USE OF BATTERY STORAGE SYSTEMS IN EV ULTRA-FAST CHARGING STATIONS FOR LOAD SPIKES MITIGATION

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In this paper, we propose a hybrid system consisting of ultra-fast electric vehicle charging stations and battery energy storage systems to improve the operation of the actual electrical network as an energy management strategy to support the integration of EVs ultra-fast charging stations and also for load spikes mitigation. The proposed control approach allows "flexible" EV users and battery energy storage systems to participate in demand response programs, which may play a crucial role in improving stability and efficiency of future smart grids.

Keywords: Electric vehicle, ultra-fast charging stations, storage, demand response, smart grids

1. Introduction

Electric mobility is expanding rapidly, thus the global car fleet has exceeded 7.2 million electric vehicles (EVs) [1] and is estimated to reach around 130 million EVs by 2030 [2]. Connecting a large number of EVs to the electricity grid can raise technical problems such as: the occurrence of local congestion (overloading power lines and/ or voltage problems), uncertainty about the forecast of consumption, the emission of harmonics in the network [3].

The literature includes numerous studies on the impact of EV integration in electricity networks [4-14]. In [4] a load control strategy is presented which aims to maximize the amount of energy that can be delivered to all EVs in a fixed period, taking into account the technical limitations of the network, using a linear programming method. However, the behavior of electric vehicle users is not taken into account in formulating the problem. In [5] a direct charging power control technique is developed to maximize the net energy supplied to the batteries and at the same time minimize the total energy cost, and in [6] the authors propose the coordination of EV charging, considering them as distributed energy resources to smooth the load curve. In the [12-14] EV charging coordination is analyzed in terms of congestion management in electricity distribution networks.

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2. Problem formulation

It is known that the current urban electricity distribution networks have been designed based on different criteria and therefore with the transition to electrification of several services (heating systems, public lighting, urban transport, etc.) are operated at the limit of their capacity and also the network elements (power lines, transformers, electrical equipment) and also most of the network elements have reached their service life.

The key issue for the integration of EV in the distribution network will be to manage demand or EV charging is carried out in periods of low demand or operation of renewable energy sources, such as EV peak load does not coincide with peak demand of the electricity network [15]. In this context, hybrid systems consisting of battery energy storage systems (BESS) and charging stations (CS) for EVs can facilitate the integration of a larger number of charging stations while minimizing investment in resizing existing electricity distribution networks [16]. On the other hand, it functions as a "buffer" installation that takes over the variations introduced by the growing number of EVs connected to the electricity grid.

Given the evolution in recent years in the field of electricity storage and Smart Grid technologies, is expected that the demand for electricity will have higher degrees of control. Thus, combined control and storage features will allow a reaction like as demand response (DR) strategy to the demand for electricity due to EV charging, these can be used efficiently to help develop daily operational programs of electricity networks. The concept of demand response services flexibility requires the aggregation of individual EVs in order to be considered economically and technically by distribution system operators (DSOs), to result in an advantageous load control strategy for both users of EV as well as for DSO.

The Electric Vehicle Supplier / Aggregator (EVS/A) is responsible for coordinating the charging of a large number of EVs and is therefore an intermediary between EVs, DSOs, TSOs and the electricity market, as well as a data collector. The characteristics of EVS/A are similar to those of an Energy Services Company (ESCo). EVS/A will participate in the electricity market to buy electricity, to meet user requirements. This process takes place in two stages:

- The aggregator will conclude a contract with each EV owner for the use of its battery for the provision of various services in the energy market, but also for EV charging services;
- The EV user when connecting the vehicle to the CS will transmit to the aggregator the current battery state of charge (SoC), the estimated departure time and the battery capacity. The prerequisite for EV owners to participate in this type of service is that their vehicles reach a satisfactory level of state of charge at the time of disconnection from the CS.

In this context, the objectives of implementing a charging strategy are:

1. Following an aggregate reference profile established by the DSO on the basis of consumption/ production forecasts the day before. BESS being the flexible element that depending on the technical conditions of the operation of the electricity network can consume or inject energy into the network in order to supplement part of the consumption due to EV charging.
2. Respect user preferences (the energy required and the time available for charging EVs) specified by the users when opting for participation to smart charging services.

