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New Method of rapid heating battery for electric vehicles at low temperature

DongcuiWang[1], Guangjian Yuan[2], Xiaoxiao Zhang[3]
[1]*Dongcui Wang (corresponding author) SAIC MOTOR, AnyanRoad 201, ShangHai, China, Wangdongcui@saicmotor.com*

Abstract

The performance of the battery at low temperature is one of the key limiting factors for the application of electric vehicles (EVs). Generally, positive temperature coefficient (PTC) heater or heat pump is used to preheat battery, which leads to a bulk size and high cost. In addition, the temperature rise rate is less than 0.8 ℃/min by using this method. In this work, one new method is applied with the motor wiring and two separated battery packs, and there is no change for inverter hardware design. With this adaption, the buck and boost circuit is formed with the two battery packs, motor wiring and inverter, which realizes the high pulse current (from 0.1C to 1.5C) between the two packs. The experimental results have shown that the battery self-heating rate can be reached up to 3 ℃/min at low temperature, proving an effective, practical and promising method for battery heating of EVs with low cost and high efficiency.

1. Introduction

As tighten regulations on fuel efficiency and exhaust emissions have been established worldwide, the popularization of eco-friendly electric vehicles (EVs) is becoming an irresistible trend [1, 2]. One common concern of EVs owners is the deteriorated battery performance, especially for operation under cold environments [3]. For example, the battery discharges at low temperature causes the reduction of battery capacity, resulting in a significant decrease in driving range [4]. In addition, battery charging in cold climates may lead to lithium plating, which will cause battery degradation and battery safety diminishment [5]. To overcome the challenges of Li-ion batteries at low temperature, preheating of EVs batteries has become an essential function to improve battery performance, cycle life and safety at extreme temperatures.

Generally, the preheating method can be classified into external or internal heating systems. In external heating, a thermal cycle container (heating pump, PTC heater, etc.) is implemented outside the battery. In this way, the heat is generated outside the battery cells and then transferred into the battery cells through conduction or convection. However, this method is limited due to the low heating speed and large energy loss caused by long distance [5]. To further simplify the heating system, battery power can also be used to produce the external heating. For example, battery pack powered the electrical wires directly, then the heated air can be blew through the batteries by the fan [6]. In this way, the battery can be heated without any off-board power and devices. However, it still suffers a huge energy dissipation and slow heating rate owing to the long heat conduction period. On the contrary, the internal heating system can heat the battery with low heat dissipation and high efficiency [6, 7]. For instance, the internal heating can be realized by a nickel foil embedded inside the battery cell [8]. In this circumstance, the temperature of batteries increases with a heating rate of 3°C/s and the energy loss reduces relatively [9]. However, the temperature of the battery may become inhomogeneous and this method can not be applied to existing batteries conveniently [10]. Recently, the internal warming of battery with voltage polarization is becoming an attractive method to realize fast and uniform heating [11], which achieve the excellent heating performance by optimizing the principle of alternate current (AC) [12-14]. However, the realization of high performance only exists under the laboratory conditions and the heating behavior cannot be reproduced in the battery cell of an EV. Furthermore, the on-board circuits have been proposed to achieve the heating of battery under any situation. In this scenario, the heat-balancing topology [15], resonant circuits [16] or integrated heater-equalizer [17] should be incorporated. However, additional electronic components (circuits) are unavoidably implemented into EVs, leading to the high cost and large size [5].

In this work, a self-internal heating system with the existing circuit of EVs has been proposed, which enables low cost and high reliability. With refined circuitry topology, the heating currents have been improved with electricity transferred between battery packs. Finally, the rapid, efficient, and harmless battery heating method is realized by using the proposed circuitry topology, which enables fast heating and low cost with the existing circuit.

2. Methodology

In contrast with traditional electric motor systems in EVs [18], two series-connected battery packs (battery 1 and battery 2) have been used, as shown in Fig. 1. The motor of EVs is connected to the battery 2 in the system. As a consequence, the closed loop is easy to implement with battery 1, battery 2, motor and inverter. The high pulse current can be generated between battery 1 and battery 2 by controlling the switch of inverter, resulting in a rapid heating for batteries. With the relays of K5 and K6, battery 1 and battery 2 realize the charge and discharge modes circularly.

