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Development of an Energy Managing Strategy and Sizing Algorithm for a Nanogrid Parking Lot for Electric Vehicles

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Summary

This paper presents an energy management strategy (EMS) and infrastructure-sizing algorithm for charging electric vehicles (EVs) from a nanogrid, comprising a photovoltaic array and a stationary battery pack. This to the utility grid connected system can be a solution for the integration of EVs in the future. The EMS is developed with a fuzzy logic controller that controls the power flow within the nanogrid with the objective to satisfy a weekly load demand of 250 kWh per charging station. The system's components are optimally sized with a genetic algorithm that minimizes a cost function including the capital and operating costs. The results prove the correct functioning of the EMS, but it was found that a nanogrid parking is not yet attractive from the economical point of view.

Keywords: energy storage, EVSE, optimization, photovoltaic, power management

1 Introduction

The popularity of electric vehicles (EVs) is increasing because of their potential of reducing fuel consumption, noise and greenhouse gas (GHG) emissions. However, the increasing amount of EVs on the road may cause huge problems in the near future. The installation of numerous charging stations will lead to a higher electricity demand and will impose additional stress on the utility grid, especially when charging is performed during daytime and during the peak hours of demand [1][2]. In particular, the cables and substation transformers will be overloaded, resulting in lower reliability, additional cost and potentially load shedding.

A possible solution to reduce the stress on the grid is to use locally available renewable energy resources (RERs), like wind, solar and hydropower, to charge EVs. However, due to their intermittent nature, an energy storage system (ESS) is required to ensure that the EV charging demand can be satisfied. This configuration, whether it is connected to the utility grid or not, is called a nanogrid [3]. It allows to charge EVs locally and highly reduce the GHG emissions of the charging process. Furthermore it increases the efficiency of power transmission due to the short distance between the RERs and the load [4]. Such a configuration needs appropriate sizing of the components and precise energy management in order to minimize the total cost, satisfying the power demand at all time and controlling the power flow between the different components.

This paper focuses on a nanogrid that delivers power to a parking lot at a workplace and proposes a smart energy management strategy (EMS), based on a fuzzy logic controller (FLC) with optimal sizing of the system components. Its application at a workplace parking avoids the inconvenience for EV owners of having to wait until their car is fully charged as they are working in the meanwhile. Furthermore, it provides the possibility for people who cannot install a charging point at home to use an EV. However, the developed strategy is not only limited to a workplace, but is suited for shopping centers, airports, train stations, hospitals, universities, etc. as well [2][5]. A weekly demand of 250 kWh per charging station is considered in this study and a feasibility study of the nanogrid is performed based on two use cases.

The paper is structured as follows: Section 2 explains the system's architecture, in Section 3 and Section 4 the functioning of the EMS and sizing algorithm are described, respectively, the results are shown in Section 5 and Section 6 concludes the paper.

2 System architecture

Many possibilities exist to build a nanogrid and the choice of its components can have an important impact on its operation and reliability. In this research, the nanogrid for EV charging, which is depicted in Figure 1, comprises 22 kW AC charging stations which can provide up to 32 A to charge the EV. Photovoltaic (PV) panels are used to generate renewable energy They are preferred to other RERs like a small scale wind turbine, because of their power production during daytime, their low maintenance cost and their easy set-up [6][7]. Moreover, with the continuous downward trend of the price of PV modules, solar power is considered as the most competitive technology for a nanogrid parking [8]. To maximize the power production of the PV array under varying weather conditions, a maximum power point tracking (MPPT) algorithm is implemented in the accompanying power converter. However, because of the intermittent nature of a PV array, a battery energy storage system (BESS), the main storage device used with PV systems, is required to increase the reliability of the nanogrid [9]. This way, the excess power from the PV array can be stored in case it cannot be used instantly, or, the BESS can provide power to the charging infrastructure in case the power delivered by the PV array is not sufficient. A lithium-ion (Li-ion) battery is considered as the best option for this task because of its outstanding characteristics compared with the other secondary battery technologies despite its higher investment cost [10][11].

