Real-time energy storage management system of a nanogrid integrating photovoltaics and V2G operation

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Abstract: The widespread penetration of electric vehicles (EVs) in the automotive market will create not only concerns about additional energy burden on power grids but also incentives to further encourage vehicle to grid (V2G) functionalities. The integration of EVs with intermittent renewables requires complex control systems due to the need to predict and manage data related to user behaviour and climate. In this study, a real-time energy storage management system was developed to accommodate V2G technology integration in a residential nanogrid considering no prior knowledge about the future system's state. The rule-based algorithm developed maximises the direct use of solar energy, ensures a user-determined driving range and provides ancillary services to the utility grid in real-time through an autonomous distributed control. The considered residential nanogrid setup was modelled via Matlab/Simulink and the corresponding results are demonstrated and discussed. From simulations, it is shown that the smart house designed integrates the V2G technology so that the nanogrid provides ancillary services to the bulk power system causing the least possible energy burden on the utility.

1 Introduction

Electric vehicles (EVs) are an alternative, promising technology in a market monopolised by internal combustion vehicles. The increase of their use can significantly reduce oil consumption and offer significant environmental benefits such as reduction of greenhouse gas emissions. However, these benefits will vary with the source of electricity used to charge the EVs [1]. Nowadays, most EVs are recharged from the bulk power system (BPS), whose energy is supplied from any available source. Therefore, it is uncertain that EVs are powered by renewable energy sources (RES). Even when there is no available energy from RES, the BPS must be supplied with additional energy produced from fossil fuel sources to meet the increased load demand. Direct use of energy from RES will be a key step to ensure that the energy consumed by the EVs is produced by RES.

Furthermore, over the last few years, solar power feed-in tariffs have been declining while the price of retail electricity for household consumers has been increasing. This implies that larger amounts of electricity must be self-consumed to achieve economic efficiency. Energy produced from domestic-scale photovoltaic (PV) plants can replace the electricity purchased by the grid. This leads to an immediate profit due to the difference between produced and consumed power. Thus, the size of an optimal cost PV system will shrink in the future, as higher self-consumption rates will be realised by smaller PV systems [2].

The energy consumption of buildings accounts for about 32% of the global consumption and it is responsible for ~30% of the total CO2 emissions related to energy [3]. In addition, the grid impact of the massive EV penetration in the utility [4] reveals a need to integrate EV charging methods into energy management systems (EMSs) that take into account consumer's needs and ensures a viable energy supply and demand. Microgrids are flexible power subsystems with the capability to stay connected or disconnected from the main power grid. They combine various distributed generation units and optimise their use to meet the power demands of small communities, hospitals and so on. The microgrid concept can be scaled down further at which point it acquires a new name, ‘nanogrid’. The concepts of microgrids and nanogrids are not mutually exclusive; in fact, the modular nature of the nanogrid delivers an opportunity to connect multiple nanogrids to form a microgrid [5]. A nanogrid can be defined as a medium-to-low voltage power grid for a single residential or small commercial building and can be considered as a ‘building cell’ of a microgrid [6, 7]. A nanogrid is usually a power distribution system, with the ability to connect or disconnect from other power entities via a gateway. It consists of local power production powering local loads, with the option of utilising energy storage and/or a control system [5]. A residential nanogrid can be transformed into a smart home by introducing a system that meets the electricity demand by managing its elasticity through an energy storage system (ESS). To ensure the environmental and economic advantages offered by EVs both to aggregators/utilities and owners, it is proposed to integrate it in a ‘smart home’ through an installed PV system.

