STM JOURNALS

Journal of
Power Electronics & Power Systems

https://journals.stmjournals.com/jopeps

ISSN: 2249-863X (Online)
ISSN: 2321-4244 (Print)
Volume 14, Issue 3, 2024
September–December
DOI (Journal): 10.37591/JoPEPS

Research JoPEPS

Efficient Cell Balancing and Protection Schemes for Electric Vehicles

B. Kusuma Kumari[1,*], G. Priyanka[2], Md. Basheera[2], M. Vasanthi[2], R. Pooja Bharathi[2]

Abstract

Efficient cell balancing and protection are critical aspects of electric vehicle (EV) battery management systems, ensuring optimal performance, longevity, and safety. Cell balancing refers to the process of equalizing the charge levels of individual cells within a battery pack to maximize energy utilization and prevent overcharging or undercharging of any cell. This promotes uniform wear and extends the overall lifespan of the battery pack. In the context of EVs, where battery packs consist of numerous cells connected in series and parallel configurations, efficient cell balancing becomes paramount to maintain pack integrity and performance. Advanced algorithms and monitoring systems are employed to continuously assess the state of charge and health of each cell, orchestrating the redistribution of energy as needed to achieve balance. Robust protection mechanisms are implemented to safeguard against potential hazards such as overvoltage, overcurrent, and overheating. Rapid detection and mitigation of anomalies are essential to prevent catastrophic failures and ensure the safety of both the vehicle and its occupants. Efforts in research and development are focused on enhancing the efficiency of cell balancing techniques, minimizing energy losses, and improving overall system reliability. As EV technology continues to evolve, advancements in cell balancing and protection will play a crucial role in accelerating the adoption of electric mobility and shaping the future of transportation.

Keywords: Cell balancing, thermal management, short-circuit, reverse polarity, battery pack

INTRODUCTION

With the impulsive increase in renewable energy sources and electric mobility, the requirement for electrical storage systems (batteries and supercapacitors) has rapidly increased [1]. Putting the stack of cells together to increase the capacity of batteries not only helps in providing more storage and power to the system but also increases the risk of damage to the system if not taken care of. Therefore, in this paper, a discussion of various risks for batteries (Li-ion) is conducted and a few protection schemes related to them are proposed. Before observing the various risks associated with the batteries, we briefly understand their various classifications (Figure 1) and their respective parameters. Batteries are mainly divided into two types: primary and secondary. Primary batteries are also called non-rechargeable batteries because once they are out of charge, they cannot be used, whereas secondary batteries are the reusable batteries that we find mostly in our mobile phones, laptops, UPS systems, etc. Compared to other available secondary batteries, Li-ion-based batteries are best suited for EV applications because they have a high-power density and an appreciable self-discharge rate, as shown in Table 1 [2].

*Author for Correspondence
B. Kusuma Kumari
E-mail: kusumatrizah@gmail.com

[1]Assistant Professor, Department of Electrical and Electronics Engineering, Gayatri Vidya Parishad College of Engineering for Women, Visakhapatnam, Andhra Pradesh, India
[2]Student, Department of Electrical and Electronics Engineering, Gayatri Vidya Parishad College of Engineering for Women, Visakhapatnam, Andhra Pradesh, India

Received Date: October 25, 2024
Accepted Date: October 28, 2024
Published Date: November 05, 2024

Citation: B. Kusuma Kumari, G. Priyanka, Md. Basheera, M. Vasanthi, R. Pooja Bharathi. Efficient Cell Balancing and Protection Schemes for Electric Vehicles. Journal of Power Electronics & Power Systems. 2024; 14(3): 9–21p.

BATTERY PERFORMANCE PARAMETERS

The performance of the battery can be estimated by considering its two terms, that is, voltage and current.

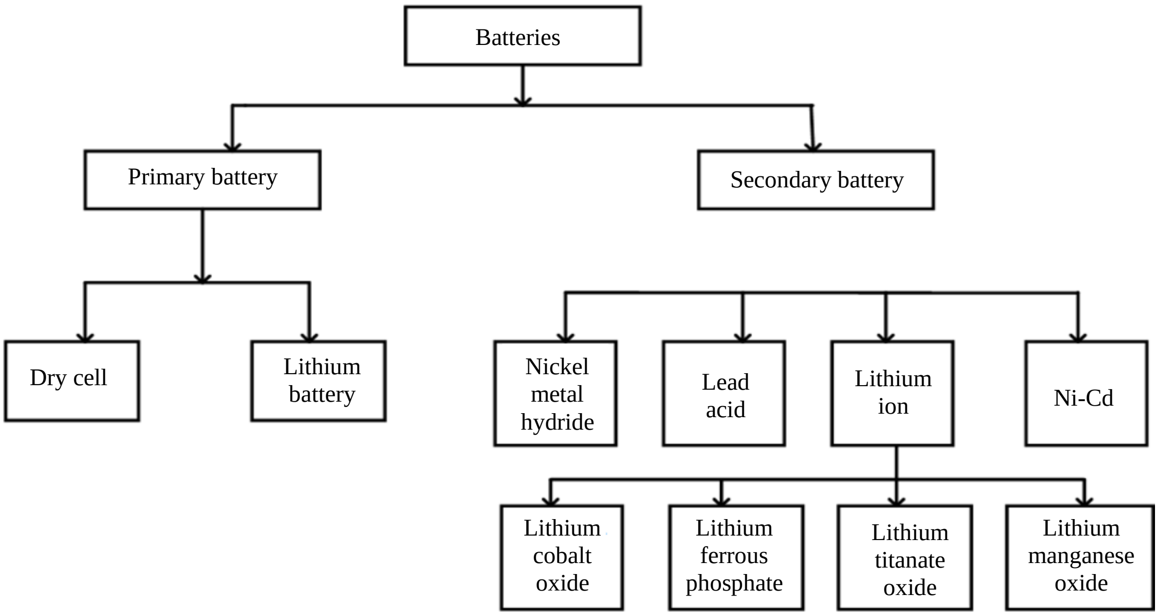

Figure 1. Block diagrams of different types of batteries.

Table 1. Comparison of various batteries.

