`RAC`$^+$: Supporting Reconfiguration-Assisted Charging for Large-Scale Battery Systems

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***Abstract*— While most existing battery cell balancing approaches were post-treatment (i.e., handling diverse voltage levels originating from different battery cell status), a pre-treatment approach, called Reconfiguration-Assisted Charging (`RAC`), was developed, which dynamically attaches a proper number of resistor arrays to each group of battery cells with similar status, preventing battery cell imbalance; note that this pre-treatment approach can be used orthogonally with existing post-treatment approaches such as active/passive balancing. Relaxing its impractical assumptions of `RAC` (e.g., all necessary resistor arrays are deployed in the target system), this paper proposes `RAC`$^+$, which realizes its practical and efficient use for the pre-treatment concept of `RAC`. The experiment results demonstrate that `RAC`$^+$ achieves the same balancing performance as `RAC` while reducing the number of required resistors by 69% compared to `RAC`. The extensive experiment results also show that `RAC`$^+$ is not only robust to various charging environments, but also proven to be effective in terms of minimizing power loss.**

***Index Terms*— Reconfiguration-assisted charging, large-scale battery system, battery cell balancing**

I. INTRODUCTION

Recently, energy storage systems and electric vehicles have been receiving attention for the effective utilization of renewable energy, which is increasingly spotlighted. Among the core elements supporting electric vehicles and energy storage systems, large-scale batteries play a crucial role [1]. One of the several challenges for effective control is known as balancing, the process of regulating the charge state among batteries, regarded as an important issue [2], [3], [4]. Without proper control of large-scale batteries, imbalances can lead to reduced battery life and shortened replacement periods, increasing the maintenance costs for energy storage systems and electric vehicles [5], [6]. Additionally, unbalanced charging and discharging can lead to a higher risk of serious safety incidents like battery explosions [7], [8]. Lastly, decreased charging efficiency can lead to inconveniences such as reduced operating times for electric vehicles [9], [10]. For these reasons, battery balancing should be carefully considered and recognized as one of the essential tasks for the successful establishment of a sustainable/renewable energy system [11].

Battery balancing techniques are mainly divided into two categories: active balancing and passive balancing [12]. Active balancing uses a balancing circuit to induce current from batteries with a higher State of Charge (SOC) to those with a lower SOC, thereby equalizing the SOC of the batteries [13], [14]. On the other hand, passive balancing applies additional resistance to the batteries, consuming the SOC of other batteries based on the one with the lowest SOC to level out the charge among them [15]. Past research on balancing, including active and passive balancing, primarily focused on performing balancing after charging. To this end, previous studies mainly concentrated on balancing circuits or strategies to shorten balancing time [16].

However, `RAC` [17], our target technique to improve, adopted a different approach from previous studies. Unlike the conventional method of performing balancing after disparities occur during the charging process, `RAC` conducted balancing simultaneously with charging; therefore, `RAC` can be used orthogonally with existing post-treatment approaches such as active/passive balancing. As the current required by a battery varies depending on its Open Circuit Voltage (OCV) and the time charged [18], it is crucial to supply the current according to the charging state. To this end, `RAC` identified and provided the necessary current information based on the battery's charging state. If a battery is supplied with a higher current than desired, the charging efficiency decreases, and the risk of battery explosion increases [19]. Conversely, if the current provided is lower than desired, the time to full charge increases, negatively impacting the user experience [20]. Therefore, it is an important issue to provide the battery with the required current.

To apply these characteristics to balancing, `RAC` considered that the battery state can vary at each charging moment due to reasons in the process, temperature differences, power loads, etc. [21], [22]. With this in mind, `RAC` proposed a system to provide the current appropriate for each OCV. Initially, `RAC` suggested categorizing batteries with similar OCVs to supply the proper current for the battery's charging state. `RAC` uses unit resistors and employs resistor arrays and on/off switches to adjust the resistance needed to provide current for each category. According to `RAC`'s design, maximum resistance is required when providing current to the battery category during the last phase of the CV charge in the CC-CV charge, where CC and CV stand for Constant Current and Constant Voltage, respectively. The resistor array calculated based on this is used in all charging sections, and the resistance suitable for the category's situation is provided through on/off switches for each unit resistor of the resistor array. The discussion on

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resistors in `RAC` concludes here, and as a result, the following problems arise.

- An unnecessarily large number of resistors and switches are required to support the system.

