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Guan, Heshi; Wu, Yang; Qin, Zian; Bauer, Pavol

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2023 IEEE 14th International Symposium on Power Electronics for Distributed Generation Systems

# Submodeling Method-Based Thermal Investigation of the Battery Energy Storage System Integrated in a 450 kW EV Charger

Heshi Guan
*Dept. DC Systems, Energy Conversion & Storage*
*Delft University of Technology*
Delft, The Netherlands
lionsanity1997@gmail.com

Yang Wu
*Dept. DC Systems, Energy Conversion & Storage*
*Delft University of Technology*
Delft, The Netherlands
Y.Wu-6@tudelft.nl

Zian Qin
*Dept. DC Systems, Energy Conversion & Storage*
*Delft University of Technology*
Delft, The Netherlands
Z.Qin-2@tudelft.nl

Pavol Bauer
*Dept. DC Systems, Energy Conversion & Storage*
*Delft University of Technology*
Delft, The Netherlands
P.Bauer@tudelft.nl

***Abstract*—The electric vehicle (EV) market is expanding rapidly. However, the main barriers to EV adoption are high vehicle costs, range issues, and charging infrastructure. Meanwhile, energy storage systems (ESS) appear as a promising solution to preventing grid overload during charging and reducing infrastructure costs. In this paper, the integration of the battery energy storage system (BESS) in a 450 kW EV charger is designed and investigated via modeling and simulation mainly from the perspective of thermal management. To explore the heat dissipation and the temperature distribution across the pack, the thermal model based on the sub-modeling technique is developed via COMSOL, and a preliminary layout and cooling strategy are determined.**

***Keywords*—fast charging, battery energy storage system, system integration, thermal management**

## I. Introduction

The electric vehicle market is one of the most dynamic clean energy sectors worldwide. According to Global Electric Vehicle (EV) Outlook 2022 [1], in 2021, over 16.5 million EVs were on the road. Therefore, it can be seen that the publicly available chargers are also expanding significantly, especially the DC fast chargers. The EV fast charger with a battery energy storage system (BESS) can boost charging power and reduce grid impact, especially during peak periods. A typical EV fast charger with a BESS consists of a grid, an AC/DC stage, and a DC/DC stage. There are two mainstream structures of EV fast chargers with energy storage based on whether the DC bus voltage is constant [2],[3], which are depicted in Fig 1. The key distinction is the existence of the DC/DC converter between the DC bus and the BESS. For the second arrangement, the DC bus voltage is related to the state of charge (SoC) of the BESS because of the direct connection. Although the terminal voltage of the BESS fluctuates with charging or discharging events, the normal operations of the front-end AC/DC stage can be guaranteed by the design of the BESS. Most importantly, the omission of the DC/DC converter will prevent larger losses and budget. For the AC/DC stage, there are different options based on the consideration of AC/DC rectification, power factor correction (PFC), and isolation, which are depicted in Fig. 1 [3].

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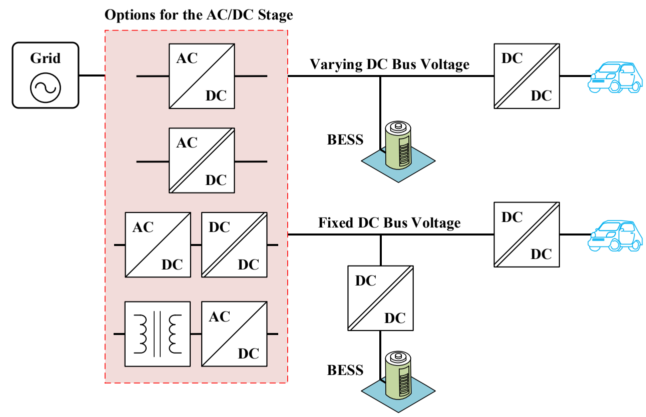

Fig. 1. Structures of EV fast chargers with the BESS.