Type	Energy efficiency (%)	Energy density (Wh/kg)	Power density (W/Kg)	Self-discharge (%/month)
Lead-acid	70–90	30–40	180	3–4
Li-ion	75–90	100–250	1800	5–10
Ni-Cd	60–90	40–60	140–180	10–15
Ni-MH	70	30–80	250–1000	30

Battery Voltage

It is the amount of charge, or "electric potential" held by the battery. This was measured in terms of volt. The general Li-ion cell holds a voltage of up to 3.7 volts. The voltage of the batteries can be increased by stacking the cells in series. SoC (State of Charge) is defined as the ratio of the amount of charge that can be extracted from the cell at a specific time to its total capacity. The circuit connected to the battery in series is shown in Figure 2.

Battery Current

The rate of flow charge is called "current" and by connecting the batteries in parallel, the capacity of the battery can be adjusted (i.e., ampere hour) A typical Li-ion battery has a 2.6 Ah rate, and when four of these batteries are connected in parallel a total of 10.4 Ah is obtained. The charge and discharge currents of the battery are generally observed at the C-rate. The general portable batteries are rated at 1 C, which indicates that a 1 Ah battery would provide 1 A for one hour. Therefore, any desired battery pack (with the required voltage and amperage) can be obtained by arranging cells in certain series and parallel connections.

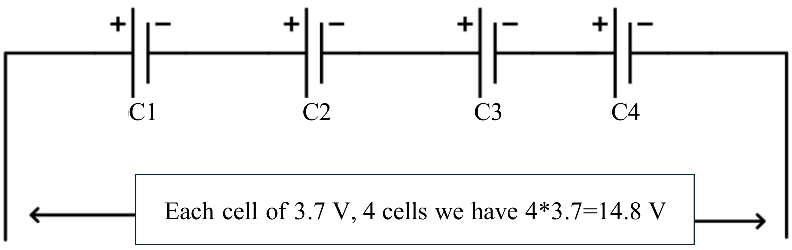

Figure 2. Batteries connected in series.

Cell Balancing Techniques

In passive cell balancing, when the voltage of a cell exceeds a certain threshold, a discharge path is created through the passive component, allowing excess charge to dissipate. This process continues until the voltages of all cells in the battery pack are balanced.

This method is simpler and more cost-effective than active cell balancing methods, but may not be as efficient, especially for high voltage differences between cells or rapidly changing voltage conditions. In addition, these methods can result in energy loss through heat dissipation in balancing components. Despite being simple to design, this passive cell balancing circuit typically has a low energy-transfer efficiency owing to energy losses caused by heat dissipation from the resistors. In this method, extra charge or energy is dissipated in the form of heat through resistors. Passive cell balancing dissipates extra energy from high-voltage cells in a series string. Equalization of the passive balancing circuit relies completely on the resistances.

This is commonly used in applications that prioritize simplicity and cost-effectiveness over efficiency, such as low-power or stationary battery systems. Overall, passive cell balancing provides a straightforward approach for maintaining balance in battery packs, although it may not be suitable for all applications owing to its limitations in efficiency and performance under certain conditions. Passive cell balancing can be categorized into two types.

1. Fixed-shunt cell balancing
2. Switched-shunt cell balancing

The simplest electronic design is used for fixed-cell balancing systems. In general, each cell has a resistor connected in parallel with it, which is utilized to remove charges in the form of heat. The fixed-cell balancing design is very simple compared to other designs. Figure 3 depicts a shunt resistor balancing circuit, where R1, R2, …, Rn are the resistances, and cell1, cell2, …, cell n are individual cells, as shown in Figure 4.

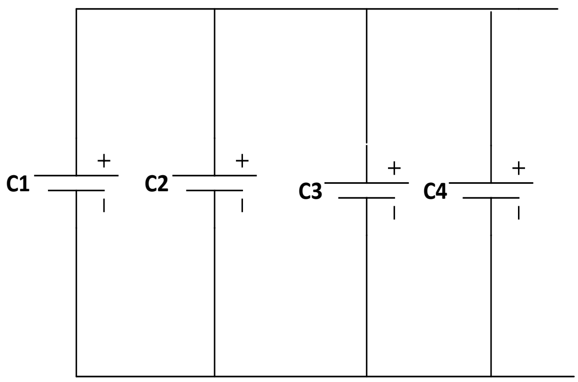

Figure 3. Batteries connected in parallel.

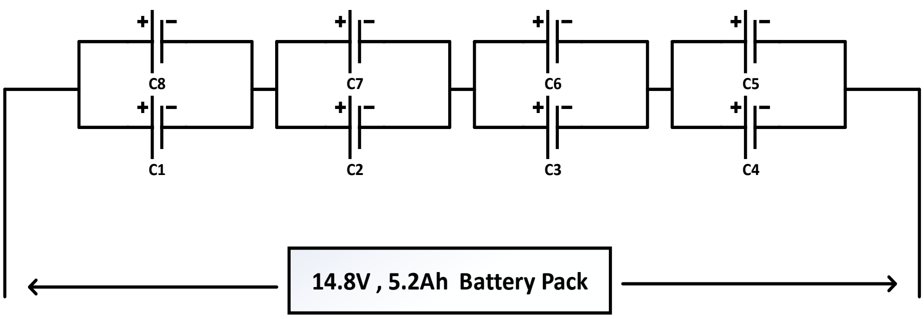

Figure 4. Batteries are connected in series and parallel combination and their resultant voltage and capacity.

According to this theory, high-voltage cells self-discharge more quickly than low-voltage cells because of their higher balancing current. However, even if the pack is evenly distributed, the circuit always loses charge, as shown in Figure 5. If the voltage decreases to a certain level, a variant of the device utilizes Zener diodes to switch off balancing, as shown in Table 2.

Switched-shunt cell passive balancing is a technique used to balance the voltages of the individual cells in a battery pack. In this method, shunt resistors were connected across each cell in the battery pack. When the voltage of a cell exceeds a certain threshold, a switch is activated to connect the corresponding shunt resistor across the cell. This allows the excess charge to be dissipated through the shunt resistor, effectively lowering the voltage of the overcharged cell. The “switched” aspect refers to the activation of switches to connect the shunt resistors only when necessary, conserving power and minimizing energy losses. Despite the term ‘passive’ in the name, this method still involves active control to manage the switching process. Switched-shunt cell passive balancing can be an effective and