In this paper, a residential nanogrid set up is designed, which consists of a PV system and a domestic battery while there is an EV connection possibility, through an off-board DC charger. To ensure system reliability, the nanogrid must avoid uncontrollable energy transactions with the grid and maintain the power balance constantly. The designed EMS focuses on energy storage management; specifically, household appliances are considered non-deferrable loads and EV charging depends primarily on the user's choices and secondarily on the BPS requirements. Herein, the last premise is achieved via frequency regulation [8, 9] implemented by an autonomous distributed control (ADC) [10]. Notwithstanding that the cooperation of PVs and EVs in a residential-scale nanogrid can be a promising solution for more sustainable mobility, few studies in the literature address this issue, namely either under self-consumption or energy purchase cost minimisation. Igualada et al. [11] focus on minimising energy costs for a residential microgrid consumer, considering the household consumption profile and the driver's mobility. In [12], the proposed control strategy aims to minimise the energy costs of a residential customer considering offline predictive models of power supply and demand, including an EV. Wi et al. [13] develop an algorithm which minimises the energy purchase cost of a residence taking into consideration weather forecast data and energy pricing. The energy management strategies developed in [14] aim to increase self-consumption rates in an apartment building focusing on rescheduling EV charging while Roseli and Sasso [15] propose a system to achieve self-consumption in an office building considering various PV performance and EV load scenarios. Van Roy et al. [16] study the cooperation of EVs and combined heat...
and power systems to achieve self-consumption in a commercial building. Finally, Di Giorgio and Liberati [17] propose a method which coordinates the microgrid sources (including the EV) to achieve both self-consumption maximisation and energy cost minimisation.

The key difference between this study and the studies in [11–17] lies in the implementation of a real-time energy storage management system (ESMS), based on a rule-based approach considering that no electrical data is known in advance. This means that the nanogrid ESMS has neither predictive features nor the capability of dynamic system optimisation. For this reason, the developed rule-based algorithm takes as input the voltage and current measurements from the nanogrid and outputs the reference power of the two batteries at each step. The designed ESMS not only ensures self-sufficiency but also acts supportively to the grid by combining both load shifting techniques and frequency regulation. This is accomplished by considering two generally independent systems: the first system consists of the PV system, the domestic battery and the domestic load and performs load shifting; the second system comprises the EV battery and the BPS and provides ancillary services to the BPS via an ADC. These systems not only alleviate the nanogrid dependence on stochastic factors but also correlate the power use profile of the nanogrid with the mains frequency.

The remainder of the paper is organised as follows. Section 2 discusses the system configuration, the inverter control scheme and the considered ESSs. Furthermore, in Section 3 the overall ESMS control approach of the smart house is presented thoroughly. The obtained simulation results are presented and discussed in Sections 4 and 5, respectively. Finally, conclusions are given in Section 6.

2. System description of the simulation model

2.1 System configuration

This paper focuses on the study and design of a residential nanogrid which consists of a PV system, an energy storage device, and the EV charger; the three aforementioned systems are connected to a DC bus. The nanogrid is also connected to the BPS, with a power injection/absorption possibility. The proposed system configuration is illustrated in Fig. 1. The PV system output power is intermittent and uncertain as it is affected by environmental conditions (radiation and temperature levels). To exploit the maximum power generated by the PV system at any time, it is necessary to use a DC–DC boost converter which operates using a maximum power point tracking (MPPT) control algorithm and is mounted to the capacitor of the DC bus, with a voltage of 800 Vrms. A 400 Vrms balanced three-phase system is assumed and a two-level, three-phase voltage source converter is used to convert energy from the DC bus to the AC output. Moreover, a three-phase LCL filter in wye configuration is used to minimise current distortion injected into the grid. This filter can achieve higher harmonic attenuation allowing to use lower switching frequencies even with relatively small inductances values [18]. Table 1 summarises the values of the electrical components used in the circuit.

From an energy point of view, a good compromise between high self-sufficiency and self-consumption is the installation of 1 kWp of nominal PV power and 1 kW of battery capacity, both per MWh of estimated annual energy consumption [2]. The appropriate battery capacity and the solar PV power for a house with an annual consumption of 14 MWh are 14 kWh and 14 kWp, respectively. To approximate the latter, we combine eight and two arrays in series and parallel with maximum output voltage $V_{\text{max}}$ and current $I_{\text{max}}$, 5.47 V and 5.58 A, respectively; this combination yields 13.735 kWp. Furthermore, the EV is powered by a lithium-ion battery with a capacity of 24 kWh.

2.2 PV system and MPPT technique

A PV array typically consists of several PV modules connected in series and/or in parallel. The PV circuit model is based on the $I–V$ equation implementation using the Simulink math blocks. However, its detailed presentation along with the equations governing its operation is beyond the scope of this paper but can be found in [19]. Furthermore, the MPPT technique chosen in this study is described thoroughly in [20].

