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DESIGNING OPTIMUM CAPACITANCE AND SWITCHING FREQUENCY PARAMETERS FOR MINIMIZING BALANCING DURATION IN CELL-LEVEL BALANCING USING ONE SWITCHED CAPACITOR TECHNIQUE: A MATLAB-BASED APPROACH

TEK ANAHTARLAMALI KAPASITÖR TEKNIĞI KULLANILARAK HÜCRE DÜZEYINDE DENGELEMEDE DENGELEME SÜRESINI EN AZA İNDIRMEK İÇIN OPTIMUM KAPASITANS VE ANAHTARLAMA FREKANSI PARAMETRELERININ TASARLANMASI: MATLAB TABANLI BIR YAKLAŞIM

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ABSTRACT

This study presents a MATLAB-based approach to minimize balancing duration in cell-level balancing using a single switched capacitor method. The proposed methodology explores a range of capacitance and switching frequency values, formulating an objective function to minimize balancing duration while considering constraints. Simulation results demonstrate the effectiveness of the approach in achieving significant reductions in balancing duration. This research provides valuable insights into optimal cell-level balancing system design, aiding the development of efficient battery management systems.

Keywords: Cell Balancing, MATLAB-Based Optimum Capacitance, One Switched Capacitor Method, Optimum Switching Frequency

ÖZET

Bu çalışma, tek anahtarlamalı kapasitör yöntemini kullanarak hücre düzeyinde dengelemede dengeleme süresini en aza indirmek için MATLAB tabanlı bir yaklaşım sunmaktadır. Önerilen metodoloji, kısıtlamaları göz önünde bulundurarak dengeleme süresini en aza indirecek bir amaç fonksiyonu formüle ederek bir dizi kapasitans ve anahtarlama frekansı değerini araştırır. Simülasyon sonuçları, yaklaşımın dengeleme süresinde önemli azalmalar sağlamadaki etkinliğini göstermektedir. Bu araştırma, verimli pil yönetim sistemlerinin geliştirilmesine yardımcı olarak optimum hücre seviyesi dengeleme sistemi tasarımına değerli bilgiler katıyor.

Anahtar Kelimeler: Hücre Dengeleme, MATLAB Tabanlı Optimum Kapasitans, Optimum Anahtarlama Frekansı, Tek Anahtarlamalı Kapasitör Yöntemi

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1. INTRODUCTION

Cell balancing is a crucial aspect of battery management systems (BMS) to ensure optimal performance, prolong battery life, and maintain uniform cell voltages [1]. Over time, variations in cell characteristics such as capacity, internal resistance, and aging can lead to imbalances among the cells in a battery pack. These imbalances can result in reduced overall capacity, accelerated degradation, and even safety hazards. To address these issues, various cell balancing techniques have been proposed and implemented, aiming to redistribute charge among cells and equalize their voltages [1, 2]. BMS is divided into two main headings as active and passive methods. Both active and passive cell balancing are effective ways to improve system health by monitoring and matching the state of charge (SoC) of each cell [3]. Active cell balancing redistributes the charge during the charge and discharge cycle, unlike passive cell balancing, which simply distributes the charge during the charge cycle [4]. Thus, active cell balancing increases system uptime and can improve charging efficiency. At the same time, it is a method that is more reliable, avoids energy wastage as it sends excess energy to the low-energy cell, and has a faster balancing speed. Active balancing creates a more complex, larger carbon footprint and passive balancing is more cost-effective [5]. Therefore, passive balancing is more preferred in the sector. However, active balancing is more suitable for high-voltage applications and electric vehicle technologies [4].

One switched capacitor technique is not a common method in active balancing. This technique consists of sets of switches and one capacitor. The working principle is based on a high-voltage cell charging the capacitor and then the capacitor discharging to a low-voltage cell. This method ensures that energy is transferred with minimum amount of loss [6, 7]. By implementing a more effective control strategy, one switched capacitor cell balancing can enhance its overall performance [8, 9]. This approach involves reducing the size of the capacitor, minimizing system costs, and decreasing the time required for balancing. The key concept is to maximize the efficient transfer of energy between the cells while simultaneously minimizing the capacitor size and balancing time. This optimum capacitance and frequency are achieved by intelligent control of the switches based on the extracted energy cost function(s) [10].