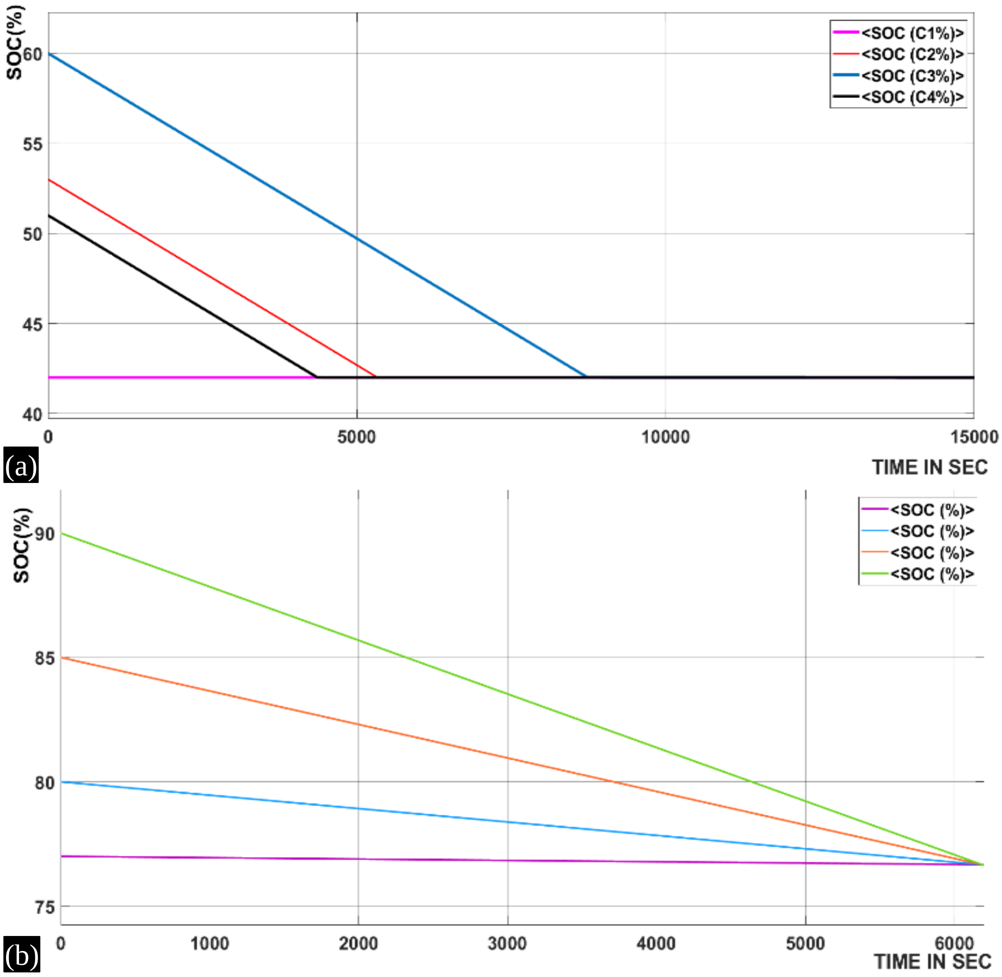

Figure 5. (a) Output waveforms of fixed-cell balancing, (b) Output waveforms of switched-shunt cell balancing

Table 2. Parameters of the various components in the simulation (fixed cell balancing).

Parameters of the various components in the simulation	
Battery pack	Cell 1: Li-Ion battery with rated Voltage of 3.6 V, 1.3 Ah, Initial state of charge 77%
	Cell 2: Li-Ion battery with rated Voltage of 3.6 V, 1.3 Ah, Initial state of charge 80%
	Cell 3: Li-Ion battery with rated Voltage of 3.6 V, 1.3 Ah, Initial state of charge 85%
	Cell 4: Li-Ion battery with rated Voltage of 3.6 V, 1.3 Ah, Initial state of charge 90%

Table 3. Parameters of the various components in the simulation (switched-shunt cell balancing).

Parameters of the various components in the simulation	
Battery pack	Cell 1: Li-Ion battery with rated Voltage of 3.6 V, 1.3 Ah, Initial state of charge 42%
	Cell 2: Li-Ion battery with rated Voltage of 3.6 V, 1.3 Ah, Initial state of charge 53%
	Cell 3: Li-Ion battery with rated Voltage of 3.6 V, 1.3 Ah, Initial state of charge 60%
	Cell 4: Li-Ion battery with rated Voltage of 3.6 V, 1.3 Ah, Initial state of charge 51%

efficient way to balance the voltages of individual cells in a battery pack, particularly for applications in which energy efficiency is important. The Zener diode in fixed-cell balancing can be replaced with a BMS-controlled switch to adapt the above concept to lithium-ion chemistries, as presented in Table 3.

Passive cell balance is achieved by removing excess charge in the form of heat through a resistor. Fixed-cell balancing and switched-shunt cell balancing simulations were performed, and waveforms were presented. Switched-shunt cell balancing is faster and more efficient than fixed-shunt cell balancing.

ACTIVE CELL BALANCING

In a lithium-ion battery bank, special protection is provided for its overcharging and over-discharging; however, owing to individual cell imbalance, the lowest voltage prevails at one cell, which leads to the activation of over-discharging for the entire battery bank. Similarly, one cell with high voltage leads to the activation of overcharging for the entire battery bank. This improper protection leads to energy loss.

The flyback converter belongs to the family of buck-boost type DC-to-DC isolated converters, which utilize a coupled inductor pair unlike that of a general AC transformer. Unlike an AC transformer that directly transfers energy continuously, the flyback converter stores energy for a moment in its core, which makes it practical for low-power applications (usually below 100 W). By tapping out the secondary side of the inductors of a flyback converter, we can provide multiple outputs.

Figure 6 indicates the undesired operation of the battery protection system [3], that is, although the other cells do not have over-discharge (or overcharge) in the battery pack when one cell is affected, the entire battery pack will activate the protection system, which is not recommended. The need to balance the battery bank is essential. There are various cell balancing techniques, as shown in Figure 7. There are two main types of cells balancing techniques. One is passive cell balancing and the other is active cell balancing. In this work, a simulation for active cell balancing (flyback converter-based) is simulated.

Figure 7 shows the various ways of cell balancing: (a) removing the excess energy using resistors (passive cell balancing), (b) Transferring Energy between cells using inductors or capacitors (active cell balancing), and (c) controlling the charging and discharging of cells [4] (advanced method in active cell balancing).

There are two types of active cell balancing methods [5]: inductors/capacitors transfer energy between the cells, control the rate of charging and discharging of cells, and balance the cells. The priority depends on the fast-balancing time and accuracy. A flyback-type fast-charging method provides good accuracy with a short balance time. Hence, this method was preferred in this study. In addition, it requires fewer switches (only one switch) and operates at a high switching frequency, which reduces the component sizes in the converter circuit. Hence, there was less loss and good efficiency. Figure 8 shows the flyback converter circuit used for balancing the lithium-ion, as shown in Table 4.