The insufficient discussion about required resistance in `RAC` leads to the problem of requiring excessive resistance for balancing as mentioned above. For instance, consider a case where `RAC` sets the total required resistance to 3570Ω and the unit resistor to 2Ω (see Table I in Section IV). To meet this, 1785 pieces of unit resistors are needed, and switches must be installed to manage these resistors effectively. Adding these components not only means an increase in board size but also signifies that there will be more complexity in managing balancing, which is not a trivial issue. However, the interesting point is that all resistors are only partially used in certain situations. Since it was calculated based on the moment requiring maximum resistance, only some of installed unit resistors are used in most charging scenarios. To pursue an efficient system and avoid unnecessary resource loss, the need for accurate resistance calculation becomes emphasized [23].

`RAC`$^+$ determines the number and size of the resistor arrays required for each category. Unlike `RAC`, `RAC`$^+$ uses a common set of resistor arrays for each category and provides individual resistor array sets for each category, clearly determining the necessary resistance information. This information can be obtained through the battery's OCV and the corresponding charging current required by the battery, without additional devices; therefore, it can be fully implemented with BMS (Battery Management System) used by `RAC`. By combining this with the obtained resistance information, the trade-off in power loss can be determined. Since categories are differentiated based on the battery's OCV, it is evident that each category requires different resistor arrays; therefore, `RAC`$^+$ (as well as `RAC`) can be applicable to batteries where OCV changes according to SOC such as NMC, LMO and NCA batteries (but this does not hold for LFP batteries [24]). The size and number of the required resistor arrays are determined based on the battery connection status information within the category. Reconfigurable batteries can change cell connections through reconfiguration [25], resulting in various lengths of battery connections. However, there are limitations to this reconfiguration which affect the efficiency and viability of the batteries.

The primary contributions of `RAC`$^+$ can be summarized as follows:

- By pre-determining the resistance needed for each category, the overall amount of required resistance has been significantly reduced.
- By changing the charging voltage, it is important to identify the changing factors such as category changes and how they change.

Through these contributions, `RAC`$^+$ has provided a more efficient and practical balancing solution for large-scale battery systems, utilizing information that BMS can identify, such as OCV information. The following sections proceed as follows. First, Section II describes `RAC`, the basis of the proposed `RAC`$^+$, which explains how categorization based on the charging state of batteries is conducted and how the connected resistors are set in an irrational manner in `RAC`. Next, Section III proposes `RAC`$^+$ in detail, including how it operates differently from `RAC` to reduce resistors. Section IV evaluates `RAC`$^+$ with experiment setup. Finally, Section V concludes the paper.

II. UNDERSTANDING `RAC`

In this section, we recapitulate the mechanism of `RAC` [17], which is a basis for `RAC`$^+$. Under `RAC`, large-scale batteries are categorized based on their similar OCV according to their charging states. Through the arrangement of resistor sets, `RAC` provides appropriate currents during the charging process to achieve balancing.

A. Required Resistors for Appropriate Current

Batteries exhibit different charging currents depending on their OCV and charging time [20]. `RAC` assumed that charging process information [26] is provided, which pertains to the required charging current based on the battery's OCV. `RAC` also assumes that the primary factor influencing the charging current is limited to the battery's OCV, which is recognized by BMS without any additional procedures. It is assumed that the incoming charging voltage from the charger is fixed. With knowledge of the charging voltage and current, `RAC` can calculate how many resistors are required based on the battery's OCV.

$$I = \left(V - \sum_{i=1}^{x} v_i\right) / \left(\sum_{i=1}^{x} r_i^0 + R\right) \tag{1}$$

In Eq. (1), symbols I, V, v_i, x, and r_i^0 represent the appropriate current for the i-th category of batteries, the charging voltage, the OCV for the i-th category, the length of the battery connection, and the internal resistance of the battery, respectively [26]. The voltage is determined as the limited value of OCV (v_i) for batteries connected in series for a certain length (x) from the charging voltage (V). The resistance is calculated by excluding the internal resistance (r_i^0) for the length (x) connected in series. The internal resistance (r_i^0) is assumed to be a fixed value as it varies insignificantly during the charging process.

B. Categorization for `RAC`

In large-scale batteries, each battery may have a different Open Circuit Voltage when starting to charge due to differences in load distribution between batteries, aging levels, and their initial conditions at the time of shipment [27]. Since batteries require charging currents according to their respective OCV, a variety of currents are needed to accommodate batteries. `RAC` categorizes batteries with similar SoC and carries out charging for each battery category. Different methods are applied in CC charging and CV charging to divide the range within $[v_{\text{cutoff}}, v_{\text{full}}]$. In CC charging, the voltage difference that arises due to the unit resistor becomes the criterion for categorization.

$$\hat{v} = (R - \bar{R}) \cdot I / x \tag{2}$$

Eq. (2), through Eq. (1), specifies that the voltage difference between the category voltage (v_i) and the voltage of the next category ($v_{\text{i+1}}$) is denoted as $\hat{v}$, where R and $\bar{R}$ are the required resistance for the i-th and (i+1)-th category of required resistance, respectively; the difference in the number of unit resistors between categories is expressed as $(R-\bar{R})$, and x represents the length of the battery connection length. Due to the characteristics of CC charging, the charging current (I) remains constant. Therefore, changes in the number of unit resistors $(R-\bar{R})$ and the length of the battery connection (x) determined by Eq. (1) become the determining factors for the variation in category voltage.

