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Electrical architecture for ultrafast charging station

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Abstract

EVs will play an important role in transport, climate change and electrification. However, there is a consensus that one of the main obstacles to full market penetration of EVs is the so-called range anxiety (fear of not having enough charge in the vehicle). Electric vehicle charging infrastructures have two opposing approaches to their use. For urban routes, where distances travelled, and EV usage times are low, on-board alternative current (AC) chargers (Level 1 and 2) can meet the charging requirements in most situations. The solution is a gradual increase of the existing electrical infrastructure and charging points, together with the integration of new energy sources to cope with the new loads. On the other hand, on highway routes, EVs require large amount of energy in a short time in order to provide a continuous trip. Nowadays, electric charging stations provide fast charging points for vehicles by connecting external chargers that supply direct current (DC) directly to the battery bank (Level 3) and these can take up to 30 minutes. However, a time of more than 10 minutes is considered to be a very long time in contrast to the time required to fill the tank of internal combustion vehicles. In this context, ultrafast charging is defined with charging time to 10 minutes or less. This report proposes the electrical architecture of an ultrafast charging station for electric vehicles (EVs), which is based on a hybrid energy distribution system made up of an AC bus and two DC buses, each one of different voltage. The proposal is the result of a statistical analysis based on Monte Carlo simulations, which uses real traffic data and stochastic models to estimate the number of vehicles, the energy required and the time to charge each EV that would access the station. Once the architecture is established, the operating modes of the station are defined, where a storage system is contemplated to provide service reliability, and which is sized following load levelling and load shifting strategies with static and proposed dynamic charge counting methods. As a result of the report, an event simulation incorporating the operating modes and a 500 kWh storage system to serve 100 EVs has been performed, in which case 99% service was achieved even under shutoff of the grid.

Keywords: Type your keywords here, separated by semicolons ;

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1. Introduction

EVs' charging in highway routes requires absorbing a great amount of energy in short time to ensure an uninterruptible travel. Charging stations provide points of fast charging by connecting external power suppliers that deliver DC current to the vehicle battery. Standards for fast charging are pointing out to maximum power levels between 50 and 150 kW, which results in charging times between 10 to 30 minutes. In this context, ultrafast charge implies charging times less than 10 minutes, and an increase of the output power suppliers up to 350 kW. The analysis of the state-of-the-art shows that the design and implementation of ultrafast charging stations is in an incipient stage, where many alternatives are open to solve the problem. The aim of this work is to contribute to the design and sizing of an ultrafast charging station (UFCS) using real traffic data to estimate the load profile of the station.

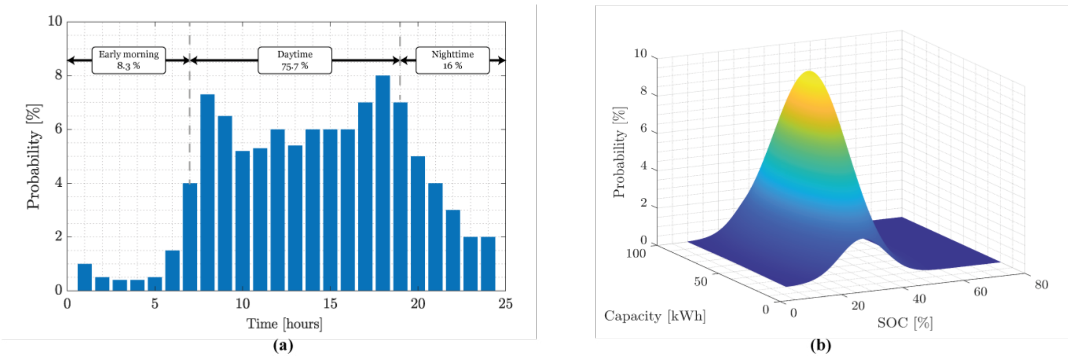
2. Load profile of station

The load profile of an UFCS can be obtained by considering stochastic assumptions regarding

- the number of vehicles accessing the station,
- the distribution of vehicles in time during a day,
- the state of charge (SOC) of the battery of each vehicle, and
- the capacity of the battery of each vehicle.

A case study corresponding to a station on the AP-7 highway in Spain connecting Tarragona and Barcelona has been considered, the traffic data having been obtained from the Spanish Ministry of Transportation, Mobility and Urban Agenda (*Ministerio de Transportes, Movilidad y Agenda Urbana* 2021). The number of EVs has been estimated from the total Spanish fleet, where in 2019 0.18 % of the total was of electric car type, this representing about 100 EVs per day. The EVs arrival time to the station has been modelled from the traffic distribution in a highway represented in Fig.1(a), in which 75% of the traffic is concentrated in the regions 8-10 a.m. and 5-7 p.m.

