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Development of A Robust System for Series-Connected Battery Packs

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***Abstract*—Series-connected battery packs consist of numerous individual batteries linked together. When a few batteries fail, it hinders the power output of the other healthy batteries, leading to a reduction in the overall power output of the battery pack. This research combines microcontroller control, power conversion, and battery health status detection technologies to develop a robust system that overcomes the problem. The developed system includes functions such as power management, troubleshooting, power supply circuit reconstruction, and battery abnormality notification, effectively enhancing the power supply capability of series-connected battery packs.**

Keywords—Robust system, series-connected battery pack, power conversion.

I. INTRODUCTION

With the progress of the times, people are becoming increasingly reliant on vehicles, among which the progress of electric vehicles is the most obvious, and the number of vehicles used is also increasing, as shown in Fig. 1.

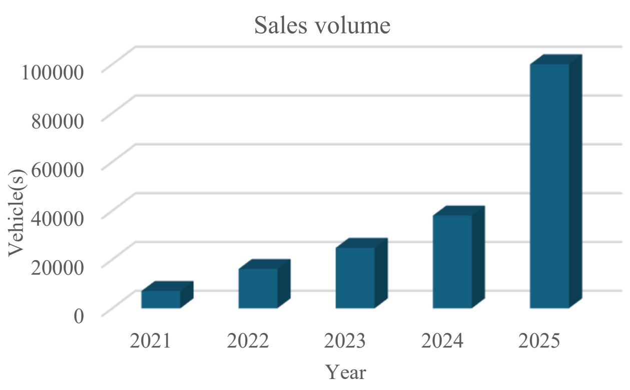

Fig. 1. The sales volume of electric vehicles in Taiwan.

The electric power required by electric vehicles is supplied by battery packs. The types of batteries used in electric vehicles mainly include lead-acid batteries, lithium manganese batteries, lithium cobalt batteries, lithium iron phosphate batteries, nickel-metal hydride batteries and nickel-cadmium batteries [1]. These batteries have low voltages, so they are difficult to use directly. Multiple single batteries need to be combined into a battery module by connecting them in series and in parallel, and then a battery pack is formed, as shown in Fig. 2, to provide enough high voltage and high current electric power for electric vehicles [2,3].

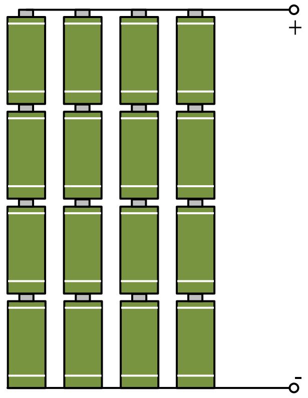

Fig. 2. Series and parallel connection of batteries inside the battery module of an electric vehicle.

In practice, electric vehicle battery packs are mostly composed of batteries of the same brand and specifications, and theoretically, the working conditions and lifespan of each battery should be consistent. However, due to factors such as differences in battery manufacturing, battery pack heat dissipation design, and vehicle usage environment, the aging rate of each battery or module in the battery pack is often different. When a battery with a shorter lifespan deteriorates or fails first, its internal resistance will increase significantly, thereby limiting the output capacity of other healthy batteries connected in series with it, resulting in a decrease in the overall power supply efficiency of the battery pack, affecting motor performance and the vehicle's range. In addition, this phenomenon may also cause users to mistakenly believe that the battery pack is completely damaged and replace it prematurely, resulting in an increase in the number of waste batteries and generating unnecessary environmental burden and social costs [4].

To overcome the above problems, a robust system for series-connected battery packs with troubleshooting and power supply circuit reconstruction functions has been developed. This system has self-diagnosis and healing capabilities, and can quickly isolate some batteries when they fail, and then rebuild the power supply circuit of the healthy batteries to continue outputting power, thereby achieving the goal of strengthening the power supply capacity of the battery pack.

II. THE METHOD

The functional block diagram of the developed robust system is shown in Fig. 3.