The circuit was built using a linear transformer [6, 7]. The two combined cell voltages will be the input to the 1:2 linear transformer. The same voltage, which is the average of the voltage of the capacitor, was applied to each secondary winding.

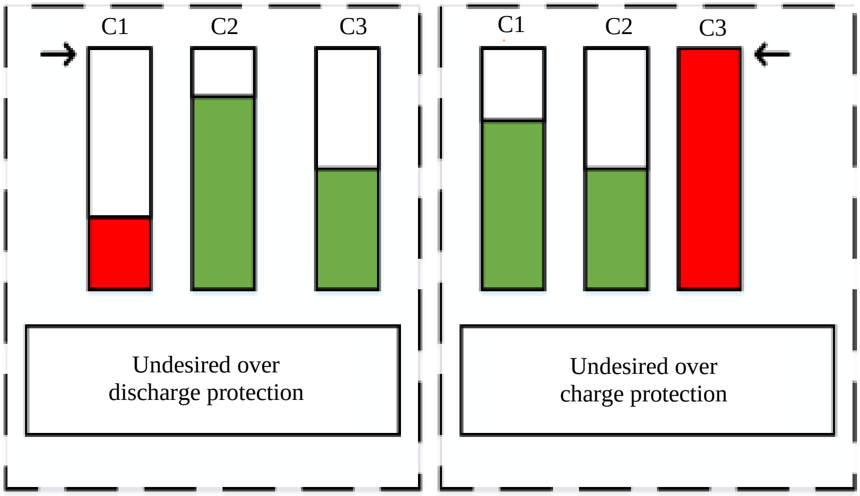

Figure 6. Imbalance in battery bank for overcharge and over-discharge.

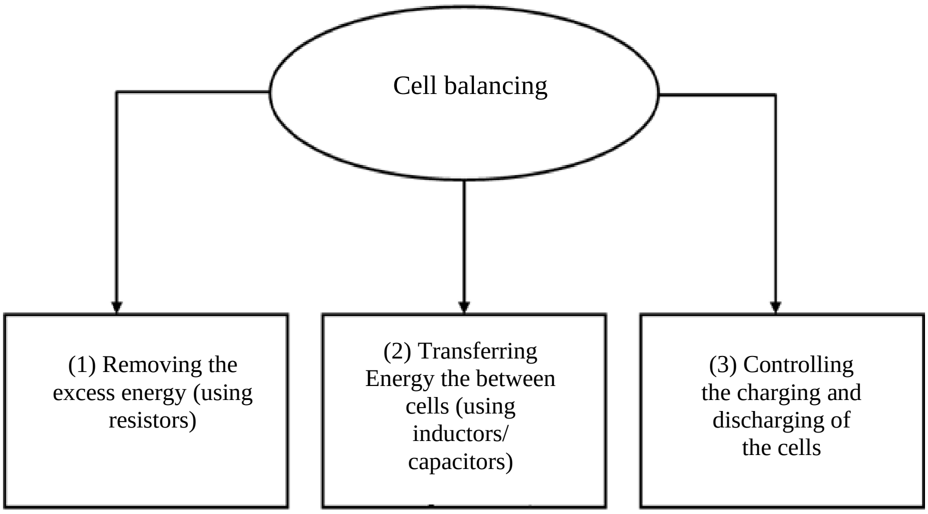

Figure 7. Various cell balancing techniques.

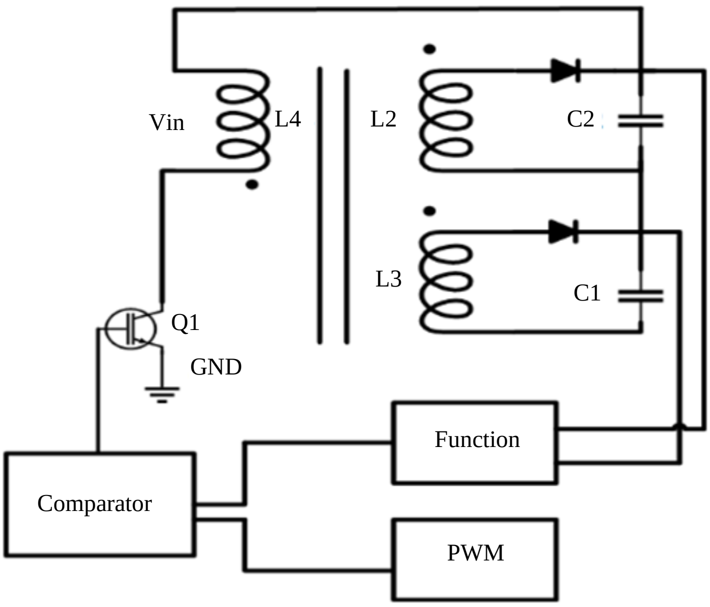

Figure 8. Circuit diagram for simulation.

Table 4. Various parameters used in simulation.

Parameters of various components in the flyback converter		
1.	Linear transformer	3 winding transformers (1:2) [v1 v2 v3] are [10 5 5] volts
2.	Diode	Forward voltage 0.8 V
3.	Pulse generator	Amplitude (1), period (0.1 sec and 0.02 sec), pulse width (50%)
4.	Capacitor (c1)	Initial voltage (3 V)
5.	Capacitor (c2)	Initial voltage (3.5 V)

The diode operates when the anode voltage is greater than the cathode voltage. If the anode voltage is not greater than the cathode voltage, the diode does not operate. When the voltages of both capacitors are equal, the switch will go into the off state with the help of a function block, as shown in Figure 9, which is called the closed-loop operation of the flyback converter. As observed in Figure 10 waveform, both the cells initially having different voltages (3, 3.5) become balanced, and the cell balancing is obtained within less than one second with little initial oscillations.

The cells start at different voltages (3 V and 3.5 V) and total voltage (6.5 V), but with a 0.41 V drop, both cells balance at 3.25 V, as shown in Figure 11. The time taken for balancing is less than 1 s, although there are small oscillations initially, as shown in Figure 12, which is less than the time required for balance in the open-loop flyback converter-based balancing.