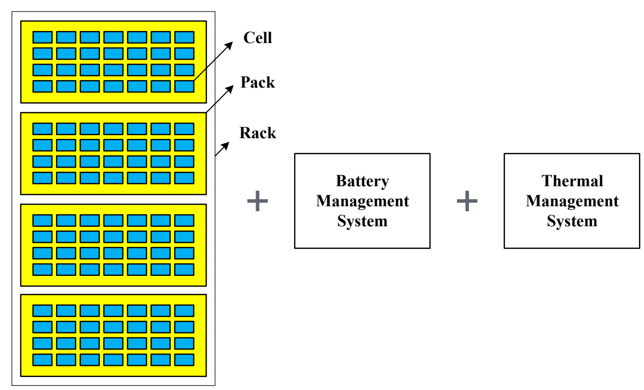

Fig. 2. The overview of the typical components in a BESS.

As depicted in Fig. 2, a typical BESS structure consists of a number of battery cells, a battery management system (BMS), and a thermal management system (TMS). Nowadays, batteries, flywheels, and hydrogen are three promising energy storage technologies, especially for the DC fast charging field [2]. Li-ion batteries are superior to alternative energy storage technologies in terms of specific energy and energy density, making them ideal for adoption in electric vehicles and related BESS systems. However, Li-ion cells are extremely delicate when exposed to heat, making thermal management of Li-ion cells and battery packs an important area of research [4]. Some

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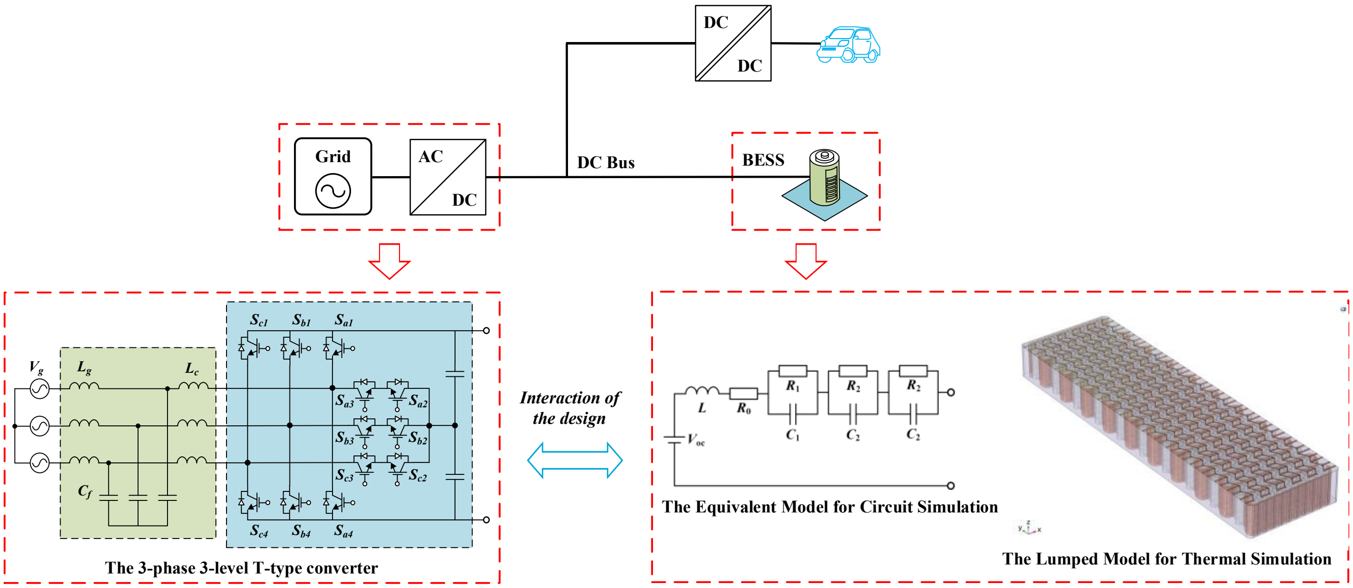


Fig. 3. The overall structure of the 450 kW EV fast chargers integrated with the BESS and the model used.

articles have performed relevant thermal simulations for small-scale battery packs [5]-[7]. Thermal simulations were also performed on only a small portion of the package rather than the entire package in some articles [8],[9]. Based on the studied literature, for large battery packs consisting of thousands of cells integrated into EV fast chargers, efficient and quick simulation remains a challenge. Therefore, this paper makes a trade-off between computation time and accuracy and adopts the method of sub-modeling, which was originally developed for mechanical stress simulation [10],[11]. By isolating the areas that are predicted to cause the highest temperature increase, it can avoid simulating the entire geometry in intricate details.

