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New Temperature-Compensated Multi-Step Constant-Current Charging Method for Reliable Operation of Battery Energy Storage Systems

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ABSTRACT Battery lifetime represents a significant concern for the techno-economical operation of several applications based on energy storage. Moreover, the charging method is considered as one of the main critical elements in defining and influencing the operating lifetime of batteries. Several charging techniques have been addressed in the literature, however almost all of them are suffering from lack of temperature feedback in order to maintain battery lifetime. This paper presents a new high-reliable charging method for battery energy storage systems (ESSs). The proposed temperature compensated multi-step constant current (TC-MSCC) method is developed based upon the modified (MSCC) charging method. It enhances the operating lifetime of batteries by employing a feedback from the battery temperature to control the duration and starting time of each charging current step. Compared with the traditional charging methods addressed in the literature, the proposed TC-MSCC method achieves faster charging than the conventional constant current (CC) and the constant-current constant-voltage (CC-CV) methods. Moreover, the proposed TC-MSCC method possesses longer operating battery lifetime with reduced thermal stresses compared to the traditional MSCC methods. The proposed charging method is verified by simulation and experimental results using 9 Ah lead-acid battery. However, the new proposed TC-MSCC method is generalized and can be applied to various types of batteries. The detailed performance comparisons and results show the superiority of the proposed methods over the most widespread charging methods in the literature.

INDEX TERMS Battery lifetime, battery charging methods, CC charging, CC-CV charging, MSCC charging, lead-acid battery.

I. INTRODUCTION

Energy storage systems (ESSs) provide several additional flexibilities for electrical power systems [1]. The ESSs can optimize the means of energy utilization in power systems by employing decoupled energy generation systems. Several studies have been presented in the literature for assessing the impacts of ESSs on the electrical power systems [2], [3], reliability enhancement [4]–[6], load frequency control [7], etc. Among ESSs, batteries are the most common storage elements in several applications, such as electric vehicles (EVs), portable devices, and renewable energy generation systems [8], [9]. The reduced cost and small size benefits have made extensive utilization of batteries in these applications. There are three main widely used battery types in the literature, including lead-acid, lithium-ion, and nickel-metal hybrid batteries. Among these battery technologies, sealed lead-acid batteries are the most popular ESSs due to their lower prices, and higher efficiency with temperature changes [10]. However, field-operating data and reports have

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shown the short lifetime operation of lead-acid batteries [11]. The thermal stresses represent the major failure causes for power components [12]–[14]. This in turn reduces the whole system reliability and source availability. Therefore, proper control and management techniques are highly required to increase the lifetime of lead-acid batteries.

The quality of the charging technique affects to a wide extend the performance and operating lifetime of sealed lead-acid batteries [15]. The main quality criteria of charging techniques are efficiency, charging time, and a lifetime of battery [16], [17]. An appropriate method for estimating battery lifetime is through the number of charging/discharging cycles that it can deliver [18], [19]. There are different categories of charging methods in the literature [20]. The widespread conventional constant current constant voltage (CC-CV) method performs battery charging within two subsequent modes; In the first mode, the battery is charged at constant current (CC) with measuring the battery voltage [21]. The CC mode is terminated when the battery terminal voltage reaches a pre-defined upper voltage limit. Then, constant voltage (CV) is applied until the charging current reaches the pre-defined small value. However, the CC-CV method is not convenient for several applications that require definite small charging time. This is because the CV mode extends the time of charging, which makes it unsuitable for fast charging applications. In addition, the CV mode reduces seriously the operating lifetime of the battery and the reliability of the whole ESSs in accordance.

Several charging methods have been developed in the literature to overcome the shortcomings of the conventional CC-CV method [22]. These methods have achieved faster and more efficient charging for batteries. Although, increased complexity and implementation burdens represent the main obstacles for these charging methods for commercial applicability. Moreover, these methods ignore their effects on the operating lifespan of batteries. The multi-step constant current (MSCC) charging methods have proven their advantages over the traditional charging methods, regarding to the charging time and efficiency [23]. In addition, the MSCC charging method is appropriate for simple implementation and easiness of commercialization in accordance. However, the optimum number of current steps has represented the main challenging task for the design of MSCC charging methods.

In the MSCC charging method, the CV period of the CC-CV method has been replaced with the CC charging period with several gradually reduced current amplitudes [24]. Thence, several steps of CC charging compose the charging profile of MSCC, wherein these steps are applied until the cut-off voltage is reached. The application of MSCC charging has higher charging efficiency and it has achieved reduced temperature rise compared to the conventional CC-CV method [20]. Moreover, higher reliability and longer lifetime can be achieved using the MSCC method due to the elimination of the CV charging cycle. However, the charging performance, including total charged capacity, time of charging, and charging efficiency represent crucial factors in evaluating the MSCC method.

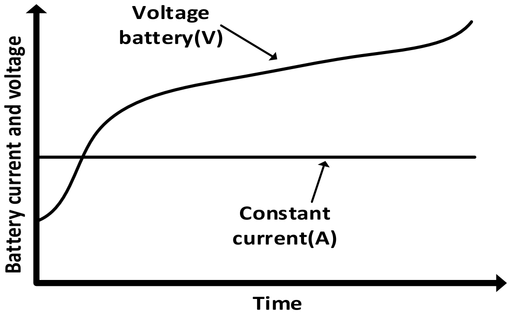
In the literature, there are several methods have been proposed for determining the optimum charging patterns and current levels for the MSCC charging method in order to optimize its charging performance. The number of current steps and the current levels are designed for achieving optimized performance. Different types of optimization methods have been applied in the literature for defining the optimum MSCC patterns, including the particle swarm optimization (PSO) algorithm, Taguchi method, ant-colony optimization, fuzzy-logic method, etc. [22]–[27].