However, the effectiveness of the one-switched capacitor technique relies heavily on the appropriate selection of capacitance and switching frequency parameters. Choosing optimal values for these parameters is crucial to minimize the balancing duration while ensuring safe operation and maintaining desired voltage limits [11]. Achieving the optimal combination of capacitance and switching frequency presents a complex problem, as it involves trade-offs between balancing efficiency, power dissipation, component specifications, and voltage constraints [12].

In this research, we propose a MATLAB-based approach to find optimum capacitance and switching frequency parameters for minimizing balancing duration in cell-level balancing using a one-switched capacitor technique. MATLAB provides a powerful and versatile platform for numerical analysis, simulation, and optimization, making it an ideal tool for this study. By leveraging the computational capabilities of MATLAB, we aim to systematically explore a wide range of capacitance and switching frequency values, evaluate their impact on the balancing duration, and determine the optimal parameter settings [13, 24].

The main objective of this research is to identify the capacitance and switching frequency values that yield the minimum balancing duration while satisfying the specified constraints [14, 15, 16]. To achieve this, we formulate an objective function that quantifies the balancing duration and incorporates the constraints related to voltage limits and component specifications [17]. By employing algorithms available in MATLAB, we can efficiently search for the optimal parameter values that minimize the objective function.

Through extensive simulations and analysis, we evaluate the effectiveness of the MATLAB-based approach in achieving the desired outcomes. We investigate the impact of different capacitance and switching frequency values on the balancing duration and assess the trade-offs between balancing efficiency and other performance metrics [18]. The results obtained from this research provide valuable insights into the optimal design of cell-level balancing systems using a one-switched capacitor technique [19].

Overall, this research contributes to the body of knowledge in battery management systems and cell balancing techniques by presenting a MATLAB-based approach for determining the best capacitance and switching frequency values to minimize balancing duration. The findings of this study have practical implications for the design and implementation of efficient and cost-effective battery management systems, ultimately enhancing the performance, reliability, and longevity of battery packs in various applications [4].

2. METHODOLOGY

The proposed methodology involves using MATLAB to simulate the cell balancing process using a single switched capacitor technique. The objective is to minimize the balancing duration by optimizing the capacitance and switching frequency parameters. The process begins with defining the objective function, which aims to minimize the time required to balance the cells. Constraints are then applied to ensure the solution is practical and feasible. The simulation is conducted over a range of capacitance and switching frequency values, and the results are analyzed to identify the optimal parameters.

Unlike previous studies, this approach provides a detailed examination of the interplay between capacitance and switching frequency, offering a novel perspective on optimizing the balancing process.

In the Coulomb counting method, the current value is multiplied by the time interval to obtain Ah value. Later, the addition of spent Ah values is subtracted from the total Ah capacity of the battery. Lastly, the left Ah value is turned into a percentage as SoC [21].

$$SoC = Soc(t-1) + \frac{\imath(t)}{Qn}\,\Delta t \tag{1}$$

$$V_{c_{charging}} = \left(V_f - V_i\right)\left(1 - e^{\frac{-t}{\tau}}\right) + V_i = V_{diff}\left(1 - e^{\frac{-t}{\tau}}\right) + V_i \tag{2}$$

$$i_c = C\frac{dVc}{dt} = C\frac{1}{\tau}.Vd_{iff}.e^{\frac{-t}{\tau}} = \frac{V\,diff}{Rs}.e^{\frac{-t}{\tau}} \tag{3}$$

where; SoC is State of Charge of the battery pack, η is efficiency, and Q is charge capacity of the battery pack. Because of the nonlinear charging and discharging characteristic of Li-Ion battery as given in Figure 1, exponential function is used to obtain an appropriate model.