In the previous work, the neutral line has been used to connect a half bridge, forming a novel fault-tolerant control method [19]. Both simulated and experimental results have verified that a feasible control strategy has been proposed. In addition, the neutral point of the motor can be returned to the midpoint of the voltage link to achieve the continuous, disturbance free operation with complete loss of one leg of the inverter or motor phase [20]. Similarly, an additional neutral line 2 has been incorporated in this work. Under this circumstance, the system realizes a boost function of voltage to 800V with the help of capacitor C1, relay K7 and neutral line 2. For example, the voltage can be boosted by inverter from DC charger to battery based on closed K6, opened K5 and K7. Nowadays, with the increasing of 600V- and above-rated IGBT modules, it has been suggested that raising the battery voltage to 800V, from the more common 400V level, can realize the design benefits [21]. However, one of the most important keys is the establishment of the 800V charging station, which is not widespread adequately in the near future [22, 23]. It is worth noting that the proposed method can also realize voltage boosting to 800V. In this way, a refined circuitry topology is presented, which is easy to implement and compatible with the existing drive circuitry in EVs, achieving both self-preheating and boosting functions.

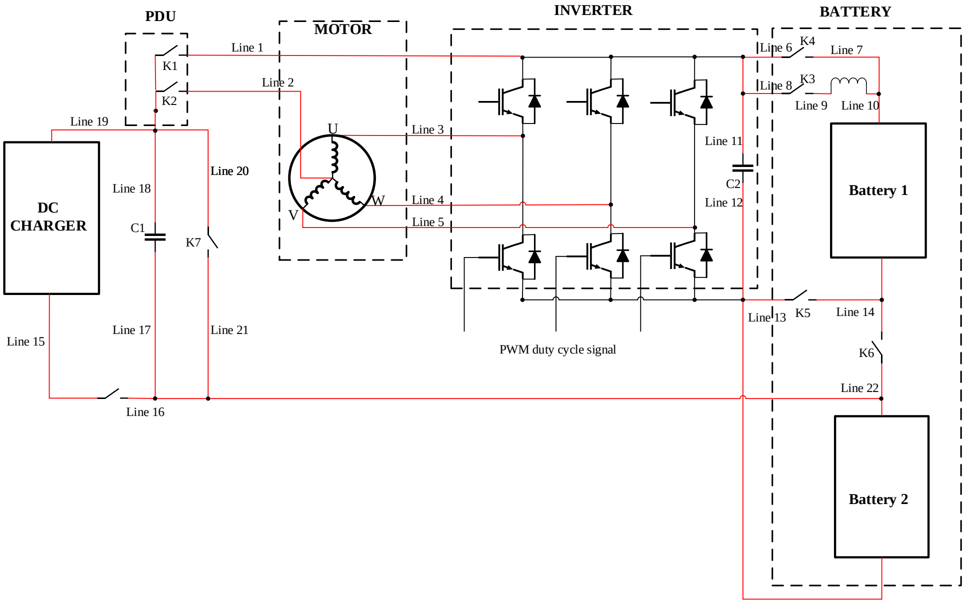

Figure 1: The diagram of self-internal heating system

3. Results and discussion

3.1 Circuit operation and heating process

In this work, the relationship between d-axis current I_d, q-axis current I_q and motor phase currents in the self-internal heating system can be described by Park-Clarke transform [24]:

$$\begin{pmatrix} I_d \\ I_q \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{pmatrix} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix} \quad (1)$$

where θ_r denotes the electrical angle of the drive motor, I_a, I_b, and I_c are motor phase currents with the same value, as shown in Fig. 2(a). As a consequence, the values of I_d and I_q are both equal to zero. Then the torque output of motor determined by I_d and I_q [25], can be written as:

$$T_e = \frac{3}{2} p \left[\psi_f + \left(L_d - L_q \right) I_d \right] I_q = 0 \quad (2)$$

where p is the number of pole pairs, ψ_f is the flux produced by the permanent magnets, L_d and L_d are the *d*- and *q*- axis synchronous inductances.