2.3 Voltage source inverter

The system inverter scope is the control of both the active and reactive power flow exchanged between the DC and the AC side of the inverter. This is accomplished by controlling the active and the reactive current component injected into the grid. Moreover, the current-controlled voltage source inverter is controlled through the sinusoidal pulse width modulation. Fig. 2 shows both the external and the inner loop of the control scheme. More specifically, the DC bus voltage is controlled by the external loop with respect to the required output power. The pertinent proportional–integral (PI) controller output is the reference active current component $i_d$ of the controller, and the reference reactive current component $i_q$ is set to zero to ensure that the reactive power flow through the inverter remains zero [21].

The phase-locked loop (PLL) plays a key role in synchronising the inverter output current with the grid voltage to achieve a unitary power factor [22]. This technique keeps the control current in phase with the grid voltage by drawing the phase angle used for the $ABC$ to $dq$ transformation by the voltages of the grid. The PLL is a phase-locked algorithm with synchronised input and output in both phase and frequency.

![Schematic diagram of the residential nanogrid configuration](image1.png)

**Fig. 1** Schematic diagram of the residential nanogrid configuration

**Table 1** Variable name and units of boost converter and inverter parameters

| Quantity       | Value | Quantity       | Value |
|----------------|-------|----------------|-------|
| $f_b$          | 5 kHz | $f_b$          | 4.05 kHz |
| $L_b$          | 5 mH  | $L_1$          | 6.3 mH  |
| $C_{pv}$       | 80 μF | $C_f$          | 0.28 mH |
| $C_{bus}$      | 5.6 mF| $R_f$          | 25 μF   |
| $f_{sb}$       | 5 kHz | $f_{sb}$       | 4.05 kHz |
| $L_{sb}$       | 6.3 mH| $L_{sb}$       | 25 μH   |
| $C_{sv}$       | 80 μF | $C_{sv}$       | 0.28 mF |
| $R_{sv}$       | 1 Ω   | $R_{sv}$       | 25 μΩ   |
| $V_{bus}$      | 800 V | $V_{bus}$      | 800 V   |

![Simulated synchronous rotating frame control scheme](image2.png)

**Fig. 2** Simulated synchronous rotating frame control scheme [18]
2.4 Nanogrid energy storage systems

PV plants, regardless of size, typically contain a DC bus between the DC–DC converter, which performs the MPPT function, and the inverter. This DC bus provides a convenient point of integration of one or more energy storage units, using the existing inverter infrastructure [23]. Moreover, DC chargers are more efficient and potentially less costly compared to AC chargers. In fact, considering the target for charging EVs directly from PV plants, DC chargers have an additional advantage; they do not require PV energy conversion from DC to AC and vice versa and the resulting process of the power factor correction [24].

The type of DC charger of the nanogrid ESS selected is the half-bridge converter (Fig. 3).

The nanogrid ESSs (the domestic battery and the EV battery) consist of the battery and the pertinent battery management system (BMS). The adopted model of the lithium-ion battery both for the domestic ESS and the EV considers the battery dynamic characteristics, such as the open-circuit voltage, the transient response and the storage time-dependent capacity; state variable of the battery model is considered the associated SoC [25]. For all power converters used (the inverter, the PV boost converter and the batteries DC chargers), an average modelling approach is applied since this work focuses on the average behaviour of the converters and not on their cycle-by-cycle response.

3 Residential nanogrid energy storage management system

The control process block depicted in Fig. 4 demonstrates the cooperation between the real-time control and the battery power allocation system (BPAS). The measurements of the system electrical quantities (solar power $P_{p,v} \text{, domestic load } P_{l,d} \text{, mains frequency } f_{g} \text{, domestic and EV battery SoC, } SoC_{d,dom}, SoC_{v,veh}, \text{ domestic and EV battery currents and voltages, } I_{b,d,dom}, V_{b,d,dom}, I_{b,v,veh}, V_{b,v,veh} \text{ and the voltage on the DC bus } V_{dc}$) as well as the power references for the EV and the domestic battery $P_{b,v,veh}^{*}$ and $P_{b,d,dom}^{*}$ are real-time propagated while the user-defined charging threshold $SoC_{v,veh}^{lim}$ is entered offline. The control time step is selected adequately small ($10^{-4}$ s) in order to follow the system state changes.

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frequency error is negligible. For frequencies above Δf\text{max}, the charge or discharge power must lie within acceptable limits for the EV battery and thus further frequency increase or decrease will not further charge/discharge the battery. When frequency deviation takes values outside the specified dead band, the EV and the BPS exchange power in order to suppress frequency fluctuation.