$$\min\{\hat{v}\} = r_u \cdot I / x_{\max} \tag{3}$$

$\hat{v}$ changes by a unit resistor (r_u) that minimizes $(R-\bar{R})$, and the battery connection length (x) reaches its maximum value when it becomes the minimum. The maximum battery connection length ($x_{\max}$) in the corresponding category refers to the maximum length of battery connection achievable without the sum of battery OCV (v_i) exceeding the charging voltage, which is, in `RAC`, for example, 30V. Using this information, Eq. (3) allows us to secure the minimum voltage value ($\hat{v}$) that can be changed by varying a unit resistor, which serves as the basis for category changes in CC charging. The process starts from v_{cutoff} and iteratively progresses until the voltage at which CV charging begins.

Subsequently, in the CV charging phase, the categories are divided based on the sensitivity of the BMS to voltage. For instance, if the BMS sensitivity is 0.02V and CV charging starts at 4.13V, the categories in the CV charging phase are constructed as $[4.13, 4.15)$, $[4.15, 4.17)$, ..., $[v_{\text{full}} - 0.02, v_{\text{full}})$.

III. DEVELOPMENT OF `RAC`$^+$

In this section, we analyze the limitations arising from the use of the categorized common resistor set in `RAC`. We then propose `RAC`$^+$, with introduction of the individual resistor sets of `RAC`$^+$ developed to overcome these limitations.

A. Motivation

`RAC` classifies batteries into various categories based on the voltage range defined in Section II-B and reconfigures the battery connections within each category. The Open Circuit Voltage (OCV) of the batteries in a category is standardized to the median OCV of the batteries belonging to that category. Each category has its unique voltage range, which results in different OCVs and charging currents for the batteries, thereby varying the resistance required in each category. Even within a single category, the required resistors, serving as means to achieve the required resistance, vary according to the battery connection length (x) as defined by Eq. (1). To accommodate these varying resistance requirements, `RAC` has introduced a common resistor set. This set is designed considering the maximum resistance required ($R_{\max}$), which is set to support a battery with a connection length of 1 at the final stage of charging.

`RAC` equips the maximum resistance ($R_{\max}$) by dividing it into unit resistors and adds on/off switches to provide the necessary resistors for each category. Additionally, the system is designed to manage each unit resistor via on/off switches, thereby precisely providing the required resistance for each category. The resistor array of $R_{\max}$, composed of unit resistors, can support only one battery connection length at a time; battery connections of the same length are connected in parallel, sharing the resistor array. Therefore, to support battery connection lengths in all categories, a resistor array for the longest battery connection ($x_{\max}$) within each category must be prepared. In summary, `RAC` creates a common resistor set for all battery connections across categories by equipping $x_{\max}$ arrays, and each array has $R_{\max}/r_u$ unit resistors and switches that can turn them on/off.

The common resistor set designed to support `RAC` introduces several problems. Firstly, there is an issue of equipping unnecessary resistors during the charging process. While $R_{\max}$ is considered for the moment requiring the maximum resistance during charging, it becomes unnecessary resistors for charging other categories in most cases, except for the moment where it supports a single battery connection in the last category. This implies that `RAC`'s resistors, being composed of unit resistors, require switch management. Managing these unnecessary resistors necessitates a large number of switches, leading to spatial and cost inefficiencies, as each switch must be able to be turned on/off and this process is repeated with every change of category. This situation leads to a waste of resources ($R_{\max}$) and an increase in the difficulty of balancing operations, as additional costs for switches are required to manage unnecessary resources. This contradicts the goal of balancing batteries, which aims for efficient resource management and reduced operational difficulty [23].

To address these issues, this paper identifies the attempt to support all categories with a single common resistor set and proposes `RAC`$^+$ as a solution. `RAC`$^+$ aims to minimize unnecessary resistors and switches while providing specialized resistors for each category, thereby enhancing resource efficiency.

B. Design Principles of `RAC`$^+$

This section explains the methods used by `RAC`$^+$ to enhance `RAC`. It will cover how the category-specific resistor sets proposed by `RAC`$^+$ differ from the common resistor sets of `RAC` and discuss their advantages. For this purpose, the paper assumes that the categories in `RAC`$^+$ are identical to those created by `RAC`, with the only difference being in the voltage aspect of the representative battery for each category. Specifically, it is assumed that the voltage of batteries within a category in `RAC`$^+$ is the average voltage of that category. For example, if a category's voltage range is between 3.2V and 3.4V, it is assumed that all batteries within that category have an OCV of 3.3V. Based on this assumption, the charging current required for a given category can be determined through charging profile. The necessary resistance for each battery connection is then determined by substituting the acquired voltage and current information of the category into Eq. (1).