The first step is to detect the health status of each battery in the battery pack. After obtaining the battery parameters of the battery pack through the battery status sensing circuit, the state of health (SoH) and internal resistance R_B of each battery are calculated according to (1) and (2). Then, the battery voltage and temperature parameters are used to determine whether the battery is healthy or faulty [5].

$$SoH = Q_B / Q_R \times 100\% \quad (1)$$

Where Q_B and Q_R represent the battery release capacity and rated capacity, respectively.

$$R_B = \Delta V_B / \Delta I_B \quad (2)$$

Where ΔV_B and ΔI_B are the changes in voltage and current of the battery, respectively.

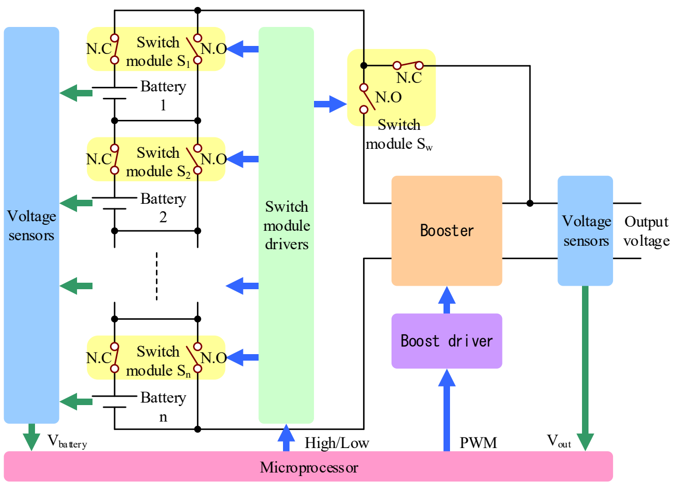

Fig. 3. The functional block diagram of the developed robust system.

When a battery fault is detected, the switch module next to the faulty battery is used to isolate the faulty battery and rebuild the power supply circuit for the healthy battery, thus eliminating the fault. In Fig. 3, each battery is connected in series with a switch Q_S, and then in parallel with another switch Q_P. These two switches together form a switch module. When there is no battery fault, all series switches Q_S are in the normal close (NC) state, while all parallel switches Q_P are in the normal open (NO) state.

The equivalent circuit before the battery failure is shown in Fig. 4. In Fig. 4, all series switches, Q_{S1}, Q_{S2} and Q_{S3} are in the NC state, while all parallel switches, Q_{P1}, Q_{P2} and Q_{P3} are in the NO state.

When a battery in the battery pack fails, the states of the switch Q_S and Q_P of that battery will be reversed to isolate the faulty battery and rebuild the power supply circuit for the healthy battery, as shown in Fig. 5.

In Fig. 5, in the series switch, Q_{S2} is in the NO state, while Q_{S1} and Q_{S3} are in the NC state. In the parallel switch, Q_{P2} is in the NC state, while Q_{P1} and Q_{P3} are in the NO state.

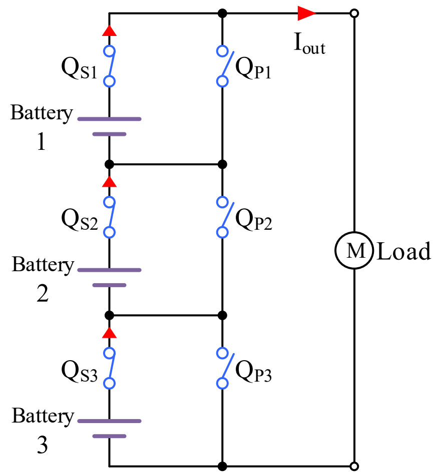

Fig. 4. The equivalent circuit before the battery failure.

