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Research Paper

Voltage equalizer enhancement of series-connected battery strings using variable duty cycle PWM of a dynamic capacitor circuit

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ABSTRACT

Electric storage systems like solar systems and electric vehicles use batteries for storing electricity due to their simplicity, efficiency, considerably small size, and dispatchability. These batteries operate on the principle of charging/discharging and require equalization for voltage balance, especially in series-connected batteries. In this research, a novel technique is presented for enhancing batteries' voltage equalization, which is based on the variable duty cycle, D, of pulse width modulation (PWM) in the dynamic capacitor technique. This method controls two energy storage elements: an inductor and a dynamic capacitor via a variable D of PWM. The presented technique was implemented on lead-acid batteries connected in series using MATLAB/Simulink. The simulation results showed that increasing D to 80% can reduce the equalizing process time from 500 seconds to just 125 seconds, with voltage differences decreasing from $800mV$ to just $2.2mV$, equalized by 99.98%. For comparison, a well-known fixed switched-capacitor technique was used, and results showed that the variation of D had no effect even after 500 seconds of the equalizing process, and the batteries' terminal difference voltages still were above $220mV$ (less than 72% equalizing). Thus, the presented technique demonstrates superior performance, highlighting the significant contribution of variable duty cycle PWM in balancing batteries' terminal voltages.

1. Introduction

In the last decades, global warming issues and increasing greenhouse emissions have led increasingly to depend more on renewable energies for supplying electricity. The major drawback of these energies is unavailability all the time [1]. Therefore, energy storage is necessary to keep supplying electricity to customers as well as store energy when there is a surplus of production. Using batteries, in general, is a promising solution to overcome the drawbacks of renewable energies [2]. The rapid charging/discharging cycles of the batteries make them suitable for most of today's applications such as PV power systems, electrical vehicles, uninterrupted power systems, etc. Currently, there are many manufacturers around the world working on designing and developing different technologies of batteries: lead-acid and lithium-ion batteries are among the most used batteries[3,4]. In general, the battery has low voltage and low capacity and to increase its voltage and capacity it needs to be connected with other batteries in combinations of series-parallel strings. Batteries in these combinations should have equal voltages, capacity (ampere-hours), types, and the same manufacturers otherwise lead to unbalancing in terminal voltages. Consequently, reduces their lifetime However, due to chemical materials and manufacturing processes, these batteries may not have the same terminal voltages [5,6]. A voltage balance that refers to an equalizer is needed to maintain their terminal voltages[7]. In the literature, there are many proposed techniques and commercial equalizer devices. Switch-capacitor methods are the most common and oldest techniques in batteries' voltage equalizers [8,9]. These techniques although they are modernized still not efficient and time-consuming, especially for large-capacity batteries [10,11]. A passive equalizer technique is based on connecting a pure resistance between all batteries' terminals, even though, this method is practically simple, it has a huge waste of energy [12,13]. On the other hand, an active equalizer technique that uses an inductor, capacitor, or coupling transformer performs better than a passive technique in less wasted energy but requires a complicated controlling circuit [14–17]. Monitoring and controlling the battery state of charge is another technique that is applied for balancing the batteries that are connected in series, however, implementing this technique requires sensors to measure the state of charge in each battery [18]. A buck-boost converter also is used for equalizing the series-connected batteries. In this technique, an inductor is connected to each battery through multiple MOSFETs which is considered a drawback of this technique especially when there are many batteries in the system [19–21]. In this research, a novel method is proposed for the series-connected batteries' voltage equalization process. The method is based on a dynamic capacitor and an inductor. A variable duty cycle, D, of PWM, is applied in switching modes for the dynamic capacitor and the inductor [22,23]. The variation of D in PWM changes the amount of stored energy in both the capacitor and the inductor. For the purpose of implementation, a complete circuit of the dynamic capacitor with variable D is designed and simulated using a MATLAB/Simulink environment for two lead-acid batteries connected in series with their standard 12V terminal voltages. The technique is tested on batteries having 800mV terminal difference voltages with variations of values of D, from 20% up to 80%. Furthermore, the results of the presented technique are compared for comparison purposes with a well-known switched-capacitor equalizer technique. Although PWM is also used in the switched-capacitor technique, variation of D does not affect reducing the equalizing process time or reducing the differences in terminal voltages. Meanwhile, the dynamic capacitor shows a significant improvement in the equalizing process both in terms of time and balancing terminal voltage when D is increased.