Example 1: We consider the following situation: the number of categories is 8; the battery voltage range is $[3.30V, 4.20V]$; and the category voltage ranges are $[3.300V, 3.506V)$, $[3.506V, 3.712V)$, $[3.712V, 3.948V)$,

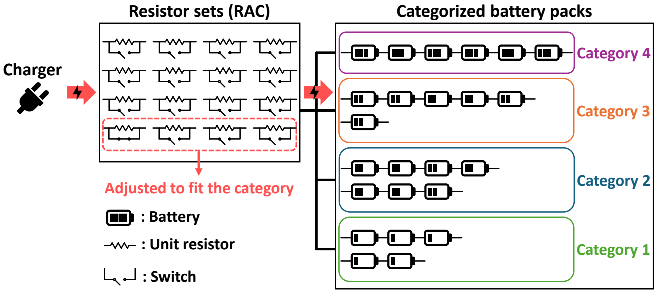


Fig. 1: A common resistor set is used in RAC, where all categories utilize one resistor set. To support this, each unit resistor is equipped with an on/off switch. When charging begins, the switches of the unit resistors are adjusted to provide the current that matches the category voltage.

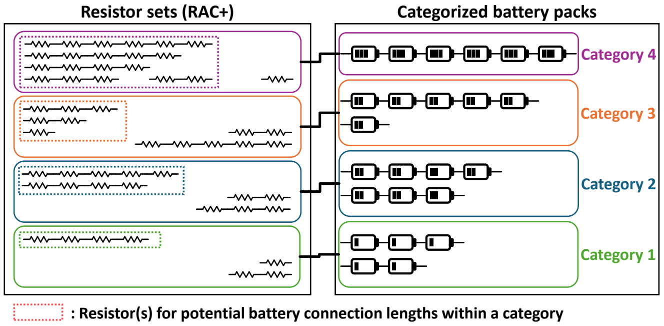


Fig. 2: An individual resistor set is used in RAC$^+$, where each category is equipped with the necessary resistors, reducing the amount of resistors needed for balancing. There is no need for switches to manage the unit resistors.

$[3.948V, 4.183V)$, $[4.183V, 4.193V)$, $[4.193V, 4.195V)$, $[4.195V, 4.197V)$ and $[4.197V, 4.200V)$. We assume that the batteries are divided into 8 categories, and each category requires a charging current based on the average of its voltage range. For instance, calculating the current based on the average of the category voltage ranges, we get values of $3.403V$, $3.609V$, $3.83V$, $4.066V$, $4.188V$, $4.194V$, $4.196V$ and $4.1985V$. The corresponding currents obtained from the charging profile for these voltages are $0.825A$, $0.825A$, $0.825A$, $0.825A$, $0.825A$, $0.398A$, $0.177A$ and $0.084A$, respectively. According to the assumption, each category needs to support the aforementioned currents. As the OCV of each category's batteries is fixed at the average voltage of that category according to the assumption, the current required by the category remains constant.

As seen in Figs. 1 and 2, RAC$^+$ calculates the necessary resistance for each category and installs suitable resistors for those categories; this differs from RAC, which calculates only for the situation where maximum resistance is needed in the worst-case scenario. Each category forms a resistor set with the calculated resistors, consisting of resistor arrays. A single resistor array can support one type of battery connection within a category, and battery connections of the same length are connected in parallel, sharing a resistor array. To proceed with balancing, it is essential to finalize the resistor set information supporting each category. This includes not only the resistors for the batteries assigned to a category right after the start of charging, but also resistors for potential battery connection lengths within a category, as shown in the small squares of each resistor category in Fig. 2.

Therefore, in Section III-C, RAC$^+$ addresses the amount of resistor and construction of sets needed to achieve balancing performance similar to RAC. This is the minimum amount of resistor that must be equipped to support the target system using the RAC$^+$ method.

C. RAC$^+$: Reduction

In RAC$^+$, to equip the necessary resistors, it is essential to accurately determine the required resistance for each category. This involves considering the number of batteries in a category and the minimum and maximum resistor based on battery length. Initially, it is assumed that the OCV of batteries within a category is uniform, being the mean voltage of the category, and batteries within the same category require the same charging current. Therefore, the required resistance (R) can be calculated as Eq. (4), which is derived by Eq. (1). This is based on assumptions about charging voltage and current, and information provided for the given category, ultimately determined by the number of batteries (x).

$$R = \left(V - \sum_{i=1}^{x} v_i\right) / I - \sum_{i=1}^{x} r_i^0 \tag{4}$$

Resistor arrays are equipped to accommodate batteries of various lengths within a category. The minimum length of a battery connection is when a battery is isolated, which is 1. Additionally, the maximum number of batteries a category can have is determined during the categorization process. This is $x_{\max}$, ensuring that battery connections do not exceed the charging voltage. Therefore, if there are resistor arrays supporting battery lengths from 1 to $x_{\max}$, it can be considered that all the necessary resistance to support that category have been equipped.