3. Mathematical model description

EV charge control is approached by iteratively solving an optimization problem that aims to minimize an objective function *A*, which is the difference between the power transfer capacity of the grid and its total load.

The objective function is presented in equation (1):

$$[MIN]\,A = \sum_{t=1}^{T}\left[P_{ref}(t) - \sum_{j=1}^{C} P_{EV}^{j}(t) - \sum_{i=1}^{B} P_{BESS}^{i}(t)\right] \tag{1}$$

where:

$P_{ref}(t)$	is	reference power (the difference between the power transfer capacity of the grid and its base load); $P_{ref}(t) = P_{\max}^{grid} - P_{base\ load}(t)$. Where $P_{base\ load}$ represent the initial load of the network without EV and BESS load; $P_{\max}^{grid}$ is the transit capacity of the electricity network.
$P_{EV}^{j}(t)$	-	control variable of the objective function and represents the charging power at the time instant *t* for the j^{th} EV; we consider the efficiency of the converter for the charging/ discharging process of battery is constant, η = 96%;
$P_{BESS}^{i}(t)$	-	charging/discharging power of the i^{th} battery (positive values indicate that the battery is charging, and negative values indicate that the battery is discharging);
t	-	the time interval index; we consider a time interval of Δt = 15 minutes, thus resulting *T* = 96 time intervals within one day.;
j	-	the index of an electrical vehicle, with *j* = 1…*C*, where *C* is the total number of EVs;
i	-	the index of an BESS, with *b* = 1…*B*, where *B* is the total number of BESS;

I^j - the initial time of the j^{th} EV connection to the CS;

F^j - the last time interval of the charging period corresponding to departure of the j^{th} EV from the CS;

The equality and inequality constraints of mathematical model are:

- *Vehicle charging power* refers to the maximum power absorbed by an EV at time *t*:

$$P_{EV}^{j}(t) \le P_{EV,\max}^{j}; \quad \forall t, \forall j = \overline{1,C}; \tag{2}$$

where $P_{EV,\max}^{j}$ represent the maximum charging power by the j^{th} EV.

- *BESS charging/ discharging power* refers to the maximum power absorbed/ injected by an BESS at time *t*:

$$-P_{BESS,\max}^{i} \le P_{BESS}^{i}(t) \le P_{BESS,\max}^{i}; \quad \forall t, \forall i = \overline{1,B}; \tag{3}$$

where $P_{BESS,\max}^{i}$ represent the maximum absorbed/ injected power by the i^{th} BESS.

- *Reserve band*, represents the maximum power absorbed from the electrical network, by all hybrid systems at time *t*:

$$\sum_{j=1}^{C} P_{EV}^{j}(t) + \sum_{i=1}^{B} P_{BESS}^{i}(t) \le P^{reserve}(t); \quad \forall t, \forall j = \overline{1,C}, \ \forall i = \overline{1,B}; \tag{4}$$

where:

$P^{reserve}(t)$ is power grid availability for EV charging; this is represented by the difference between the maximum transit capacity of the electricity network and its total initial load at time *t*:

$P^{reserve}(t) = P_{\max}^{grid} - P_{grid}(t)$

$P_{\max}^{grid}$ - the transit capacity of the electricity network, representing the maximum power that can be delivered from the source taking into account the technical characteristics of the source node (nominal power of the transformer, cable section of the first feeder);

$P_{grid}(t)$ - the total initial load of the electrical network at time *t*, disregarding the EV charge.

- *Evolution and limits of the state of charge* of EV and BESS; this category of restrictions refers to the variation over time of the SOC and its technical limits, as follows:

- The evolution of the state of charge over time is directly proportional to the charging power according to relation (5):

$$SoC^{j}(t) = SoC^{j}(t-1) + \frac{P_{EV}^{j}(t)\cdot \Delta t}{E_{EV,nom}^{j}}\cdot \eta; \quad \forall t, \forall j = \overline{1,C}\ ; \qquad (5)$$

where:

$SoC^{j}(t)$	represent	state of charge of battery at time *t* for the *j*th EV;
$E_{EV,nom}^{j}$	-	nominal capacity of battery for the *j*th EV;
η	-	efficiency of the converter for the charging/ discharging process.