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Nomenclature

C	Capacitor (F)	PWM	Pulse Width Modulation
C_f	Filter Capacitor (F)	R_L	Inductor internal resistance (Ω)
D	Duty cycle of PWM	R_{LC}	Inductor-Capacitor Resistance (Ω)
i_L	Inductor Current (A)	t	Time (s)
i_{LC}	Inductor-capacitor current (A)	V_b	Battery Voltage (V)
L	Inductor (H)		

This is the major contribution of the presented technique in this research for enhancing the equalizing process of terminal battery voltages by reducing the differences between terminal voltages in a shorter timespan, which is a major requirement for the battery equalization process.

2. Battery Equalizer System

A typical series-connected battery system which was used in this research is shown in Fig. 1. The system consists of three main parts: battery bank, voltage measurement, variable duty cycle of PWM, and the equalizer. The equalizer in this research is a dynamic capacitor technique.

3. Dynamic capacitor circuit analysis

The electrical circuit diagram of the dynamic capacitor is shown in Fig. 2. The main components are an inductor, L, a capacitor C, and two switches, S_1 and S_2. Both elements L and C act as storage components in which their energies are controlled through the operation modes of two switches. These switches open and close their circuits in opposite to each other, that is, when S_1 is open S_2 is closed, and vice versa [7, 24]. For simplicity, four modes are taken to describe the operation of the dynamic capacitor.

Operation mode 1

In the first mode, S_1 is closed (On) and S_2 is opened (Off), and the equivalent circuit in this mode is an R_L circuit as shown in Fig. 3. Under the assumption that elements in mode 1 are in states where their initials are zeros, therefore, the current passed in this circuit is given by Eq. 1.

$$i_L(t) = \frac{V_b}{R_L}\left(1 - e^{-\frac{R_L}{L}Dt}\right) \tag{1}$$

where V_b is battery voltage, i_L is the inductor current, R_L is the inductor internal resistance, and D is the duty cycle of PWM.

Operation mode 2

In the second mode, switch S_1 is Off, and switch S_2 is On, and the equivalent circuit diagram that represents this mode is an R_{LC} circuit as shown in Fig. 4. The stored energy in the inductor in mode 1 during time t will be the initial current condition to the circulating current i_{LC} in mode 2. Thus, the current in this mode is simplified as present in Eq. 2 and Eq. 3.

$$I_{LC}(s) = \frac{(sL + R_{LC})\, i_{L(0)} + L\ i'_{L(0)}}{L\left(s^2 + \frac{R}{L}s + \frac{1}{LC}\right)} \tag{2}$$

$$i_{LC}(t) = i_{L(0)} e^{-\frac{R_{LC}}{2L}(1-D)t}\left[\cosh A - \frac{\sqrt{C}\left(\frac{R}{2L} - \frac{L\, i'_{L(0)} + R_{LC}\, i_{L(0)}}{L\, i_{L(0)}}\right)\sinh A}{\sqrt{0.25CR_{LC}^2 - L}}\right] \tag{3}$$

$$\text{where } A = \frac{\sqrt{0.25CR_{LC}^2 - L}}{L\sqrt{C}}(1-D)t$$

The R_{LC} is the combination of inductor and capacitor resistors, $i_{L(0)}$ is the inductor current just before switching mode 2, and $i'_{L(0)}$ is the first derivative of the inductor current which is given by Eq. 4.

$$i'_L(t) = \frac{V_b}{L}\ e^{-\frac{R_L}{L}t} \tag{4}$$

Operation mode 3

This mode is similar to mode 1 but with energy storage in the inductor due to circulating current, i_{LC}, in mode 2. Let represent this current in mode 3 as $i_{LC}(0)$, then Eq. 1 becomes as present in Eq. 5.

$$i_L(t) = \frac{V_b}{R_L}\left(1 - e^{-\frac{R_L}{L}Dt}\right) + i_{LC(0)}\ e^{-\frac{R_L}{L}Dt} \tag{5}$$