Example 2: We consider the following situation: the charging voltage is $30V$, the category voltage range is $[3.30, 3.50)$, the maximum battery connection length is $x_{\max} = 7$, and the internal battery resistance is 0.06Ω. We assume that the battery voltage is $3.4V$ along with a constant charging voltage of 30V and the category voltage range $[3.300, 3.506)$. At this point, the necessary resistance (R) can be calculated using Eq. (4). With fixed values of V ($30V$), r_i (0.06Ω), v_i ($3.4V$) and I ($0.825A$), the battery length (x) becomes the determining factor for the resistor (R). For instance, when the battery connection length is 1, the result can be derived as follows: $0.825 = (30 - 3.403)/(0.06 + R)$. Solving this gives a resistance (R) of 32.18Ω. Furthermore, when the battery length is at its maximum ($x_{\max}$), the equation becomes $0.825 = (30 - 3.4 \cdot 7)/(0.06 \cdot 7 + R)$, resulting in a resistance (R) of 7.09Ω. In this way, we can calculate the resistors supporting battery connections from length 1 to $x_{\max}$, thus determining the extent of the resistor arrays required for balancing the current for that category.

Length	1	2	3	4	5	6	7
Voltage = 3.4V	32.18Ω	27.99Ω	23.81Ω	19.62Ω	15.44Ω	11.25Ω	7.07Ω
3.61V	31.93Ω	27.49Ω	23.06Ω	18.63Ω	14.19Ω	9.76Ω	5.32Ω
3.83V	31.66Ω	26.96Ω	22.26Ω	17.55Ω	12.85Ω	8.15Ω	3.45Ω
4.07V	31.38Ω	26.39Ω	21.40Ω	16.41Ω	11.42Ω	6.43Ω	1.44Ω
4.188V	31.23Ω	26.09Ω	20.95Ω	15.82Ω	10.68Ω	5.55Ω	0.41Ω
4.194V	64.78Ω	54.18Ω	43.58Ω	32.99Ω	22.39Ω	11.79Ω	1.19Ω
4.196V	145.73Ω	121.96Ω	98.19Ω	74.43Ω	50.66Ω	26.89Ω	3.13Ω
4.198V	307.11Ω	257.07Ω	207.03Ω	157.00Ω	106.96Ω	56.93Ω	6.89Ω

TABLE I: Required resistance for each category by RAC^{+}.

If the resistance required for each category can be determined, it is easy to know the amount of resistance required to support the entire system. Since the resistor set is composed of unit resistors just like RAC, a certain amount of resistance can be provided by adjusting with an on/off switch. We have identified the required resistance for each battery connection length in each category. Based on this information, by comparing the required resistance for each connection length in each category and preparing for the moment with the highest resistance requirement, we can support the entire system. For example, if there are seven categories as in the example above, and the following resistances are required to support a single battery connection in each category: 32.18Ω, 31.93Ω, 31.66Ω, 31.38Ω, 31.23Ω, 64.78Ω, 145.73Ω and 307.11Ω; then by preparing a resistor set to support 307.11Ω, we can support a single battery connection in all categories.

This configuration method requires fewer unit resistors and switches for balancing compared to RAC. For example, in the case of Example 1, the resistor set for RAC must secure 510Ω for the worst case, calculated based on the maximum length of battery connection (7), requiring about 3570Ω. If the unit resistor is set to 2Ω, it would need 1785 unit resistors and an equal number of switches to manage them. However, the resistor set for RAC^{+} only requires the resistors necessary for each category, needing about 1106Ω and allowing for the composition of 553 unit resistors without additional switches.

IV. EVALUATION

In this section, we present evaluation results. Starting from the explaining experiment setup, we compare the performance between RAC and RAC^{+}. We then evaluate the impact of charging environment to the performance of RAC^{+}. Finally, we validate the optimal battery connection length.

A. Experiment Setup

In this section, we conducted battery emulation to evaluate RAC^{+}. For the battery emulation, we experimented with the NCR18650 battery [26] to obtain its electrical characteristics, which exhibits a voltage range of $3.3V$–$4.2V$ and a capacity of $2900mAh$.