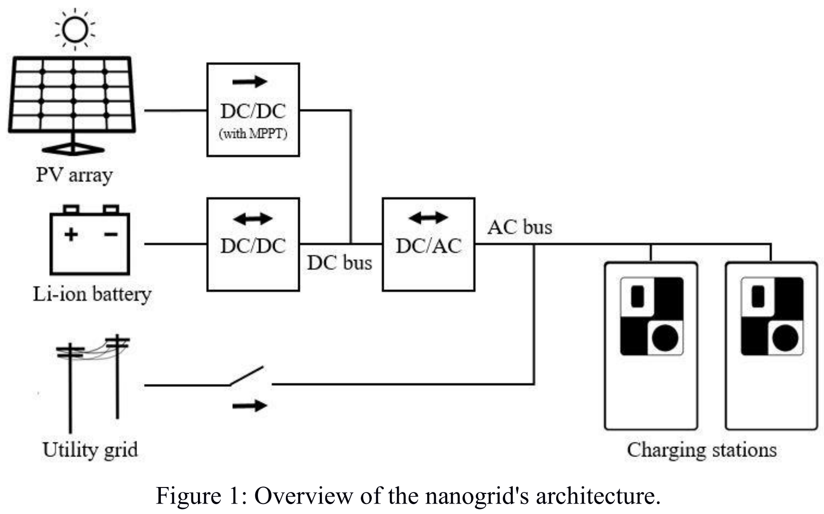

Figure 1: Overview of the nanogrid's architecture.

In the optimal use case, it would be possible to isolate the nanogrid from the utility grid, but due to the environmental conditions in Belgium and the large seasonal variations in irradiance, it is impossible to operate the nanogrid parking in islanded mode for a whole year. Therefore, the nanogrid can be connected to the utility grid in case both the PV array and the BESS cannot provide enough power to the charging infrastructure. However, in order to not exceed the load threshold of a building, the power that can be taken from the grid is limited, e.g. to 10% of the maximum total load. Furthermore, power converters are required to connect the different components with each other as both the PV array and BESS supply DC power, while the utility grid and charging infrastructure operate on AC power. DC charging is not considered in this paper. The chosen configuration of the nanogrid contains both an AC and a DC bus because with this so called hybrid topology, fewer power converters are needed, which leads to a higher efficiency of the system [12]. It should be noted that power can only be taken from the grid, either to charge the BESS or supply the charging stations, and not sent back to it, meaning that the excess power from the PV array is always stored inside the BESS. This decision is made because of the grid's power limitation that is imposed. In case the battery pack is completely charged, the PV array is disconnected from the nanogrid until an EV needs to be charged.

3 Energy management strategy

The control of a nanogrid is in general executed on three levels. The primary level ensures normal operation of the power converters, the secondary level deals with power quality control and the tertiary level aims to introduce intelligence to achieve an optimal operation of the nanogrid [13][14]. This paper only focuses on the tertiary level for which an EMS is developed. An EMS is necessary if more than one energy source is used to supply one or more loads, which is the case for this nanogrid parking [15]. To control the power flow between the components under different weather conditions, a smart and reliable rule-based EMS with fuzzy logic (FL) is developed as it is very effective with small scale and fast varying systems [13][14]. Especially the latter is of utmost importance as weather conditions can change quickly and so to be efficient the EMS should adapt quickly to these changes. Furthermore, the EMS aims to satisfy the load demand at all times, to decrease the use of the utility grid and to protect the Li-ion battery pack.

The following inputs are used for the EMS: solar irradiance, current delivered by the PV array, state of charge (SoC) of the stationary battery pack and current demanded by the charging infrastructure. Based on these inputs, the EMS determines which components should be connected to the nanogrid and which should not with if-then rules. The FLC is used to decide how the stationary battery pack should operate. Based on the SoC and the difference in current between what is asked by the charging stations and what is delivered by the PV array, the charging (negative current) or discharging (positive current) rate of the battery is determined.

$$I_{\mathrm{net}} = I_{\mathrm{demand}} - I_{\mathrm{PV}} \tag{1}$$

$$I_{\mathrm{bat}} = \%_{I_{net}} . I_{\mathrm{net}} \tag{2}$$

where I_{demand} is the current consumed by the charging infrastructure, I_{pv} the current delivered by the PV array and I_{net} the difference between them. I_{bat} is the battery current and $\%_{\mathrm{Inet}}$ is the percentage of I_{net} that the battery should deliver or store. For example when $\%_{\mathrm{Inet}}$ is 100%, the battery will deliver or store the total amount of I_{net}.