Operation mode 4

This mode is similar to mode 2, but energy storage, which is represented by the circulating current in the previous mode, is the effect of i_L in Eq. 5. Therefore, $i_{L(0)}$ and $i'_{L(0)}$ are taken from Eq. 4 and Eq. 5 to get Eq. 6.

$$i'_L(t) = e^{-\frac{R_L}{L}Dt}\left(\frac{V_b}{L} - \frac{R_L}{L}\ i_{LC(0)}\right) \tag{6}$$

Continuous modes

After mode 4, the circulating current in RL and RLC circuits continues as long as PWM controls the operations of the sequence of operation for both switches, S1 and S2.

4. Variable PWM duty cycles

PWM generates two pulse trains for controlling the operation of both switches, S_1 and S_2. These two pulses are in reverse to each other, such that S_1 is On and S_2 is Off, simultaneously, and vice versa in each cycle. The PWM duty cycle D is the pulse period the output is On. The duty cycle is defined by Eq. 7, [25]. where t_{on} and t_{off} are switching times for both switches accounted when S_1 is On, S_2 is Off, and vice versa. Figure 5 shows the PWM pulses when D is 50%, that is, the pulse periods are equal, that is t_{on} equals to t_{off}. Figure 6 and Fig. 7 show the PWM pulses for D are 20% and 80%, respectively.

$$D = \frac{t_{on}}{t_{on} + t_{off}} \tag{7}$$

5. Dynamic capacitor operation under variable duty cycles

Figure 8 shows the five-mode operations of the dynamic capacitor circuit (shown in Fig. 1) for D is 50%, and the values of elements in the circuit are given in Table 1. The current substantially decreases when the duty cycle is decreased, and the current is raised as the duty cycle is increased. The current in five-mode operations for duty cycles 20% and 80% are shown in Fig. 8, Fig. 9 and Fig. 10, respectively. As shown in these figures, the maximum current reaches around 200A when D is 50% and it decreases to just above 100A for 20% of D. The current reaches around 250A when D becomes 80%. Changing duty cycles changes the energy storage energies in both the inductor and capacitor, this will affect the batteries' voltage (energy) when they are connected to the dynamic capacitor circuit.

Table 1. Dynamic capacitor element values.

Element	Value	Element	Value
R_L	0.04Ω	L	0.3 H
R_{LC}	0.05Ω	C	200μF
PWM Frequency	50mHz	Vb	12V

6. Equalizing battery voltages simulation and results

In this research, two batteries are used for implementing the aforementioned technique. Both batteries are the same type and the same capacity, and they are connected in series. The type of battery has been chosen to be a lead-acid battery rated 12 V and 200 Ah. This type of battery is used for most domestic PV energy systems for their affordable price and acceptable charging/discharging rates. The model of this battery has been taken from the MATLAB/Simulink library, and the test bench for the aforementioned technique of dynamic capacitor with variable PWM duty cycles was carried out using MATLAB/Simulink. Figure 11 shows the simulation diagram of the dynamic capacitor and the two lead acid batteries.

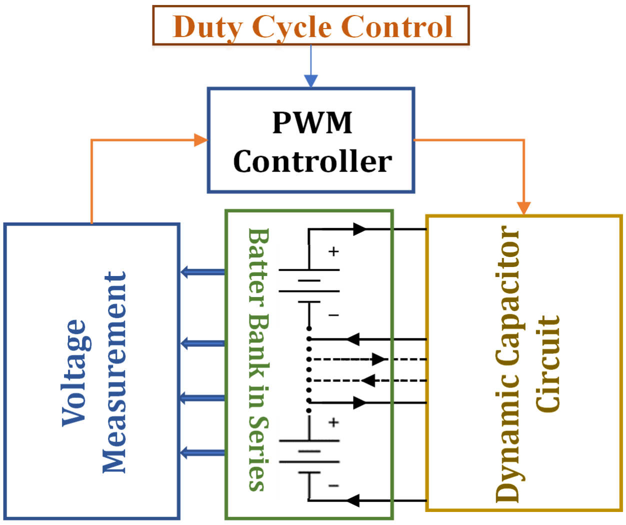

Figure 1. Battery equalizer system.

