Responses to Reviewers' Comments for Manuscript SPACE-D-23-00082

Maximum Allowable Current Determination of RBS By Using a Directed Graph Model and Greedy Algorithm

Addressed Comments for Publication to

Space: Science & Technology

by

Dr. Cheng Qian, on behalf of all authors

Dear Dr. Tian,

On behalf of my co-authors, we thank you very much for giving us an opportunity to revise our manuscript, we appreciate editor and reviewer very much for their positive and constructive comments and suggestions on our manuscript entitled “Maximum Allowable Current Determination of RBS By Using a Directed Graph Model and Greedy Algorithm”(ID:SPACE-D-23-00082).

We have studied reviewer’s comments carefully and have made revision which marked in red in the paper. We have tried our best to revise our manuscript according to the comments. Specially, this manuscript has been retouched by the professional organization, to further improve the readability. Attached please find the revised version, which we would like to submit for your kind consideration.

We would like to express our great appreciation to you and reviewers for comments on our paper. Looking forward to hearing from you.

Thank you and best regards.

Dr. Cheng Qian, on behalf of all authors

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2023.9.17

Authors' Response to Reviewer 1

Comment 1:

The authors should explain the most important achievements of the proposed method quantitatively, in the abstract.

Response:

Thanks for the reviewer's valuable feedback. We have carefully considered this suggestion and made the following modifications to address the reviewer's concern:

By introducing the shortest path (SP) of the battery, the greedy algorithm transforms the enumeration of switch states in the brute force algorithm into the combination of the SPs, resulting in more efficient computation of the maximum allowable current (MAC). We have also provided a theoretical estimation of the improvement, which is proportional to $2^{N_s-N_b}N_s\log_{10}N_b$ for an RBS with N_b batteries and N_s switches.

Here is the specific content we added in the abstract:

> This paper proposes a method to calculate the MAC of arbitrary RBSs using a greedy algorithm in conjunction with a directed graph model of the RBS. By introducing the shortest path of the battery, the greedy algorithm transforms the enumeration of switch states in the brute-force algorithm into the combination of the shortest paths, which greatly increases the efficiency with which the MAC is determined. The directed graph model, based on the equivalent circuit, provides a specific method for calculating the MAC of a given structure. The proposed method is validated on two published four-battery-RBSs and one with a more complex structure. The results are the same as those of the brute-force algorithm, but the proposed method significantly improves the computational efficiency ($N_s2^{N_s-N_b}\log_{10}N_b$ times faster than the brute force algorithm for an RBS with N_b batteries and N_s switches, theoretically). The main advantage of the proposed method is its ability to calculate the MAC of RBSs with arbitrary structures, even in scenarios with random isolated batteries.

We hope the above content provide a more quantitative explanation of the achievements of our proposed method in the abstract.

Comment 2:
The literature review in the introduction section is very short, and the related works, especially the works published in recent years, have not been well reviewed and compared, and the conclusions about the existing research gaps have not been presented.

Response:

Considering the Reviewer's suggestion, we have expanded the literature review in the introduction section to provide a comprehensive overview of the existing RBS structures [1–7] and related works on structure analyses [8, 9]. Although many RBS structures have been proposed for different purposes, such as dynamically adjusting the output voltage , increasing energy utilization efficiency, and improving the system's ability to recover from battery failures, these structures also bring challenges in design and control of the systems. Therefore, several works on structure analyses, like the maximum switch current and the short-circuit problem, have been proposed to tackle these challenges recently. However, determining the MAC of RBSs remains blank accroding to our literature review. A straightforward method is to enumerate all possible switch states. But this method has exponentially increasing computational complexity with the number of switches, and is too ineffection to apply.

