Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2022) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

Transport Research Arena (TRA) Conference

Development of Smart Charging Scheduling and Power Management Strategy of a PV-ESS based Scalable EV Charging Station

Shahid Jaman[a,b], Boud Verbrugge[a,b], Assel Zhaksylyk[a,b], Thomas Geury[a,b], Mohamed El Baghdadi[a,b], Omar Hegazy[a,b]*

[a]*MOBI-EPOWERS Research Group/ ETEC Department, Vrije Universiteit Brussel (VUB),1050 Brussel, Belgium*
[b]*Flanders Make, 3001 Leuven, Belgium*

Abstract

This paper describes smart power management and charging scheduling strategy for a multiple port electric vehicle (EV) charging station, connected to battery storage systems and renewable energy sources. The charging station can charge different types of EVs, like electric scooters and passenger cars at different power levels. The energy management optimizes the usage of the power sources to fulfill the charging demand by analyzing the overall load demand, the electricity tariff, and the information provided by the EV user. The station's control system is set up to satisfy the charging demand primarily with a solar photovoltaic (PV) array and an energy storage system (ESS) as a battery. In the case of PV power generation and battery power shortage, it draws power from the grid to fulfill the charging demand. Additionally, a charging scheduling strategy is described in this paper in which the charging current setpoint for each charger is estimated by an optimization process in the local charger controller. The overall system management and charging scheduling are simulated and verified in the MATLAB/Simulink environment.

Keywords: electric vehicle (EV), power management, smart charging scheduling, modular, scalable, PV, ESS;

1. Introduction

Electric vehicles (EVs) are becoming increasingly popular due to their ability to reduce global pollution and are thus seen as the best alternative to traditional internal combustion engines. The price, driving range, and charging time are the key challenges for potential EV customers [1][2]. Automobile manufacturers are boosting battery capacity to address the issue of range anxiety. Thus, EV charging power also rises to keep charging times within acceptable

* Corresponding author: Omar Hegazy. Tel.: +32-488-819954
E-mail address: omar.hegazy@vub.be

Peer-review under responsibility of the scientific committee of the Transport Research Arena (TRA) Conference