## II. Interaction between the Front-end Converter and the Battery Energy Storage System

The overall structure of the 450 kW EV fast charger integrated with the BESS selected in this paper is shown in Fig. 3. Typically, several differences should be considered in the design of the front-end AC/DC PFC converter for EV fast chargers with energy storage compared to the ones without. Firstly, a high-power rating could be shared by the BESS, which can reduce the size and cost of this stage. Secondly, a bidirectional converter is worthwhile due to the potential economic return of the grid services provided by the BESS. It turns out that the 3-phase 3-level T-type converter is one of the optimal selections for its superior performance, especially for applications with low voltage and medium switching frequencies [12], [13]. The research on the BESS in this integration focuses mainly on two aspects, one is its influence on the modulation and control of the front-end AC/DC converter, and the other is the thermal performance of the BESS. The former involves the equivalent circuit of a BESS for simulations, whilst the latter necessitates appropriate thermal modeling of battery packs, which is also the focus of this paper.

## III. Battery Selection and Sizing

In this section, the parameters of the three RC-link model of several different types of cutting-edge cylindrical 18650 battery cells are compared according to data from [14]. Based on the adaptation to the entire system, the following basic requirements for BESS are proposed:

a) The ratio of BESS to the grid-side power supply is set to 2:1 for grid assistance and easy implementation.

b) Given the available information on electric vehicles [15], it is assumed that the capacity of an EV battery is 100 kWh. Thus, during one charging cycle, the BESS is designed to provide at least 2/3 of its capacity (67 kWh).

c) Due to the overall structure of the EV charger, the terminal voltage of the BESS must be stable for the front-end converter to prevent over-modulation. In the case of SVPWM, the peak value of the grid-side phase voltage $V_m$ and the DC bus voltage $V_{dc}$ should meet the equation $V_{dc} > 2V_m/M_{max}$, where $M_{max}$ is the maximum value of the modulation index, which is 1.15 for SVPWM. Therefore, the DC bus voltage must be over 565.6V by calculation.

d) Since the total power required to be provided is 450 kW, the power the BESS can provide is at least 300 kW. Therefore, the maximum allowable C-rate at discharge should also meet the system demands.

e) Considering the energy loss converted to heat mainly caused by the internal impedance, the efficiency of BESS needs to be controlled at around 95%.

In a BESS, the individual battery cells can be connected either in series or in parallel, depending on the specific requirement. The number of series connections has the most significant impact on the terminal voltage of the entire battery pack, which has an effect on the voltage of the DC bus and determines whether or not the T-type converter functions appropriately. Furthermore, assuming that the number of serial cells has already been determined, the number of parallel cells (or the total number) will mainly affect the loss of the battery


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TABLE I. THE NUMBER OF SERIES AND PARALLEL CONNECTION OF DIFFERENT BATTERIES

| Model | Minimum number of series | Minimum number of parallel | Minimum total number |
|---|---|---|---|
| LG Chem INR18650MJ1 | 270 | 86 | 23220 |
| LG Chem INR18650HG2 | 208 | 49 | 10192 |
| LG Chem INR18650M26 | 236 | 98 | 23128 |
| Sony Murata Konion S18650VTC6 | 205 | 42 | 8610 |
| Sony Murata Konion US18650VTC5A | 359 | 102 | 36618 |
| KeepPower P1834J | 379 | 144 | 54576 |
| Nitecore 18650 NL1835HP | 379 | 86 | 32594 |
| Samsung INR18650-30Q | 203 | 39 | 7917 |

pack. Based on the analysis above, it can be summarized as the following formula:

$$N_s V_N I - R_i N_s I^2 / N_p = P_o \tag{1}$$

$$V_t = P_o / I \tag{2}$$

$$\eta = P_o / \left( N_s V_N I \right) \tag{3}$$

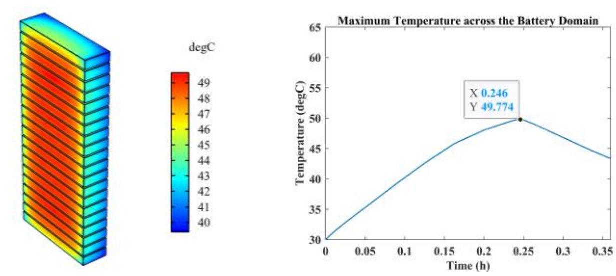
where $N_s$ is the number of the serial connections, $N_p$ is the number of parallel connections, $V_N$ is the nominal voltage of a single battery cell, $I$ is the current flowing through the BESS, $R_i$ is the internal impedance of a single battery cell, $P_o$ is the output power of the BESS, $V_t$ is the terminal voltage of the BESS, and $\eta$ is the efficiency of the BESS.