On the other hand, the capacity and SOC of the battery of the EVs have been characterized by means of Gaussian distributions with expected values $\mu = 62$ kWh and $\mu = 35\%$ respectively, and corresponding standard deviations $\sigma = 24$ kWh and $\sigma = 7.5\%$ as illustrated in Fig.1(b). Taking into account commercial data and charging requirements, the range 20 kWh to 100 kWh for the battery capacity and 0.2% to 50% for SOC have been considered in the analysis.



(a) (b)

Fig. 1. (a) Typical traffic distribution on a highway during a day (Hõimoja et al., 2012); (b) Gaussian variables of SOC and capacity EV battery (Li et al., 2018).

With the mentioned stochastic models, we have implemented a Montecarlo-based algorithm with the following constraints: i) no input nor output queues in the station, and ii) an unlimited number of charging points.

Besides, the following three charging protocol cases have been considered: case 1) charge with a reference of constant power of 350 kW to reach 80% of SOC, case 2) charge with a reference of variable power for a charging time of 10 minutes, case 3) similar than case 2 but with a charging time of 5 minutes. When the estimated power exceeds 350 kW in cases 2 and 3, the output power is limited, and the corresponding charging time is calculated.

Load profiles with 25, 50, 100, 200 and 300 EVs per day have been simulated, the three first values corresponding to 25, 50 and 100 % of the possible EVs circulating in AP7 highway. The 200 and 300 values are load extrapolations. For each simulation, 1000 iterations have been performed reproducing the same number of operation days of the station. Table 1 shows a summary of the simulations by illustrating the station occupation percentage according to the number of vehicles charged simultaneously in each case. Case 3 would correspond to an intermediate situation between an ideal maximum power dispatching and a process with a relatively relaxed charging time and can be used as a reference for comparative purposes. Under a low or moderate load demand, the station could work with only 4 points of ultrafast charging 99 % of the time. A supervising system could handle the queue time and ensure a continuous service due to the low probability of a higher occupation.

Table 1. Station occupancy for different charging cases.

Occupancy	**Case 1**					**Case 2**					**Case 3**				
	25	**50**	**100**	**200**	**300**	**25**	**50**	**100**	**200**	**300**	**25**	**50**	**100**	**200**	**300**
Empty	92.26	85.24	73.43	56.03	44.46	84.46	72.20	54.62	35.01	25.61	91.78	84.49	72.21	54.47	42.89
1	7.33	13.24	21.25	28.22	28.52	13.88	21.98	28.20	25.88	20.19	7.77	13.82	21.94	28.38	28.20
2	0.39	1.41	4.53	11.29	16.16	1.55	4.91	12.00	18.67	17.73	0.42	1.56	4.92	12.00	16.75
3	0.02	0.11	0.70	3.42	7.19	0.11	0.80	3.93	11.35	14.55	0.02	0.13	0.81	3.89	7.89
4	0.00	0.01	0.08	0.84	2.62	0.01	0.10	1.00	5.62	10.21	0.00	0.01	0.11	1.01	3.02
5 or more	0.00	0.00	0.01	0.20	1.05	0.00	0.01	0.25	3.47	11.71	0.00	0.00	0.01	0.25	1.25

Taking into account the simulation results and limiting the station with 4 points of ultrafast charge, an electrical architecture for the charging station is proposed (D. Zambrano-Prada et al, 2021) based on an AC bus plus two DC buses as illustrated in Fig. 2.

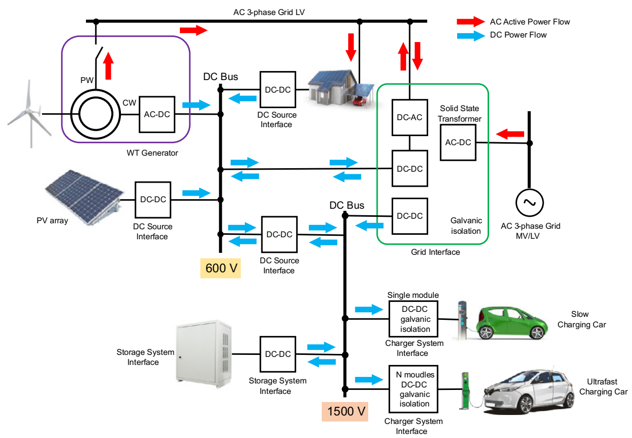


Fig. 2. Electrical architecture for UFCS.