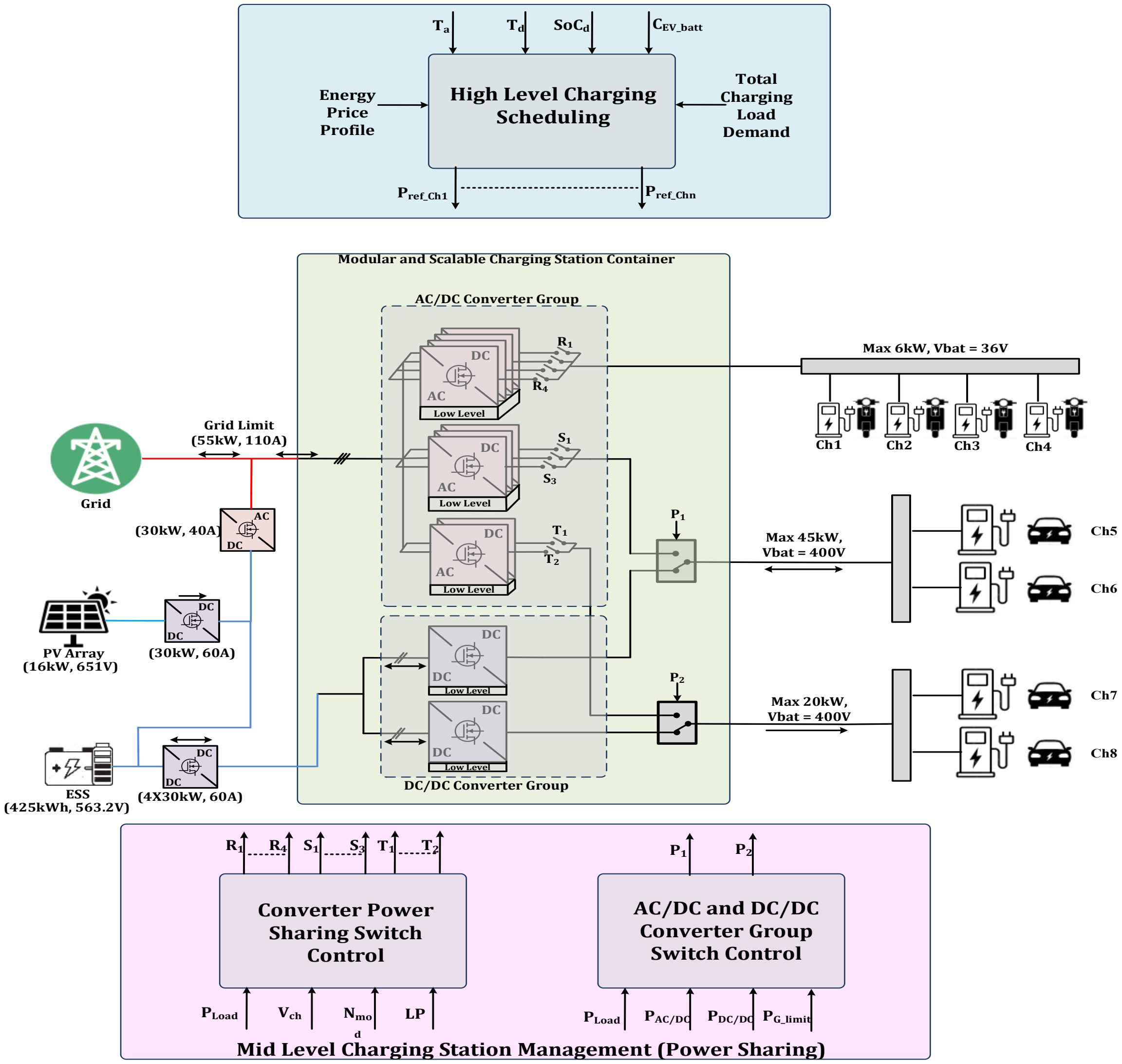

Fig. 1: High power modular and scalable charging station layout concept with multilevel charging station management.

bounds which prompted the industry to develop rapid charging systems (50kW and greater) [3]. The industrial developments also highlight the necessity to increase the power of the fast-charging system (FCS) to reduce the charging duration. For example, Siemens proposed a 150kW charger [4], ABB announced a 350-kW charger in 2018 [5], and Enercon a 600-kW charger [6]. Since the charging capacity is increasing, it is not a feasible solution to build such a high-power EV charging solution with a single power electronic (PE) module. The modular and scalable charging station is one strategy to provide such high charging power conveniently. Modularity means multiple PE converters are combined to provide the necessary charging power. Nevertheless, such a high-power modular charging system may face several serious challenges. First, it requires high initial investment costs [7, 8] because the installation works involve upgrades in the power infrastructure such as the introduction of new transmission and distribution lines. Although the total cost of ownership (TCO) of fast charging equipment is about 5 times higher than that of conventional chargers, its return on investment is, in many cases, faster, since it allows to serve more vehicles a day. Another key challenge is the poor quality of FCS's impact on the voltage stability of the distribution network [9–11]. This system can cause, in fact, voltage fluctuations and flickers, which, however, can be almost completely mitigated with the use of both smart charging algorithms and on-site distributed energy resources [11]. In this paper, a smart energy management strategy and charging scheduling are described and simulated in MATLAB/Simulink. In this strategy, the rule-based mid-level power management selects the energy source to charge the EVs. Some magnetic contactors are responsible to connect the modular EV charger to the energy source. On the other hand, charging schedule is also discussed to optimize the charging cost for the charger's user.