Here is the specific modification we made in the introduction:

> Recently, various types of RBSs with different flexibility and reconfigurability have been designed to meet application requirements. For example, Ci et al. [1] proposed an RBS structure that dynamically adjusts the battery discharge rate to fully exploit the available capacity of each battery. Jan's [2, 3] structures reconfigure

structures with variant batteries in series to reach the (constantly changing) voltage requirements during electric vehicle charging. As shown in Fig. 1a, the structure proposed by Visairo et al. [4] changes the system's output voltage based on the load conditions, thereby reducing the power loss of the voltage regulator during the power supply process and improving the efficiency of energy use. Also, to enhance the energy efficiency of the system, Lawson et al. [5] and He et al. [6] proposed simplified structures that have fewer switches than Visairo's design. Kim et al. [7] improved the system's ability to recover from battery failures by introducing multiple ports into the structure.

The complex structure between batteries and switches gives RBSs flexibility but also creates challenges in the design and control of the system. Thus, several approaches to analyze the RBS structure and performance have been proposed to tackle these challenges. For instance, Han et al. [8] derived an analytical expression for the maximum switch current during battery system reconfiguration for a specific RBS structure. This helps guide the selection of switches and supports the design of RBS hardware. Chen et al. [9] proposed a systematic approach based on sneak circuit theory to fundamentally avoid the short-circuit problem of RBSs: They thoroughly analyzed all paths between the cathode and anode of each battery in the RBS and identified paths that only contain switches as short-circuit paths for pre-checking before system reconfiguration.

In spite of the maximum switch current mentioned above, the maximum allowable current (MAC), defined as the maximum allowed current under the constraints of the battery cell, is another critical indicator of RBSs that needs to be evaluated during the design or control of the system. The MAC helps the designers assess whether the RBS meets the output current requirements and contributes to the formulation of appropriate and safe management strategies for the battery management system. Unfortunately, few studies have analyzed the RBS structure to determine the RBS MAC. An intuitive and straightforward method is to enumerate all possible switch states and calculate the output current of the system under each reconfigurated structure. However, this method is inefficient and time-consuming, especially for RBSs with a large number of switches.

Thanks again for the reviewer's comments, which have greatly improved the quality and comprehensiveness of our manuscript.

Comment 3:
It is necessary for the authors to clearly state research contribution and achievements as bullet points at the end of the Introduction section.

Response:

We appreciate and accept your suggestion and have added a clear statement of the contributions in the second-to-last paragraph of the Introduction, as shown below:

The main contributions of this paper can be summarized as follows:

- An efficient method is proposed to determine the MAC of RBSs with arbitrary structures, including scenarios with isolated batteries.
- The greedy algorithm is applied to solve the MAC problem, the computational complexity of which is greatly reduced compared with the brute-force algorithm.
- An improved directed graph model is introduced; it considers the voltage, the internal resistance, the MAC of the battery, and the external load to analyze the current of the RBS.

Comment 4:

The authors need to present the complexity of their proposed method and compare it with some other state-of-the-art or successful classic methods.

Response:

We totally agree with the reviewer's suggestion. It is indeed necessary to analyze the complexity of the proposed method and compare it with other existing methods.

We have derived the average time complexity of our proposed greedy algorithm-based MAC determination method to be approximately $O(2^{N_b} N_s^2 \log_{10} N_b)$, where N_b and N_s are the number of batteries and switches, respectively. However, as mentioned in our response to Comment 2, there is a blank in the literature regarding MAC determination methods. The brute force method, the most straightforward and intuitive method, is used as a benchmark for comparison, the time complexity of which is $O(2^{N_s} N_s^3)$. Since the number of switches in RBS is typically 3 to 5 times the batteries[10–15], the method we proposed is theoretically more efficient than the brute force method. It has been validated by the case study in the manuscript.