In addition, multi-objective optimization methods have been presented in the literature for optimizing various performance objectives. The main performance objectives including charging efficiency, charging time, and cumulative temperature rise of the battery [27], [28]. In the existing MSCC methods in the literature, the charging patterns are controlled through the feedback from the battery voltage [27]. The pattern is terminated when the measured battery voltage reaches the cut-off voltage level of the battery. Moreover, the cumulative temperature rise of the charging process lacks for preventing the temperature rise of the battery. Thence, the existing MSCC charging methods do not guarantee reliable operation of the battery system due to their dependency only on the cut-off voltage and cumulative temperature rise.

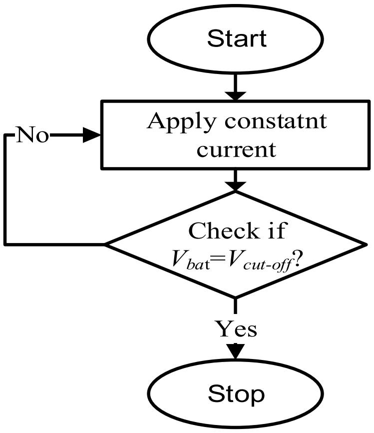
Stimulated by the above-mentioned critical issues of conventional charging methods, this paper presents a new charging technique for battery energy storage systems. The main contributions of this paper can be summarized as follows:

- A new high-reliable MSCC charging method for batteries is proposed for increasing the operating lifetime of battery ESSs. The proposed method is temperature compensated MSCC (TC-MSCC) method, which is based on a modified MSCC charging method.
- The proposed TC-MSCC method enhances the operating lifetime of lead-acid batteries by employing feedback of battery temperature to control the duration and starting of each CC step.
- The proposed TC-MSCC method achieves faster charging than traditional CC and CC-CV charging methods. Moreover, the proposed TC-MSCC method possesses longer operating battery lifetime with reduced thermal stresses compared to traditional MSCC methods.

The remaining of the paper is as follows: Section II presents the charging profiles for various conventional charging methods. The various electrical, thermal, and lifetime models of battery ESSs are presented in Section III. Section IV details the proposed TC-MSCC charging method and its implementation. The simulation and experimental results of the proposed method are presented in Section V, and Section VI, respectively. Performance comparison of the new charging method with the addressed charging methods is provided in Section VII. Finally, the conclusion of the paper is included in Section VIII.

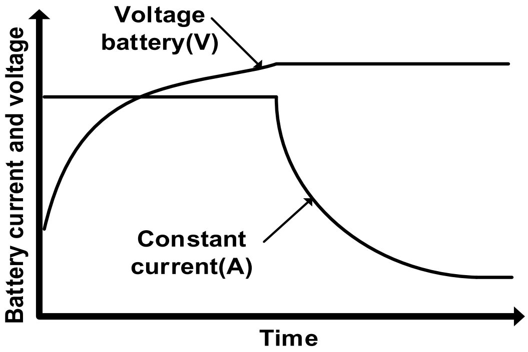


(a) Current and voltage waveforms

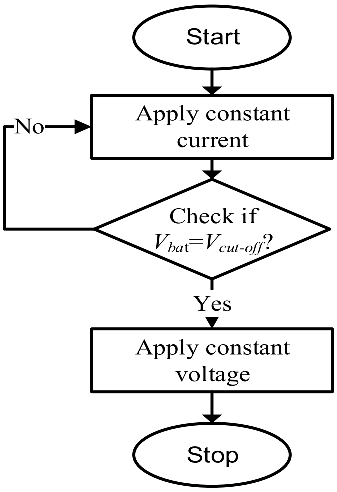


(b) Flowchart of the Charging algorithm

FIGURE 1. **Constant Current (CC) charging method.**



(a) Current and voltage waveforms.



(b) Flowchart of the Charging algorithm

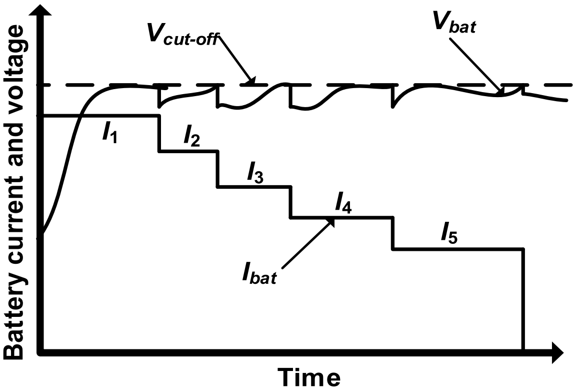
FIGURE 2. **Constant-current constant-voltage (CC-CV) charging method.**

II. CONVENTIONAL CHARGING METHODS FOR BATTERIES

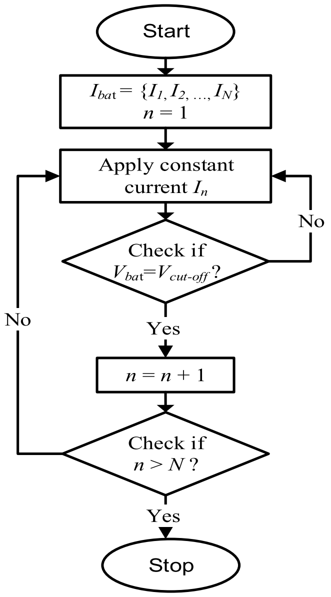
For many different types of batteries, some of the best battery charging techniques are available. The method of charging the battery is a vital element in determining the battery lifetime. CC, CC-CV, and MSCC charging methods are the main charging methods in the literature, almost all of them are different in charging time, battery temperature, etc. Fig. 1(a) shows the current and voltage waveforms of the battery during the CC charging method. The charging algorithm for the CC charging method is shown in the flowchart shown in Fig. 1(b).