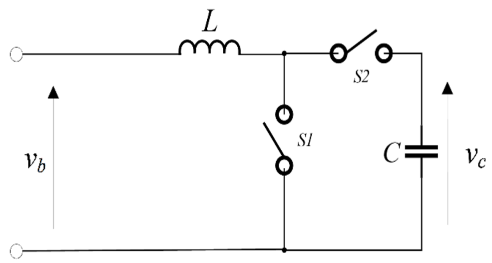

Figure 2. Main dynamic capacitor electrical circuit diagram.

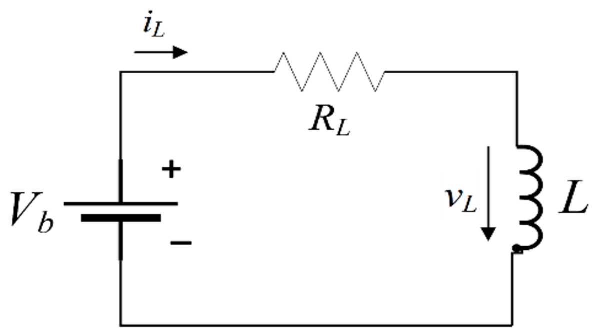

Figure 3. Switch operation mode 1 equivalent circuit.

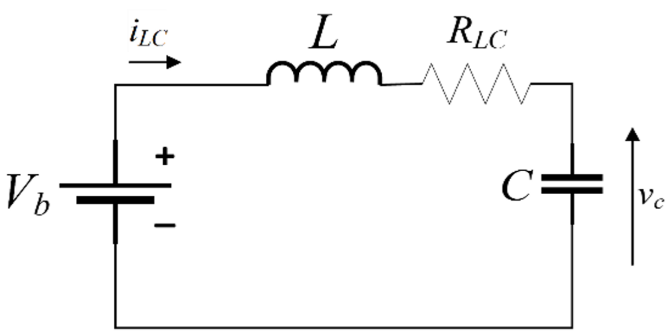

Figure 4. Switch operation mode 2 equivalent circuit.

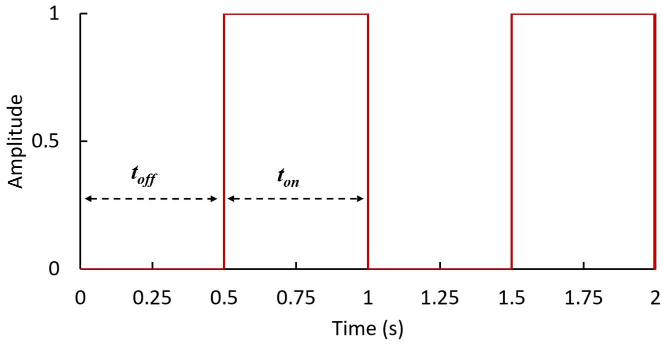

Figure 5. PWM waveform for D is 50%.

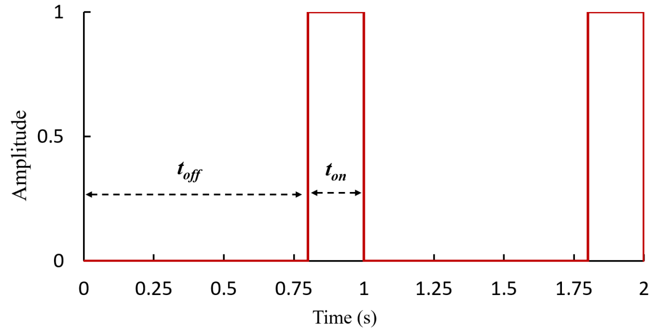

Figure 6. PWM waveform for D is 20%.