Based on the formula above, the minimum serial number of each battery is obtained through the requirements for the DC bus voltage, and then the minimum parallel number is obtained through the requirements for the BESS losses. Taking Samsung INR18650-30Q as an example, the total number is first set to a minimum value, which is based on the required battery capacity. The terminal voltage gradually rises as the number of series increases, eventually reaching the predetermined level of 700V. After the selection of the minimum serial number, the number of parallels is increased while the losses of BESS are decreased until they reach 5%. Furthermore, if the losses other than those caused by the internal impedance of the battery are ignored, and the total number of the battery remains unchanged, then the losses of BESS also remain the same. Besides, the non-integer number of parallel will be adjusted to an integer in the actual number design.

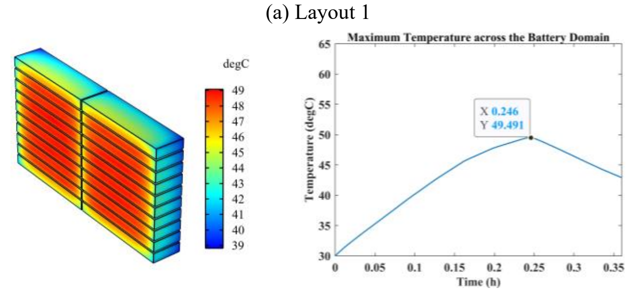
As shown in Table I, Sony Murata Konion US18650VTC6 and Samsung INR18650-30Q require the least number of battery cells at 8610 and 7917, respectively. At the same time, when both weight and price are taken into account, the Samsung INR18650-30Q is the superior option to the Sony Murata Konion US18650VTC6 [16]. For further thermal simulation, the total number of one single pack of batteries will be selected as 400 Samsung INR18650-30Q cells, and the number of serial connections is 10 and the number of parallel connections is 40, respectively.

## IV. THERMAL SIMULATION OF THE BATTERY ENERGY STORAGE SYSTEM

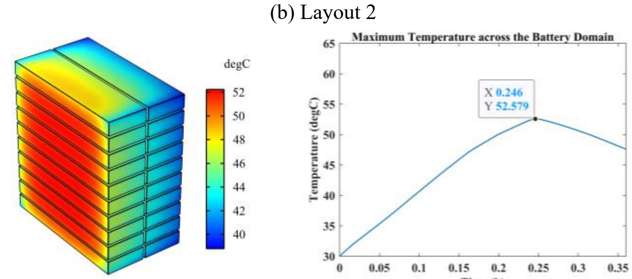
Keeping the batteries at a suitable temperature is one of the challenges of integrating the BESS into the EV fast charger, which is critical to their performance and longevity. Air cooling, liquid cooling, and phase change material (PCM) cooling are primary cooling technologies for the BESS [3]. Because of its




(a) Layout 1




(b) Layout 2




(c) Layout 3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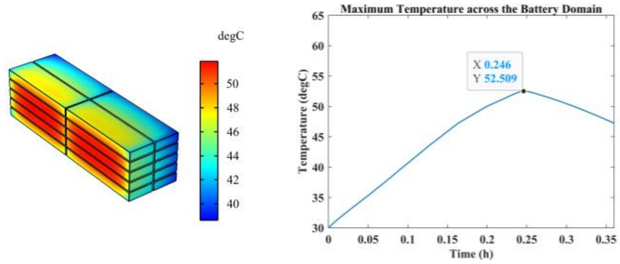
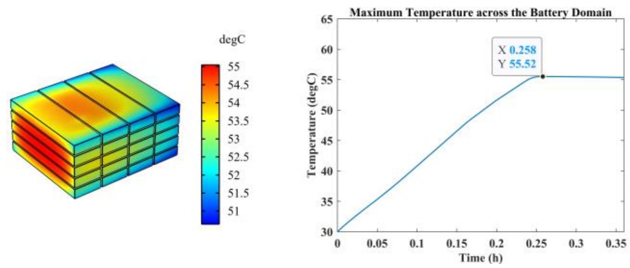