PROTECTION SCHEMES

Lithium-ion batteries have their best life cycles in the temperature range of 20–40°C. The general cause for the temperature increases in the battery is the internal resistance, which is very small (in the range of 5–30 mΩ). When the current flows through this internal resistance, it opposes the flow of the current and produces heat, as shown in Figure 13.

$$H = I^2R \tag{1}$$

H: Heat
I: Current
R: Resistance

Apart from internal resistance, Thermal runaway in a battery occurs when the rate of internal heat generation exceeds the rate at which heat can be expelled. This initiated an unstoppable chain reaction. The temperature rose rapidly within milliseconds, the energy stored in the battery was suddenly released, and a temperature of approximately 400°C was reached. Thus, the battery becomes damaged, and fire erupts, which cannot be extinguished using conventional means. The main reasons for the occurrence of thermal runaway are internal/external short circuits and battery overcharging. There are many techniques to rectify this and obtain battery cooling, a few of which are Heat Sinks, Air Cooling, Liquid cooling, phase change materials, and thermoelectric cooling.

Thermoelectric Cooling

Among the different methods of cooling the battery pack, thermoelectric cooling systems [8] rely on electricity for cooling, which is preferred for closed systems. This is also known as “solid-state cooling” because there is no liquid refrigerant running through the machine. It works based on the thermo-Peltier effect, which is the reverse principle of the See Beck effect, as shown in Figure 14, that is, the electric current flowing through the material will result in one side absorbing heat and the other emitting it. Thus, an electronic refrigerator was obtained.

Reverse Polarity Protection

When the circuit is connected in reverse polarity, it damages the system. A simple method to protect the circuit is to use diode. If we connect the power backward, no current flows through the diode, and thus, our circuit is safe. However, diode heat is generated, and power is wasted.

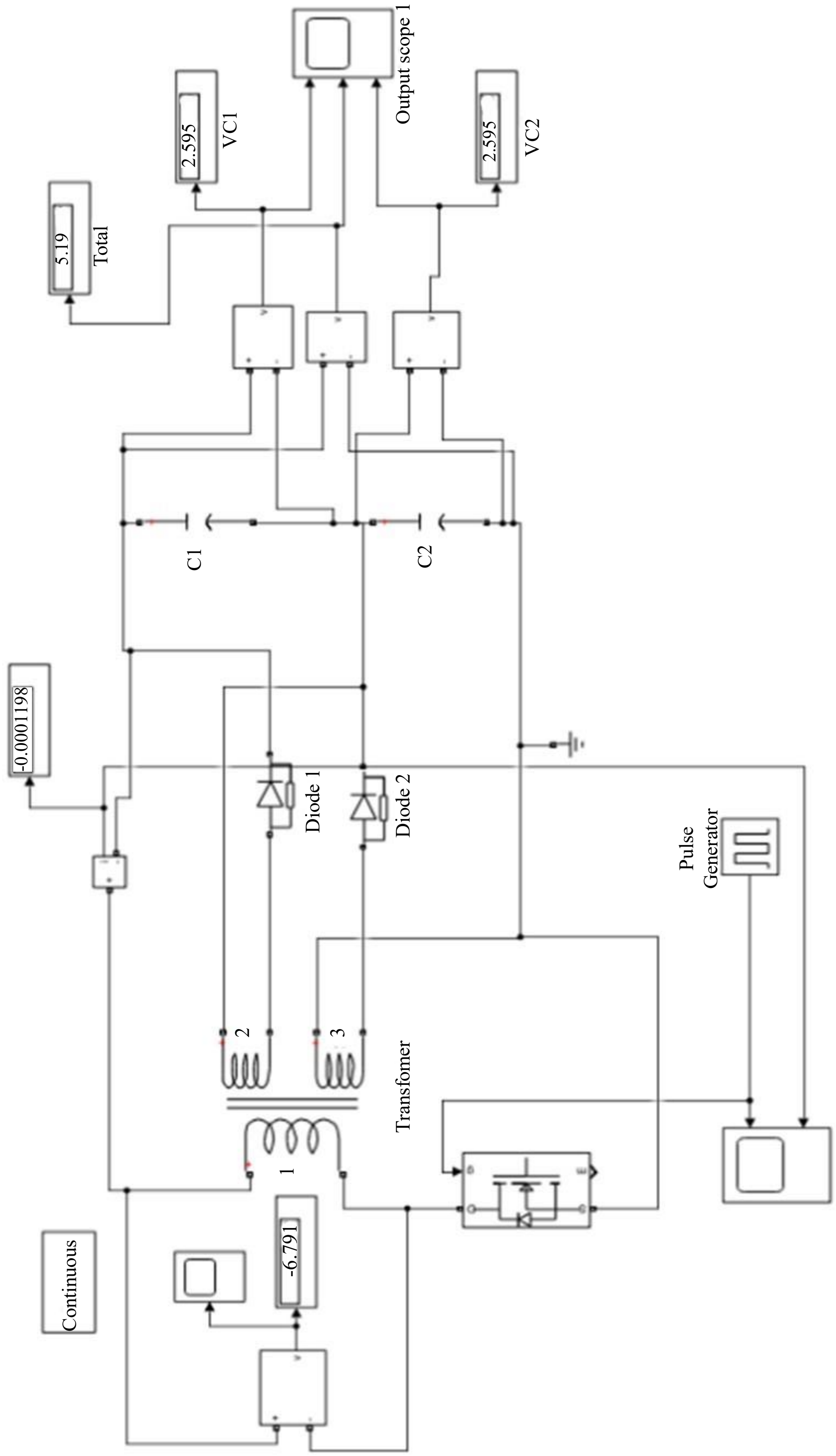

Figure 9. Simulation of open loop Flyback converter-based cell balancing.

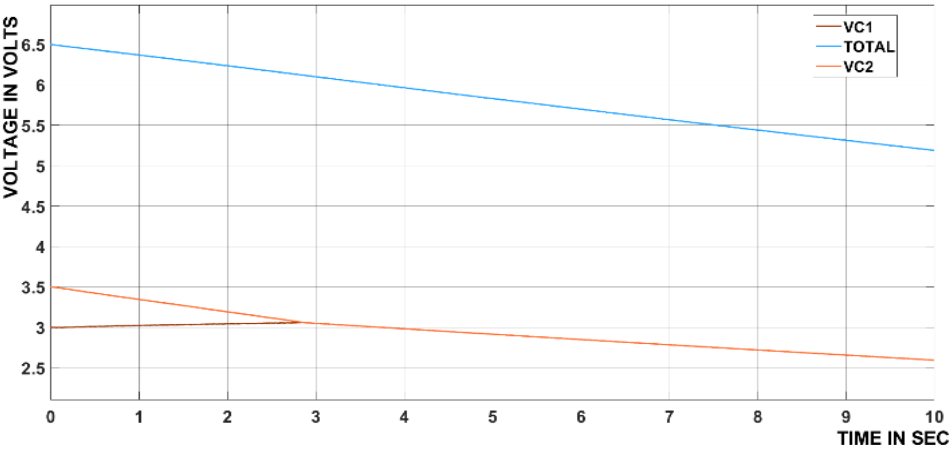

Figure 10. Waveforms of open-loop flyback converter-based cell balancing.