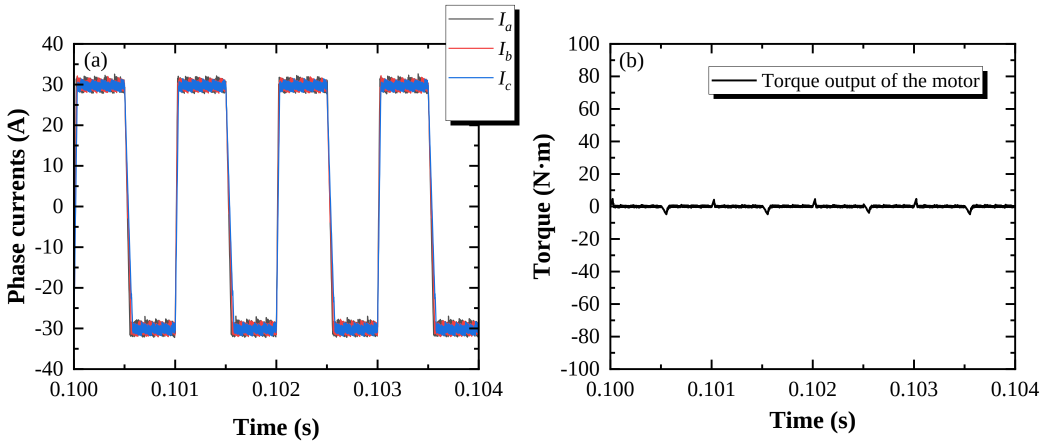

Figure 2: (a) The phase currents of the motor, (b) the torque output of the motor.

Generally, battery heating is usually operated before driving an EV, when the speed of EV is zero. An effective way for static motor is zero-torque output, as shown in Fig. 2(b). In principle, there are two operation modes (boost mode and buck mode) in the refined circuitry topology. In the boost mode, battery 1 can be charged by an increased voltage from battery 2, through the winding and insulated gate bipolar transistor (IGBT). On the contrary, in the buck mode, battery 2 can be charged by a decreased voltage from battery 1. Circularly, a battery charging and discharging circuit is formed, as shown in Fig. 3 and Fig. 4. Heat is generated while the currents flow through the battery, inverter and motor due to the Joule effect. Considering the identical motor currents, a higher current of battery can be generated due to the electricity transfer in the buck and boost circuit, resulting in a larger battery polarization and more heat inside the cells. Consequently, a faster heating process is expected and the heating power P_{heat} can be calculated based on Joule's law:

$$P_{heat} = I_{eff} U_o \quad (3)$$

where I_{eff} is equivalent heating current, as shown in Fig. 3. U_o is the voltage of battery, as shown in Fig. 4, which is related to the Duty cycle D and the input voltage U_i:

$$U_o = \frac{1}{1-D} U_i \quad (4)$$

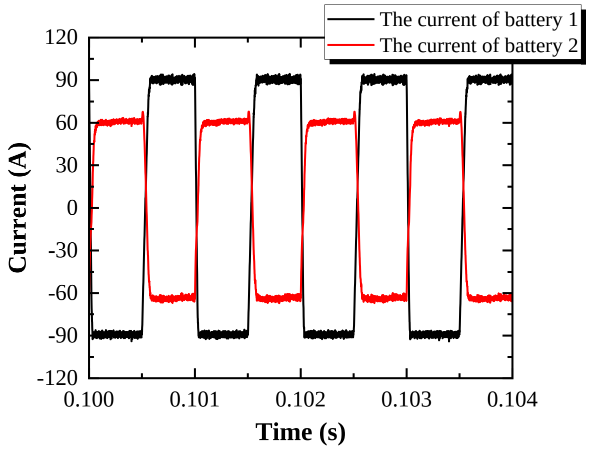

Figure 3: The currents of battery 1 and battery 2.

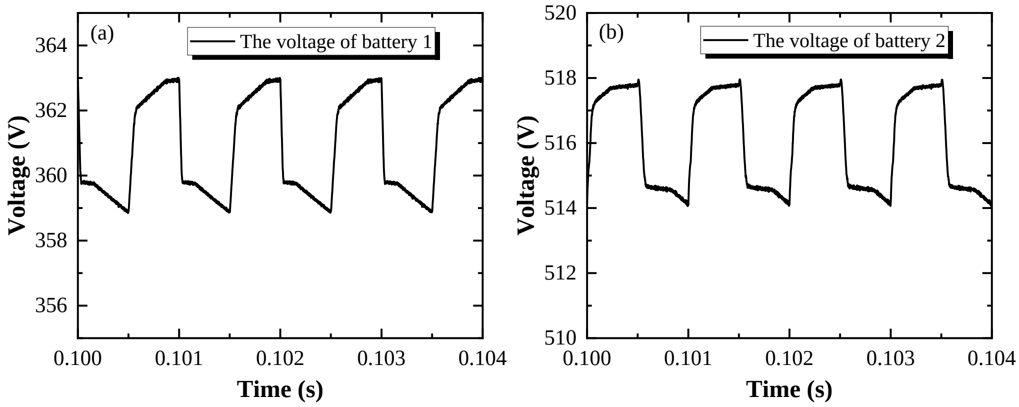

Figure 4: The voltages of battery 1 and battery 2.