2. Smart Power Management for Scalable High Power Charging Station

2.1. Scalable High Power Charging Station Description

A high-power modular and scalable charging station is depicted in Fig.1. Each EV charging port is connected to modular and scalable power converters. The charging station can serve 150kW charging power for different types of the electric vehicle. In this work, we considered 3 categories of charging ports. The one category consists of 4 charging ports for light electric

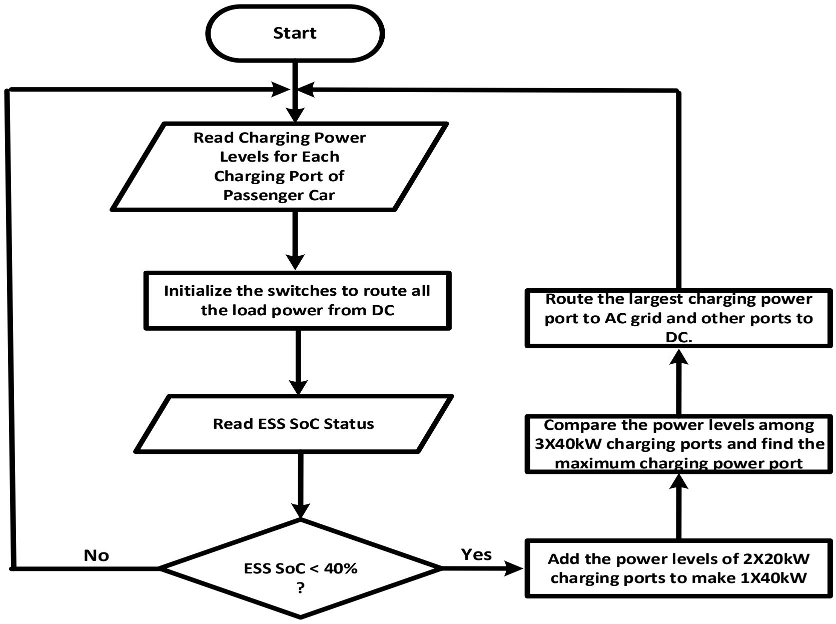

Fig. 2: Power flow switching algorithm between AC grid and DC supply

vehicles (LEVs) and each charging port rated 1.5kW. These charging ports are supplied by 4 different AC/DC converters. When multiple LEVs connect to the charging ports, a dedicated module management strategy allows activating the required AC/DC power converter module to fulfill the charging demand. Similarly, 2 charging ports with V2G facility (15kW each) and 2 unidirectional charging ports (10kW each) are considered for passenger cars. All charging ports are supplied either by a group of AC/DC converters or by a group of DC/DC converters. The mid-level management strategy coordinates all the PE converter groups during the charging process.

The modular and scalable charging station is developed in MATLAB/Simulink to simulate the charging station operation and mid-level management strategy. In this work, 3 modular AC/DC groups are considered to supply the charging ports. Group 1 consists of 4 AC/DC modules (each rated power 1.5kW) connected to the charging port of a light electric vehicle (LEV) to fulfill a charging demand up to 6kW. Additionally, two other AC/DC converter groups which consist of 3 and 2 modules (rated power 15kW and 10kW respectively) are responsible for fulfilling the charging demand of passenger cars up to 45kW and 20kW respectively. The output voltage levels of the AC/DC converter for passenger cars are 500Vdc and 36Vdc for LEVs. The DC/DC converters are also used to supply the charging port with power from solar photovoltaic (PV) panels and energy storage systems (ESSs) when a grid limitation is applied. A magnetic contactor switch model is controlled by a mid-level management strategy to switch between the AC/DC and DC/DC converter groups. There are 3 different charging load profiles with a maximum 45kW, 20kW and 6kW considered during the simulation of the charging station operation. A 16kW, 651V solar PV array is modeled to charge the ESS during daylight. A 425kWh, 563.2V ESS is implemented by using the LFP battery stack specification which is mentioned in Table 1. The solar module specification is also shown in Table 1 below:

Table 1: Solar PV and Energy Storage System (ESS) Specification

Solar PV Array Specification			**ESS Stack Specification**		
Parameter	**Value**	**Unit**	**Parameter**	**Value**	**Unit**
Model	Sundragon i250-60P		Battery Type	LFP	
Maximum Power Output	250	W	Cell Capacity	250	Ah
Open Circuit Voltage	37.3	V	Energy	141	kWh
Short Circuit Current	8.5	A	Nominal Voltage	563.2	V
Voltage @ MPP	31.1	V	Minimum Voltage	492.8	V
Current @ MPP	8.03	A	Maximum Voltage	633.6	V
Panel Area	1632*995	mm^2			
Cell Type	Polycrystalline Si				
Cell Size	156*156	mm^2			
Operating Temperature	-40 to +85	°C			

2.2. Mid-Level Management Strategy

The mid-level management allows power-sharing among the modules during charging. More specifically, if the charging power demand exceeds the rated power of the converter, this management activates another power converter module to fulfill the power demand. This strategy works based on a dynamic resource allocation technique. The total requested current is calculated as a sum of the reference d-axis currents received from all modules in the system. Based on the total requested current, and the current rating per module, the system calculates how many modules need to be active by using Eq. 1.

$$N_{active} = \frac{I_{d\,tot}^{*}}{I_d^{rated}} \tag{1}$$

Then, based on its logical position, the module identifies if it needs to be active. If the system is to stay active, it calculates its reference d-axis current by dividing the voltage loop PI's output I_{dtot}^* by the number of active modules as given in Eq. 2.

$$I_d^* = \frac{I_{d\,tot}^{*}}{N_{active}} \tag{2}$$

This equation considers that all modules are rated equally [12]. This logic enables equal current sharing and allows the system to adjust to varying loads and only keep the necessary number of modules active. This improves the efficiency in systems with a variable load like EV charging. There is also a management strategy shown in Fig. 2 above that allows the switching between the AC/DC and DC/DC group by controlling P_1 and P_2 during charging based on the total charging demand (kW), the total AC/DC converter power ($P_{AC/DC}$), the total DC/DC converter power ($P_{DC/DC}$) and the ESS state of charge status (%SoC). This approach sets P_1 either to 1 or 0. If $P_1 = 0$, it means that the switch routes the power from the AC/DC converter group to the charger, and if the reverse ($P_1 = 1$) happens, then the charging port is connected to DC/DC group.

2.3. High-Level Management and Charging Scheduling

The detailed discussion of high-level management strategy is out of focus for this paper. However, we used the genetic algorithm (GA) to generate the current set points for each charging port by optimizing the charging cost. The high-level management system for 50kW based on a genetic algorithm (GA) is described in [13]. This is an evolutionary optimization technique that uses the principles of natural selection of a population, such as a crossover and mutation, to obtain an optimal solution for a mathematical problem [14]. It is employed in the management strategy because it can deal with multiple variables at once and quickly find near-optimal solutions [15]. The GA aims to minimize the charging cost for the EV operator while satisfying the requirements and constraints of the EV and grid operators. The decision variables are the level of the charging current at each time interval in which the charging process is divided. The latter is done based on the available information of the dynamic electricity price (which is likely to be introduced with the increasing penetration of RERs into the distribution grid) and the load profile of the grid.

3. Results and Discussions

The EV driver sends a charging request to the charging station via a mobile app. The high-level management system takes the EV user information as an input to estimate the optimal current demand. To simulate the high-level charging scheduling, the user information shown in Table 2 is considered

Table 2: EV user information for charging facility

	Arrival Time	Depart. Time	Initial SoC (%)	Charging Period (h)
EV1: LEV1	2am	14pm	64%	13
EV2: LEV2	2am	14pm	29%	13
EV3 LEV3	11am	23pm	55%	13
EV4: LEV4	13pm	24am	50%	12
EV5: PC1	18pm	24am	77%	7
EV6: PC2	12pm	24am	16%	13
EV7: PC3	8am	20pm	48%	13
EV8: PC4	13pm	24am	6%	12
EV9: PC5	10am	13pm	43%	13
EV10: PC6	5am	17pm	67%	13