When the battery is almost empty, the power that the battery can deliver is lowered so that the battery can be used for a longer time, although with reduced power. This is done to limit the power supply needed from the utility grid. Overnight, when electricity is cheaper, the battery pack can be charged with power coming from the grid to ensure that the estimated demand of the next day can be satisfied. To protect the battery from being damaged and to lengthen its lifetime, the FLC stops discharging the battery when it reaches a SoC of 20%.

Table 1 shows the relation of the fuzzy sets assigned to the inputs and output of the controller. For I_{net} the fuzzy sets are negative (N), positive small (PS), positive medium (PM) and positive big (PB), for the SoC they are low (L), medium (M), high (H) and very high (VH), and for the charging current I_{bat} they are very low (VL), medium (M), high (H) and very high (VH). Each of these fuzzy sets spans a certain range of values of the input or output variable, and are zero outside this range. The ranges are described by membership functions, representing the fuzzy sets. The operation of the FL controller is very sensitive to the definition of these membership functions. It was noticed that a different range coverage can disrupt the proper functioning of the EMS. Figure 2 shows the membership functions related to the input variables I_{net} and SoC.

Table 1: Relation between the fuzzy sets of the inputs and the output of the FL controller.

I_{bat}		I_{net}			
		N	PS	PM	PB
SoC	L	VH	VL	VL	VL
	M	VH	VH	H	M
	H	VH	VH	VH	VH
	VH	VL	VH	VH	VH

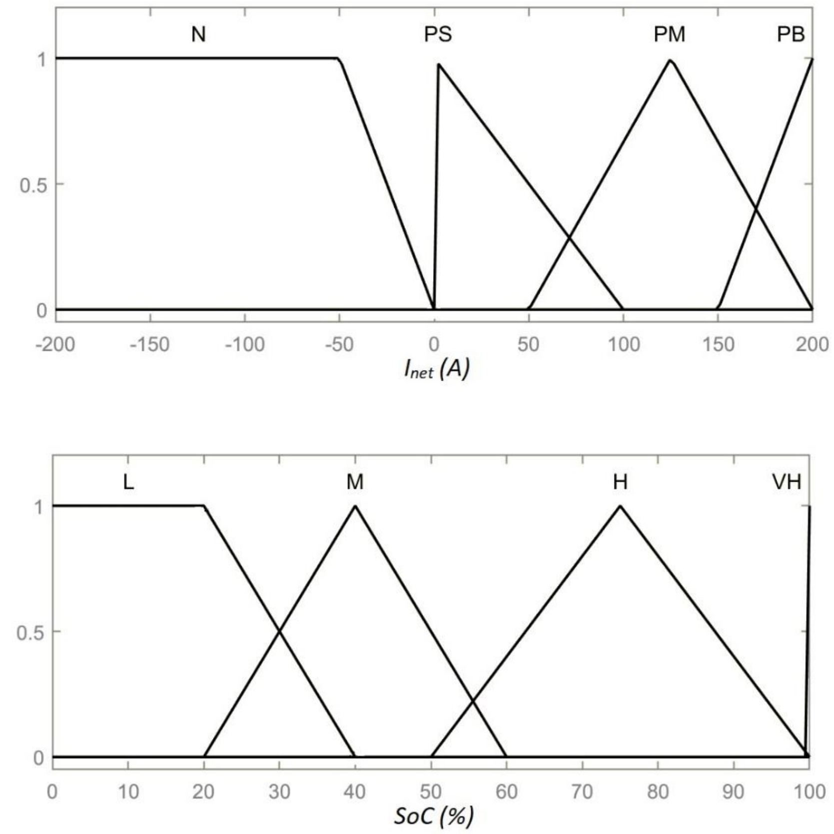

Figure 1: Membership functions related to the input variables (top: I_{net}, bottom: SoC).