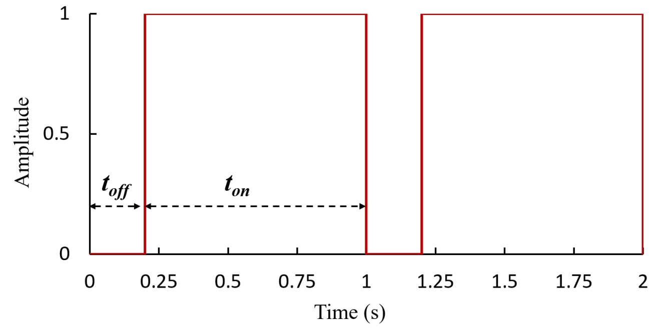

Figure 7. PWM waveform for D is 80%.

The model was applied on 800mV different voltages of batteries. The parameters are the same as they are given in Table 1 except the PWM frequency was changed to 1kHz. Cf_1 and Cf_2 are used as filters, and their values are set to 10μF. The simulation results for duty cycles 20%, 50%, and 80% are shown in Fig. 12, Fig. 13, and Fig. 14, respectively. As shown in simulation results, when D is 20%, the equalizer can balance both battery voltages up to 540mV difference (equalizing up to 95.5%) ($Vb1 = 12.95V$ and $Vb2 = 12.41V$) after 500 seconds. When D was increased to 50%, the difference in voltages between the two batteries was reduced to 30mV (equalizing up to 99.75%) ($Vb1 = 12.69V$ and $Vb2 = 12.66V$) after 500 seconds. The difference falls below 2.2mV (equalizing up to 99.98%) ($Vb1 = 12.6422V$ and $Vb2 = 12.64V$) when the duty cycle has been increased to 80% and it took just 125 seconds, and becomes 0V (100% equalizing) in 500 seconds. Overall, by increasing D to 80%, the equalizing process has been improved by more the 99.98%. Furthermore, increasing the duty cycle, D, of PWM has reduced the settling time for reaching the promised equalizing goal in a much shorter time, almost by 75%. As depicted in Fig. 13 and Fig. 14, the equalizing voltage reached its promised value in just 125 seconds when the duty cycle was 80%, while after 500 seconds, it still did not reach the best equalizing value when the duty cycle was 50%.

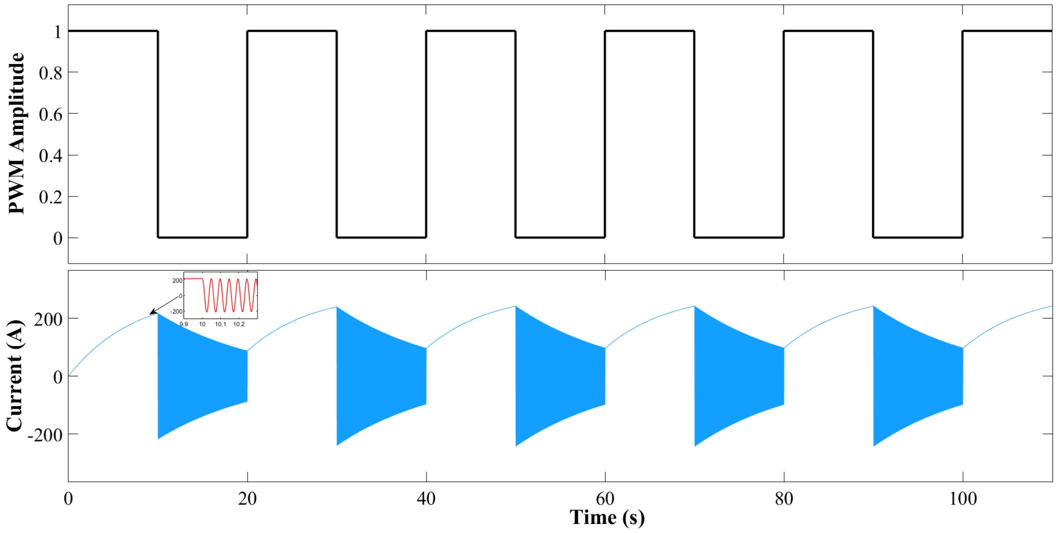

Figure 8. Current in five-mode operations when D is 50%.

