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Control of hybrid renewable energy and storage-integrated multi-energy microgrid with electric and gas boiler, electric vehicle, and household loads

Ehsan Hosseini · Pablo Horrillo-Quintero · Pablo García-Triviño · Carlos Andrés García-Vázquez · Higinio Sánchez-Sainz · Luis M. Fernández-Ramírez

Abstract A hybrid renewable energy sources (RES) microgrid supported by battery storages (BS) is designed in this paper to feed residential demands including electric vehicle (EV), electric boiler (EB), and household loads. A gas boiler (GB) is also considered in the proposed microgrid to evaluate an entire thermal bus through the GB, EB, and an underfloor heating system. A constant-speed wind turbine (WT) and a PV power system are considered as RES to reduce the dependency of energy on the grid. Great importance is placed on the thermal and electrical power balance between sources and loads; hence, a fuzzy logic (FL)-based energy management system (EMS) is designed in this respect. The EMS was evaluated using Simulink under various weather conditions and thermal/electrical demands. The results show that the proposed EMS controlled the BS power and satisfied the requested demands under all conditions, while hardly intervening in the grid power.

1. Introduction

Microgrids (MGs) adopted with RES are receiving more attention every day because they use fewer gas resources and more natural resources [1]. Among natural resources, wind and solar energies have become more interesting, and nowadays, WT and PV power sources are merged into hybrid microgrids [2]. To support RES during a lack of natural energy or to save available energy, BS systems are integrated into power systems [3].

MGs can operate in an isolated state and consume or save generated energy in a disclosed circuit. Another state is grid-connected MGs, in which the available energy communicates with a master grid to supply and absorb power through a common coupling point [4]. MGs can be multi-energy types composed of various types of energy production and consumption, such as gas, electricity, and hydrogen [5], which are flexible enough to incorporate various units. A novel multi-energy microgrid (MEMG) adopted for residential use includes thermal and electrical components. The thermal part consists of the GB, EB, underfloor heating, water heating, cooling systems, and other thermal equipment [6]. In the electrical part, in addition to residential loads, EVs can be included as an electrical load, and sufficient potential power must be considered for charging Evs.

Small-scale MEMG was introduced primarily for local industries and residential uses, where both electricity and gas energy are commonly used. Nowadays, RES with the support of various energy storage and gas energy supplies the thermal/electrical energy needs of MEMG. The MEMG configuration varies according to the application to be designed. Typically, an MEMG consists of various units that interconnect with each other.

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These units can be: 1) electrical renewable sources such as PV and WT systems; 2) energy storage systems such as electrical batteries, supercapacitors, hydrogen tanks, and heat/cooling storage units; c) energy conversion systems from hydrogen to electricity or vice versa, such as electrolyzers and fuel cells, or other energy conversion system types such as electrical heat pumps or chillers; d) transmission systems, which can be natural gas, hydrogen networks, or electrical; and e) various demand units that can be hydrogen loads, electrical, or thermal [7].

The coordinated operations, control across, and stability assessment of MEMGs are completely dependent on the modelling of the microgrid. Hence, various environments, open-source modelling tools, and toolboxes have been introduced in this regard that MESMO [8] and FLEDGE [9] are among them. The Util toolbox introduced for Simulink is the CARNOT toolbox, which includes thermodynamic and energy-engineering models [10]. The library in this toolbox provides common components of a thermal system.

In addition to the modelling, to achieve an efficient MEMG, there must be bidirectional collaboration between the thermal and electrical parts. Hence, a common focus of most studies is the utilization of natural electrical sources, such as RES, for generating thermal power. The objective is to reduce reliance on gas in the thermal loop, which is a positive direction in the context of sustainable and environmentally friendly energy systems. [11] focused on the intricate coupling of electric-thermal power flow, which presents notable challenges owing to the differing response times. In [12], an optimal planning method for a heating system was proposed that considers intra-hour dynamics as constraints for energy dispatch and unit sizing. The method was tested on an MEMG and the results were compared with those obtained using a traditional steady-state approach. The outcomes of the tests apparently validated the effectiveness and improvement achieved by the proposed method. In [13], a three-stage model was developed specifically for optimizing the operation of a MEMG. This model likely addresses various aspects of the MEMG's operation and management, including its grid-connected mode and dynamic transition to the island mode.