Once the current that the battery pack should provide or store is determined, it is checked if the utility grid should inject power. This is verified by expressing that:

$$I_{grid} = min(I_{demand} - I_{PV} - I_{bat}, I_{lim}) \quad (3)$$

where I_{grid} is the current that the utility grid should inject into the nanogrid and I_{lim} the current limit imposed on the utility grid.

The sum of the currents produced by the PV array, provided by the battery and, if needed, provided by the utility grid finally gives the current generated inside the nanogrid:

$$I_{gen} = I_{PV} + I_{bat} + I_{grid} \quad (4)$$

This current is sent to the charging infrastructure and divided over the different charging stations according to their contribution to the total demand.

4 Sizing algorithm

Next to an EMS, it is also important to have an appropriate sizing of the system components (PV array, BESS and grid connection) in order to guarantee the lowest overall cost of the nanogrid while ensuring the highest possible reliability [7]. The variables that should be optimized are the number of parallel strings of the PV array, the number of parallel strings of the battery pack and the limited amount of power that the grid can supply, as only these three variables have on influence on the current flow inside the nanogrid. For this purpose a genetic algorithm (GA) is used because of its capability of finding a global optimum without getting stuck in a local one [16]. It searches for a global optimal solution, i.e. the optimal size of the aforementioned parameters, by minimizing a cost function including the total cost of ownership (TCO) over the entire lifetime of the nanogrid parking. To do so, the algorithm uses genetics and natural selection, comparable with Darwin's theory of evolution [18].

The TCO is given by the sum of the capital expenditures and the operational expenditures. The capital expenditures include the investment cost of all the different components: PV array, battery pack, power converters, feeders and the charging infrastructure.

$$C_{\text{CAPEX}} = C_{I,\text{pv}} + C_{I,\text{bat}} + C_{I,\text{DC/DC,pv}} + C_{I,\text{DC/DC,bat}} + C_{I,\text{DC/AC}} + C_{I,\text{feeder}} + C_{I,\text{station}} \tag{5}$$

The operating expenditures include the maintenance cost of the PV array and the battery pack, the replacement cost of the battery pack, as its lifetime is considered to be lower than the one of a PV system, and the electricity cost for using the power coming from the grid. In addition, the return by letting the EV users pay to charge their car is taken into account into the operational cost:

$$C_{\text{OPEX}} = C_{M,\text{pv}} + C_{M,\text{bat}} + C_{R,\text{bat}} + C_{E,\text{grid}} - C_{E,\text{station}} \tag{6}$$

When sizing the components of the nanogrid, attention should be paid to the limitations of the installation site. In other words, the optimal solution is not the one which returns the lowest cost, but the one which returns the lowest cost while fulfilling the imposed technical and practical constraints, which are:

- The area needed for the installation of the PV array cannot exceed the allocated area.
- The volume needed for the battery pack cannot exceed the allocated space.
- The load demand should be satisfied at all times, i.e.

$$I_{\text{gen}}(t) = I_{\text{demand}}(t), \forall \text{t} \tag{7}$$

When one or more of these constraints are not met, an extra penalty cost is added to the total cost to exclude the particular solution from the optimization process.

To ensure the nanogrid parking can be operated during a whole year, sizing is performed in worst-case weather conditions. In Belgium, these conditions occur during winter, when the sun shines on average 5 hours per day at an irradiance of 400 W/m², for three days a week [19]. The average weekly load profile per charging station used to size the components is shown in Figure 2. It is considered that the demand on Monday and Friday is higher than during the other days of the week because on Friday, EV users will ask for more range to avoid charging during the weekend, and on Monday, to compensate for not having charged during the weekend.