The experiment was conducted based on information from the NCR18650 battery, using the charge and discharge records of the NCR18650 battery to determine the SOC-OCV relationship. The charging current corresponding to the obtained OCV was checked in the NCR18650 data sheet. The unit resistance used in the experiment was 2Ω; the charging voltage was provided at 10–$30V$; and the voltage sensitivity of the BMS was assumed to be 0.002V, which are the same as the previous studies for comparison. The categories were calculated based on OCV and unit resistance. In the experiment, the battery connections were allocated to the battery lengths that each category has. The resistance values in the results represent the values when there is one battery connection in the corresponding position in Table I.

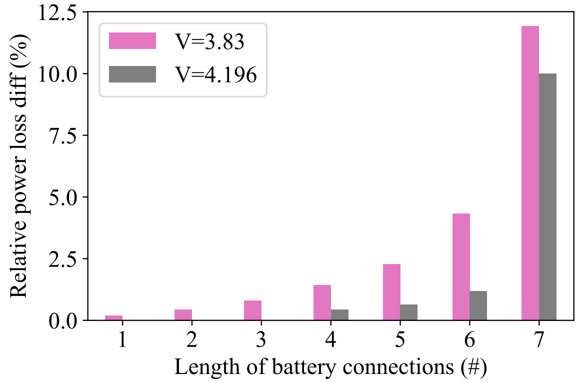


Fig. 3: The relative difference in power loss for balancing between RAC and RAC^{+}.

The voltage categories for the batteries we used were divided as follows. The CC charging was categorized into $[3.300V, 3.506V)$, $[3.506V, 3.712V)$, $[3.712V, 3.948V)$, $[3.948V, 4.183V)$ and $[4.183V, 4.193V)$. The CV charging was categorized into $[4.193V, 4.195V)$, $[4.195V, 4.197V)$ and $[4.197V, 4.200V)$. Each battery was allocated to one of the categories based on its corresponding OCV value.

B. Comparing RAC and RAC^{+}

To evaluate the advantages of RAC^{+}, we compared the resistance required for RAC^{+} and RAC, and the power loss that occurs during charging them.

In order to proceed with balancing, RAC^{+} required fewer resistors than RAC. RAC required 7 arrays of 510Ω resistors, resulting in a total of 3570Ω of resistance. In other words, 1785 units of 2Ω resistors were needed. On the other hand, as shown in Table I, RAC^{+} required a certain amount of resistance for each category. Since RAC^{+} also uses unit resistors like RAC, it only needs to prepare for the maximum resistance required in each column (battery connection length). The comparison of the required total amount of resistance for each length of battery connection is shown in Table II. The required resistance for each category, calculated based on the charging current of the batteries within the category, is determined to a decimal point. However, since the unit resistors available are in 2Ω increments, RAC^{+} ensures that if the required

Length	1	2	3	4	5	6	7	total
RAC	510Ω(255)	510Ω(255)	510Ω(255)	510Ω(255)	510Ω(255)	510Ω(255)	510Ω(255)	3570Ω(1785)
RAC$^+$	307.11Ω(154)	257.07Ω(129)	207.03Ω(104)	157.00Ω(79)	106.96Ω(54)	56.93Ω(29)	7.07Ω(4)	1099.17Ω(553)

TABLE II: The amount of resistance and the number of unit resistors (2Ω) by RAC and RAC$^+$, according to the battery connection length.

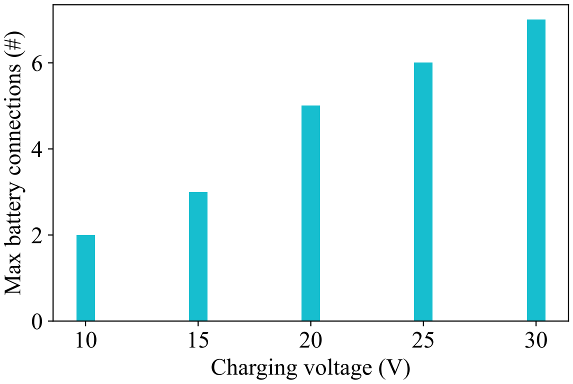


Fig. 4: The difference in maximum length of battery connections according to varying charging voltages.