It is seen that, in this charging method, a constant current is applied to charge the battery regardless the battery state of charge (SoC) until the battery terminal voltage V_{bat} reaches the cut-off voltage level $V_{cut-off}$, which is defined according to the manufacturer datasheet. The CC charging method is the simplest charging method from the implementation point of view. Since the charging time and charging capacity are highly dependent on the charging current level of the battery, this method cannot achieve the rated battery capacity. Fig. 2 shows the current and voltage waveforms in addition to the charging algorithm of the two-stage CC-CV charging method. In this method, the CC charging mode is firstly applied and the battery voltage begins to rise with time. When the battery voltage reaches the cut-off voltage, the CC mode is terminated and CV is applied. This method can provide better-charging capacity than in the CC charging method due to the employment of the CV charging pattern. However, the CC-CV charging method requires long charging time due to the slow CV charging pattern, which makes it unsuitable for several fast-charging applications.

An additional disadvantage of the CV charging pattern is the lack of battery current control, which results in increased temperature of the battery, short operating lifetime, and reduced overall system reliability. On the other hand, Fig. 3(a) shows the current and voltage waveforms for the conventional MSCC charging method. The charging algorithm for this method is shown in Fig. 3(b). It can be seen that the MSCC method begins with applying the CC method with the first level until the battery voltage reaches the cut-off voltage level. Then, the subsequent current level is applied in the CC charging manner until the cut-off voltage level is reached. The algorithm is repeated until the full charge is reached, and the algorithm is stopped in accordance. The MSCC method can effectively enhance the charging capacity of the battery, in addition to achieve fast charging. Moreover, battery current control can be achieved in this method. However, the conventional MSCC method lacks for limiting the instantaneous thermal stresses of the battery, which is a critical factor for



(a) Current and voltage waveforms.



(c) Flowchart of the Charging algorithm

FIGURE 3. The waveforms and algorithm of the conventional MSCC charging method.

the battery lifetime. In the provided analysis in this paper, the number of current steps are set to five steps as in the widely employed MSCC charging methods in the literature [24]. However, optimized number of steps and current levels can be determined and applied for the new proposed TC-MSCC method, which is out of scope of the current paper.

III. COMPREHENSIVE BATTERY MODELLING

Proper modeling of battery ESSs is crucial for assessing the various charging methods. The thermal stresses, including the temperature of the battery, affect the available maximum capacity of the battery, the internal resistance, and voltage of open-circuit, in addition to the degradation rate and thermal runaway of the battery. Full control of the operating temperature of the battery during charging is highly required for safe and reliable operation of batteries by managing its temperature to be always under the predefined threshold. Electrical coupled with thermal behavior of the battery are obtained through the electro-thermal modeling of battery.

Fig. 4 shows the multi-disciplinary modeling of batteries according to the literature. The model contains four related models and stages as following:

- ***Firstly***, the electrical model provides the relationship between the battery parameters and operating point with the terminal voltage of the battery. This model is based on the generic battery modeling as in [29], wherein the model parameters can be extracted directly with the identification methods in the literature [30], [31]. The battery internal voltage can be obtained using (1) as follows:

$$E = E_0 - k \times \frac{Q}{Q - it} + A_b \times \exp\left(-B \times it\right) - Pol_{res} * i^* - C \times it \quad (1)$$

where, E_0 represents the thermodynamic voltage of the battery, K and B denote to polarization and exponential time constants, respectively. Whereas Q represents the capacity of the battery, i^* and it denote to the filtered and integral battery currents, respectively. The voltage slope of the polarization is denoted by C, and the internal resistance of the battery is denoted by R_{in}. The polarization resistance Pol_{res} can be determined using (2) as follows [32]:

$$Pol_{res} = k \times \frac{Q}{Q - it}\left(1 - u\left(t\right)\right) + k \times \frac{Q}{it - 0.1Q} u\left(t\right) \quad (2)$$

where $u(t)$ represents the charging/discharging status of the battery ($u(t)$ equals to 1 during charging, and $u(t)$ equals to zero during discharging operation).

- ***Secondly***, the power losses calculation stage provides the internal consumed power losses during the charging operation of the battery. Usually, the power losses of the battery include three main components, including polarization losses, resistive, and reversible losses. The power losses during the charge operation can be modelled using (3) follows:

$$P_{loss} = \left[E_o\left(T_{bat}\right) - V_{bat}\left(T_{bat}\right)\right] \times i + \frac{\partial E}{\partial T} \times i \times T_{bat} + \Delta P \quad (3)$$

where $E_0(T_{bat})$, $V_{bat}(T_{bat})$ represents the internal and terminal voltages of the battery at the estimated battery temperature T_{bat} with charging current i of battery. Whereas ΔP and $\partial E/\partial T$ represent the additional reversible power losses in the battery during charging and the temperature coefficient of open circuit, respectively.