*LEV: Light Electric Vehicle, *PC: Passenger Car

The high-level management strategy generates the charging current reference by optimizing the charging cost. The system schedules the charging process of each EV between the arrival and departure time of the EV user including charging and V2G facility. In this work, a multiport charging station is considered, as shown in Fig. 1, with an average charging demand of around 150kW. Moreover, the EV battery capacity is 16kWh considered 100% state-of-charge (SoC) with a voltage of 500V for passenger cars and 36V for LEV, and 90% SoC is considered fully charged. It is assumed that the 10 EV is performed charging in the different time frames, each with a maximum charging rate of 1.5kW, 20kW, and 40kW including V2G services. To schedule the charging profile, a linear energy cost model is implemented. The charging scheduler tries to schedule the charging facility by minimizing the charging service cost. Therefore, a smart EV charging scheduler allows the charging from the grid at a lower energy tariff than conventional scheduler which is shown in Fig. 3 below.

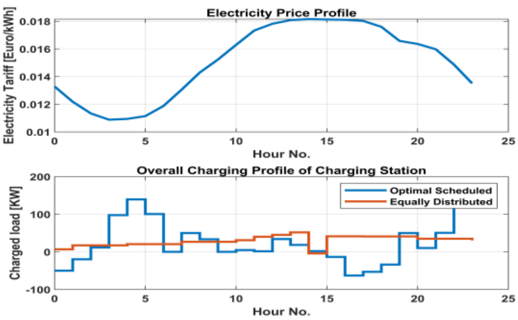

Fig. 3: Charging station load with electricity tariff.

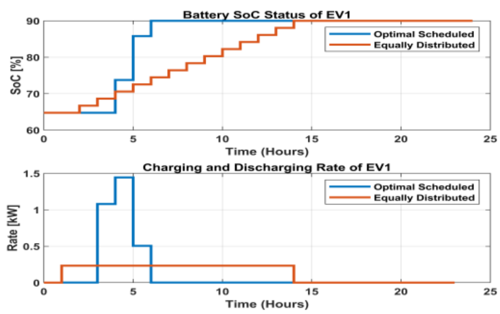

Fig. 4: Charging rate of LEV1 with SoC status.

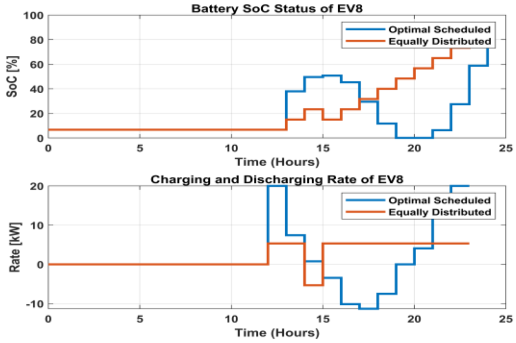

Fig. 5: Charging rate of passenger car 4 with SoC status including V2G.

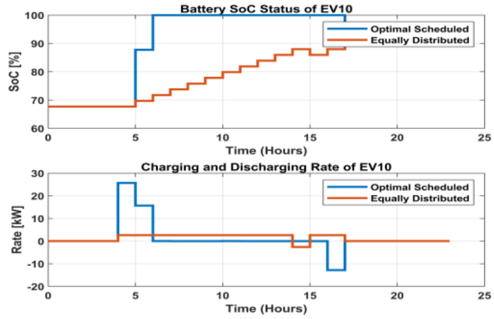

Fig. 6: Charging rate of passenger car 6 with SoC status including V2G.

In Fig. 4, the LEVs are using a high charging rate and they are fully charged within 4h with optimal scheduling. Moreover, the optimal scheduler allows the passenger cars to charge and discharge within the requested time frame to optimize the charging cost as shown in Fig. 5 and Fig. 6. The high-level management strategy can schedule fast charging because of the mid-level management which activates the modular power-sharing. When high power charging is scheduled, multiple power converters are activated to fulfill the high charging demand. For example, each LEV charging port has a maximum power rating of 1.5kW. The mid-level management strategy can combine 2 modular power converters when an LEV demands a charging power of 3kW. A similar strategy is valid for passenger cars. Fig. 7 and Fig. 8 depict the modular power converter activation to respond to the corresponding charging demand.