The detailed derivation and discussion of the above points have been added to the revised manuscript under the Discussion subsection. Here is the specific content:

> The literature contains no report on an algorithm for calculating the MAC of an RBS. The brute-force algorithm, which goes through all possible switch states, is the most straightforward way to determine the MAC and is used as a benchmark for the proposed greedy algorithm. If an RBS has N_b batteries and N_s switches and the corresponding directed graph has N nodes, 2^{N_s} iterations are required to traverse all reconfigured structures. Calculating each reconfigured structure using Eqs. (7)–(10) requires matrix inversion and matrix multiplication, which has a time complexity of $O(N^3 + 2N^2 N_b + N^2 N_s + N N_b^2)$. Therefore, the time complexity of the brute-force algorithm is $O((N^3 + 2N^2 N_b + N^2 N_s + N N_b^2) 2^{N_s})$. The greedy algorithm proposed in this paper requires that SP be found for each battery, which requires N_b iterations.

Each SP can be obtained by several applications of Dijkstra's algorithms. Therefore, the total time complexity for calculating all SPs is $O\big(N_b(N_b+2N_s)\log_{10} N\big)$. According to Appendix 1, the RBS can reconfigure $C_{N_b}^{N_{\text{set}}}$ structures by selecting N_{set} batteries from N_b batteries, which gives $\sum_{N_{\text{set}}=1}^{N_b} C_{N_b}^{N_{\text{set}}}/N_b \approx 2^{N_b}N_b^{-1}$ on average. Thus, with the bisection method, the time complexity of the greedy algorithm is $O\big((N^3+2N^2N_b+N^2N_s+NN_b^2)2^{N_b}N_b^{-1}\log_{10} N_b + N_b(N_b+2N_s)\log_{10} N\big)$. Based on currently proposed RBS structures [10–15], the number N_b of batteries, N_s of switches, and N of nodes are quantitatively related as follows: $N_s \approx (3\text{–}5)N_b$, $N \approx N_s$. After simplifying, the time complexity of the method with greedy algorithm is $O(2^{N_b}N_s^2\log_{10} N_b)$, while it is $O(2^{N_s}N_s^3)$ for the method with brute force algorithm. Therefore, as the RBS grows, especially in the number of switches, the greedy algorithm gains an advantage over the brute-force algorithm. This is confirmed by the number of structures required to determine the MAC in the previous section. Compared with the brute-force algorithm, the method based on the greedy algorithm is 3 000 to 48 000 times more efficient, which is theoretically $N_s2^{N_s-N_b}\log_{10} N_b$ times according to the above time-complexity analysis. This benefits from two key points:

(1) The SPs guide the RBS to reconfigure reasonable structures rather than blindly going through all possible structures. This reduces the complexity from 2^{N_s} to 2^{N_b}, which is the main reason for the improvement in efficiency.

(2) The bisection method further accelerates this process, reducing the complexity from 2^{N_b} to $2^{N_b}N_B^{-1}\log_{10} N_b$.

Comment 5:

The authors don't discuss the limitations of the study correctly.

Response:

We are sorry for our negligence of the limitations of the study. As far as we are concerned, although the method we proposed is strongly efficient than the brute force method, it still has a exponential relationship with the number of batteries. That means unsufferable time will be costed for systems with large number of batteries.

Here is the specific content we added in the discussion:

> However, the greedy algorithm proposed in this paper still contains exponential terms in the time complexity, which means it may not be able to handle extremely large RBS structures having large N_b.

> **Comment 6:**
> Some typos should be double check.

Response:

We are very sorry for our incorrect writing, and have carefully checked the manuscript and corrected the typos.

> **Comment 7:**
> The author should explain more why solution quality of their proposed approach is much better than the others?

Response:

We appreciate the reviewer's concern regarding the explanation of why the solution quality of our proposed approach is better to others. However, after careful literature research, we would like to clarify that there are currently no existing works on the MAC determination of RBSs that we could compare our solution with. Therefore, it is not possible to directly compare the solution quality of our proposed approach with others.

Comment 8:

Authors should mention some novel works in the field in the introduction, specially refer to this 2023 reference: An efficient lightweight algorithm for scheduling tasks onto dynamically reconfigurable hardware using graph-oriented simulated annealing, which uses graph-based method. Mention and refer to it in the introduction section.