- ***Thirdly,*** the thermal model is employed for determining the operating temperature of the battery. The Thevenin equivalent electrical modeling is often used for its simplicity in determining the thermal behavior of power components. The presented model in [33] is utilized for determining the internal temperature of the battery T_{bat},

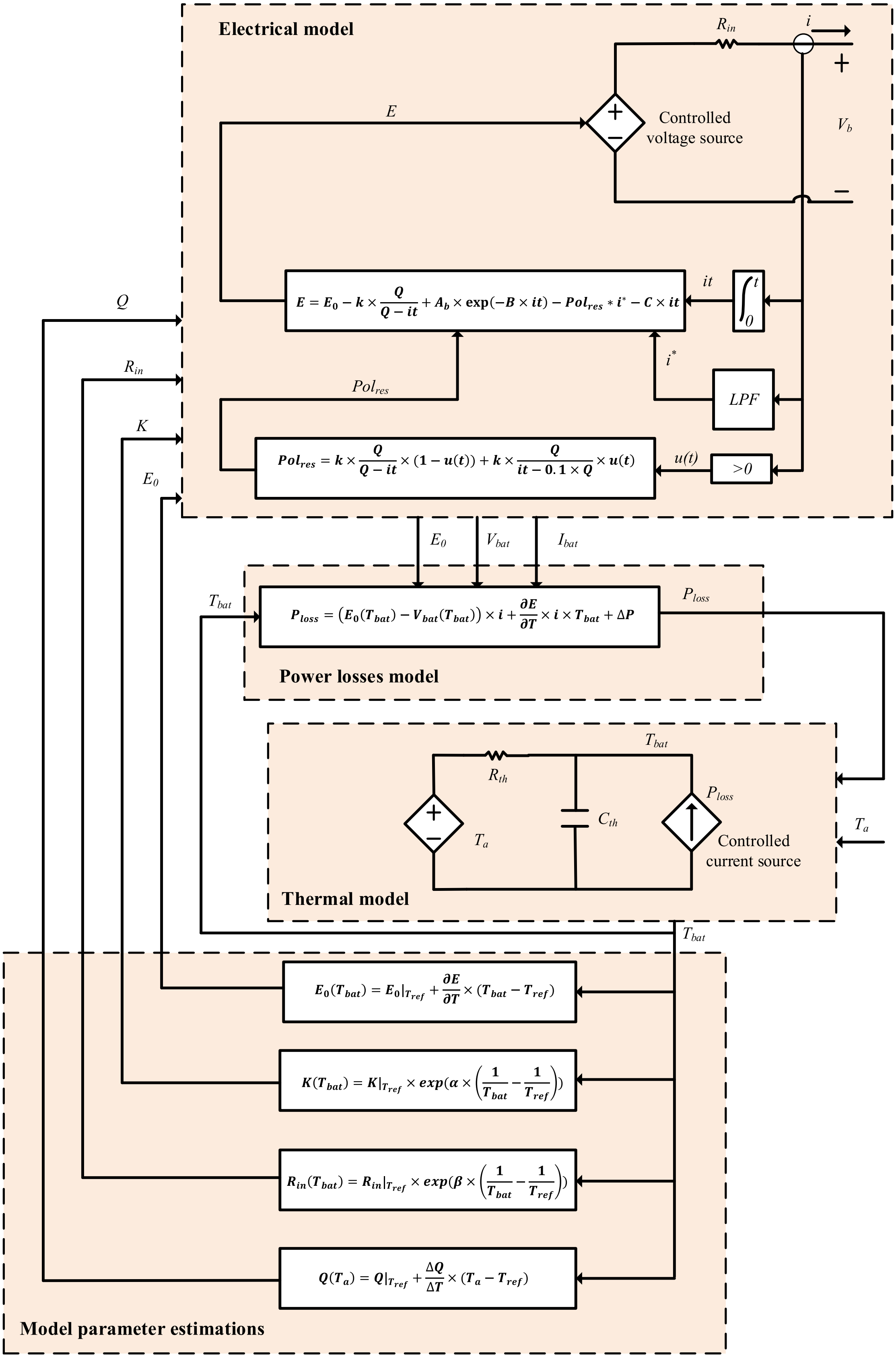


FIGURE 4. Comprehensive modeling of battery energy storage systems.

wherein the power losses are used as equivalent controlled current source as a stressor for generating thermal effects of the charging method. The parameters R_{th} and C_{th} represent the Thevenin equivalent thermal resistance and capacitance, respectively, and they are obtained by using experimental tests as in [29].

- ***Fourthly***, the model update parameters stage provides the model with the effect of temperature on battery performance. In order to include the impact of the battery temperature on the battery model, the thermodynamics voltage E_0, the polarization constant K, and the internal resistance R_{in} are calculated using the reference values at the reference temperature T_{ref} according to Nernst and Arrhenius laws [29] as follows:

$$E_0\left(T_{bat}\right) = E_0|_{T_{ref}} + \frac{\partial E}{\partial T} \times \left(T_{bat} - T_{ref}\right) \tag{4}$$

$$K\left(T_{bat}\right) = K|_{T_{ref}} \times exp[\alpha \times \left(\frac{1}{T_{bat}} - \frac{1}{T_{ref}}\right)] \tag{5}$$

$$R_{in}\left(T_{bat}\right) = R_{in}|_{T_{ref}} \times \exp[\beta \times \left(\frac{1}{T_{bat}} - \frac{1}{T_{ref}}\right)] \tag{6}$$

$$Q\left(T_a\right) = Q|_{T_{ref}} + \frac{\Delta Q}{\Delta T} \times \left(T_a - T_{ref}\right) \tag{7}$$

where β and α represent the constants of Arrhenius for internal and polarization resistances, respectively. The $\Delta Q/\Delta T$ denotes the temperature coefficient of battery capacity. The dependency of the battery capacity on the operating current and temperature has been investigated in the literature. The capacity $Q(I_{bat}, T_{bat})$ as a function of the battery current I_{bat}, and battery temperature T_{bat} is written as follows [32]:

$$Q\left(I_{bat}, T_{bat}\right) = \frac{K_C * Q_{ref}(1 + \frac{T_{bat}}{-T_{bat}})^{\varepsilon}}{1 + (K_C - 1)(\frac{I_{bat}}{I_{bat,ref}})^{\delta}} \tag{8}$$

where Q_{ref} and $I_{bat,ref}$ are the reference capacity and current of the battery according to the battery manufacturer datasheet. The parameters ε, δ, and K_c are constant parameters, which are defined by the experimental tests. It can be seen from (8) that the battery capacity is dependent on a wide extent on the battery temperature. The identification of battery model parameters has not been covered in this paper, however, more details can be found in [29].