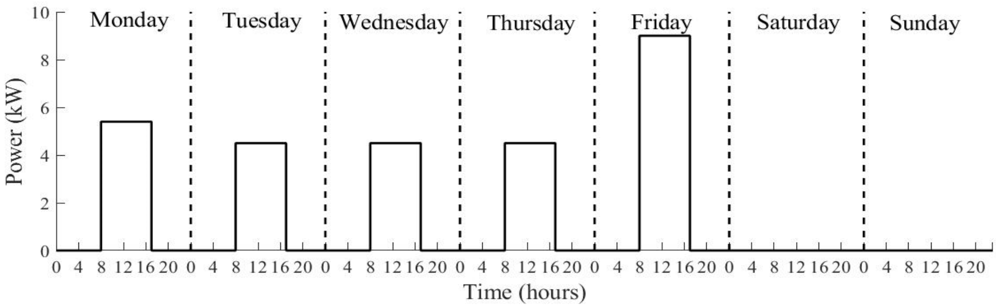

Figure 2: Average weekly load profile for one charging station.

5 Simulation results

The verification of the EMS and the sizing algorithm is done based on two use cases. The first one represents a big industrial company that has five 22 kW charging stations on its parking, but the power that the utility grid can supply is limited at the highest to 15% of the total maximum load (i.e. 17 kW). The area available to install the PV array is 1000 m², while for the battery pack there are no size limitations. The second use case represents a smaller company, with three 22 kW charging stations, that has little space to install a PV infrastructure, only 75 m² are available, and also the power demand of the building, which is considered to be 8kW, should be satisfied by the nanogrid. For this use case the utility grid can still supply power up to 75% of the maximum load (i.e. 56 kW). With these constraints the optimal size of the nanogrid was computed by the GA. The results can be seen in Table 2.

Table 2: Results of the sizing algorithm.

	Use case 1	Use case 2
Number of charging stations	5	3
Maximum load	110 kW	74 kW
Peak power PV	130 kWp	7 kWp
Capacity battery	629 kWh	389 kWh
Power from grid	12 kW	30 kW
Total cost (over 20 years)	€150 000	€220 000

First of all, it can be noticed that for both use cases the sizing result complies with the constraints. Secondly, the total cost over the entire lifetime of the nanogrid parking is extremely high. Moreover, it indicates that such a nanogrid is not profitable from the economical point of view as no profit can be made after 20 years. However, with the decreasing cost for both PV panels and Li-ion batteries, it might become an attractive solution to solve problems related to grid overloading in the future. Furthermore, it can be seen that the cost for a nanogrid parking for use case 2 is higher than for use case 1, although the size of the PV array and the battery is much smaller. This can be explained by the fact that the utility grid can provide more power, increasing the electricity bill significantly, and due to the lower amount of charging stations, which means there is less income from charging.

With the knowledge of the appropriate size of the components, the operation of the nanogrid for both use cases is studied in different weather conditions. Figure 3 shows the behavior of the nanogrid for a use case 1 during a sunny day (with a random charging load pattern).

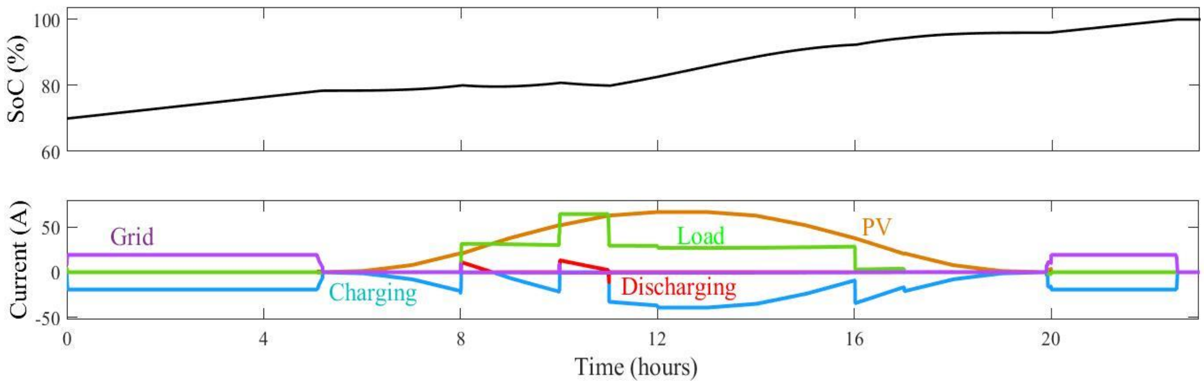

Figure 3: Simulation of a sunny day for use case 1 (top: SoC of the battery pack; bottom: current flow between the different components).