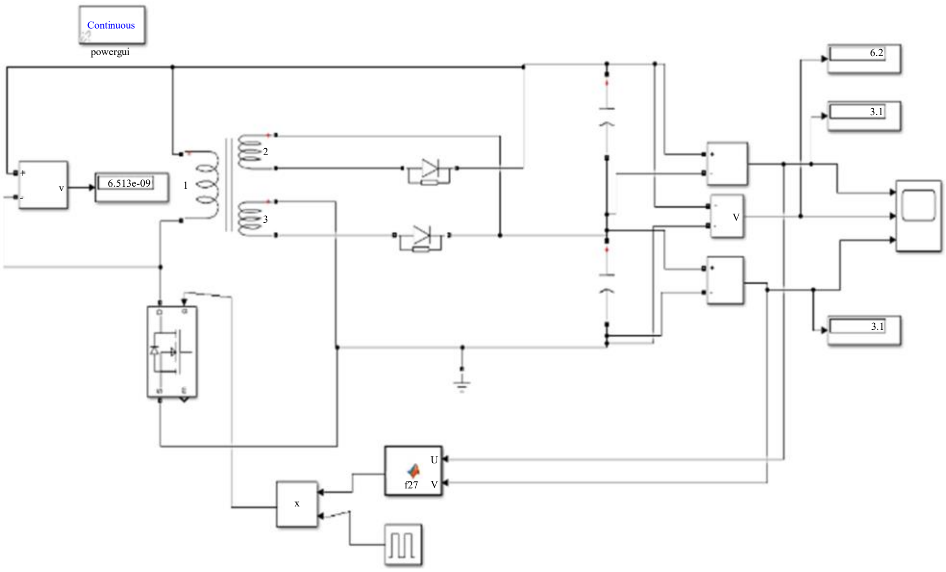

Figure 11. Waveforms of closed-loop flyback converter-based cell balancing.

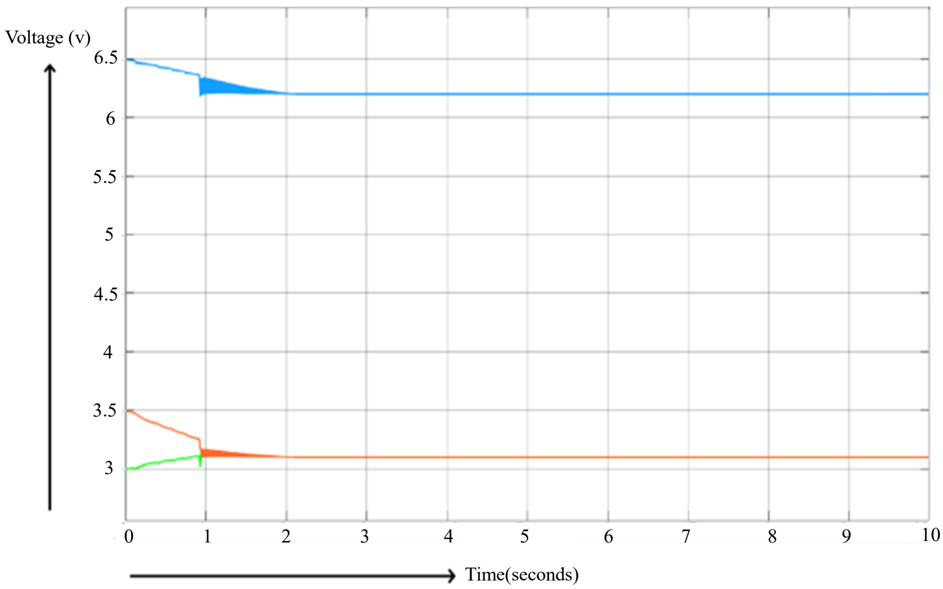

Figure 12. Waveforms of closed-loop flyback converter-based cell balancing.

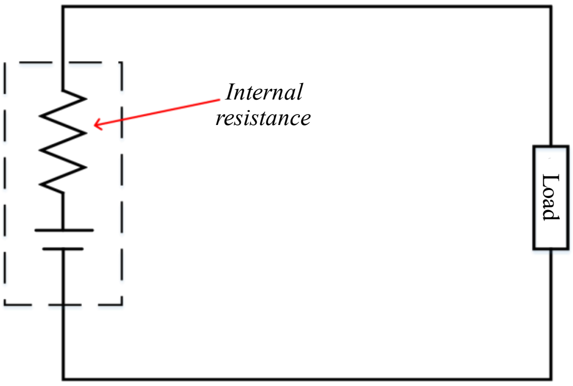

Figure 13. Circuit diagram for battery with internal resistance.