In [14], the study focused on a renewable-energy-based heat and power system. The researchers conducted dynamic modelling of each module within the system. In addition, a real-time regulation method is proposed to address fluctuations in renewable energy and stabilize the overall energy supply. This indicates an effort to improve the reliability and efficiency of the system by dynamically adapting it to variations in renewable energy sources.

Moreover, in [15], the same authors extended their work by proposing a system that leveraged surplus renewable energy to meet heating demands. This suggests an integrated approach in which excess renewable energy, which might otherwise go unused, is used for heating purposes. The study

likely involved dynamic modelling of the system to capture its behaviour under changing conditions.

Furthermore, a coordinated control method was implemented in the system described in Ref. [16]. This coordinated control method is likely designed to enhance the operational control flexibility, meaning that the system can adapt and optimize its performance in various scenarios. This could involve balancing energy production and consumption in real time to ensure the efficient use of surplus renewable energy to meet heating demands.

Static and dynamic EMS have been developed for MEMGs to achieve thermal and electrical balancing. The following reflects the key differences in their approaches to managing energy resources: Static EMS relies on pre-established strategies that are typically based on historical data or predefined rules. Hence, it may not efficiently adapt to real-time fluctuations in the energy demand or account for transient modes. Dynamic EMS involves real-time monitoring and control of energy usage. Its adaptability is that it can efficiently respond to real-time changes in demand by adjusting the production levels. However, factors such as weather conditions and the state of charge of energy storage systems are considered.

Most previous studies have discussed a statistical model along with a short-time interval evaluation, focusing on economic optimization and power balancing. A few studies [14,15,16] that focused on the dynamic modelling and control of MEMGs did not consider an overall evaluation of a practical MEMG and real-time assessment. This work presents an almost 5-hours real-time simulation with varying conditions of power production and consumption. In this regard, an MEMG that contains electrical and thermal components has been developed. The electrical part contains WT and PV systems as electrical sources supported by the BS, and the produced power feeds an EV and household loads. For the thermal part, the equipment and buses were designed using the CARNOT Toolbox and connected to the electrical part. A dynamic FL-EMS was designed for the proposed MEMG to manage power and temperature based on the available power and the needs of electrical/thermal consumers.

The remainder of this paper is organized as follows. In Section 2, an overview of the MEMG is provided with the coordination between the thermal and electrical aspects as well as the thermal load elements. Section 3 discusses the FL-EMS of the proposed MEMG. Section 4 presents and evaluates the simulation results. Finally, Section 5 briefly discusses the system under study, and concludes the paper.

2. Multi-energy microgrid

The suggested MEMG connected to a three-phase 400V grid is shown in Fig. 1, which is composed of a 15-kW wind

turbine, an 18-kW PV plant, 26.6-kWh BS with a nominal voltage of 345V, an 11-kW EV, a considerable household electrical load, and a thermal part. A solar wholesale ASW-300M type of PV in 6 parallel string with 10 series-connected modules and 300W maximum power is chosen. A simple model of the Simscape generator is chosen as WT generator that produce power with ideal angular velocity source to generate a wind pattern. Lithium-Ion type of battery with 76 Ah capacity and 65% initial charge is driven from Simulink library as the function of BS. The variable electrical load is designed with look up tables, gains, and switches to provide different outputs along with the simulation. The EV in this model is of a semi-fast charging type with nominal voltage of 376V, in which a full charge takes 3 h. A plug-off controller is applied to stop the power consumption when the EV battery state of charge (SOC) is 100%.

Regarding the thermal part, the valve water must be warmed and circulated between a GB, a 23 kW EB with 300-liter water storage, and 10-kW underfloor heat.

The foremost goal is utilizing the RES and BS in order to feed requested demand without the grid power backup. For the PV cells, a perturb-and-observe MPPT algorithm was applied to optimize the utilization of the sun. In this way, as much solar energy as possible is captured, and the PV efficiency is increased.

As the intermittent characteristics of WT and PV power systems do not allow a 24-hours energy exploitation, the existence of a BS is necessary. On the other hand, the requests for power from electrical and thermal loads are considered significant here; a BS with a decent capacity is integrated in the proposed MEMG. When the MG suffers from a lack of adequate RES power, the BS enters to support production and satisfy the loads, or during the period when the produced power is beyond the requested power, additional energy can be saved in the BS to be used in the low RES production.