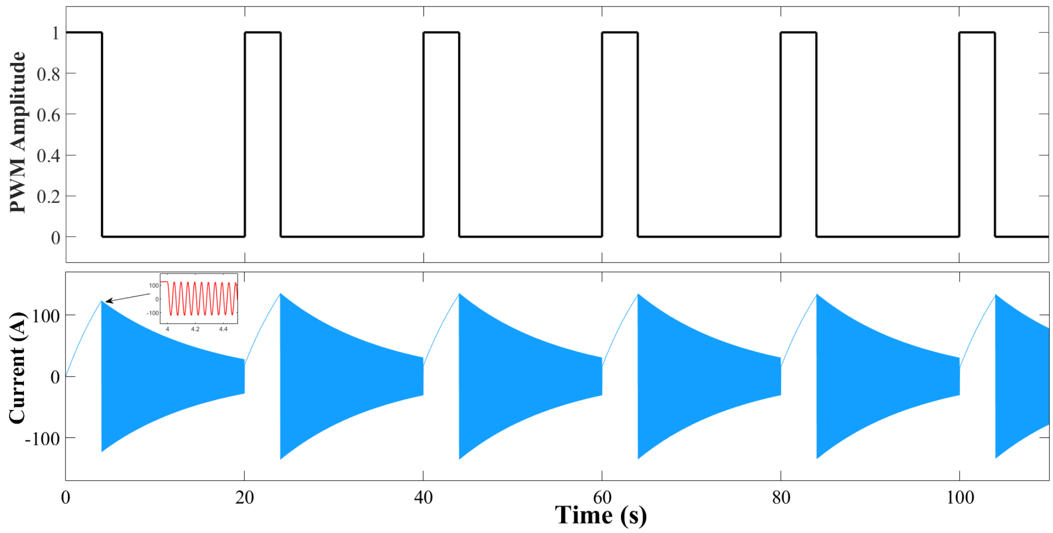

Figure 9. Current in five-mode operations when D is 20%.

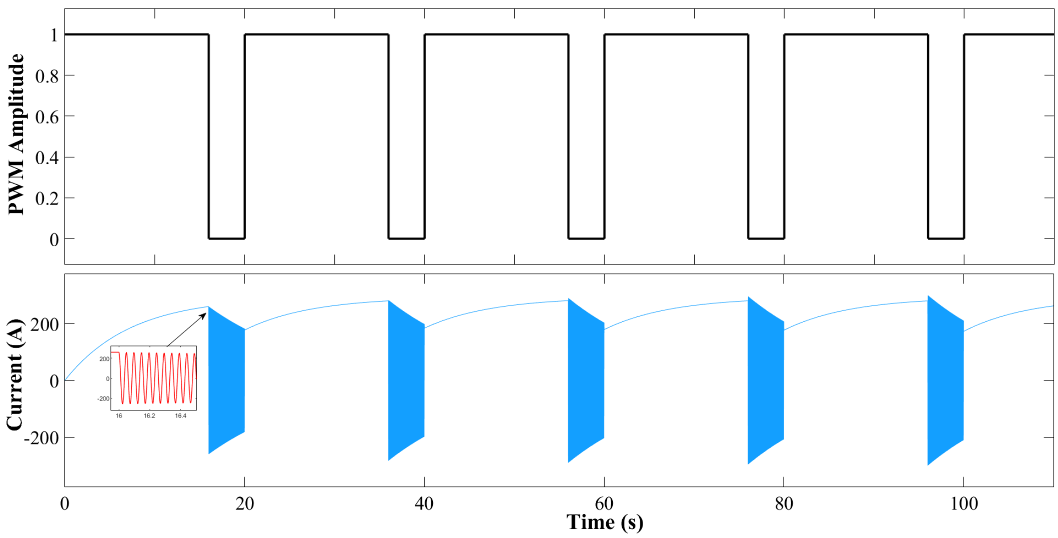

Figure 10. Current in five-mode operations when D is 80%.