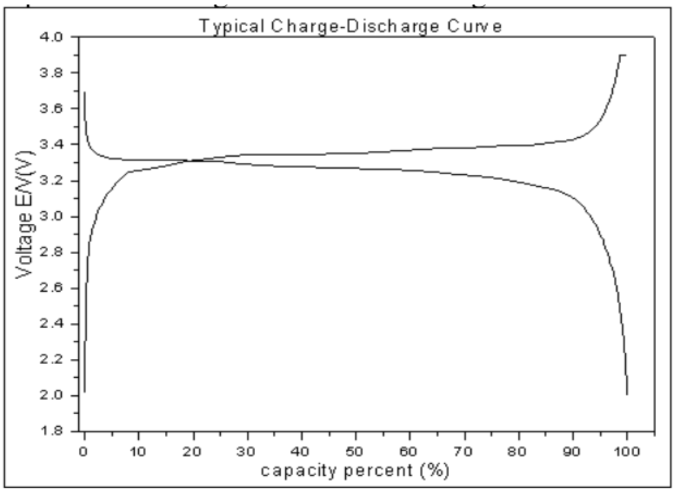


Figure 1. Li-Ion charge-discharge curve [20]

Figure 2 shows the amount of energy capacitor can be charged and discharged on various values of duty cycle [22, 23]. The duty cycle refers to the amount of time a signal is on during a given period. Therefore, the decision of providing 0.9 of the periods for the charging process will result leaving only 0.1 for the discharging process which will cause capacitor to not fully discharge its energy into the low-voltage cell during balancing [25]. Because of that, even though energy transferred seem to increase with the duty cycle, due to the fundamentals of the term of duty cycle, 0.5 gives the best results for energy transfer during balancing [26, 27]. The charging and discharging formulas are given (4) and (5) respectively.

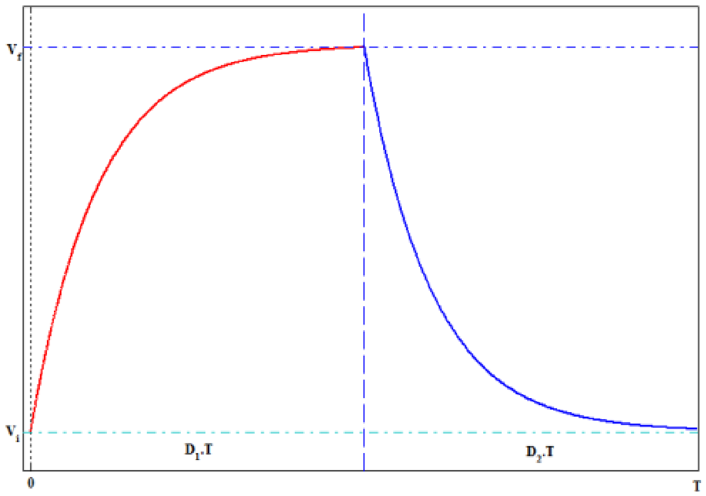


Figure 2. Charge and discharge graph of the balancing capacitor [1]

$$\int_0^{DT} v_C . i_C \, dt = C . V_{diff} \left\{ \left[\frac{V_{diff}}{2} . e^{\frac{-2D}{\tau.F}} - V_f . e^{\frac{-D}{\tau.F}} \right] - \left[\frac{V_{diff}}{2} - V_f \right] \right\} * F \qquad (4)$$

$$\int_0^{DT} \left[V_{diff} . e^{\frac{-t}{\tau}} + V_i \right] . \left[\frac{-V_{diff}}{R_{seq}} . e^{\frac{-t}{\tau}} \right] dt = C . V_{diff} \left\{ \left[\frac{V_{diff}}{2} . e^{\frac{-2D}{\tau.F}} - V_i . e^{\frac{-D}{\tau.F}} \right] - \left[\frac{V_{diff}}{2} + V_i \right] \right\} * F \qquad (5)$$

Figure 3 also states that increasing the switching frequency over 500 Hz does not provide a significant difference in terms of the amount of energy transferred between cells and the capacitor. Therefore, switching frequency is chosen to be 500 Hz.Based on the capacitor values already existing on the market, such graphs are drawn by only changing the capacitor value as shown in the Figure 4. Since the duty cycle is determined as 0.5 and switching frequency is 500 Hz, those graphs are obtained to determine the best capacitor value capacitor value as 4.7 µF for the most amount of energy transfer.