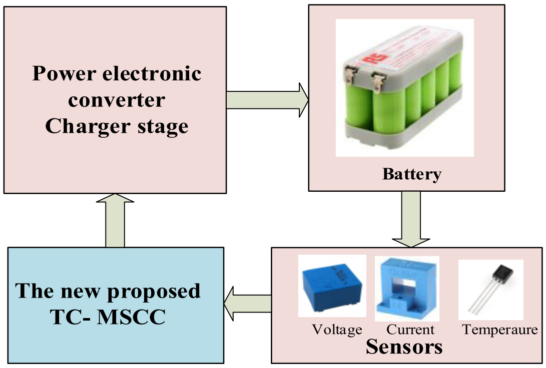


FIGURE 5. Schematic diagram of the proposed battery charging methodology.

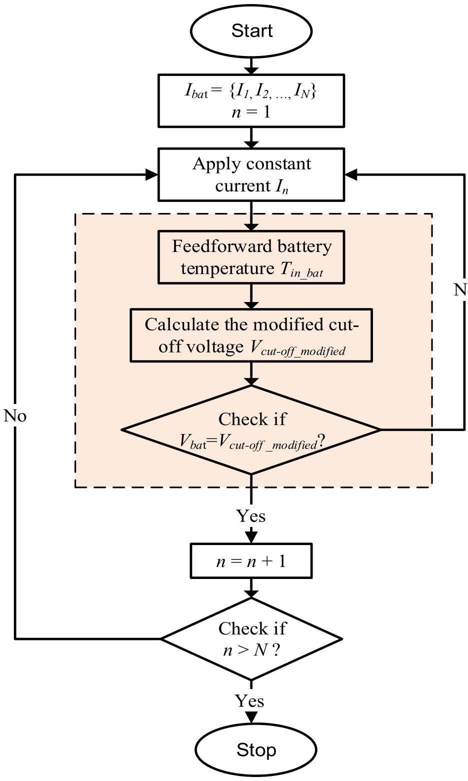


FIGURE 6. The battery charging algorithm using the proposed modified MSCC method.

IV. THE PROPOSED TC-MSCC CHARGING METHOD

Stimulated by the aforementioned multidisciplinary analysis of the battery ESSs, a new charging method is developed for improving the reliability of battery ESSs. The proposed TC-MSCC method is based on modifying the traditional MSCC charging method by controlling the battery temperature. A schematic diagram of the battery ESS with the proposed TC-MSCC charging method is shown in Fig. 5. It is seen that the battery temperature is employed for compensating the independency of MSCC charging on the instantaneous temperature of the battery. The proposed charging scheme controls the charging current and timing of each step application according to the temperature compensated criteria of the proposed TC-MSCC charging method. Moreover, Fig. 6 shows the charging control algorithm for the proposed TC-MSCC battery charging method. The proposed method modifies the charging algorithm of the traditional MSCC charging method: Firstly, the optimized charging currents are obtained as in the traditional MSCC charging method and the charging controller applies the first CC charging current I_1. Afterward, the proposed TC-MSCC charging method utilizes the measured battery temperature in order to provide compensation for the temperature compensated cut-off voltage value $V_{cut-off\_\text{modified}}$. When, the value of the measured battery voltage reaches the value of the estimated modified cut-off

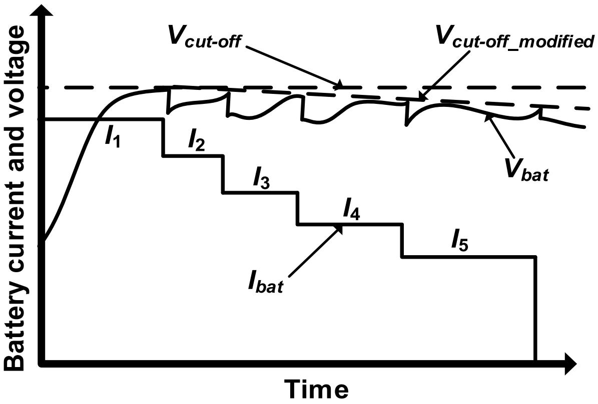


FIGURE 7. Battery current and voltage waveforms of the proposed modified MSCC charging method.

voltage $V_{cut-off\_modified}$, the proposed charging algorithm terminates this charging pattern and applies the subsequent charging pattern. This process is repeated for the whole charging patterns until the battery reaches the full charge condition.

The estimation of the modified cut-off voltage has to be properly made in order to prolong the operating lifetime of the battery. The battery manufacturers recommend in their datasheets with modifying the cut-off voltage of the lead-acid batteries according to the battery temperature changes. The proposed TC-MSCC charging method adjusts the value of the cut-off voltage according to the measured battery temperature. The modified cut-off voltage $V_{cut-off\_modified}$ can be estimated as follows:

$$V_{cut-off\_modified} = V_{cut-off\_norm} + K_m \times (T_{bn} - T_b) \quad (9)$$

where $V_{cut-off\_norm}$ represents the normal cut-off voltage from the battery datasheet at the normal battery temperature T_{bn}. whereas, K_m represents the slope of the cut-off voltage with temperature changes, and T_b denotes to the measured battery temperature. Fig. 7 shows the modified charging waveforms of the battery current and voltage for the proposed TC-MSCC charging method. The proposed TC-MSCC charging method applies the CC charging patterns as in the conventional MSCC charging method. However, the main difference is the dependency of the termination time of each pattern on the modified cut-off voltage $V_{cut-off\_modified}$. The updated value of the cut-off voltage is obtained using (9). Therefore, the proposed TC-MSCC charging method can extend the battery operating lifetime by compensating the cut-off voltage according to the measured battery thermal stresses. Thence, the battery temperature can be controlled, which can lead to reliability improvement of the whole battery ESS power system.