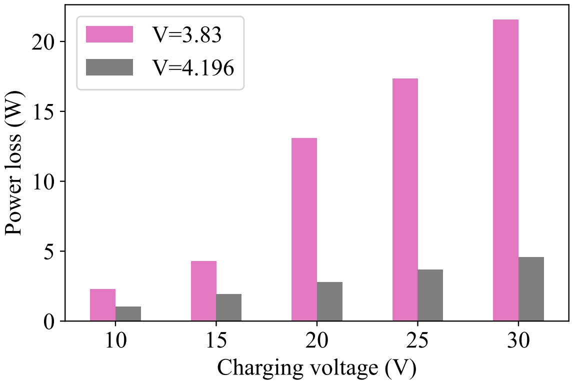


Fig. 5: The difference in power loss that occurs with varying charging voltages, when battery category voltage is $4.194V$ and the length of battery connection is 1.

resistance is not a multiple of 2Ω, an additional unit resistor is provided. For example, to support a resistance of 307.11Ω for a battery with a length of 1, 154 unit resistors (totaling 308Ω) are supplied. Thus, a discrepancy arises in the total resistance needed, and the sum of resistances made up of unit resistors. Generally, resistors should be prepared based on the almost fully charged state, but in the case of a length of 7, more resistors are required at the beginning of charging. This phenomenon occurs because the increase in voltage of the category (from $3.4V$ to $4.198V$) is greater than the decrease in charging current (from $0.825A$ to $0.084A$). Thus, RAC$^+$ can achieve sufficient balancing with only 553 units (154+129+104+79+54+29+4=553 in Table II) of 2Ω resistors to support each battery connection, which requires 69% fewer resistors compared to RAC (that requires 1785 units of 2Ω resistors).

RAC$^+$ generated less power loss from resistance because it uses fewer resistors. Fig. 3 shows the percentage by which RAC$^+$ generated less power loss compared to RAC during the balancing process when charging voltages are 3.83V and 4.196V, respectively. It can be observed that the difference in power loss increases as the length of the battery connection becomes longer. This occurs due to the difference in how RAC and RAC$^+$ predict the voltage of the battery. This discrepancy leads to more significant differences in power loss as the number of batteries in the connection increases, confirming that longer battery connections result in greater power loss differences. Consequently, as the number of long battery connections increases, the performance gap between RAC$^+$ and RAC also becomes larger. However, when the category voltage is $4.196V$, the power loss of RAC is $0.10W$ while the power loss of RAC$^+$ is $0.11W$, resulting in a numerical difference of $0.01W$.

C. Impact of Charging Environment

We now evaluate how the charging environment affects the power loss of RAC$^+$ and the maximum number of battery connections. The charging voltage of the system can vary depending on the charging environment. We examined RAC$^+$ by changing the charging voltage between 10V and 30V, assessing RAC$^+$'s power loss and maximum battery connection length, and also examining the power loss relative to the maximum battery connection length.

We first examined the maximum length of battery connections which is determined by the charging voltage. A lower charging voltage results in a shorter maximum connection length of the battery. As illustrated in Fig. 4, the maximum connection length of the battery when charged at $10V$ was shorter than when charged at $30V$. The problem that arises with a shorter maximum battery connection length is that the variety of resistances proportional to the maximum connection length decreases. As the variety of resistances decreases, the number of batteries sharing the same resistance increases, which amplifies power loss during the charging process. As the number of battery connections sharing a resistance increases, power loss increases exponentially according to the power formula.

To evaluate the power loss under different charging environments, we compared the power loss across varying charging voltages and maximum lengths of battery connections.

First, we examined how the power loss changes under various charging voltages. As shown in Fig. 5, power loss decreases as the charging voltage decreases. Although the extent of reduction varies depending on the category voltage and battery connection length, the trend remains consistent. The power loss decreased because the amount of resistance required to support the appropriate current for the battery is reduced as the charging voltage decreases. However, as shown in Fig. 4, the maximum battery connection length is small, resulting in many battery connections sharing the same

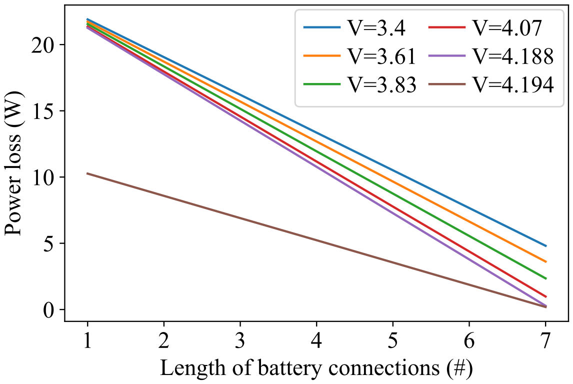


Fig. 6: Power loss according to the length of battery connections for each category, with charging voltage of 30V.

resistance. In small systems that can be supported with fewer battery connections, a lower charging voltage is advantageous. However, in large-capacity battery systems with many batteries, as mentioned earlier, the number of battery connections sharing the same resistance increases. Consequently, charging with a lower voltage ultimately leads to a significant increase in power loss.

