid the use of the local grid to feed the thermal and electric loads. Therefore, a Li-ion BESS was chosen to smooth out the fluctuations of the PV power plant. Furthermore, the BESS SOC was controlled between the upper and lower thresholds to maintain the BESS in a secure state.

The MEMG was tested under different irradiations, water consumption profiles and electric load profiles in a 4.5 h simulation. The results showed an adequate response of the proposed EMS for the MEMG, managing the operating mode of the electric and gas boilers based on the power available in the PV power plant and the BESS. For the three temperature modes, the dynamic EMS demonstrated its ability to dynamically control the MEMG as a whole and the components that constitute it, in response to significant changes in PV production, heat and electrical consumption, and reference temperatures, while operating properly the heat and electrical networks without local grid consumption, and operating the MEMG as an islanded MG.

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