- The solid-state transformer (SST) is the interface between the medium voltage (MV) AC grid and each of the three buses of the charging station. In a clear-cut contrast with a classical low-frequency magnetic transformer, the SST increases the power density and improves the system's efficiency.
- The energy storage system (ESS) is used to ensure the peak of demand of the charging points of 1.5 MW, which is constrained by a maximum value of the MV AC grid supply of 630 kVA. Besides, the ESS gives flexibility to the energy management and economic viability to the station.

- The 1500 V DC bus is devoted to the charge of the EV limiting the maximum current to 1000 A. This high voltage allows the reduction of the number of modules in the charging points using dc-to-dc switching converters of voltage step–down nature that allow high levels of output current. The ESS is located in this bus for the direct flux of power.
- The 600 V bus works as an intermediate element in the power flux between the 1500 V bus and the low voltage AC network. The renewable energy generators are located here.

3. Operating modes

Table 2 summarizes the seven operating modes considered in the UFCS according to the proposed architecture. The modes reflect the power flux distribution within the 1500 V DC bus regarding the AC grid, ESS, and charging points as expressed in equation (1), in which P_{grid} is the power supplied by the AC grid, P_{ESS} is the power delivered by the ESS and P_{EV} is the power demanded by the EVs charge. Thus, a representative equation defining the current state in the station is associated for each operating mode in Table 2.

$$P_{grid} + P_{ESS} = P_{EV} \quad (1)$$

Note that in grid-tied operation, the ESS will only provide the necessary power when the AC grid cannot satisfy the upper bound of the charging demand defined by the maximum available power of the grid $|P_{grid\,max}|$. In standby, ESS will work in continuous charging state supplying $|P_{ESS\,charging}|$ until SOC reaches a value of 90%.

In the different operating modes of islanding, the ESS will charge the EVs until a SOC less or equal than 40% is attained, in which case it will dispatch the corresponding energy to the vehicles in charge at this moment, but it will be subsequently disconnected from the service, and it won't be reconnected until a new source of energy enters into the system and the recharging of the ESS starts. A trade-off between the way of use and the life cycle in lithium batteries has established the operating range of the ESS. Also, the ESS maximum usable power $|P_{ESS\,max}|$. has been defined as the limit of the discharging power.

Table 2. Modes of operation for UFCS.

Mode	Description	Representative equation
	Grid-tied operation	$P_{grid} > 0$
Direct loading	The power required to charge the EVs is only supplied by the grid. The remaining energy can be used to recharge the ESS.	$P_{grid} = P_{EV} + \lvert P_{ESS\,charging}\rvert$
Complementary loading	The maximum power delivered by the grid is reached. The power flow is shared between the grid and the ESS. Hence, both elements supply the required power together.	$P_{ESS} = P_{EV} - \lvert P_{grid\,max}\rvert$ $SOC_{ESS} > 0.4$
Limited loading	The maximum combined power between the grid and the ESS is reached. In this situation the charging points are limited by the value of the deliverable power.	$P_{EV} = \lvert P_{grid\,max}\rvert. + \lvert P_{ESS\,max}\rvert$
Standby	In the absence of power demand, the batteries are charged waiting for service.	$P_{grid} = \lvert P_{ESS\,charging}\rvert$ $SOC_{ESS} < 0.9$
	Islanded operation	$P_{grid} = 0$
Autonomous	There is no reliability in the grid. The power demand is supplied by the ESS. The maximum output power is limited to the maximum power delivery of the ESS.	$P_{ESS} = P_{EV}$
Burnout stage	There will be no service availability for any vehicle arrival because the available energy in the ESS is running out.	$SOC_{ESS} \leq 0.4$
Disconnection	After the UFCS enters in Burnout mode and the last EV has been dispatched, no service is provided until the grid is active again.	$P_{EV} = 0$

4. Energy management system

4.1. Energy management strategies

Fig. 3 interprets the EVs battery model according to the required energy to reach a SOC value of 80% from the arrival SOC value. For 100 EVs, the station will require an energy level of 2.8 MWh in a day course, this calculation being based on the average value of the energy shown in the figure. This implies that each vehicle increases in 1.16 kW the daily power consumption.