(d) Layout 4



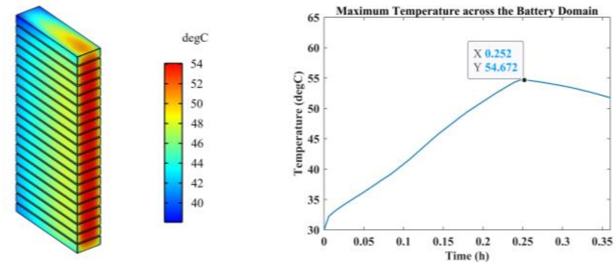

(e) Layout 5

Fig. 4. The distribution of temperature across all battery packs with air cooling along the x-axis for 5 different layouts.

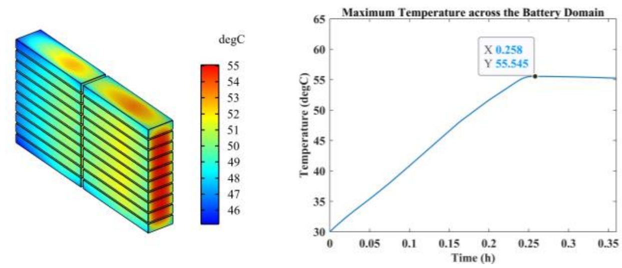
simplicity and low cost, air cooling is commonly used to achieve heat dissipation by utilizing mechanical devices to circulate air.

To investigate the design of the thermal management of the BESS by comparing different layouts of battery packs under certain air cooling, the method of sub-modeling is adopted. The fundamental concept behind sub-modeling is to initially model and simulate the global model of the entire geometry without taking details into consideration. The results of the global model are then utilized to obtain the boundary condition for the full-scale model.

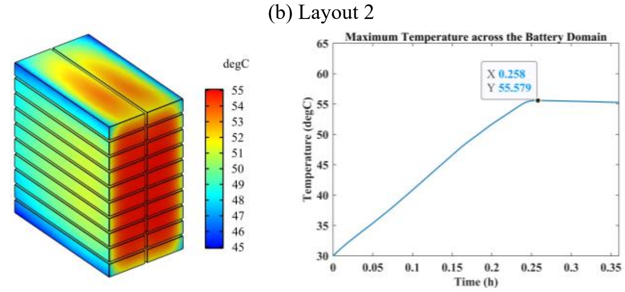
The sub-modeling process mentioned is applied to the thermal simulation of Li-ion battery packs in COMSOL. To explore the impact of the layout of battery packs on the overall heat dissipation, a single battery pack is firstly simplified as a cube of the same size. Air cooling is to utilize the convection of working fluid to cool down the batteries. Therefore, each configuration is evaluated for two different airflow directions by setting the velocity field of fluid in the simulation, namely along the x-axis and the y-axis direction. The maximum temperature and the distribution of temperatures across all battery packs with air cooling along the x-axis are shown in Fig. 4 and Fig. 5. At each setting, the maximum temperature of the battery packs keeps rising because they discharge at a constant current from 0 to 0.24h. After that, the battery packs stop discharging, so the maximum temperatures show different levels of temperature drop due to the airflow. From the results of the simulations, it is obvious that the cooling for Layout 1 and 2 have the best heat dissipation performance, and the maximum temperature can be kept below 50 °C even at the end of the discharge period. In addition, it can also be further proved that the overall heat dissipation effect and the temperature distribution both improve when the airflow is directed to follow a path with a shorter geometric length when repeating the thermal simulation with air cooling along the y-axis. After completing the investigation of the system-level battery pack layout and air cooling, the focus will return back to a single battery pack. Layout 1 will be selected as an example due to its superior cooling effect. As is depicted in Fig. 6, the full-scale model of the target single pack is included in the global model consisting of 3, 5, and 7 packs for a faster simulation, meanwhile maintaining the same air cooling conditions. Finally, the simulation results in Fig. 7 indicate that, as the number of packs contained in the global model increases, the maximum temperature of the target pack increases to a certain extent but is limited. Therefore, it can be inferred that the upper and lower two packs next to the target