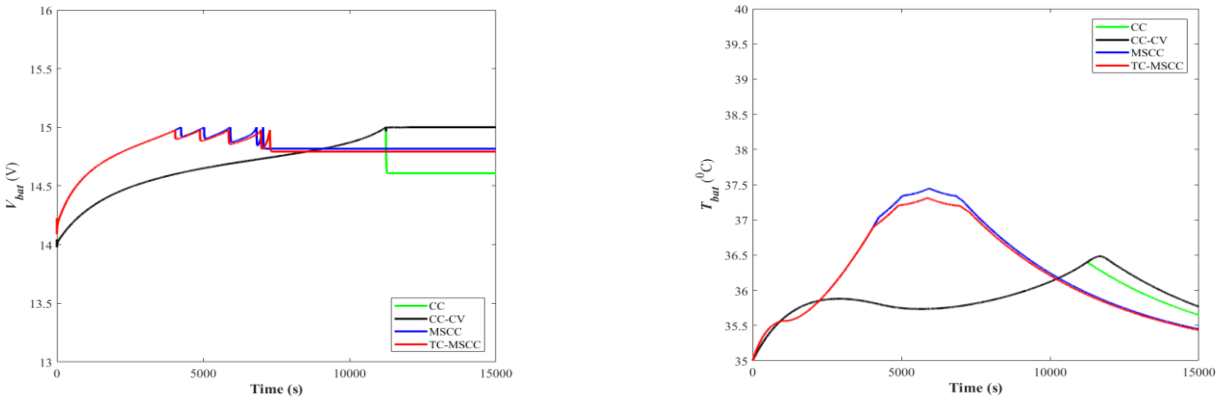
V. SIMULATION RESULTS

A simulation case study has been performed for assessing the performance of the new proposed TC-MSCC charging method using 9 Ah, 12 V battery in the Matlab Simulink platform. The new proposed TC-MSCC has been simulated and compared with three conventional charging methods, namely CC, CC-CV, and conventional MSCC. The comparison criteria include the battery terminal voltage (V_{bat}), battery charging current (I_{bat}), battery temperature (T_{bat}), and SoC. The four charging methods are programmed using the Matlab function property in order to control the charging/discharging behaviour. Fig. 8(a) compares the battery terminal voltage behavior between the four charging methods. It can be seen that the main difference between the CC, and CC-CV charging methods is the additional CV phase in the CC-CV methods. The two methods are highly dependents on the applied CC level. From another side, the MSCC, and the proposed TC-MSCC employ various CC levels to achieve fast charging with maximum SoC. Feedback from the battery voltage is needed in the conventional MSCC method to control the transition to the following level. Whereas, battery temperature feedback is employed in the proposed TC-MSCC to control the transition between levels. The duration of each CC charging level is dependent on the sensed battery temperature. Fig. 8(b) shows the corresponding current waveforms for the four charging methods. The CV charging phase in the CC-CV method adds an additional decaying current level compared to the CC method. In addition, the transition times between various CC levels in the proposed TC-MSCC method is different from the conventional MSCC due to the temperature compensation behavior. The performance of the battery temperature of the four charging methods is shown in Fig. 8(c). The battery temperature of the CC, and CC-CV methods is highly dependent on the employed CC level. From another side, the proposed TC-MSCC achieves lower battery temperature in comparison to the conventional MSCC method. The SoC performance comparison between the four charging methods is shown in Fig. 8(d). It is clear that the conventional MSCC and the proposed TC-MSCC methods achieve faster charging compared with the CC, and CC-CV methods. Higher CC levels in the CC, and CC-CV methods can achieve faster charging. However, a compromise between the charging speed and maximum SoC is needed in these methods.

VI. EXPERIMENTAL RESULTS

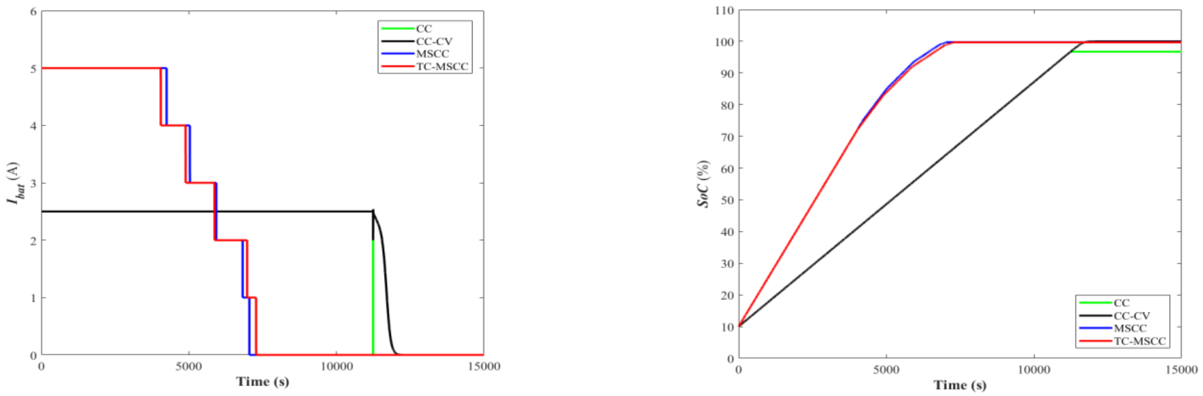
The new proposed TC-MSCC has been implemented experimentally and compared with the conventional MSCC method. The battery charging system shown in Fig. 5 has been implemented for the experimental prototyping. The new proposed TC-MSCC has been implemented using Arduino microcontroller kit. Whereas, additional Arduino microcontroller has been programmed and utilized for data acquisition with the LabVIEW platform. The main parameters for the system are summarized in Table 1. The ambient temperature T_a is kept very near to the reference temperature T_{ref} during the experimental tests. Therefore, the update of $Q(T_a)$ with temperature change in (7) is assumed constant and the simple Amper-hour integration method is employed for estimating battery SoC during the test.