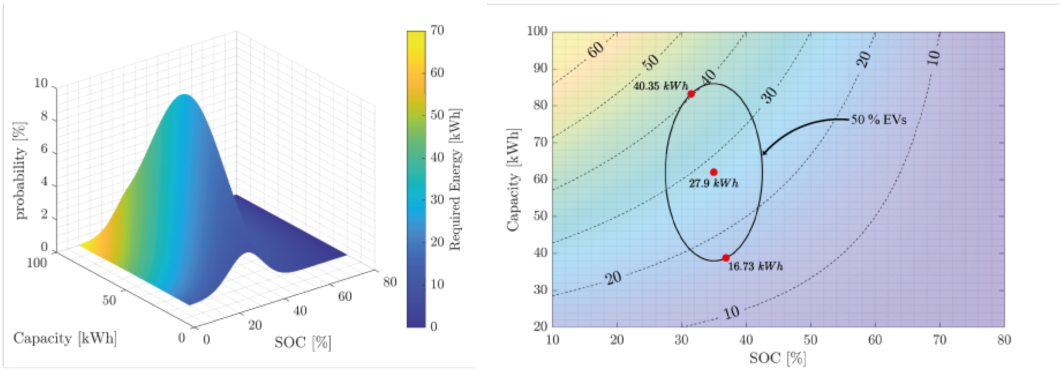


Fig. 3. Required energy to attain 80 % SOC in the EV battery.

All the energy consumed by the station will be eventually supplied by the grid but the power flow between the ESS and the grid to cover the demand is not constant and depends on the technical and economic constraints of the station. The adopted method for energy management will establish the ESS dimensions and its optimal levels for charge/discharge. Assuming that the effective capacity is that of capacity of the ESS included in the operating range, e.g., between 40 and 90% of SOC, a high autonomy level of the station would correspond to an effective capacity of 2.8 MWh and a maximum discharging power of 1.5 MW.

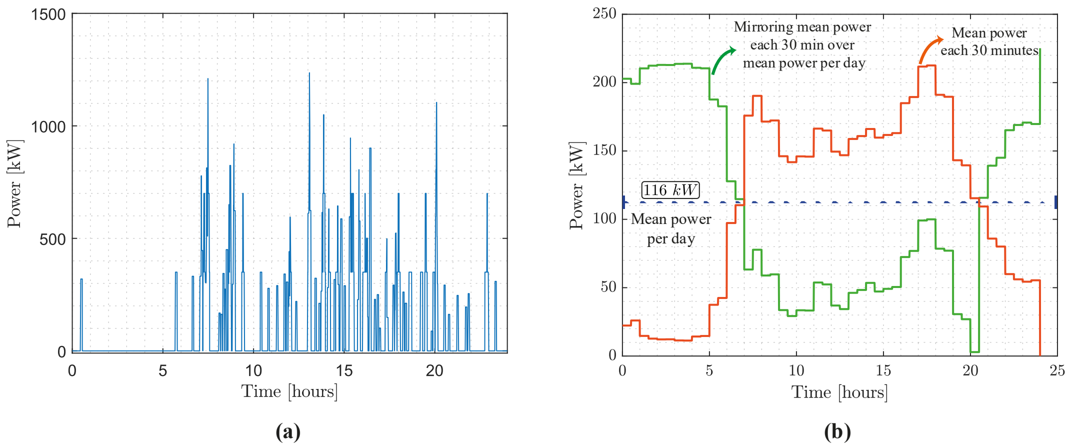


Fig. 4. (a) Demanded daily power profile of 100 EVs predicted by Montecarlo simulation; (b) Average consume profile for 1000 days predicted by Montecarlo simulation.

Fig. 4(a) shows the demanded power profile by the four charging points during one operating day following the charging protocol in case 3, which allows knowing the power distribution in the charging events. Fig. 4(b) presents three curves of average consumption, i.e., the total daily average demand (blue), the mobile average each 30 minutes (red) and a mirroring curve of the average with respect to the daily average (green). The simulation has used 1000 profiles to obtain the average values of the demand. From the curves in Fig. 4(b), three strategies for energy management can be established:

(i) **Load leveling at constant power:** A constant and continuous power consumption is established for $|P_{ESS\ charging}|$ equal to 116 kW for the operating modes connected to the grid.
(ii) **Load leveling at average power:** The value of $|P_{ESS\ charging}|$ is limited to the average consumption profile each 30 minutes in the operating modes connected to the grid. The battery supplies and absorbs more power in the grid consumption peak hours.
(iii) **Load shifting:** The ESS charge is carried out in the station low traffic hours and is then supplied during the peaks of demand relieving the pressure on the grid.