Because the battery is not fully charged at the beginning of the day, it is charged with current from the utility grid. Once the PV array produces current, the battery is charged with it, until the first EV is connected to the nanogrid parking. Then it is used to charge the EV. It can be seen that most of the time, the load demand can be satisfied with current from the PV infrastructure only. The battery is further charged with the excess current from the PV array. It happens twice that the PV production is not sufficient to satisfy the load demand. In these cases the battery pack needs to be discharged. At the end of the day, the utility grid is again used to charge the battery until it reaches a SoC of 100%.

The latter can be seen as a limitation of the EMS, because, supposing that there are two consecutive days as shown in Figure 3, the grid will provide power at night while it is not necessary as the next day excess power from the PV array can be used to charge the battery pack. To resolve this, the EMS should make decisions based on accurate weather forecasts. Another limitation that can be observed is the uncontrolled way the charging process occurs. EVs immediately start charging with a fixed constant power from the moment they are connected to the charging station. To maximize solar EV charging, the EMS should match the EV load profiles to the PV generation as closely as possible. This implies that charging should be performed at a variable charging rate [20][5].

Figure 4 shows the same use case but now for a cloudy day, meaning that the PV array produces a current that is almost not noticeable. It can be observed that for this scenario the battery is discharged from the moment a load is connected to the nanogrid. The discharge current follows the same profile as the load, which indicates that the demand can always be satisfied by the battery pack. The simulation results thus prove the correct functioning of the EMS and the sizing algorithm, as the main objective of the nanogrid, which is to satisfy the EVs' charging demand at all time, is fulfilled. However, also for this scenario, weather forecasts can improve the EMS. If, for example, there is no sunshine for a whole week, the BESS will not be able to provide power for the whole week. In this case, the EMS will need to limit the power that can be supplied to the charging stations, so that the battery pack can be used each day of the week.

The EMS can even be further improved by considering ageing of the stationary battery pack. When considering the relation between the current rate and its impact on the lifetime of the battery, it might at some point be more profitable to supply extra power from the grid, although the battery could provide it, to lengthen the lifetime of the battery pack. This requires a more complex TCO calculation.

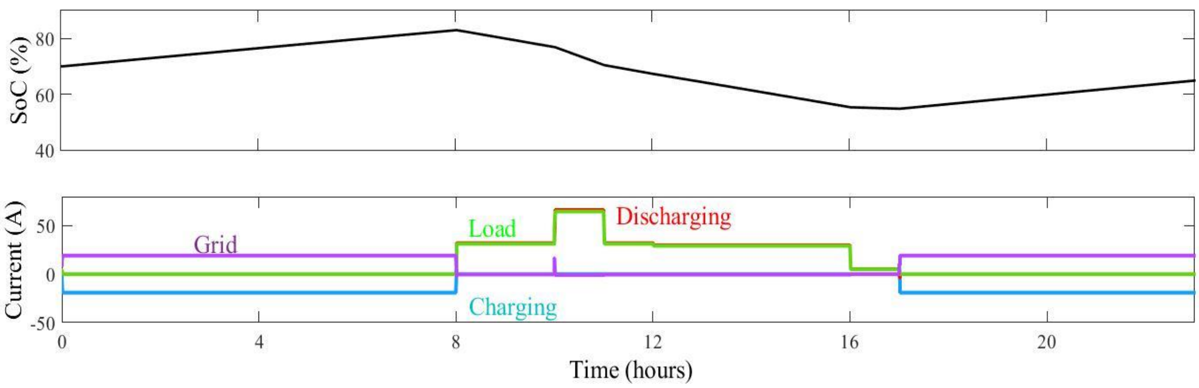

Figure 4: Simulation of a cloudy day for use case 1 (top: SoC of the battery pack; bottom: current flow between the different components).