Moreover, the dead band introduced aims to reduce frequent battery charge/discharge, since the EV must not react if the frequency error is negligible. For frequencies above Δf\text{max}, the charge or discharge power must lie within acceptable limits for the EV battery and thus further frequency increase or decrease will not further charge/discharge the battery. When frequency deviation takes values outside the specified dead band, the EV and the BPS exchange power in order to suppress frequency fluctuation.

The BPAS determines the power references, P^\text{veh}\text{max} and P^\text{dom}\text{max} at each iteration, depending on the input data. Then, the BMS produces appropriately coordinated power signals to the chargers of the batteries. The ancillary services are only provided when the EV is connected to the nanogrid. If the EV is not connected to the system or its battery is fully charged, then the domestic battery switches to load shifting mode. The flowchart shown in Fig. 9 describes in detail the power allocation for both batteries through a decision-making process, for all cases considered (see (3)), where \Delta f = f^* - f^\text{g}.

In the present study, the excess power resulting from the PV output power and domestic load difference is stored in the domestic battery for later use by household loads when PV power is no longer available. However, control decisions are coupled over time by integrating V2G functionalities with consumer driving choices. Decision making may be more difficult if the practical operational limitations of the installation (e.g. batteries’ capacity, and charging levels) are also considered. The proposed algorithm ensures that the active power measured at the point of common coupling (PCC) with the utility, P^\text{g}, does not depend on stochastic factors such as PV power fluctuation, domestic load and domestic battery SoC but on the mains frequency, under the applied ADC. This contributes to control the stochastic nature of consumer power use profile, as seen from the BPS and transform the nanogrid into an active element of the power system.

Initially, the EV SoC is checked. If the current EV SoC, i.e. SoC^\text{veh}, is less than the limit set by the user, then the EV will be charged as a priority with its maximum power, regardless of the PV plant and the BPS power availability. This option aims to eliminate the drivers range anxiety, as the EV battery will be charged at the specified threshold, SoC^\text{veh} as soon as possible. Given that the EV
If the current EV SoC is above the defined threshold, then the V2G mode is enabled and in the general case, the EV power exchange is based on the droop curve of Fig. 10. The domestic and the EV battery power allocation may differ depending on their SoC, charging margins, the PV output power and the household load.

This control scheme does not favour direct power injection from the PV plant to the BPS since it aims to meet the current household load, the EV charging needs and an energy amount intended for load shifting. Thus, the domestic battery power is intended to meet the domestic load whereas the EV battery power is intended to suppress the mains frequency deviation.

From the abovementioned, the domestic battery power will not be influenced by this phenomenon since its power only depends on the power balance between the PV plant and the domestic loads. Thus, a frequency step change will result in a change of the EV battery power and consequently to the power measured at the PCC. The evaluation of the BMS will be conducted only through the EV battery since both the domestic and the EV battery share a similar converter and control system. As can be seen from Figs. 5–7, the DC–DC converter tracks the battery’s power reference through its current reference.

4 Simulation results

In order to clarify both the robustness of the system subcomponents and the proposed algorithm’s performance, several case studies are analysed.

4.1 Evaluation of the system’s robustness

To evaluate the system’s stability, we consider first, a random irradiation profile and second, a step change of the mains frequency. The solar radiation, the PV voltage and current, the boost converter duty cycle and the DC bus voltage are presented in Figs. 10a–d, respectively. For a solar irradiance profile with ramp changes between 600 and 1200 W/m², the PV output voltage fluctuates between 480 and 504 V, while the PV output current follows the irradiance profile fluctuating between 15.8 and 33.8 A.

Furthermore, the boost converter duty cycle takes values between 0.37 and 0.4 while the DC bus voltage manifests minor deviations from the nominal value over the simulation period (<0.5 V).