In the three cases, $|P_{grid\ max}|$ =600 kW and $|P_{ESS\ max}|$=800 kW.

4.2. Sizing of the ESS

Assuming the demand curves of Fig. 4(b) as the average power supplied by the grid during the station operation, a value of the ESS capacity can be obtained by integrating the difference between the power demand profile in Fig. 4a and the average power. The method only establishes the static capacity or reserve of the total energy and does not reflect the ESS charging/discharging dynamics. As compensation, Fig. 5 shows the ESS charging/discharging dynamics along one operating day for the three proposed strategies assuming an infinite capacity. Thus, the ESS capacity can be calculated as the range between the maximum absorption value and the maximum supply value, i.e., the difference between the maximum and minimum value of each curve in Fig. 5. Table 3 summarizes the resulting average value of the ESS capacity after having applied the respective static and dynamic approaches to 1000 simulated days.

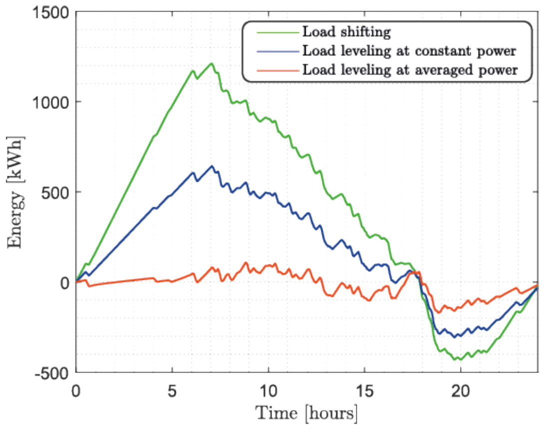


Figure 5. ESS charging /discharging dynamics during one operating day for different energy management strategies.

Table 3. Energy capacity of the ESS for the three energy management strategies and two calculation approaches.

Energy management strategy	Calculation approach	
	Static [kWh]	*Dynamic* [kWh]
Load levelling at constant power	3.100	1.220
Load levelling at average power	2.500	500
Load shifting	3.800	2.350

4.3. Event simulation

To summarize the above features, Fig. 6 illustrates a simulation of one working day of the UFCS, where the control of the operating modes described in Section 3 is implemented with the charging protocol of case 3. An initial value of 50% SOC and 500 kWh capacity are assumed, the latter value being calculated by means of the load leveling at average power method described in the previous section.

In addition, a simple algorithm has been implemented to manage the service queues and the occupancy of the charging points. It prioritizes the order of arrival to the station and allows the supply of power demanded by the client provided that the level of power is available. In cases of unpredicted variations in the station available power, the power to deliver to the connected vehicles is automatically recalculated to distribute among them the real available power. In case of absence of energy for more than 10 minutes, the service is finished off.

To simulate the human interaction, an additional occupancy time of 1 minute and a half has been considered to take into account the manual connection and disconnection of the car for input and output of the station, respectively. In case that an entering car find the station in complete occupancy situation, it has to wait up to 10 minutes and leave the station after this lapse of time if no service is provided. This also happens if the charging time is higher than 30 minutes after having recalculated the dispatching power to the vehicle.