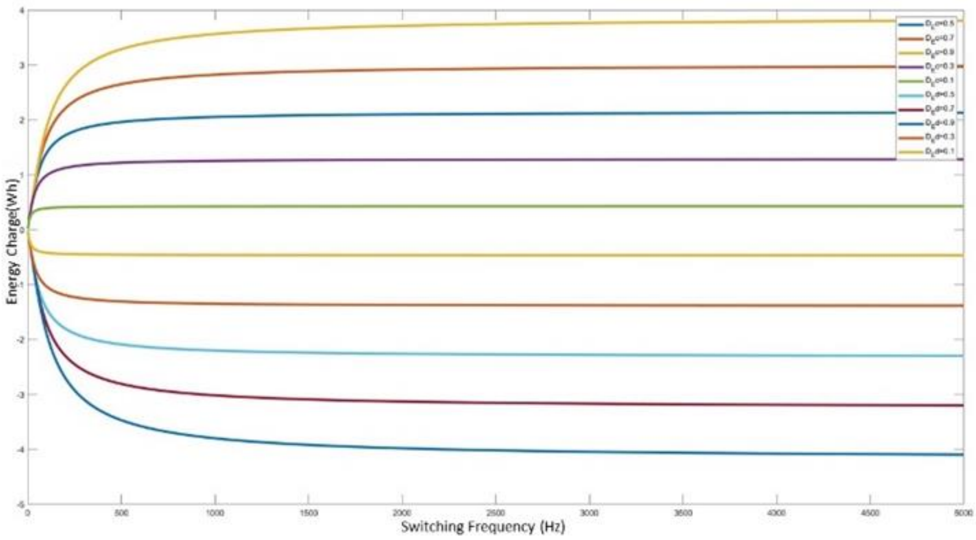


Figure 3. Energy Charge & Discharge Graph Depends on Duty Cycle

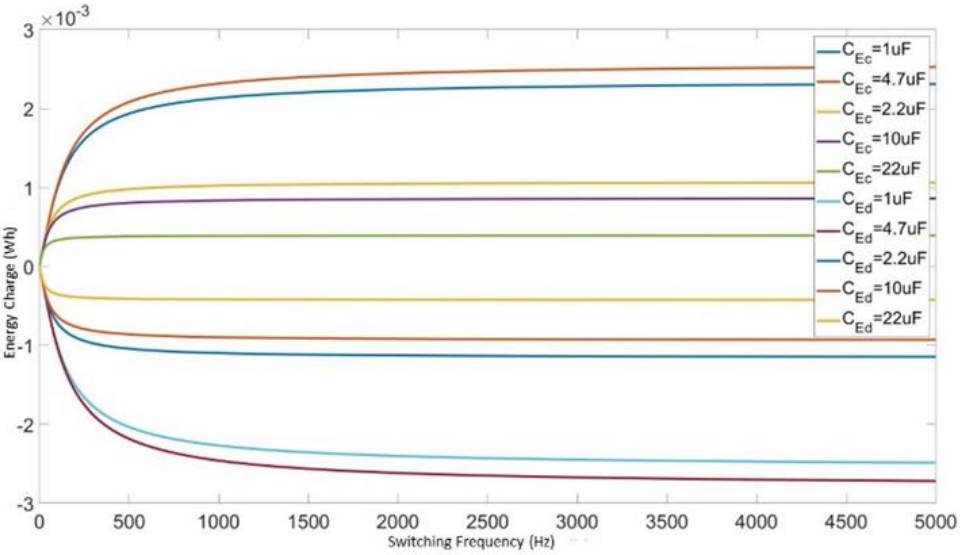


Figure 4. Capacitor Comparison

3. SIMULATION RESULTS AND DISCUSSION

Simulations were performed to evaluate the effectiveness of the proposed approach. The MATLAB simulation environment was used to model the cell balancing process, considering various capacitance and switching frequency values. The results indicate that the proposed method can significantly reduce the balancing duration compared to traditional methods. These findings demonstrate the potential of the proposed approach for improving the efficiency of battery management systems.