The relation (5) regarding the evolution of the state of charge of the batteries also applies in the case of BESS, considering the fact that BESS have in composition the same type of batteries as EV.

- *The initial state of charge of the EV batteries* represents the state of charge of the battery when the EV is connected to the charging station:

$$SoC^{j}(t) = SoC_{init}^{j} \qquad t = I^{j}\ ;\ \forall j = \overline{1,C}\ ; \qquad (6)$$

- *Maximum state of charge of the EV batteries*. This restriction ensures that as long as EV is connected to the CS, the SoC does not exceed the maximum value of its storage capacity:

$$SoC^{j}(t) \le SoC_{\max}^{j} \qquad \forall t, \forall j = \overline{1,C}\ ; \qquad (7)$$

- *Technical limits of the BESS state of charge*; this restriction is important in order to maintain a proper "health" of the batteries, in order to avoid their full discharge or maximum charging so as not to degrade the operating properties of the batteries. Most battery manufacturers recommend their use between 20-85% of the state of charge:

$$SoC_{\min}^{i} \le SoC^{i}(t) \le SoC_{\max}^{i}, \qquad \forall t, \forall i = \overline{1,B}\ ; \qquad (8)$$

where $SoC^{i}(t)$ represent state of charge of i^{th} *BESS* at time *t*; $SoC_{\min}^{i}$ and $SoC_{\max}^{i}$ represent the lower limit, respectively the upper limit of the state of charge for the *i*th BESS.

- *Desired/ final state of charge*, by which we ensure that the state of charge of a battery when disconnected from the CS, $SoC^{j}(t)$, is at least equal to the user's desired state of charge, $SoC_{desired}^{j}$:

$$SoC_{final}^{j}(t) \ge SoC_{desired}^{j} \qquad t = F^{j}\ ;\ \forall j = \overline{1,C}\ ; \qquad (9)$$

• *Grid capacity*, which ensures that the total power consumed at the level of the electricity network does not exceed the transit capacity of the network, in this sense avoiding the occurrence of network congestion:

$$P_{grid}(t)+\sum_{j=1}^{C}P_{EV}^{j}(t)+\sum_{i=1}^{B}P_{BESS}^{i}(t)\leq 0.9\cdot P_{\max}^{grid}; \quad \forall t\ ;\ \forall j=\overline{1,C}\ ;\forall i=\overline{1,B}; \quad (10)$$

The coefficient 0.9 has been chosen in order to maintain a transmission margin in the grid.

4. Case study

4.1. Description of the test microgrid

The case study uses the scheme of a microgrid originally presented in [17], but which has been updated in terms of distributed generation sources connected to the test microgrid (Fig. 1). The test microgrid consists of 32 nodes, connected to 218 consumers and 10 ultra-fast charging stations (with charging powers up to 150 kW) that will serve to charge 100 EVs with battery capacities between 20 and 60 kWh, respectively different connection and disconnection times. Node 0 (bus 0) represents the source node and is the connection point between the electrical distribution network and the test microgrid.