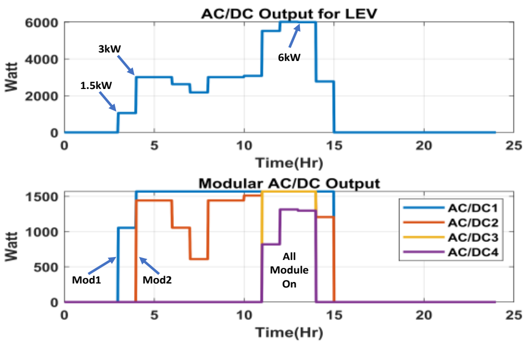

Fig. 7: 6kW modular AC/DC converter power-sharing for LEV.

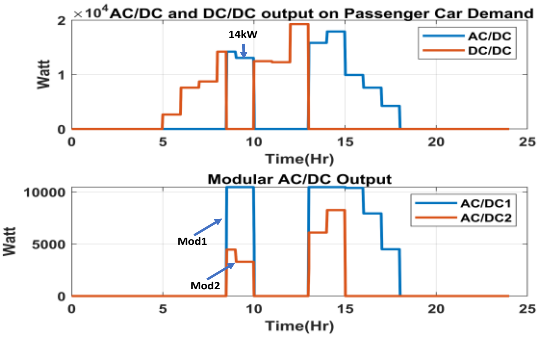

Fig. 8: 20kW modular AC/DC converter power-sharing for a passenger car.

Since the charging station site has a grid limitation of 55kW, the charging station is not able to provide charging power from the grid all the time. When the overall charging demand is greater than 55kW, the mid-level management strategy provides some charging power from the PV-ESS system by switching the P_1 and P_2 switches. The mid-level management strategy thus decides if the charging power flow comes either from the PV-ESS system or from the grid, depending on the grid availability, the produced PV power and the ESS SoC Status. The switching between the AC/DC and DC/DC converter groups for 40kW and 20kW charging demand is shown in Fig. 9 and Fig. 10. The ESS voltage, SoC status, and solar power are shown in Fig. 11. It is noticeable that the ESS supply the charging load during the day between 5.00 am – 10.00 am. However, the grid is also switched to charge when it is available during that time. The ESS SoC status becomes very low at the end of the day. In the absence of PV power, the mid-level management strategy allows the charging of ESS from the grid at higher charging rate to perform charging for the next day. Fig. 12 shows that the grid limitation is not violated by mid-level management system.

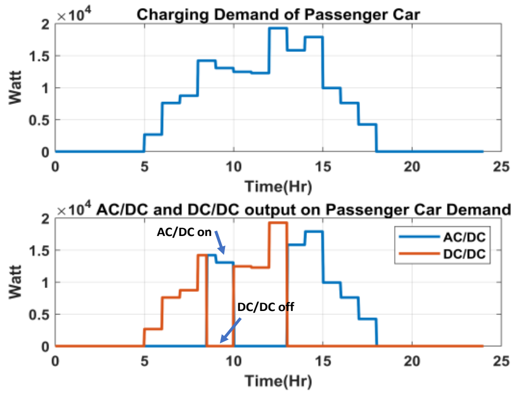

Fig. 9: AC/DC and DC/DC switching during 20kW charging.

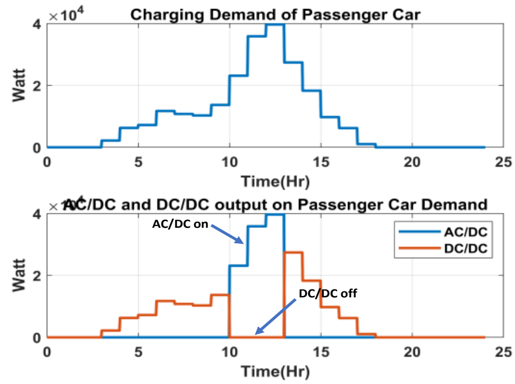

Fig. 10: AC/DC and DC/DC switching during 40kW charging.