To incorporate thermal elements into the simulation, the CARNOT toolbox was added to the Simulink library, which allows dynamic modelling. Constraints in process control,

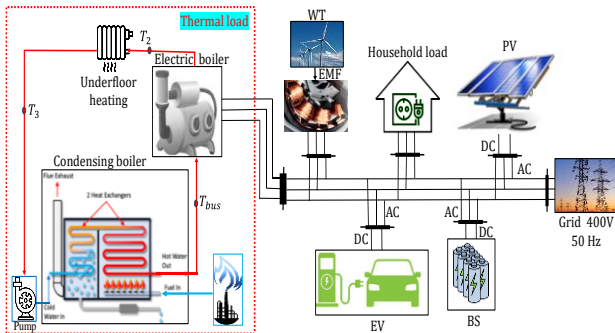


Fig. 1. MEMG

such as delay times, burner initialization, and combustion process, were neglected in this work. Water is considered a heat carrier that circulates through thermal elements.

A multi-node model was employed on the water-side of the furnace in the combustion chamber of the boiler. In this manner, hot water is produced by circulating cold water through a heat exchanger. In this model, a condensing boiler is adopted that incorporates two heating exchangers that facilitate the transfer of heat between the water and burning fuel.

Another element used in this model for heating water is the EB, which consumes electrical energy. The introduced water mass flow is heated by the electrical power supplied from the electrical side of the MG. In the EB design, insulation layers were considered to decrease energy consumption and minimize heat dissipation. Moreover, a thermal node was defined in the model to account for ambient thermal losses.

On the proposed thermal side, the water circulation between elements is expressed as follows: First, electrical pumps were used to pressurize the water throughout the building supply pipes to enter the GB. The water was then heated in the GB using its heat exchangers. To heat the water to a higher temperature, an EB was used and connected to the GB through a thermal bus. The electric boiler is powered by the electrical side of the MEMG. The electric boiler temperature (T_{EB}) is controlled through a hysteresis control cycle, where the turn on temperature (T_{EB}^{min}) and the turn off temperature (T_{EB}^{max}) are regulated according to the EMS. The bus temperature (T_{bus}) must be suitable to specific thermal loads, such as hot water and underfloor heating. A PI controller was used to maintain the desired temperature by reducing the gap between the gas boiler and the thermal bus.

3. Energy Management System

A Mamdani-type fuzzy logic energy management system (FL-EMS) is proposed to set specific powers and temperatures based on system operation. The FL-EMS oversees the RES productions (WT and PV) and loads electricity consumption (P_{load}) and based on the gap between production and consumption and BS SOC value, determines the EB power, EB turn-off temperature (T_{EB}^{max}), and thermal bus temperature. Fig. 2 shows the FL membership functions (MFs) of the inputs and outputs, where in (a) five MFs are chosen based on the system modes (lack of RES energy or enjoying additional energy) between [-23 23] kW, in (b) BS SOC values are considered as follows: until 20% is low charge level, between 20% and 80% is medium charge level, and then is defined as high charge level. The outputs are shown in Figure 2. (c). EB with 9.2 kW capacity has been defined with low-medium-high MFs for its output powers, as shown in Fig. 2. (d). EB operation is defined with 3 MFs

and maximum temperature of 60°, and finally Fig. 2. (e) shows definition of 2 MFs for (T_{bus}) between 30° and 35°. The FL-EMS uses two parameters, net gross power (P'_{NET}) and BS power (P_{BS}), calculated as following:

$$P'_{NET} = P_{RES} - P_{load} \quad (1)$$

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

Table. 1 represents the FL rules with acronyms as: low (L), normal (N) and high (H) for BS SOC, and positive high (PH), positive (P), zero (Z), negative high (NH), negative (N) for P'_{NET} , and zero (Z), low (L), normal (N) and high (H) for BS powers. The proposed rule-based table enables dynamic EB adjustment power based on the available power after feeding loads.

As an example, when the BS SOC value is sufficiently high, and P'_{NET} is above zero, the EB operates as the main heat source, rather than consuming gas by GB to produce heat, and if it is possible to charge BS. On the contrary, when the BS SOC value is insufficient and P'_{NET} is below zero, EMS reduces the EB power and discharges BS.