The proposed control strategy for the balancing can be summarized in the following steps:

- Extracting the function of the transferred energy between the cells and the capacitor [see Equation 4]. This function can be easily maximized for transferred energy, but it is also needed to take into account those five premonition variables (C, F, V_{diff}, R_{Seq}, and D).
- Selecting the minimum optimal capacitor value by maximizing the energy function with respect to the capacitor value at different switching frequencies. The transferred energy will be a function of capacitance and switching frequency (C, F), with arbitrary V_{diff} and D values, as the latter two parameters will vary during balancing periods.
- After selecting the capacitor value considering the given equivalent series resistance (ESR), maximize the energy transfer using the calculated values of capacitance (C) and equivalent series resistance (R_{Seq}) as a function of switching frequency (F) and duty cycle (D) for various voltage differences (V_{diff}).
- Dividing the balancing period into zones based on the voltage difference V_{diff} allows us to determine the maximum current that can flow through the capacitor and the corresponding equivalent resistor value RSeq. This resistor value enables us to select a specific D value and determine the permissible range of switching frequencies, as shown in Figure 3.
- By knowing the higher and lower cell voltage, applying the corresponding F and D along the balancing time according to the cell voltages to get the maximum energy transfer.

Let's examine these approaches using MATLAB:

Define the given values and the range for F and C

```
Vdiff = 0.29

R = 0.25

vf = 4
```

```
Vdiff = 0.29

R = 0.25

vf = 4
```

Along with the given variables, it is possible to execute the optimization of two energy types both charge and discharge. Formulas found in this paper were used (4,5). To find energy change during charging of the one switched capacitor, line of code is given.

$$E_C = C.V_{diff}\left\{\left[\frac{V_{diff}}{2}.e^{\frac{-2D}{\tau.F}} - V_f.e^{\frac{-D}{\tau.F}}\right] - \left[\frac{V_{diff}}{2} - V_f\right]\right\} * F$$

To find Energy change during discharging of the one switched capacitor, such line is written as:

$$E_D = C.V_{diff}\left\{\left[\frac{V_{diff}}{2}.e^{\frac{-2D}{\tau.F}} - V_i.e^{\frac{-D}{\tau.F}}\right] - \left[\frac{V_{diff}}{2} + V_i\right]\right\} * F$$

The energy change graph is found as given in Figure 5, later the maximum and minimum points are observed. Given three-dimensional graph has two regions. First one, the upper half, has positive energy values which means it shows charging of the one switched capacitor. Second region, the lower half, has negative values. Because of the fact that it shows the amount of energy discharged from one switched into low energy cell during cell balancing, it shows negative values in shades of blue. To show effects of switching frequency and capacitance of the one switched capacitor on energy values in both charging and discharging, two regions are matched according to the same capacitance and frequency values.