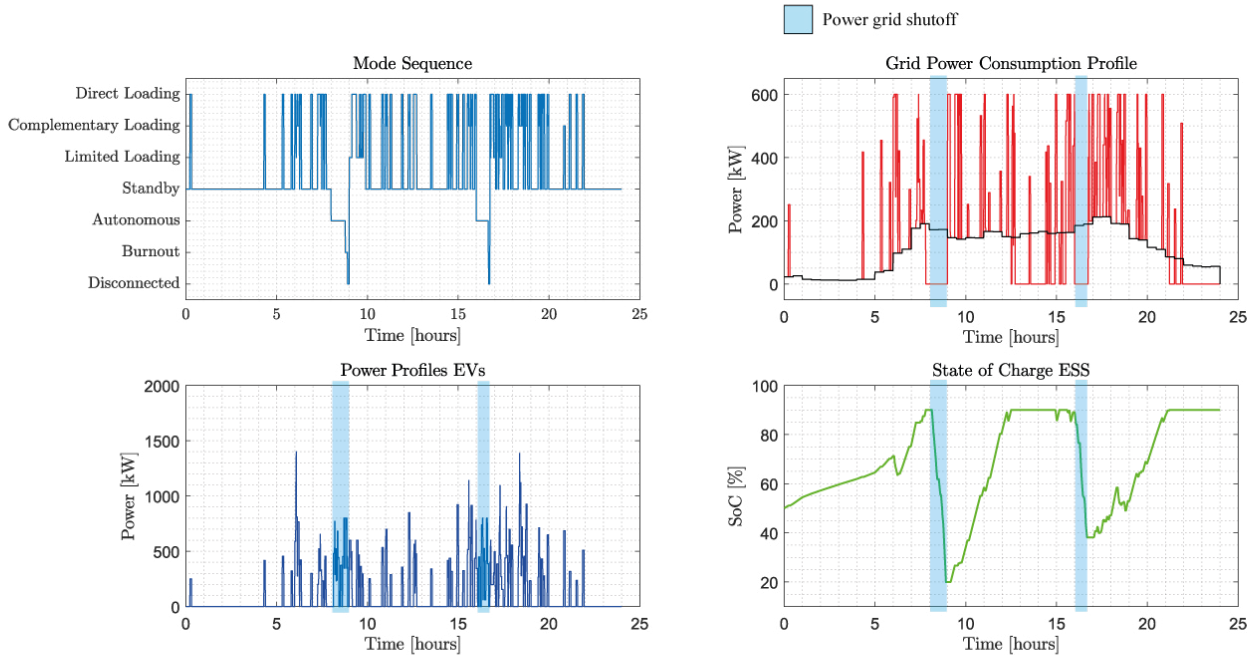


Fig. 6. Simulation of a daily demand of UFC points with two shutoffs of grid.

Two grid shutoffs of 45 and 30 minutes respectively have been considered in the simulation in order to observe the operating modes, the transition among them and the power and SOC progress along a day as illustrated in the subfigures of Fig. 6. The shutoffs can be identified by two blue rectangles in three subfigures. The power illustration shows the grid power consumption on the one hand and the power demand of the charging point on the other hand. Besides, it can be observed the rapid decrease of SOC during the two shutoffs.

In spite of the unpredictable events, only one vehicle cannot attaint a complete charge in our simulation because it has to wait more than 30 minutes. The battery works within its usable range and the total energy supplied by the grid to the station is 3.2 MWh, i.e., 0.4 MWh above the expected average value.

5. Conclusions

The work here reported has presented a procedure to define the electrical architecture of a UFCS considering as a case study a charging station located in the AP-7 highway between Tarragona and Barcelona, Spain. A Montecarlo simulation has been performed based on stochastic models of the capacity of the vehicle's battery and their SOCs together with real data of the highway traffic. The simulation has estimated the possible charging profiles of the station and predicted its degree of occupancy. It has shown that 4 points of ultrafast charging are sufficient to cover a power demand of up to 300 EV per day with an output power limited to 1.5 MW. In terms of demanded energy and average daily power, it has been estimated that each vehicle represents a consumption increment of 28 kWh and 1.2 kW, respectively.

The proposed electrical architecture uses three buses namely, an AC bus of 230/400 V and two DC buses of 600 V and 1500 V, the latter being the current supplier in the charging points. The value of 1500 V has been established to keep the total output current below 1000 A. Seven operating modes have been defined, which take into account both grid connection and islanding, their main goal being a versatile supervision irrespective of the primary energy source conditions.

On the other hand, the ESS capacity has a strong dependence on the energy management system. Two main management techniques have been considered, i.e., leveling and load shifting. The leveling approach distributes proportionally the demanded energy of the charging points between the grid and the ESS. Conversely, the load shifting uses the low demand hours to recharge the ESS and dispatch the demanded power in higher demand hours reducing then the use of the grid. In principle, the leveling approach requires lower capacity levels in the ESS at the expense of a continuous use of the grid. In addition, a calculation of the ESS capacity based on the charge/discharge dynamics has been explored, which results in up to 1/5 value reduction with respect to that obtained by means of charge counting calculation.

The simulation has also verified the operating modes of the station and the transition among them. It has also proved the correct operation of a leveling–based energy management for a 500 kWh ESS and 5 minutes charge resulting in 99% occupancy and a complete range of charge/discharge of the ESS even in the case of two electricity shutoffs.

Acknowledgements

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