Figs. 11a and b show the response of the EV battery power and the active power at the PCC because of the frequency step change. The settling time of the EV battery power response is 0.006 s while the corresponding time for the power measured at the PCC is 0.0029 s demonstrating the system’s robustness. It is worth mentioning that the difference between the two settling times is due to the different time constants of the DC–DC converter and the power measurement system.
to the delay introduced by the inverter and the LCL filter response. In Fig. 12, the voltage and current of phase A measured at the PCC are shown. When the frequency deviation is negative – thus, the EV battery reference power, as well – the voltage and the current waveforms are in phase, the battery is discharged and the power flows to the grid. Correspondingly, after the power reference step change, the frequency deviation is positive the phase lag between the voltage and the current is 180°, the battery is charged and the power flows to the DC side of the inverter.

4.2 Evaluation of the ESMS performance

To explain the operational details of the proposed ESMS, a 30 s simulation case study is discussed below, in which $f_g = 50$ Hz and $\text{SoC}_{veh}$ is selected 70%. Also, the considered frequency fluctuation range is set as $\Delta f \in (-0.05, +0.05)$ and the considered dead band is set as $\Delta f \in (-0.01, +0.01)$. The mains frequency, the PV power and the domestic load profiles are illustrative and selected to assess the nanogrid performance under various operating conditions. For example, the variation of solar power and domestic load represent the shadow made by a cloud and switching on/off household appliances, respectively.

In order to examine the operational details of the proposed algorithm, a 30 s simulation is presented in Fig. 13. The PV output power and the domestic load are shown in Fig. 13a, the domestic battery power and SoC are shown in Fig. 13b, the EV battery SoC is shown in Fig. 13c and the power absorbed from the grid, the EV battery power, as well as the mains frequency are shown in Fig. 13d. Initially, the EV battery SoC is less than $\text{SoC}_{veh}$ (i.e. 70%), the EV charging power is maximum (7.2 kW) and independent of the mains frequency. At this stage, the PV power is supplied to the EV battery and household loads while the resulting excess (about 3.72 kW) is charging the domestic battery. When $\text{SoC}_{veh} = \text{SoC}_{veh}^d (t = 2.4$ s), the V2G mode can be activated; however, the mains frequency is below 50 Hz up to 7.8 s and the EV battery remains inactive. Throughout this period $P_g$ remains practically zero – ~250 W due to system losses.
Then, during the period between 7.8 and 25.7 s, the EV battery power is following the mains frequency in accordance with the ADC described by (5). During this time, \( P_g \) is substantially collinear with \( P_{b,veh} \) and differ only by the losses in power converters. At the same time, domestic battery is charged with the excess power resulting from the difference between the generated PV power and the domestic load up to 9.13 s and the pertinent SoC is increasing (Fig. 13b). Subsequently, during the period between 9.13 and 19.78 s, the domestic consumption outstrips the PV power and the domestic battery is discharged with equal power to meet the demand. Then, due to the PV power increase and the domestic consumption reduction, the excess PV power is charging the domestic battery until its SoC becomes 90% (\( t = 25.8 \) s) wherein the end of charge is set. The resulting excess power is added to the reference battery power so that \( P_g \) follows the ADC. Thus, even though frequency deviation is negative, the EV battery is charged with a power of about 1.5 kW.

As shown in Fig. 13d, the active power exchange with the BPS, \( P_g \) follows the mains frequency, regardless of the PV power, the domestic load and battery SoC. This implies that the nanogrid acts supportively to the BPS given that the user driving requirements have been covered. What is more is that \( P_g \) is frequency independent when the EV SoC is less than the user-defined SoC or frequency deviation is negative (\( t<7.8 \) s). Nevertheless, the control scheme ensures that even in these cases, the nanogrid does not absorb power from the utility exploiting the available PV power.

As shown both by the algorithm of Fig. 9 and the simulation results, the PV power is utilised in each case at least by one system battery and direct power injection to BPS is not favoured, unless all batteries are fully charged. Therefore, by coordinating the ESSs charging process, the nanogrid not only meets the user energy needs (electric appliances and EV charging) but also provides frequency regulation.

Subsequently, a 5 h scenario based on a historical database of a PV unit, the mains frequency measurements, and a domestic load is presented in Fig. 14 in order to provide an overview of the system’s performance. The active power measured at the PCC along with the mains frequency is illustrated in Fig. 14a while the EV battery SoC is shown in Fig. 14b. It is clearly seen that the active power measured at the PCC follows a similar trend with the mains frequency apart from the intervals during which either the EV battery is deemed inadequately charged or the mains frequency is below 50 Hz and the EV battery SoC has reached the minimum set.