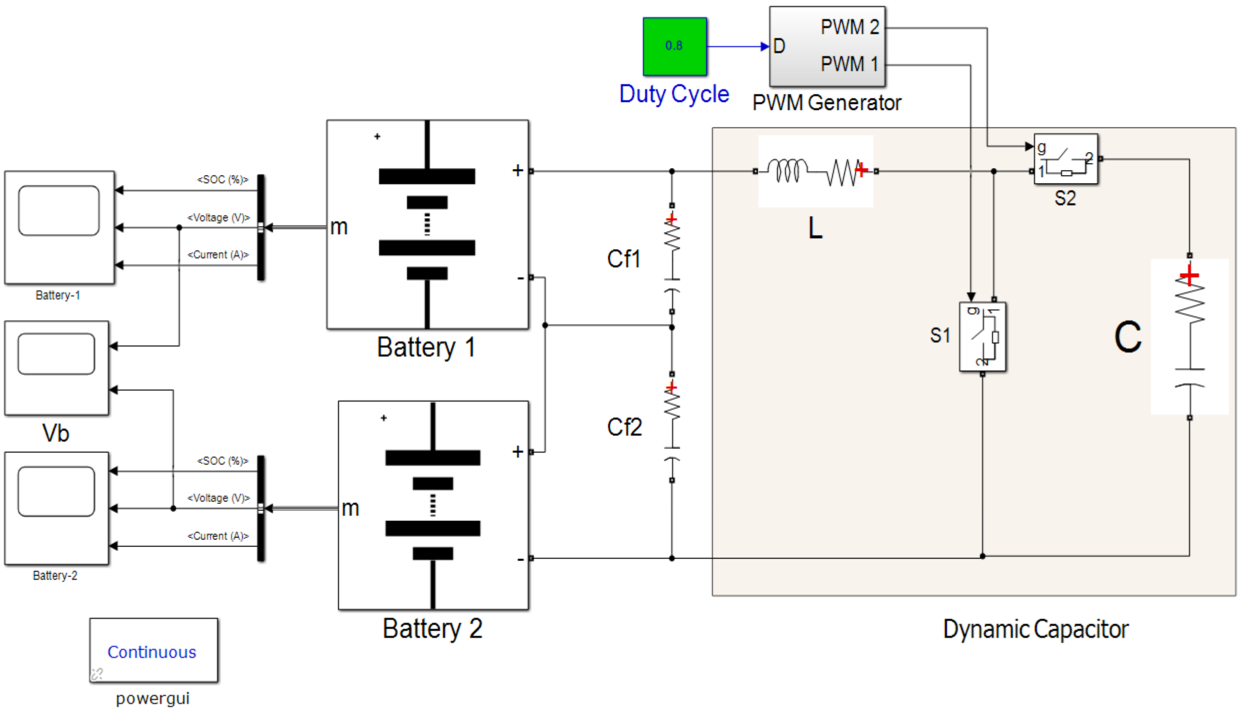

Figure 11. MATLAB simulation diagram.

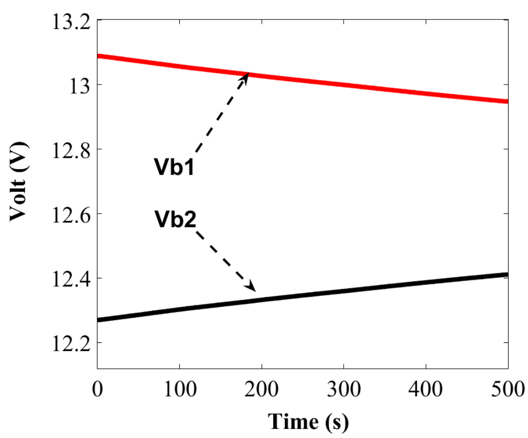

Figure 12. Battery voltages for D is 20%.

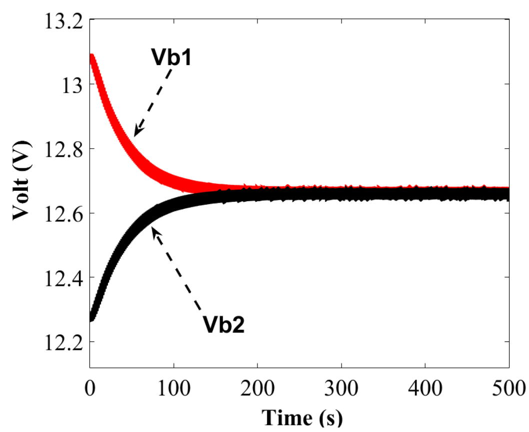

Figure 14. Battery voltages for D is 80%.