Response:

Thanks to the reviewer's suggestion, we have introduced two novel works in the RBS structure analysis field in the introduction, which respectively study the maximum switch current [8] and the short-circuit problem [9]. We believe that these works represent the innovation and recent advances in the field of RBS structure analysis.

The reviewer also mentioned the work "An efficient lightweight algorithm for scheduling tasks onto dynamically reconfigurable hardware using graph-oriented simulated annealing", sepcially. After carefully reading and fully discussion, we reached a conclusion that this paper is not relevant to our research. Although this paper uses a graph-based method, whose name is similar to the method described in our paper, it mainly studies the task scheduling problem in time series. While our research is about the maximum allowable current of RBS structure, which belongs to the field of structure analysis. Therefore, we think it is not appropriate to include this paper in our introduction and will not cite it.

Comment 9:

Authors need to explain about the accuracy, sufficiency and reliability of their results? How do they verify and validate the results?

Response:

Thanks for the reviewer's valuable feedback. We have carefully considered the reviewer's question. In response, we complemented the computation and validation with the brute force method and provided more detailed explanation and discussion.

In the Case study section of the paper, we investigated three RBS structures, two of which are from published literatures [4, 5] and the other is designed by ourselves, as shown in Figs. 1a, 1b, and 1c, respectively. The results of the three RBS structures calculated by our proposed method are shown in Tabs. 1, 2 and 3, respectively. The results by brute force method are shown in Tabs. 4, 5 and 6, respectively.

On the one hand, as shown in the Tabs. 1 – 6, the reconfigured structure results from greedy algorithm are consistent with the results from the brute force algorithm. Since the brute force algorithm enumerates all possible reconfigured structures, it ensures that we obtain the global optimal solution. On the other hand, the output current of the system calculated by our directed graph model is consistent with the experience and common sense. To illustrate this, the RBS in Fig. 1c is taken as an example here. The four batteries in this system can be divided into two groups: gourp g_A has B_1 and B_2; group g_B has B_3 and B_4. The relationship between the two batteries in each group can be switched between series and parallel by reconfigurating the structure. While the two groups can only connect in series or disconnect. Therefore, this system's MAC is the maximum of the MAC of the two groups (i.e., $\max[\mathrm{MAC}(g_A), \mathrm{MAC}(g_B)]$). Both g_A and g_B are the two-battery and degenerated structure of the RBS in Fig. 1b, and have the same MAC (i.e., 2). Therefore, the MAC of the RBS in Fig. 1c is 2, consistent with the result shown in Tab. 3.

We hope the above content can address the reviewer's concerns.