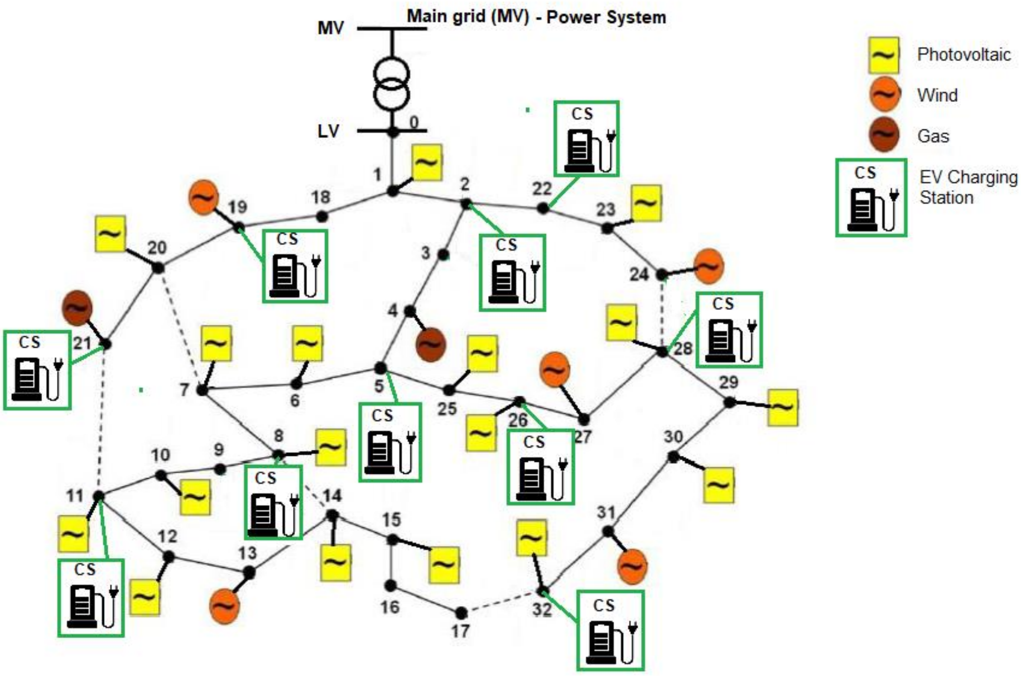

Fig. 1. The scheme microgrid (generic form)

Fig. 2 shows the consumption curve of the microgrid (average hourly consumption - blue line), but the maximum capacity of the source node, respectively the transport capacity of the first feeder between node zero and node 1 of the microgrid ($P_{\max}^{grid}$ = 8400 kW, red line). From Fig. 2 it can be seen that during the peak load (between 18:00 - 20:00) the load of the microgrid reaches and even exceeds the maximum capacity of the source node, so that any additional consumption introduced by the connection of ultra-fast charging stations would cause even more problems with congestion within the test microgrid.

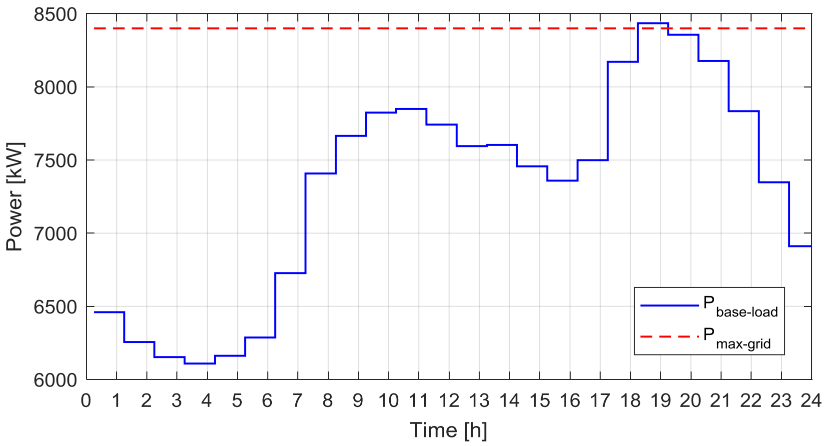

Fig. 2. Load curve of the microgrid

The following are two scenarios for the operation of the microgrid: (*i*) in the presence of charging stations without BESS and (*ii*) in the presence of charging stations with BESS (hybrid systems). These two scenarios will relate to the reference case, which is represented by the base load (initial load) of the test microgrid. In all of the scenarios is considered a smart charge strategy of EVs.

4.2. Scenario test microgrid and EV charging

The available power for EV charging is represented by the difference between the maximum capacity of the microgrid and its basic load. Fig. 3 shows the power reserve for EV charging at hourly intervals. According to Fig. 3, in the time interval 18:00 - 19:00 the available power is "negative" because the basic load of the microgrid exceeds its maximum capacity and consequently the storage systems of the hybrid systems (charging station + BESS) can store or inject additional energy into the mains to eliminate or reduce the level of congestion in the microgrid. The highest power reserve for EV charging is during the night when the basic load of the microgrid is lower and the periods with the lowest power reserve are during the morning and evening load peaks.