Fig. 9 shows the terminal voltage comparison between the conventional MSCC and the new proposed TC-MSCC. It is



(a) Battery voltage

(c) Battery temperature



(b) Battery current

(d) Battery SoC

FIGURE 8. **Simulation results and comparisons between CC, CC-CV, conventional MSCC, and proposed TC-MSCC.**

TABLE 1. **Parameters for the experimental prototype.**

Component	Description
Battery Type	Lead-acid battery
Battery capacity	9 Ah
Battery terminal voltage	12 V
Battery cut-off voltage	15 V
Controller	Arduino MEGA microcontroller
Data acquisition	Arduino MEGA microcontroller + LabVIEW program
Current, Voltage, and temperature Sensor	LEM HX 10-P/SP2, voltage divider, LM35

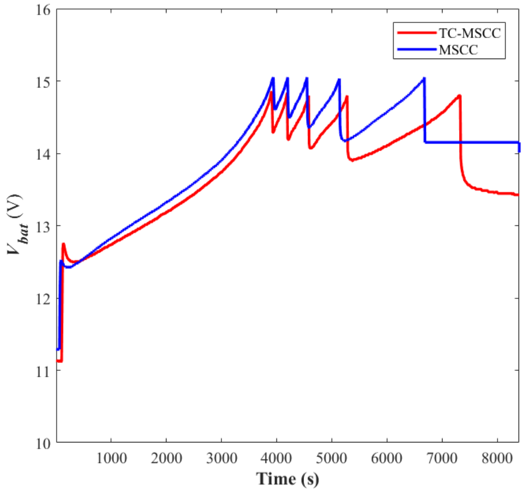


FIGURE 9. **The experimental results of the battery terminal voltage between conventional MSCC and the new proposed TC-MSCC method.**

seen that the conventional MSCC method employs the various CC steps for charging the battery, whereas the transition between the CC levels is achieved through the feedback of the terminal voltage of the battery. From another side, the new proposed TC-MSCC method employs a temperature compensation of the terminal voltage for the transition between the various CC steps.

The terminal voltage of the battery in the new proposed TC-MSCC decreases with a slope due to the temperature compensation during the charging cycle. This in turn helps to improve the lifetime of the battery and hence the reduction of the replacement costs.

Fig. 10 shows the measured experimental current of the battery at the conventional MSCC and the new proposed TC-MSCC method. The same current levels are applied at both the conventional MSCC and the proposed TC-MSCC

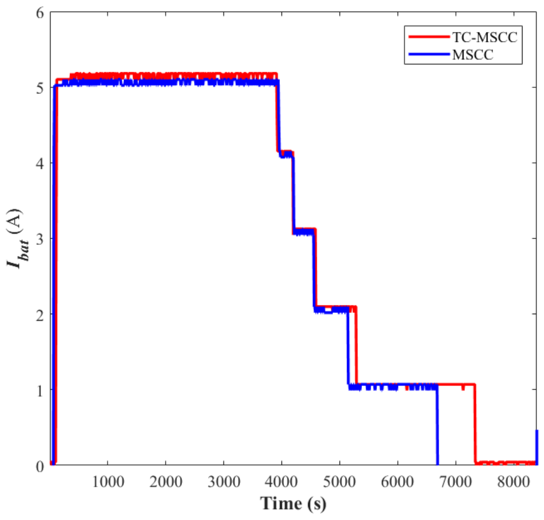


FIGURE 10. The experimental results of the battery charging current between conventional MSCC and the new proposed TC-MSCC method.

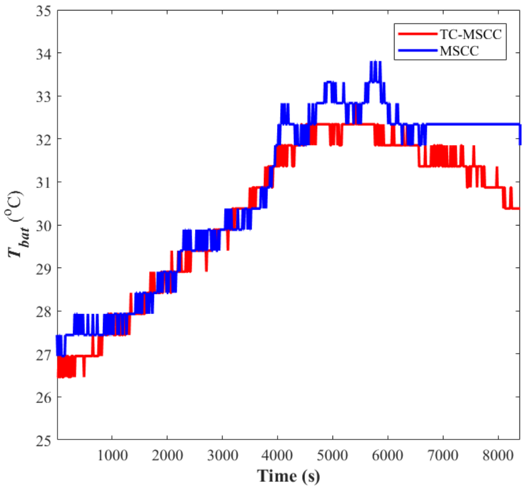


FIGURE 11. The experimental results of the battery temperature between conventional MSCC and the new proposed TC-MSCC method.

methods. Whereas, the duration of each CC step is controlled through the applied charging method. In the proposed charging method, the duration depends on the measured terminal voltage of the battery and the measured battery temperature. Whereas, the conventional MSCC charging method is controlled by only the terminal voltage of the battery.

Fig. 11 shows the comparison of the measured battery temperature of the experimental case study between the conventional MSCC and the new proposed TC-MSCC method. It can be seen that the new proposed TC-MSCC method preserves the lower internal temperature of the battery than the conventional MSCC method. The peak temperature of the conventional MSCC method reaches about 34 °C, whereas the new proposed TC-MSCC method reaches about 32 °C. This in turn causes lower thermal stresses in the proposed TC-MSCC than the conventional MSCC method. Accordingly, a longer lifetime of the battery is obtained and higher reliability of the whole system is achieved.