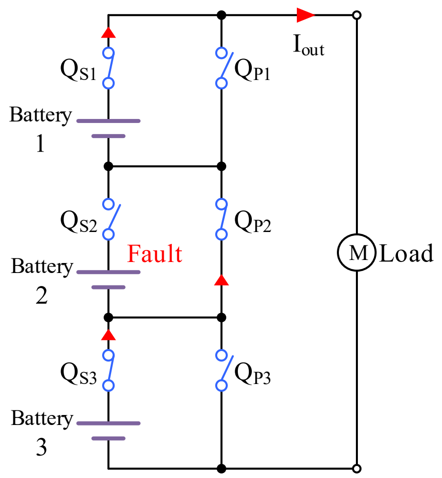

Fig. 5. The equivalent circuit after the battery failure.

The switching on and off is controlled by a microcontroller. When the faulty battery is isolated and the power supply circuit of the healthy battery is rebuilt, the voltage of the power supply circuit will be lower than the original rated voltage, so it must be boosted to overcome this problem. The boost circuit designed in this study is a synchronous boost converter, and the output voltage of the boost circuit is determined by the microcontroller and the pulse width modulation (PWM) drive circuit [6].

Fig. 6 shows the boost circuit designed in this study, which consists of a MOSFET switch Q_1, an inductor L_1, a capacitor C_1, and a diode D_1. When the switch Q_1 is triggered to conduct by the microcontroller, the power supply Vs charges the inductor L_1. Then, the switch Q_1 is turned off by the microcontroller. Currently, the voltage polarity of the inductor L_1 is reversed. The power supply V_s and the voltage of the inductor L_1 are connected in series and added together, and then output to the external load through the diode D_1. The output voltage V_o is shown in (3). The output voltage Vo can be changed by adjusting the value of the duty cycle D. In this way, the voltage of the battery power supply circuit can be restored to the rated value by the PWM control signal of the microcontroller for use by the external load.

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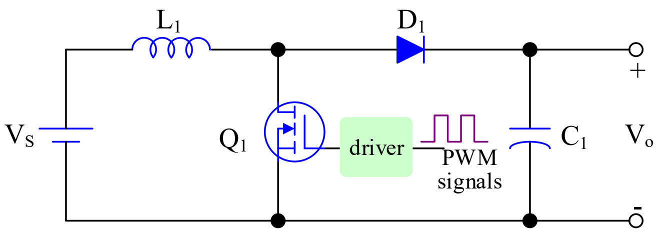

Fig. 6. The emplyed boost circuit.

$$V_o = V_S /(1-D) \quad (3)$$

Where D is the duty cycle of the PWM signal.

III. RESEARCH RESULTS

Fig. 7 shows the physical diagram of the developed control circuit board, where the microcontroller is the Arduino Nona control board, its digital signal processor is the ATmega328, the synchronous boost converter control element is the IRF640, and the gate drive element is the TLP250. The battery pack used in this study consists of three lithium battery modules connected in series, as shown in Fig. 8. The rated voltage of a single lithium battery module is 14.2V, so the rated voltage of the entire battery pack is approximately 42.6V.

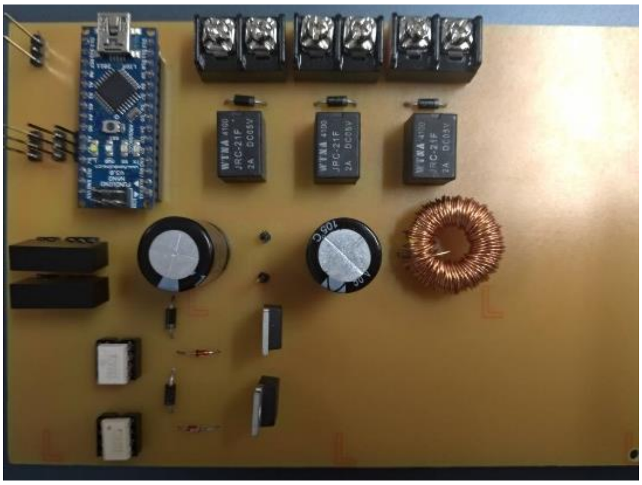

Fig. 7. The physical diagram of the developed control circuit board.