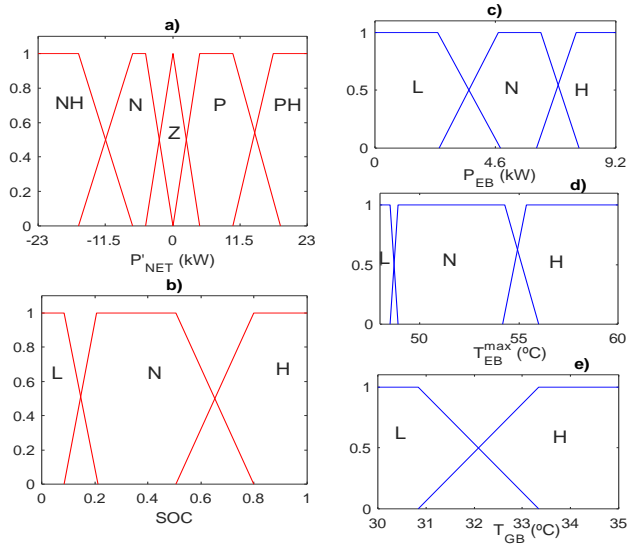


Fig. 2. Membership functions: a) Gross net power (P'_{NET}), b) BES SOC, c) electric boiler power (P_{EB}), d) electric boiler turn-off temperature (T_{EB}^{max}), and e) temperature in the thermal bus (T_{bus}).

Therefore, the FL-EMS ensures both thermal and electrical power balances, whereas the grid hardly intervenes in power exchange.

4. Results and discussion

In this section the proposed FL-EMS for the MEMG is validated by simulation results. A 16000 second simulation in a variant thermal/electric pattern source and demand is tested. The generator speed of the WT and solar radiation are considered variable on the source side, and the hot water mass flow, underfloor heat (UH) demand, and household electrical demands are variable on the load side. The initial SOC values of the EV and BS were set to 20 % and 65%, respectively, to ensure an almost full charge of EV and a BS charge/discharge in a safe range. WT works between 3000 to 8500 second with 15 kW output power, PV starts with 17.95 kW power generation, and its production is reduced along with the simulation, household electrical load gently requests power until 9000th second and after that asks for 5 kW to 20 kW power.

Fig. 3. illustrates the electrical power balance for the source output power and the load power consumption. This shows that when the EB turns-on and RES cannot satisfy the electrical demands, the BS backsups production. Before 9000s, where the power production is high and household demand is not high, the BS is in charging mode most of the time, and after 9000s when the EB works, the BS starts discharging with 0 to 20 kW output power variations depending on the EMS decision.

The EV starts charging from the start of the simulation with 11 kW power consumption until the 5000th second, and when it arrives at the 100% SOC value automatically, it is disconnected from the system. The most important power plot in this Fig is the grid power to prove whether the FL-EMS works properly for all simulation conditions. As can be seen, the grid power was almost zero for all 16000 second simulation. This means that the MEMG is not dependent on the grid and can satisfy demand without the help of the grid.

Table. 1. Fuzzy rules

P'_{NET}	NH			N			Z			P			PH		
	L	N	H	L	N	H	L	N	H	L	N	H	L	N	H
soc	L	N	H	L	N	H	L	N	H	L	N	H	L	N	H
P_{EB}^{pu}	Z	Z	N	Z	N	N	Z	N	H	N	N	H	H	H	H
T_{EB}^{max}	L	L	N	L	N	H	N	N	H	N	N	H	N	H	H
T_{bus}	H	H	H	H	H	L	H	H	L	H	H	L	H	L	L

Moreover, if the power is exceeded, it is stored in the BS for pick-demand time.

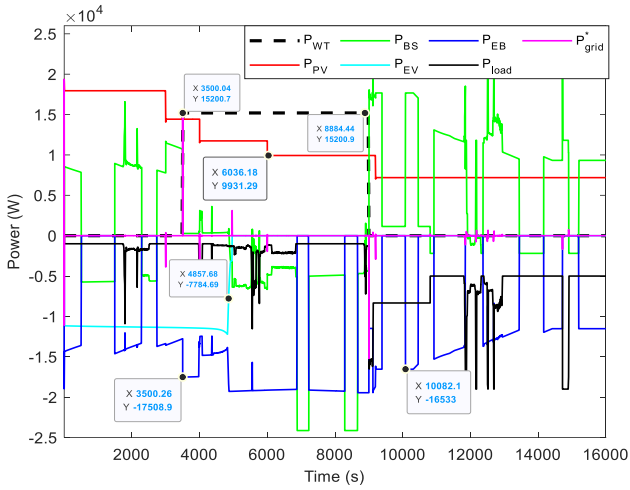


Fig. 3. Electrical power productions and consumptions.