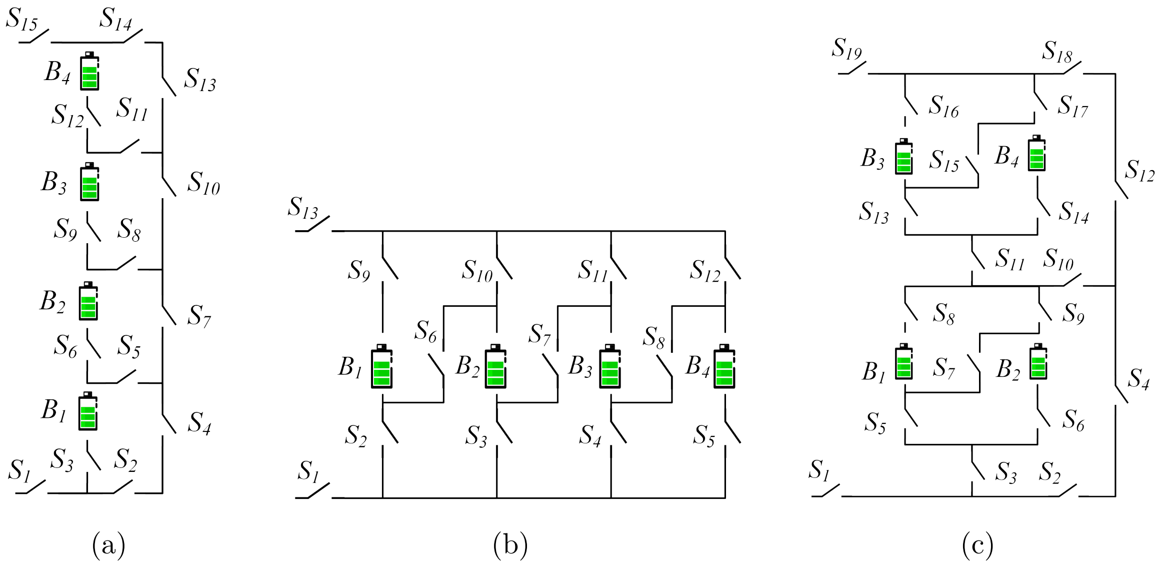

Figure 1: The four-battery RBS structures proposed by (a)Lawson[5], (b)Visairo[4] and (c)this paper.

Table 1: MAC Calculating result of the RBS structure in Figure 5a with our method.

Structure	Figure 5a with 4 batteries and 15 switches
Switch ON	S_1,S_3,S_5,S_7,S_{10},S_{13},S_{14},S_{15}
I_o	$u_b/(R_o + r_b)$
$\boldsymbol{I}_b$	$[u_b/(R_o + r_b), 0, 0, 0]$
$\max \eta$	1
computed structure count	11

Table 2: MAC Calculating result of the RBS structure in Figure 5b with our method.

Structure	Figure 5b with 4 batteries and 13 switches
Switch ON	S_1,S_2,S_3,S_4,S_5,S_9,S_{10},S_{11},S_{12},S_{13}
I_o	$4u_b/(4R_o + r_b)$
$\boldsymbol{I}_b$	$[u_b/(4R_o + r_b), u_b/(4R_o + r_b), u_b/(4R_o + r_b), u_b/(4R_o + r_b)]$
$\max \eta$	4
computed structure count	1

Table 3: MAC Calculating result of the RBS structure in Figure 5c with our method.

Structure	Figure 5c with 4 batteries and 19 switches
Switch ON	S_1,S_3,S_5,S_6,S_8,S_9,S_{10},S_{12},S_{18},S_{19}
I_o	$2u_b/(2R_o + r_b)$
$\boldsymbol{I}_b$	$[u_b/(2R_o + r_b), u_b/(2R_o + r_b), 0, 0]$
$\max \eta$	2
computed structure count	11

Table 4: MAC Calculating result of the RBS structure in Figure 5a with brute force method.

Structure	Figure 5a with 4 batteries and 15 switches
Switch ON	S_1,S_3,S_5,S_7,S_{10},S_{13},S_{14},S_{15}
I_o	$u_b/(R_o + r_b)$
$\boldsymbol{I}_b$	$[u_b/(R_o + r_b), 0, 0, 0]$
$\max \eta$	1
computed structure count	32768

Table 5: MAC Calculating result of the RBS structure in Figure 5b with brute force method.

Structure	Figure 5b with 4 batteries and 13 switches
Switch ON	S_1,S_2,S_3,S_4,S_5,S_9,S_{10},S_{11},S_{12},S_{13}
I_o	$4u_b/(4R_o+r_b)$
$\boldsymbol{I}_b$	$[u_b/(4R_o+r_b), u_b/(4R_o+r_b), u_b/(4R_o+r_b), u_b/(4R_o+r_b)]$
$\max \eta$	4
computed structure count	8192

Table 6: MAC Calculating result of the RBS structure in Figure 5c with brute force method.

Structure	Figure 5c with 4 batteries and 19 switches
Switch ON	S_1,S_3,S_5,S_6,S_8,S_9,S_{10},S_{12},S_{18},S_{19}
I_o	$2u_b/(2R_o+r_b)$
$\boldsymbol{I}_b$	$[u_b/(2R_o+r_b), u_b/(2R_o+r_b), 0, 0]$
$\max \eta$	2
computed structure count	524288

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