Finally, a weekly simulation scenario is cited to evaluate the nanogrid performance under different climate conditions, domestic consumption and driving patterns. The PV output power and the domestic load are shown in Fig. 15a, the domestic battery power and SoC are shown in Fig. 15b, the mains frequency is presented in Fig. 15c, the EV battery SoC is shown in Fig. 15d and the power

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Fig. 13 30 sec simulation scenario
(a) PV output power and domestic load, (b) Domestic battery charging power (left axis) and SoC (right axis), (c) EV battery SoC, (d) Power measured at the PCC with the utility, EV battery power (left axis) and mains frequency (right axis)

Fig. 14 5 h simulation scenario
(a) Active power measured at the PCC and the mains frequency, (b) EV battery SoC

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measured at the PCC, $P_g$ is shown in Fig. 15c. If the EV is not connected to the nanogrid, SoC_{veh} is considered unknown. The minimum desired SoC, as well as the disconnection and reconnection times of the EV are summarised in Table 2.

The goal of the first system (the PV system, the domestic battery and the domestic load) is to maintain the nanogrid power balance zero when the EV is not connected to the grid while the goal of the second system (EV battery and BPS) is to provide frequency regulation to the utility. From Fig. 15d, it is shown that the EV SoC fluctuates above the minimum desired SoC, exchanging energy with the grid according to the mains frequency. In addition, the energy margin is increased for a higher desired EV SoC and connection duration (e.g. sixth day of the simulation). Furthermore, the power at the PCC remains zero when the EV is not connected to the nanogrid while it follows the mains frequency otherwise. This does not happen in only two cases:

- the EV is not connected to the grid, the domestic battery is fully charged (Fig. 15b), and the excess solar power is injected into the utility (Fig. 15c). This phenomenon is observed on the first and fifth day of the simulation due to the large difference between the locally produced and consumed energy.
- the EV is connected to the grid but its SoC is not yet the desirable one. In this case, the EV is charged at the maximum possible power until the minimum SoC is reached.

5 Discussion

One of the most notable merits of the proposed control scheme is that the inverter control is independent of the MPPT control and the ESMS developed. The inverter control method allows power transfer from or to the DC side while maintaining a unitary power factor on the AC side of the inverter. This is significant as in this application the battery total capacity is selected to provide active power ancillary services to the utility through frequency regulation.

Furthermore, the inverter control is independent of the MPPT control and the ESMS developed. The inverter control method allows power transfer from or to the DC side while maintaining a unitary power factor on the AC side of the inverter. This is significant as in this application the battery total capacity is selected to provide active power ancillary services to the utility through frequency regulation. In addition, the application of three different and independent controls gives the system the advantage of reduced complexity and easy scalability, as well.

Furthermore, the proposed control system determines at each time step the charging power of each battery considering the real-time voltage and the current measurements from all the electrical parts of the plant. This increases the system reliability since its performance is based on the actual conditions of the nanogrid. This reduces the computational complexity of the system thanks to the simple structure of the decision-making system implemented by the flowchart.

A significant asset of the decision-making system is based on the adequate battery charge; the nanogrid uses all the available power sources (PV unit and utility grid) to charge the EV battery to the desired SoC. When the EV battery is considered sufficiently charged, the EV is allowed to participate in the Ancillary Service Program of the utility. Thus, the SoC of the EV battery is expected to oscillate between the minimum desired charging state and the point that is considered fully charged. The degree of participation of the vehicle battery in this programme depends on the amount of battery capacity that the user is willing to ‘sacrifice’.

6 Conclusion

In this study, the ‘smart home’ concept was examined from the energy standpoint. The term ‘smart’ refers to an energy system that interacts with the user and the BPS, offering a real-time solution that satisfies as much as possible both sides. The PV system integration is the key component of the ‘smart house’ which is simulated through a residential nanogrid. The proposed ESMS applies a co-ordinated control to the two incorporated batteries (EV’s and domestic) defining power allocation at each time step.

The simulation results show that the exchangeable power between the nanogrid and the BPS does not depend on the intermittent nature of domestic consumption and PV generation but only depends on the applied ADC, constrained by the user driving needs satisfaction. Therefore, the proposed algorithm not only relieves the user from range anxiety but also decouples the nanogrid power use profile from stochastic factors and correlates it with the BPS requirements.

7 References

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