Fig. 4. shows the storage state of the charge values for the BS and the EV. Regarding the EV, it starts charging from a small SOC value and after one hour and a half it reaches to the full charge state and remains off for the rest of the simulation. Regarding the BS, it is charged and discharged depending on the requirements of the MEMG. For the first half of the simulation, it is almost charging all the time, and for the second half, it is discharged frequently that from 80 % SOC arrives at 40 % value.

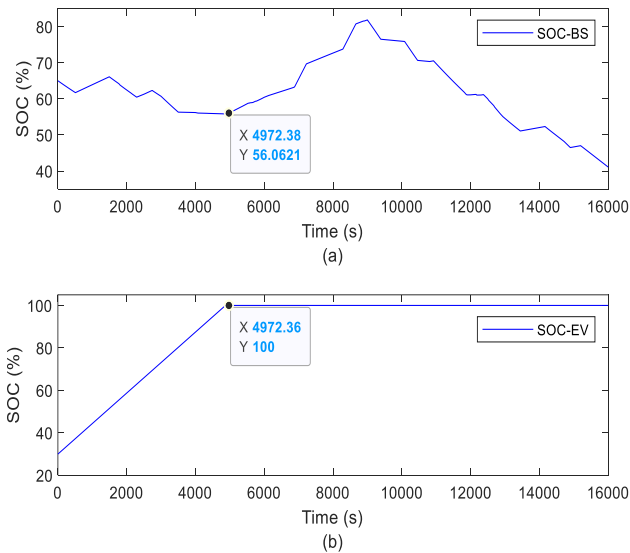
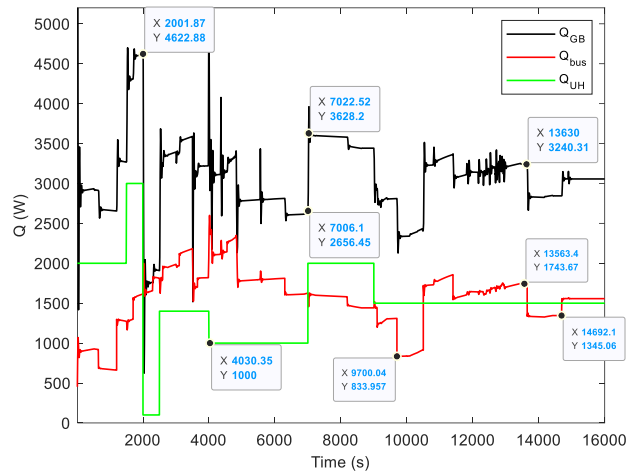
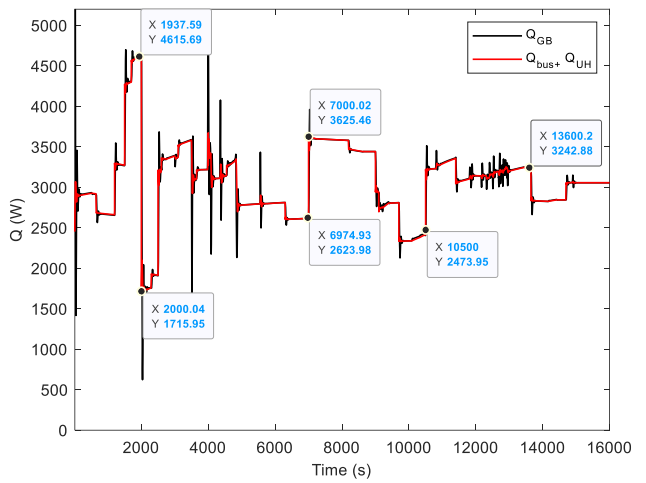


Fig. 4. SOC values for (a). BS, (b). EV.