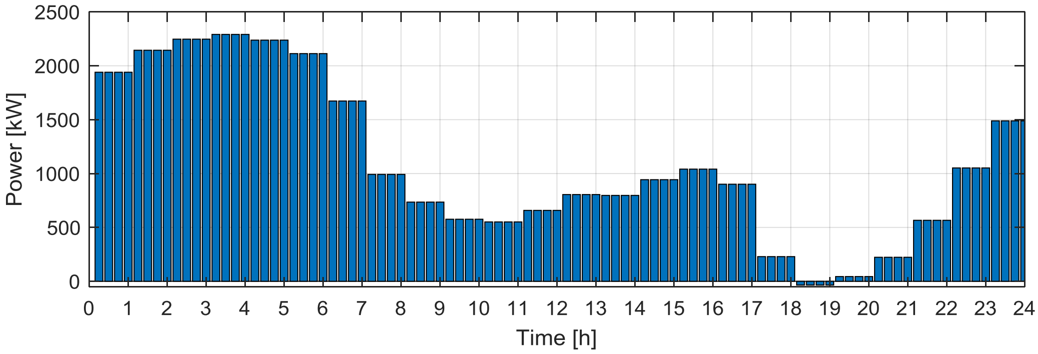

Fig. 3. Available power for EV charging

Fig. 4 shows the additional load generated by the EV load, related to the power reserve of the microgrid for EV charging. At the same time, it is observed that, both at the peak of the morning and at the peak of the evening, the connection of the EV to the microgrid in order to charge the batteries generates congestions by exceeding the reserve band of the network.

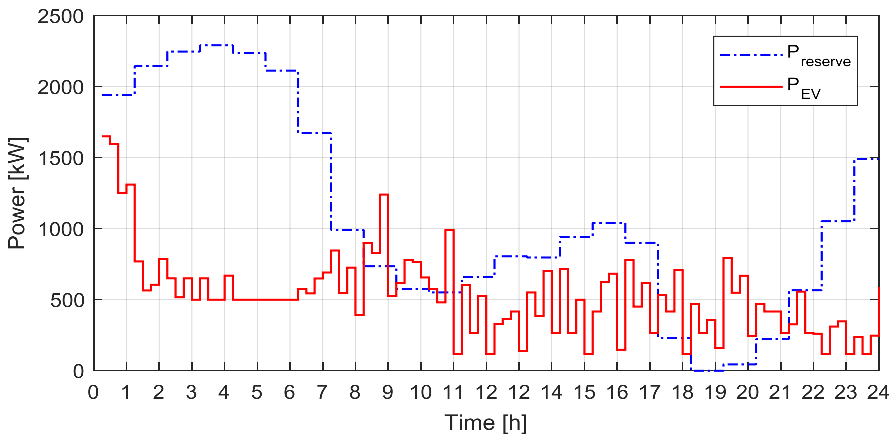

Fig. 4. EV charging demand curve versus microgrid power reserve curve

4.3. Scenario test microgrid and hybrid systems

This scenario analyzes the role and impact of BESS installed in hybrid systems in order to facilitate the integration into the electrical network of ultra-fast charging stations.

Fig. 5 shows the load curve of the hybrid systems reported to the power reserve of the microgrid. From Fig. 5 it can be seen that BESS systems can take over part of the load due to EV charging so as not to exceed the power reserve of the microgrid in any time interval during the 24h.