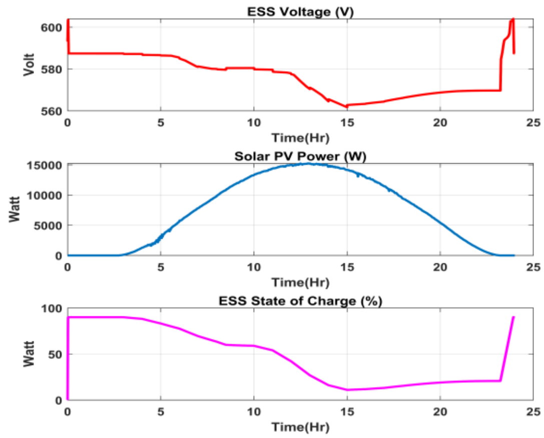

Fig. 11: PV power, ESS State of Charge, and ESS voltage status during charging.

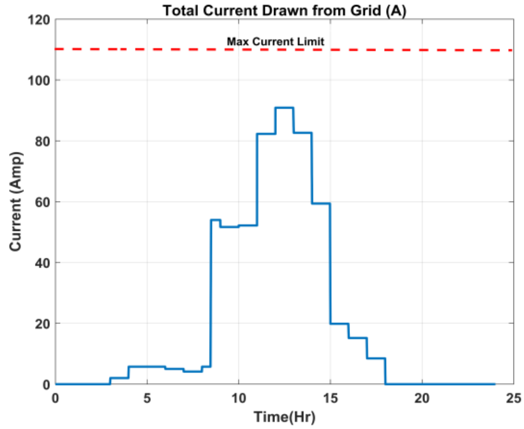

Fig. 12: Overall charging station current drawn from the grid. The grid limitation is around 110A.

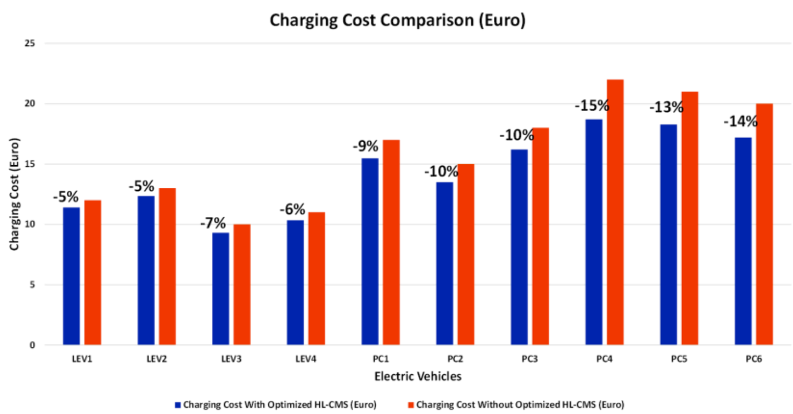

Fig. 13: Charging costs comparison between multiple EVs connected to the charging ports based on optimized and uniform charging scheduling.

The hourly charging cost data analysis shows that the smart charging station power management and high-level charging scheduling strategy reduce 10-15% of the charging cost for EV users. The charging costs comparison between optimized charging scheduling and uniformly distributed scheduling for each EV consumer is depicted in Fig. 13.

4. Conclusion

In this paper, a modular and scalable high-power charging station concept is discussed. Moreover, a mid-level energy management strategy consisting of modular power electronic converter activation and a converter group management strategy is also discussed. Finally, the high-level charging scheduling method is also discussed with charging cost optimization. The charging station with multilevel energy management strategies is simulated in the MATLAB/Simulink platform. The results show that the management strategy responds well to the high charging power demands. Additionally, the high-level charging scheduling algorithm outputs a charging rate profile for multiple EVs which reduces the charging cost up to 15% compared with uniform charging scheduling, while satisfying the user requirements and grid limitations if any.

Acknowledgments

This work was supported by the Horizon 2020 Programme of the European Commission under grant agreement no. 875131 (eCharge4Driver project). We, as authors, also acknowledge Flanders Make for the support to our research group.