Fig. 5 shows thermal EMS result, where the heat production must be equal to heat consumption. The GB consumed gas to maintain the thermal bus temperature at its reference value. The heat generated by the GB is wasted and consumed when it circulates through thermal components.



(a)



(b)

Fig. 5. Heat exchanges: (a) GB heat, bus heat, and UH (b) heat balance.

Therefore, it is crucial to balance heat production and consumption. Fig. 5. (a) shows the heat values for the GB, EB, and UH nodes, respectively. The heat of the GB is more than all as it must be, and the heat after the UH has the lowest values, as it consumes heat to increase the water temperature in the pipes. Fig. 5. (b). justifies thermal balancing because the summation of Q_{bus} and Q_{UH} is equal to Q_{GB} .

Fig. 6. shows the node temperatures along with the simulation after GB (T_{bus}), EB (T_2), and UH system (T_3). As stated previously, $T_{bus} > T_2 > T_3$ based on heat production or consumption. T_{bus} varies between 23° to 26° , and its value reduces during heat exchanges with the environment and thermal elements.

Fig. 7. illustrates the GB and EB temperatures for all 16000s simulation. The water temperature must be sufficiently high, as hot water is normally used for showers. Hence, the EB output temperature varies between 50° and 60° . The PI controller for adjusting the GB temperature performs well, as it maintains T_{bus} at the reference value.

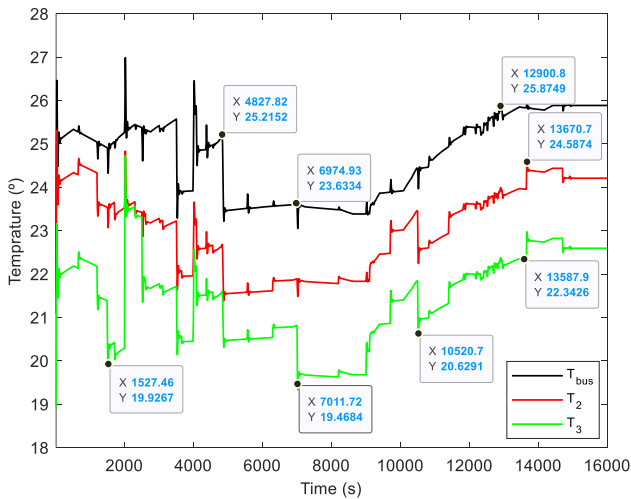


Fig. 6. Temperature of the nodes.

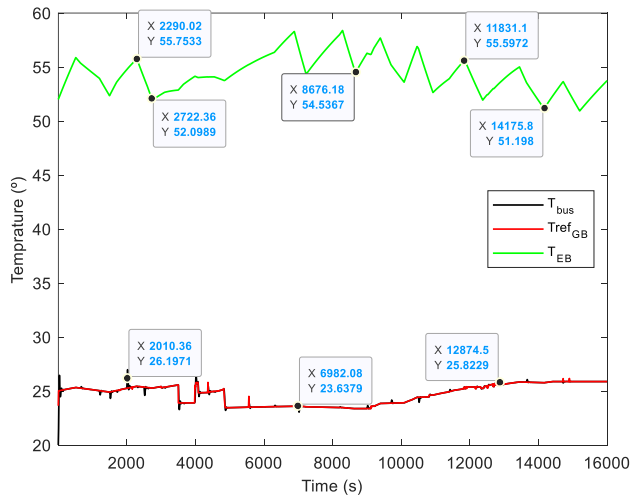


Fig. 7. Temperatures of GB and EB.

5. Conclusions

A dynamic study of a multi-energy microgrid was executed to assess a practical model with both thermal and electrical balancing for a residential load composed of various thermal and electrical requests. The MEMG was tested under various conditions, including variant electric/thermal profiles, different levels of RES production, and various water consumption profiles. The simulation results prove that the proposed FL-EMS appropriately activates the electric boiler and sets the bus temperature based on model conditions. Moreover, a secure operation of the BS is performed to prevent battery aging by maintaining the BS SOC value within a safe range. By the EMS, dependency on the grid is almost zero as the posed EMS satisfies the loads without the help of the grid and stores the excess RES energy in the BS. For the future works, the battery of the EV can also be considered as a load and also as a source of power by adding its charging level as another input and the power as another output of fuzzy EMS.

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