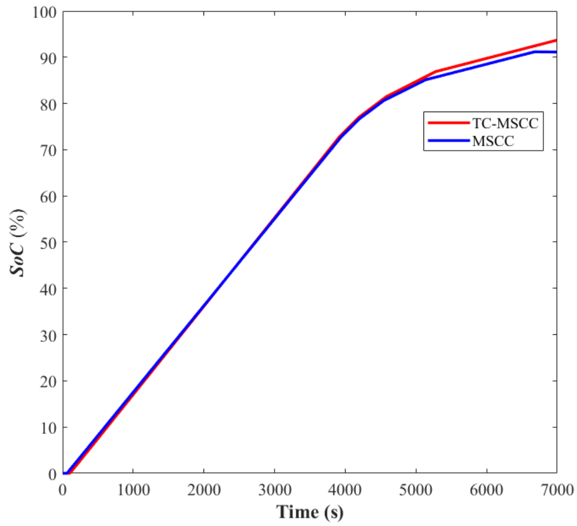


FIGURE 12. The experimental results of the battery SoC (%) between conventional MSCC and the new proposed TC-MSCC method.

TABLE 2. Performance comparison between the experimental results.

Component	Conventional MSCC	Proposed TC-MSCC
Peak Battery Temperature (°C)	34	32
Maximum SoC (%)	91.14	93.68
Battery temperature compensation	×	√

Fig. 12 compares the SoC of the battery of the experimental case study between the temperature of the experimental case study between the conventional MSCC and the new proposed TC-MSCC method. The maximum achieved state of charge of the new proposed TC-MSCC method reaches 93.68 %, whereas the conventional MSCC method achieves maximum SoC of 91.14 %. Therefore, the new proposed TC-MSCC method has a higher utilization of the battery than the traditional MSCC method.

VII. PERFORMANCE COMPARISON

Table 2 summarized the comparison of the main obtained experimental results between the new proposed TC-MSCC method and the conventional MSCC method. The new proposed TC-MSCC method preserves lower battery temperature than the conventional MSCC method.

This is a direct result of the temperature compensation of the terminal voltage of the battery in the mew proposed TC-MSCC charging method. The reduced temperature of the battery improves its lifetime and the whole system's reliability in accordance. In addition, the new proposed TC-MSCC method can achieve a higher maximum SoC of the battery in comparison with the traditional MSCC method. The new proposed method benefit also the compensated terminating voltage of each CC level, which enables more safe operation of the battery ESSs. Table 3 compares the performance of the new proposed TC-MSCC with the

TABLE 3. Performance comparison of different charging methods.

Parameter	CC Charging	CC-CV Charging	Conventional MSCC	Proposed TC-MSCC
Sensors	V_{bat}	V_{bat}	V_{bat}	V_{bat} , T_{bat}
Time to charge	*Slow*	*Medium*	*Fast*	*Fast*
Reliability	*Very low*	*Low*	*Medium*	*Very high*
Maximum achievable SoC	*Low*	*Medium*	*High*	*Very high*

conventional CC, CC-CV, and MSCC charging methods. The comparison criteria include the employed sensors, time to charge, reliability of the battery, and the maximum obtainable SoC.

A. SENSORS CRITERIA

It can be seen that the conventional charging methods employ the terminal voltage of the battery to terminate and/or transition between the levels. Whereas, the new proposed TC-MSCC method employs the battery temperature in addition to the battery terminal voltage for the transition between various CC levels.

B. TIME TO CHARGE CRITERIA

The conventional CC charging method requires lower current levels for ensuring the safe operation of the battery, whereas the CC-CV method can achieve better performance regarding the charging time due to employing two steps transitions. From another side, the employment of several levels in the conventional MSCC and the new proposed TC-MSCC methods helps to achieve the fast charging of the battery.

C. RELIABILITY CRITERIA

The conventional CC charging method achieves very low reliability because of its sensitivity to the employed current level. Moreover, conventional CC-CV suffers from low reliability due to the high current in the CV charging mode. The conventional MSCC employs feedback of the terminal voltage of the battery, which controls the transition between the different CC levels. From another side, the additional battery temperature sensor in the new proposed TC-MSCC method improves the battery operating reliability due to the compensation of the terminal voltage of the battery.

D. MAXIMUM ACHIEVABLE SoC CRITERIA

The CC charging method has to compromise the time to charge with the maximum obtainable SoC by choosing the CC charging level. Higher charging currents would make the charging process faster on the cost of lower obtainable SoC. The conventional CC-CV charging method can achieve better SoC than the CC charging method due to the employment of the CV mode. Whereas, the MSCC and the new proposed MSCC methods can achieve higher levels of SoC due to utilizing several CC charging levels. They perform the continuous transition between the different levels until the full charge of the battery is obtained.

VIII. CONCLUSION

This paper presents a modified temperature compensated MSCC (TC-MSCC) charging method for lead-acid battery ESSs. The new proposed MSCC charging method can achieve a longer operating lifetime for lead-acid batteries through employing feedback of battery temperature to control the duration and starting of each CC step. The new proposed method has achieved a reduced peak temperature of the battery of 32 °C compared with the 34 °C in the conventional MSCC method. The proposed TC-MSCC method can preserve longer operating battery lifetime with reduced thermal stresses. Moreover, the new proposed TC-MSCC method achieves faster charging than the traditional CC method and the CC-CV method in the literature. The new proposed charging method can achieve the maximum achieved state of charge of 93.68 % in comparison with 91.14 % in the traditional MSCC method. Comprehensive comparisons show the superior performance of the proposed methods over the most prevalent charging methods in the literature.

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