References

[1] G. Berckmans, M. Messagie, J. Smekens, N. Omar, L. Vanhaverbeke, and J. Van Mierlo, “Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030,” Energies, vol. 10, no. 9, 2017.

[2] L. Noel, G. Zarazua de Rubens, B. K. Sovacool, and J. Kester, “Fear and loathing of electric vehicles: The reactionary rhetoric of range anxiety,” Energy Res. Soc. Sci., vol. 48, no. October 2018, pp. 96–107, 2019.

[3] H. Khalkhali and S. H. Hosseinian, “Multi-stage stochastic framework for simultaneous energy management of slow and fast charge electric vehicles in a restructured smart parking lot,” Int. J. Electr. Power Energy Syst., vol. 116, 2019.

[4] Siemens. Product leaflet triberium. [Online]. Available: https://w5.siemens.com/web/cz/cz/corporate/portal/home/produkty a sluzby/IBT/mereni a regulace/Documents/Triberium%20Fast%20Charger%2050%20kW.pdf

[5] Abb leaflet terra hp. [Online]. Available: http://new.abb.com/news/detail/4439/abb-powers-e-mobility-with-launch -of-first-350-kw-high-power-car-charger

[6] Enercon e-charger 600 leaflet. [Online]. Available: https://www.enercon.de/fileadmin/Redakteur/Service/EC E-Charger 600 en web.pdf

[7] Ashkrof P, de Almeida GH, Arem CB (2020) Analysis of the effect of charging needs on battery electric vehicle drivers’ route choice behaviour: a case study in the Netherlands. Transp Res PartD: Transp Environ. https:// doi. org/ 10. 1016/j. trd. 2019. 102206

[8] Gjelaj M, Træholt C, Hashemi S, Andersen PB, 2017 Cost-benefit analysis of a novel DC fast-charging station with a local battery storage for EVs. In: 52nd international universities power engineering conference (UPEC), Heraklion, https:// doi. org/ 10. 1109/ UPEC. 2017. 82319 73

[9] Febriwijaya YH, Purwadi A, Rizqiawan A, Heryana N (2014) “A study on the impacts of DC fast charging stations on power distribution system.” International conference on electrical engineering and computer science (ICEECS), Kuta https:// doi.org/ 10. 1109/ ICEECS. 2014. 70452 33.

[10] Zhu X, Mather B, Mishra P (2020) “Grid impact analysis of heavy-duty electric vehicle charging stations” IEEE power & energy society innovative smart grid technologies conference (ISGT), Washington, DC, USA, https:// doi. org/ 10. 1109/ ISGT4 5199. 2020. 90876 51

[11] Tu H, Feng H, Srdic S, Lukic S (2019) “Extreme fast charging of electric vehicles: a technology overview.” IEEE Transactions on Transportation Electrification. https:// doi. org/ 10. 1109/ TTE. 2019. 29587 09.

[12] A. Zhaksylyk, H. Rasool, T. Geury, M. El Baghdadi and O. Hegazy, "Masterless Control of Parallel Modular Active front-end (AFE) Systems for Vehicles and Stationary Applications," 2020 Fifteenth International Conference on Ecological Vehicles and Renewable Energies (EVER), 2020, pp. 1-6.

[13] B. Verbrugge, M.A.Monem, T. Geury, J. V. Mierlo and O. Hegazy “Development of a real-time scheduling and optimization algorithm for a high-level charging management system” 33rd Electric Vehicle Symposium (EVS33) Portland, Oregon, June 14 - 17, 2020.

[14] J. H. Holland, “Genetic Algorithms,” vol. 267, no. 1, pp. 66–73, 1992, doi: 10.2307/24939139.

[15] J. García-Álvarez, M. A. González, and C. R. Vela, “Metaheuristics for solving a real-world electric vehicle charging scheduling problem,” Appl. Soft Comput. J., vol. 65, pp. 292–306, 2018, doi:10.1016/j.asoc.2018.01.010.