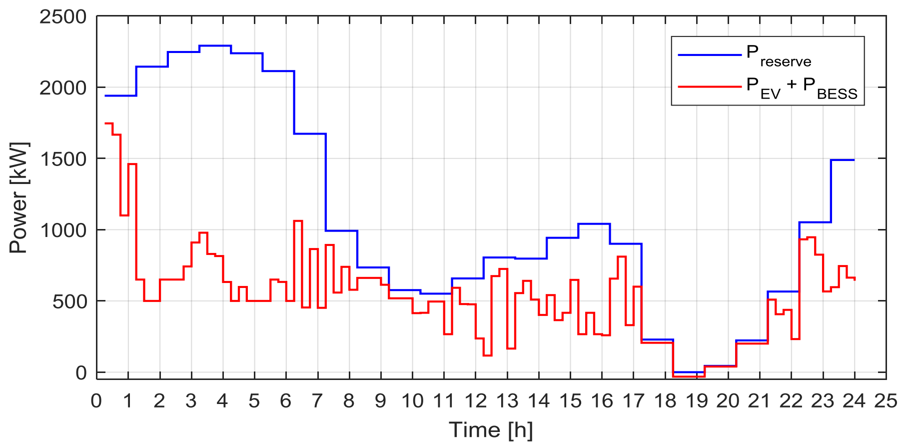

Fig. 5. Hybrid systems demand curve versus microgrid power reserve curve

Fig. 6 shows the comparison between total load curves of the scenarios presented above.

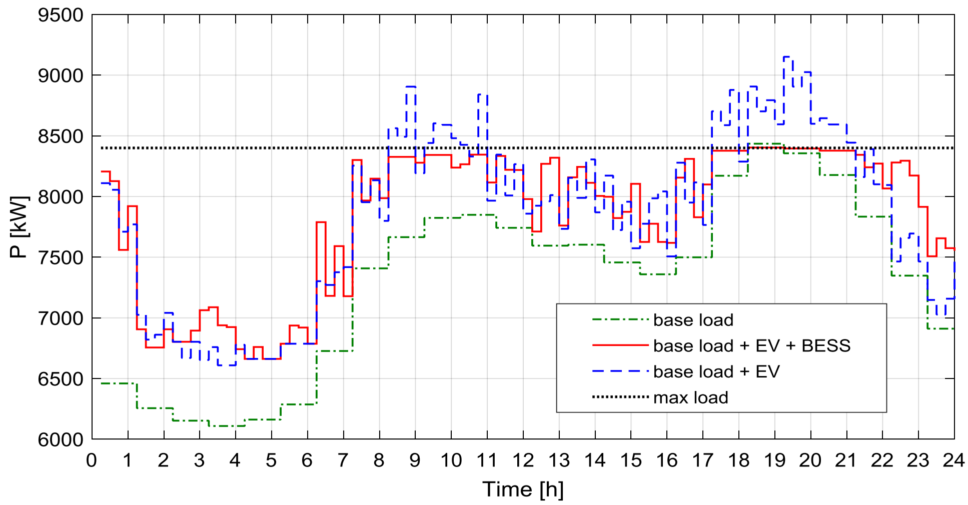

Fig. 6. Load curve of the microgrid considering EV charging, with/ without BESS

The case of connecting the 10 ultra-fast charging stations without BESS storage systems (blue line) shows that the additional load for charging EV batteries leads to exceeding the maximum allowable load of the microgrid on several occasions and for considerable time periods.

In the absence of EV charging, the maximum value of the microgrid base load was 8435 kW, in the time interval 18:00 - 19:00, and with the introduction of charging stations, respectively EV charging, the new maximum value of the load is 9151 kW, at 19:00, thus registering an increase of approximately 8.5% of the peak load.

The red line from Fig. 6, shows the load curve of the microgrid in the presence of the 10 hybrid systems (charging station with P_{max_CS} = 150 kW + BESS with P_{max_BESS} = 50 kW).

The introduction of BESS in parallel with the ultra-fast charging stations makes the total load of the microgrid no longer exceed its maximum capacity and functions as a buffer installation that takes over the variations and peaks of the extra load due to EV charging. Even more than both during the initial load peak, between 18:00 and 19:00, BESS injects energy into the microgrid and compensates for the 34 kW that exceeded the maximum allowable value of the microgrid. The aggregate curve of the 10 BESSs is shown in Fig. 7.