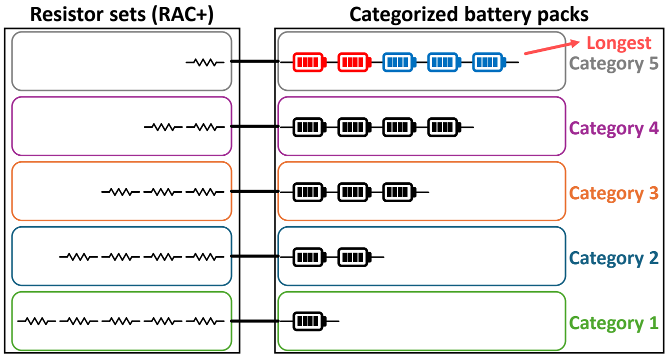
In the same category, as the length of battery connections increases, we can see that the resistance decreases, which affects power loss. We experimentally confirmed that power loss decreases as the length of the battery connection increases. Fig. 6 shows the results of how much power loss occurs in each category depending on the battery connection length when the charging voltage is set to $30V$. Consistent with the computational results verified by $\texttt{RAC}^{+}$, power loss decreases as the battery connection length increases. This again confirms that configuring battery connections to have longer connections is efficient for balancing.

D. Validation of Optimal Battery Connection Length

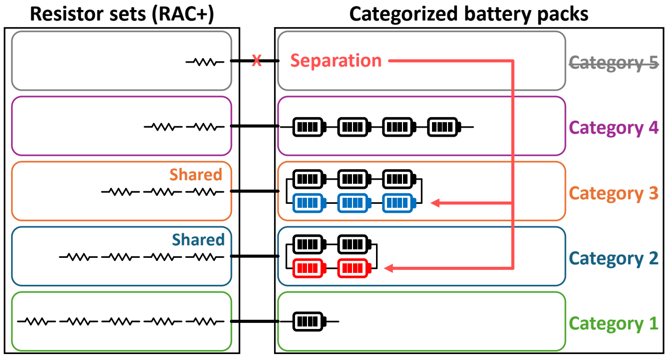
In this subsection, we validate our maximizing battery connection length strategy, compared with approaches that utilize fewer connections. We first propose a battery connection separating method, which enables utilizing less number of battery connections and then evaluate the performance based on battery connection length.

Separating a battery connection into existing other connections guarantees the operation of $\texttt{RAC}^{+}$, removing the longest battery connection category, as seen in Fig. 7. When separating battery connections, it is imperative to separate them into two other connections to minimize the overhead, specifically the increased power loss occurred from balancing. The battery connections are separated into shorter ones and share the resistor array. While this approach allows for reducing the required resistors in specific categories, the shared resistor array incurs additional power losses due to the concentrated current load. Note that the power loss from resistance is proportional to the square of the current.

To validate the optimality of our approach to maximize battery connection length, we compared the changes in power loss when removing the resistor array with the longest battery connections by the separation method. The charging voltage and category voltage were set to 30V and 3.83V, respectively.



(a) Selecting the longest battery connection (the top battery connection of the category) in the category with a disconnecting method.



(b) The battery connections that were in the area marked in light gray have been separated into red and blue battery connections and sharing resistor arrays.

Fig. 7: Increasing power loss by disconnecting the longest battery connection.

As shown in Fig. 8, removing the category of the longest battery connection with separation highly increased power losses. Even a single separation resulted in a four times increase in power loss from the resistors for a battery connection length of four. When separation was performed three times, the power loss increased nine times for the three battery connections. Although the three successive separations reduced the number of required resistors by 21%, this approach is not effective considering the significant rise in power losses.

V. CONCLUSION

In this paper, we present $\texttt{RAC}^{+}$, which enables cell balancing during charging with fewer resistors. Compared to the target previous work $\texttt{RAC}$, $\texttt{RAC}^{+}$ achieves a 69% reduction in the number of required resistors without any additional requirements, which also results in decreased power loss. Also, the extensive experiment results demonstrate that $\texttt{RAC}^{+}$ is not only robust to various charging environments, but also proven to be effective in terms of minimizing power loss.

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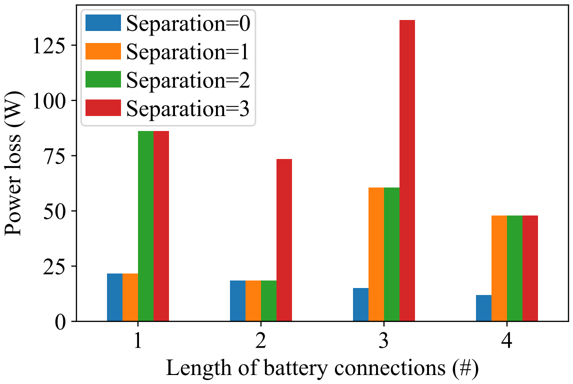

Fig. 8: Power loss according to the length of battery connections for max length, with the charging voltage of 30V and the category voltage of 3.83V.

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