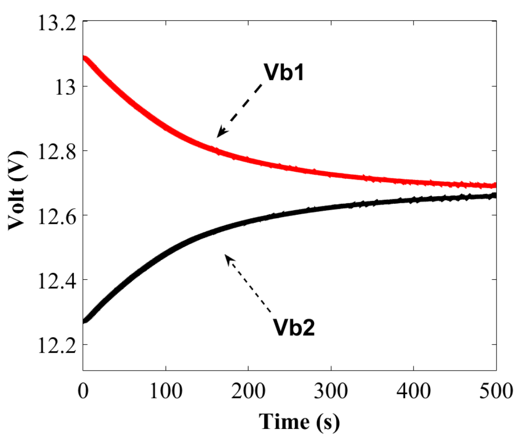

Figure 13. Battery voltages for D is 50%.

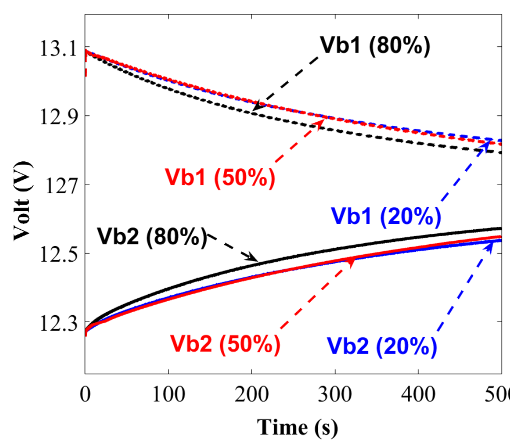

Figure 15. Variation of duty cycles of the switched-capacitor technique.

For comparison and validation of the proposed technique, a switched-capacitor technique was applied to the same type and size of batteries. The capacitance size was chosen to be $2000\mu F$, and the PWM frequency was set at 1 kHz. The duty cycles used were 20%, 50%, and 80%, respectively. These results are shown in Fig. 15. The differences after 500 seconds of equalizing process are as follows: at a duty cycle of 20%, the difference is 290V (equalizing up to 97.6%) ($Vb1 = 12.83V$ and$Vb2 = 12.54V$), and at $D = 50\%$, the difference is 270mV (equalizing up to 97.75%) ($Vb1 = 12.82$ and $Vb2 = 12.55$). The difference reaches 220mV (equalizing up to 98.2%) ($Vb1 = 12.79V$ and $Vb2 = 12.57V$) when D is 80%. As it is clear from the different values, the variation of the duty cycle does not have much impact on reducing the equalizing process, and the difference in voltages between the two connected batteries is not much reduced even after a long time of the switched-capacitor equalizing technique process.

7. Conclusion

The research introduces a novel approach to enhancing the equalization of two series-connected lead-acid batteries through a variation in duty cycle. Comparing two techniques: the dynamic capacitor technique (proposed in this research) and the switched-capacitor technique (the most commonly used technique). The simulation results indicate that the dynamic capacitor technique generally achieves faster equalization. Furthermore, manipulating the duty cycles of PWM, which govern the switches' operations, improves the equalization process. Specifically, the simulation results demonstrate a direct correlation between the duty cycle variation of PWM and the performance of the dynamic capacitor technique, resulting in nearly fourfold acceleration of the equalization process with higher duty cycles. Moreover, increasing the duty cycle enhances the voltage balances by minimizing the voltage differences between the series-connected batteries; for instance, at a duty cycle, D, of 80%, the voltage difference was merely 2.2 mV. Notably, this enhancement is exclusive to the dynamic capacitor technique, showing negligible impact when employing the switched capacitor technique. This is considered the major contribution of the proposed technique. By addressing the limitations of traditional methods and demonstrating superior performance in reducing voltage differentials and accelerating the equalization process, our approach has the potential to significantly enhance the longevity and overall performance of battery systems. Thus, it represents a substantial advancement in battery management in power system backup technologies, and it is encouraged to implement the proposed technique for future work on other types of batteries, like lithium-ion batteries.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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