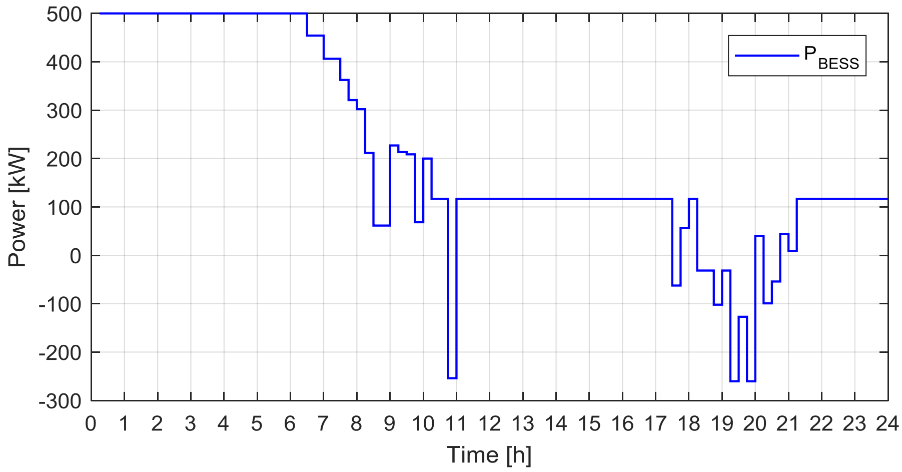

Fig. 7. Aggregated load curve of the BESS systems

According to the aggregate load curve of BESS systems, it is observed that they charge during the night, so that later during peak loads they can inject energy back into the grid, just as when an EV starts the charging session and absorbs a large power of on the network, part of this power can be compensated by the BESS system so as to avoid congestion.

Fig. 8 shows the aggregate load curve related to the EV charging. Given the random process of connecting EVs to charging stations during a day, the profile of the load curve will show large variations. All these variations that generate a number of problems of the electrical network, such as: variations of the voltage level in the network nodes , uneconomical operation of the electricity grid and generation sources because they must be dimensioned for the peak values of the total grid load, for a very large number of EVs frequency variations may occur in power systems.

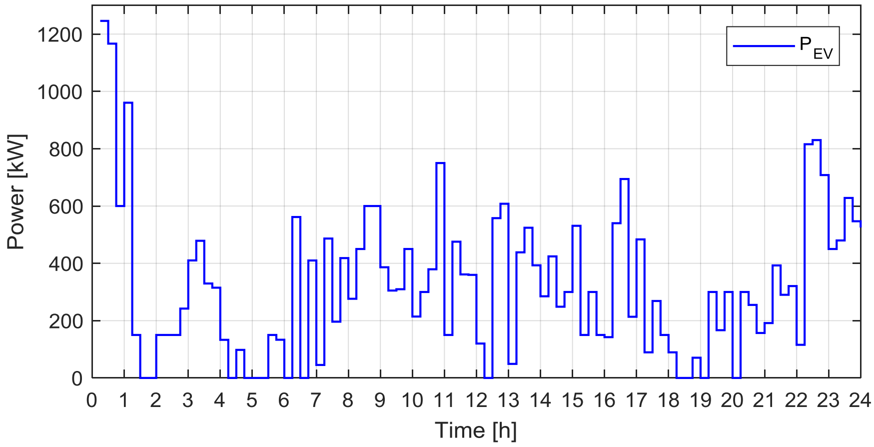

Fig. 8. Demand curve corresponding to EV charging

5. Conclusions

This paper presents an approach to the integration of ultra-fast EV charging stations into actual electricity distribution networks.

The analysis of the results shows that by using BESS in a hybrid system "charging station + BESS" allows the integration of such charging stations that need very high powers, of the order of 150 - 350 kW, respectively charging a large number of EVs without major investments are needed in modernizing and resizing the current electricity distribution networks.

In scenario without BESS, the additional load caused by EV charging generate a new peak load higher with 8.5% compared to initial peak load. By using hybrid systems with BESS, the total load of the microgrid did not exceed its transit capacity. Also, applying an intelligent EV charging strategy in collaboration with the presence of BESS, the latter represent a buffer installation that takes over the introduced power variations of connecting / disconnecting EVs from the mains, and during peak loads can inject energy back to the grid acting as a distributed energy source.

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