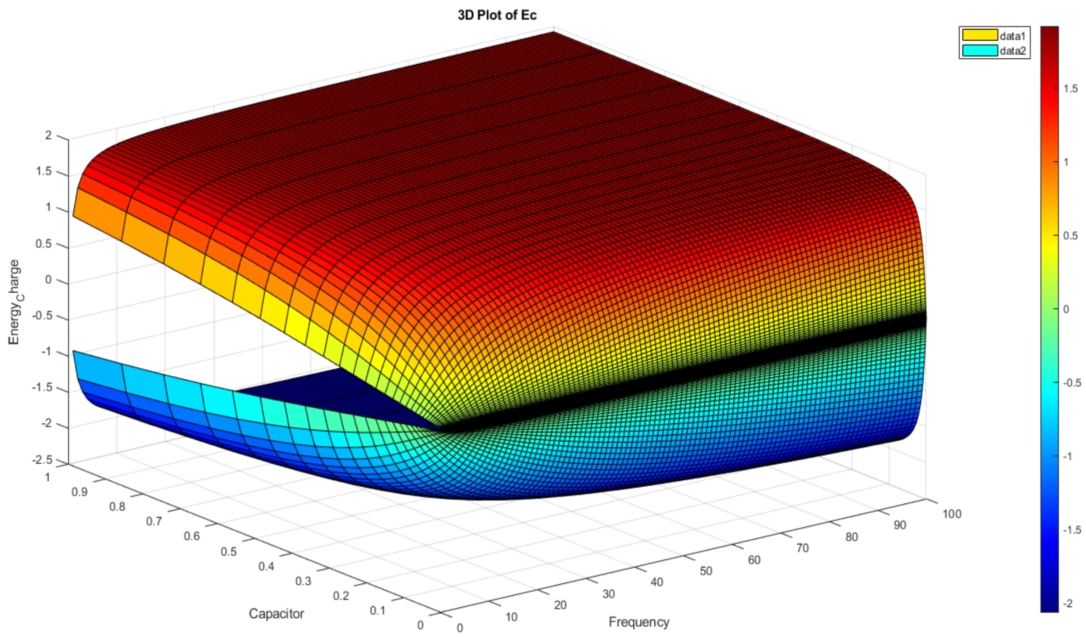
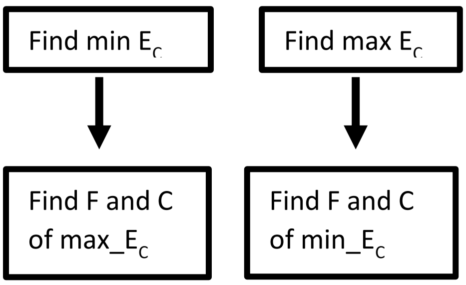


Figure 5. 3D-Plot of energy changes of battery pack

Max and Min value;



Energy charge has the maximum value at C=1 F and F=9901 Hz, minimum value at F=1 Hz and C=10^(-6) F.

Those values are 1.94 Wh/h for maximum and 1.12x10^(-6) Wh/h for minimum.

4. CONCLUSION

In general, the utilization of active balancing is not as prevalent as passive balancing in various applications within the field. There are numerous methods, approaches, and variations of applications when it comes to active balancing, making it challenging to select components for a specific application. Furthermore, the single switched capacitor technique is not commonly applied in a wide range of active balancing methods, adding to the uncertainties. The challenge involves not only choosing component types but also determining the values of these components, which are heavily dependent on the switching frequency controlled by the BMS. Consequently, the effectiveness of the single switched capacitor technique relies on these selections. Considering the available data, the proposed control strategy for balancing Li-ion batteries using a single switched capacitor involves optimizing transferred energy variables such as capacitance, voltage difference, equivalent series resistance, switching frequency, and duty cycle.

By determining the optimal values for these parameters, energy transfer can be maximized during the balancing process. Dividing the balancing period into voltage-difference-based zones helps identify the maximum current and corresponding equivalent resistor value for efficient balancing. Applying the appropriate switching frequency and duty cycle based on cell voltages allows for optimal energy transfer. On the other hand, scalability and system integration play important roles in designing a BMS. Given the Vdiff, Vf, and Vi variables are 0.29V, 4V, and 3.71V, respectively, the solution presented in this paper is applied for cell balancing between two 3.7V Li-ion cells. Also, this method can be adapted for large-scale battery packs by adjusting the variables. The results obtained from the simulations indicate that optimizing capacitance and switching frequency parameters can lead to significant reductions in balancing duration. This improvement can enhance the overall performance and efficiency of battery management systems. However, implementing the proposed method in real-world applications may present challenges. Factors such as the accuracy of the model, variations in cell characteristics, and environmental conditions can affect the performance of the balancing system. In summary, this control strategy aims to achieve maximum energy transfer during each cycle of cell balancing, resulting in reduced balancing time for applications such as decreasing charging duration in EVs or reducing charging time in micro-grid systems using grid power during off-peak hours. ”

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