When a battery module malfunctions or overheats, the microcontroller receives this information through voltage, current, and temperature sensors. It then outputs a control command to the switching module to isolate and bypass the faulty battery, reconnect the remaining healthy battery modules in series, and boost the voltage to the rated voltage before outputting power. Fig. 9 shows the voltage waveform of the battery pack when one battery module malfunctions; the voltage drops to approximately 25.6V when the malfunction occurs.

The synchronous boost converter then boosts the voltage, as shown in Fig. 10, where the waveform shows that its output voltage is approximately 42.4V.

Fig. 8. The photo of the battery module used.

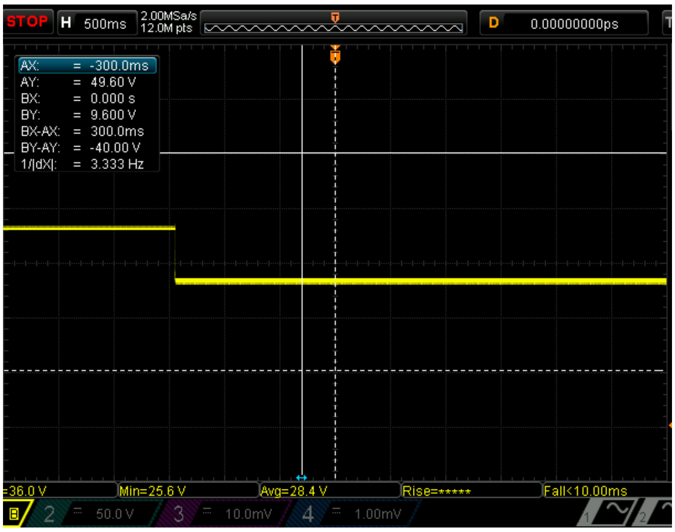

Fig. 9. The voltage waveform of the battery pack when one battery module fails.

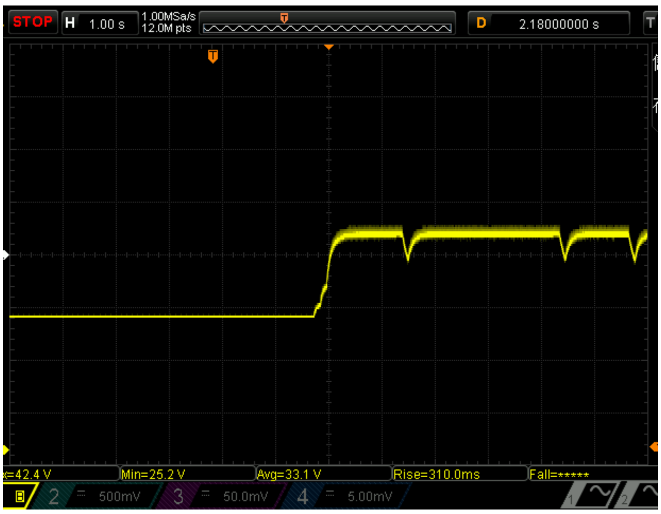

Fig. 10. The waveform diagram of synchronous boost module boosting voltage to rated voltage.

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IV. CONCLUSIONS

This robust system effectively increases the energy utilization rate and range of series-connected battery packs, extends their lifespan, reduces the number of discarded batteries, and mitigates environmental problems [7,8], thus demonstrating practicality and innovation. This research has successfully developed this robust system, which can be widely applied to battery packs in various electric vehicles to improve their range. The contributions of this research are as follows:

1. It fully utilizes the remaining power of each battery module in the battery pack, improving energy efficiency and avoiding waste;
2. It prevents healthy battery modules from being mistakenly considered depleted and discarded, reducing the generation of discarded batteries and mitigating environmental problems;
3. It extends the range of the battery pack, thus extending the driving range of electric vehicles and increasing public willingness to use electric vehicles.

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