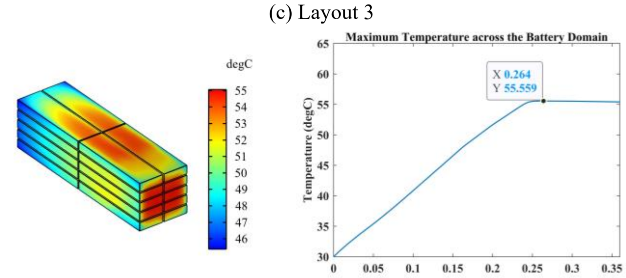

(a) Layout 1



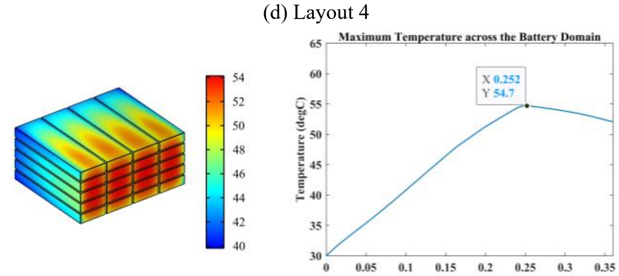

(b) Layout 2




(c) Layout 3




(d) Layout 4




(e) Layout 5

Fig. 5. The distribution of temperature across all battery packs with air cooling along the y-axis for 5 different layouts.



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battery pack have the greatest influence on the maximum temperature of the target pack. Even if only these two packs are considered, it can significantly reflect the influence of the global model on the target pack.

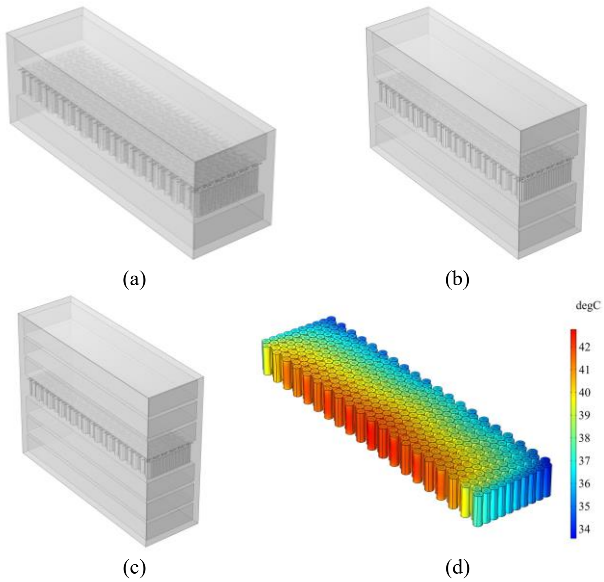


Fig. 6. (a) – (c) The full-scale model included in a global model of 3, 5 and 7. (d) The temperature distribution of the target pack in the full-scale model.

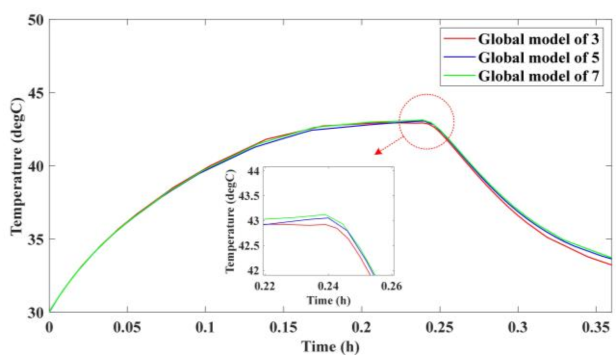


Fig. 7. The maximum temperature for full-scale models included in a global model of 3, 5 and 7 packs, respectively.

## V. Conclusion

This paper designs the battery selection and sizing of the BESS integrated into a 450 kW EV fast charger and examines heat dissipation across the Li-ion battery packs by sub-modeling technique. First, the battery pack is sized by selecting from several cutting-edge 18650 batteries and proposing basic requirements according to the practical situation. Subsequently, the single battery pack is simplified as a cube to complete a preliminary design of the layout inside the BESS utilizing the global model, and then, the full-scale model shows that the greatest influence on the maximum temperature of the target pack comes from the nearest neighbor battery packs, which allows it to simplify the thermal simulation of large-scale battery packs.

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