Finally, Figure 5 shows the behavior of the nanogrid for use case 2 during a cloudy day, with the battery completely depleted at the start of the day. Because the battery is charged overnight, the SoC has considerably increased before an EV is connected to the nanogrid. However, halfway through the day, the utility grid needs to provide additional power because the battery cannot satisfy the demand on its own. Here the influence of the FLC on the battery operation can be clearly observed. The battery does not discharge anymore in a linear way, but it starts to decay in an exponential way so that it can be used for a longer time, while still being able to satisfy the load demand of the building and the charging stations so that, over the whole day, less current is needed from the utility grid.

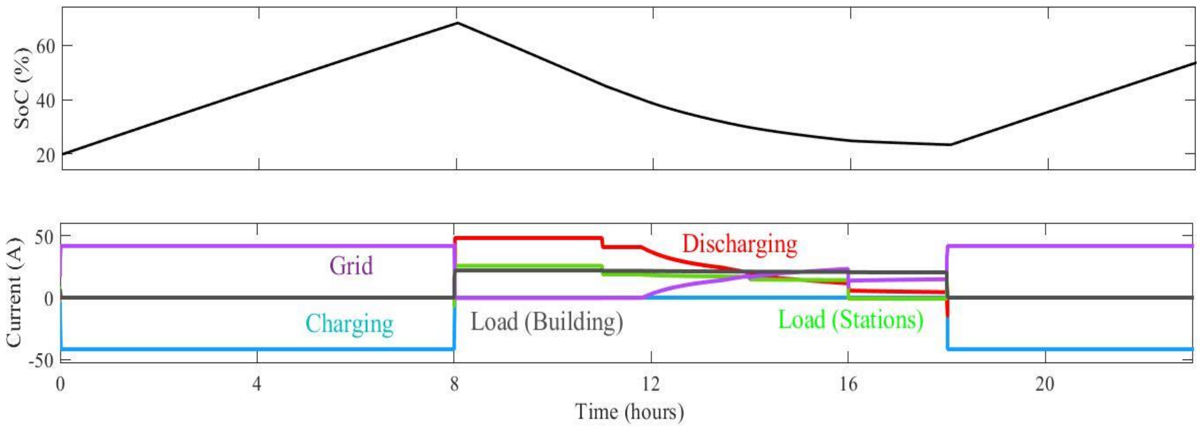

Figure 5: Simulation of a cloudy day for use case 2 (top: SoC of the battery pack; bottom: current flow between the different components).

6 Conclusions

In this paper, an EMS was developed for a nanogrid parking for EVs. Such a nanogrid consists of a PV array, a stationary BESS, a connection to the utility grid and EV charging infrastructure. It has the advantage that EVs can be charged using green energy and that it reduces the stress on the utility grid, making it possible to install more charging stations at workplaces. To satisfy a weekly demand of 250 kWh per charging station, a rule-based EMS and sizing algorithm was developed. They proved their correct behavior based on multiple simulations of two use cases. However, several improvements, like accurate weather forecasts or controlled charging, can still be made to the EMS for a more efficient and cost-effective operation.

Regarding the sizing of the components of the nanogrid it is found that for a big company with 5 AC charging stations of 22 kW, a PV array of 130 kWp, a stationary battery pack of 629 kWh and a grid connection that can provide up to 12 kW, are required to operate the nanogrid correctly under average Belgian weather conditions, assuming that the available area for installing PV panels is 1000 m^2. For smaller companies who do not have the space to install a large PV array, a battery pack of 389 kWh and a grid connection of 30 kW are sufficient to provide power to 3 charging stations and the workplace building simultaneously.

By comparing the cost of both use cases, it is found that it is more beneficial to put a bigger battery pack and a PV array than to use more power from the utility grid. However, this might change when component ageing is considered. The feasibility study has shown that a nanogrid parking lot, whatever its size, is not yet attractive from the economical point of view, as the TCO for 20 years, which is the considered lifetime of the system, is higher than €150 000. However, with the decreasing cost of both PV panels and Li-ion batteries, a nanogrid parking lot might become a potential solution for electricity problems in the near future.

Acknowledgments

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