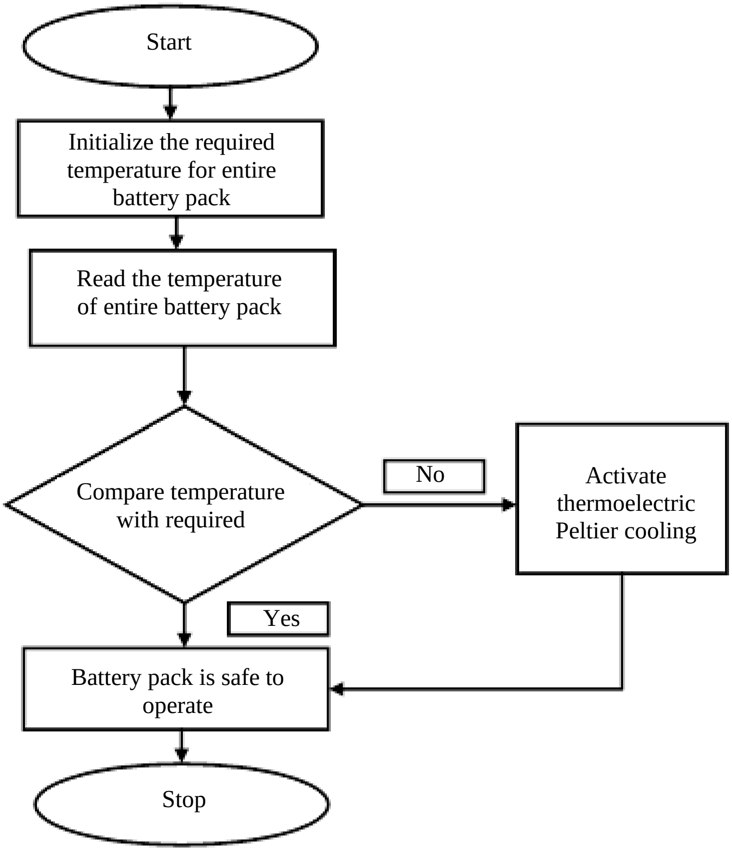

Figure 14. Flowchart for temperature control using thermoelectric cooling.

This effect can be reduced to some extent by using a Schottky diode, but the best way is to use a MOSFET (p-channel or n-channel) [9] by properly connecting the terminals (gate, drain, source). When the power is connected properly, the circuit functions normally; when it is connected in reverse, the MOSFET turns off and the circuit is protected. Although there is negligible resistance (RDS, which is approximately 26 milliohms) [10], further use of the resistor and Zener diode can limit the gate voltage to suitable limits.

The simulation circuits are shown in the Figures 15(a) and 16(a) operate with respect to the mode of connection of the battery to the MOSFET, that is, during normal operation, the input voltage and load voltage are the same, as shown in Figure 15(b); during reverse polarity, no load voltage is provided even though the input voltage is provided to the load because the MOSFET connected between the load and battery is not activated, as shown in Figure 16(b).

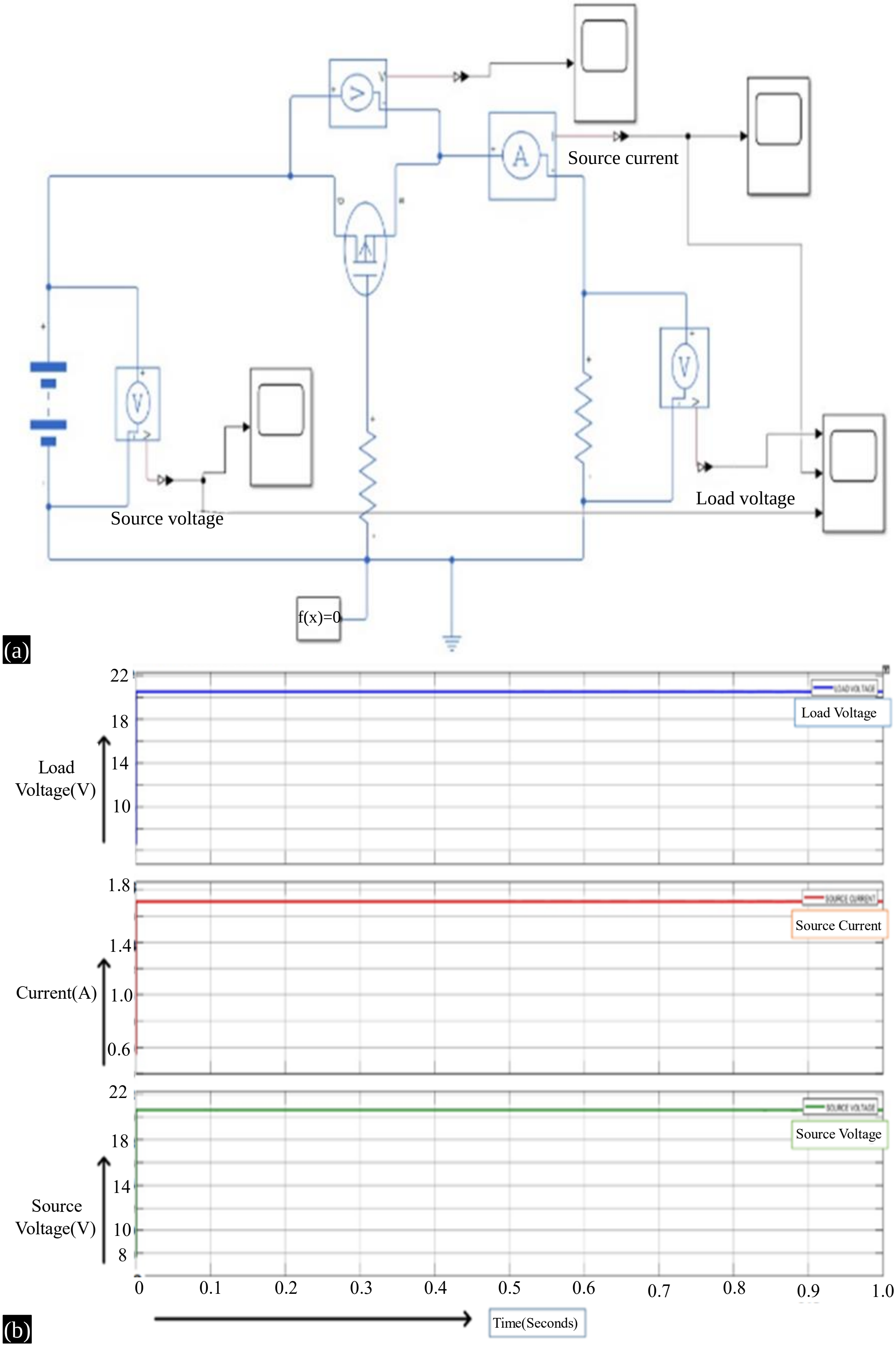

Figure 15. (a) Simulation of reverse polarity protection connected in normal operation, (b) Normal operation with output voltage and current.

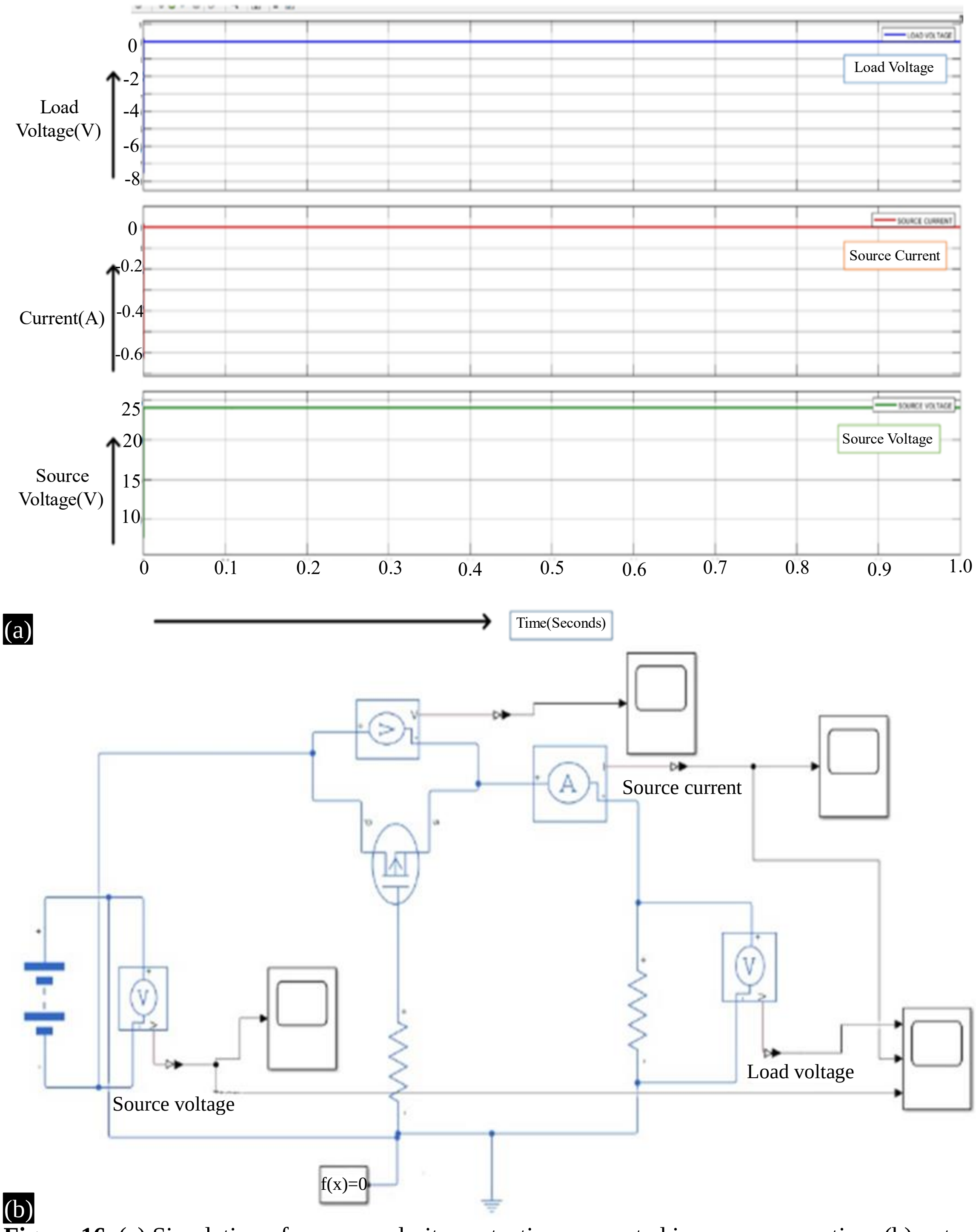

Figure 16. (a) Simulation of reverse polarity protection connected in reverse operation, (b) output voltage and current are zero with the reverse operation.

CONCLUSIONS

In this work, efficient cell balancing and different protection systems for lithium-ion batteries are discussed with possible simulations using MATLAB. The future scope of this work with respect to cell balancing includes performing a simulation model of flyback converter-based balancing with a greater number of cells and obtaining the hardware model. In terms of protection systems, the future scope includes verifying the protection systems with the latest protection modules (ICs such as TP4056 and BQ79652) available on the market by various manufacturers and comparing their performance with the presented ones. In thermal management, the development of a heat sink combined with a thermoelectric Peltier module is required to obtain a safe and efficient system.

REFERENCES

1. Miao Y, Hynan P, von Jouanne A, Yokochi A. Current Li-ion battery technologies in electric vehicles and opportunities for advancements. Energies. 2019;12:1074. DOI: 10.3390/en12061074.
2. Biswas MM, Azim MS, Saha TK, Zobayer U, Urmi MC. Towards implementation of smart grid: An updated review on electrical energy storage systems. Smart Grid Renew Energy. 2013;4:122–32. DOI: 10.4236/sgre.2013.41015.
3. Qi J, Dah-Chuan Lu D. Review of battery cell balancing techniques. Australas Univ Power Eng Conf (AUPEC). 2014. p. 1–6. DOI: 10.1109/AUPEC.2014.6966514.
4. Omariba ZB, Zhang L, Sun D. Review of battery cell balancing methodologies for optimizing battery pack performance in electric vehicles. IEEE Access. 2019;7:129335–52. DOI: 10.1109/ACCESS.2019.2940090.
5. Cao Y, Li K, Lu M. Balancing method based on flyback converter for series-connected cells. IEEE Access. 2021;9:52393–403. DOI: 10.1109/ACCESS.2021.3070047.
6. Koraddi S, Samprita KV, Yadgir KS, Biradarpatil LM, Nayak SV. Analysis of different cell balancing techniques. Int Conf Adv Technol (ICONAT). 2022. p. 1–4. DOI: 10.1109/ICONAT53423.2022.9725863.
7. Farzan Moghaddam A, Van den Bossche A. Flyback converter balancing technique for lithium based batteries. 8th Int Conf Mod Circuits Syst Technol (MOCAST). 2019. p. 1–4. DOI: 10.1109/MOCAST.2019.8741893.
8. Alaoui C, Salameh ZM. A novel thermal management for electric and hybrid vehicles. IEEE Trans Veh Technol. 2005;54:468–76. DOI: 10.1109/TVT.2004.842444.
9. Pop P, Petrasuc G, Plesa CS, Neag M, Salajan T. Reverse polarity protection for automotive NMOS LDO. Int Semicond Conf (CAS). 2021. p. 235–8. DOI: 10.1109/CAS52836.2021.9604200.
10. Debele GM, Qian X. Automatic room temperature control system using Arduino UNO R3 and DHT11 sensor. 17th Int Comput Conf Wavelet Act Media Technol Inf Process (ICCWAMTIP). 2020. p. 428–32. DOI: 10.1109/ICCWAMTIP51612.2020.9317307.