3.2 The effect of battery current on the heating rate

To verify the effect of battery current on the heating rate, a lab test has been carried out with ambient temperature of -30 °C. The battery cell is 200Ah with a 20% state-of-charge (SOC). The experimental results can be seen in Fig. 5 that the heating rate increases with the increasing battery current. It should be mentioned that the heating rate is related to the battery capacity, SOC and temperature, etc. In the lab test, a high-capacity battery has been used to verify the trend between battery current and heating rate according to the project. The heating rate will be increased if low-capacity battery has been used. In addition, the heating rate in the lab test is limited to the equipment. Actually, the phase current and battery current is relatively high in 800V driving system. Therefore, the maximum heating rate can be reached up to 3 ℃/min at low temperature. The reason of the trend between battery current and heating rate can be explained as follow.

Generally, the equivalent circuit model of battery can be divided into ohmic resistance, polarization resistance and polarization capacitance [26]. For example, the second order Thevenin model [27] of battery is shown in Fig. 6, with ohmic resistance R_o, electrochemical polarization resistance R_{pa}, and concentration polarization resistance R_{pc}. The equivalent capacitances, which include electrochemical polarization capacitance C_{pa} and concentration polarization capacitance C_{pc}, are applied to describe the transient response pf battery during the discharging and charging transits. As a consequence, the battery heating is influenced by current frequency and amplitude [6, 28, 29]. Therefore, a high RMS of charging and discharging battery current is necessary for the rapid heating rate.

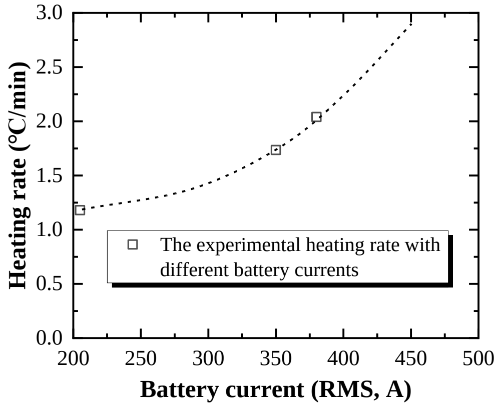

Figure 5: The relationship between the battery current and heating rate.

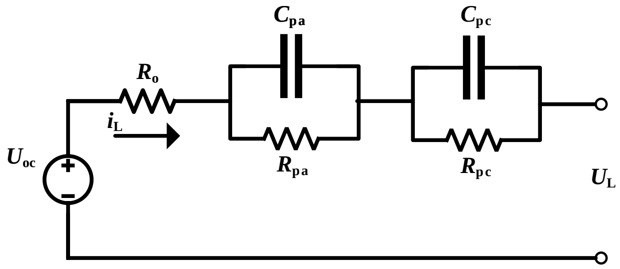

Figure 6: The second order Thevenin model of the battery with ohmic resistance, polarization resistance and polarization capacitance.

3.3 Comparison of heat currents provided by traditional and proposed methods

The battery charging process of traditional pulse heating method has been illustrated in Fig.7. As the rotor speed is 0, the alternating current can be realized by the positive and negative voltage of U_d. For example, with positive voltage of U_d, The voltage equation involves a term of back electromotive force (EMF) on the inductance, which can be described as:

$$U_d = -\omega_r L_q I_q + I_d * R + L_d * \frac{dI_d}{dt} \tag{5}$$

$$U_q = -\omega_r L_d I_d + \omega_r \psi_f + I_q * R + L_q * \frac{dI_q}{dt} \tag{6}$$

where the ω_r is electric angle, L_q and L_d are the inductance of *q* axial and *d* axial, *R* is the phase resistance. As a consequence, with a value of 0 of ω_r, the current I_d can be written as:

$$\frac{dI_d}{dt} = \frac{U_d \text{-} I_d * R}{L_d} \tag{7}$$

The equivalent circuit model of the battery has been shown in Fig. 6. Considering a value of 0 of I_q, the voltage of battery U_E can be described as:

$$U_E = I_{bat} * R_o + I_{Ra} * R_{pa} + I_{Rc} * R_{pc} + U_c \tag{8}$$

$$I_d = I_{bat} + I_c \tag{9}$$

$$I_c = C_2 \frac{dU_c}{dt} \tag{10}$$

where I_c is the capacitive current, U_c is the capacitive voltage.

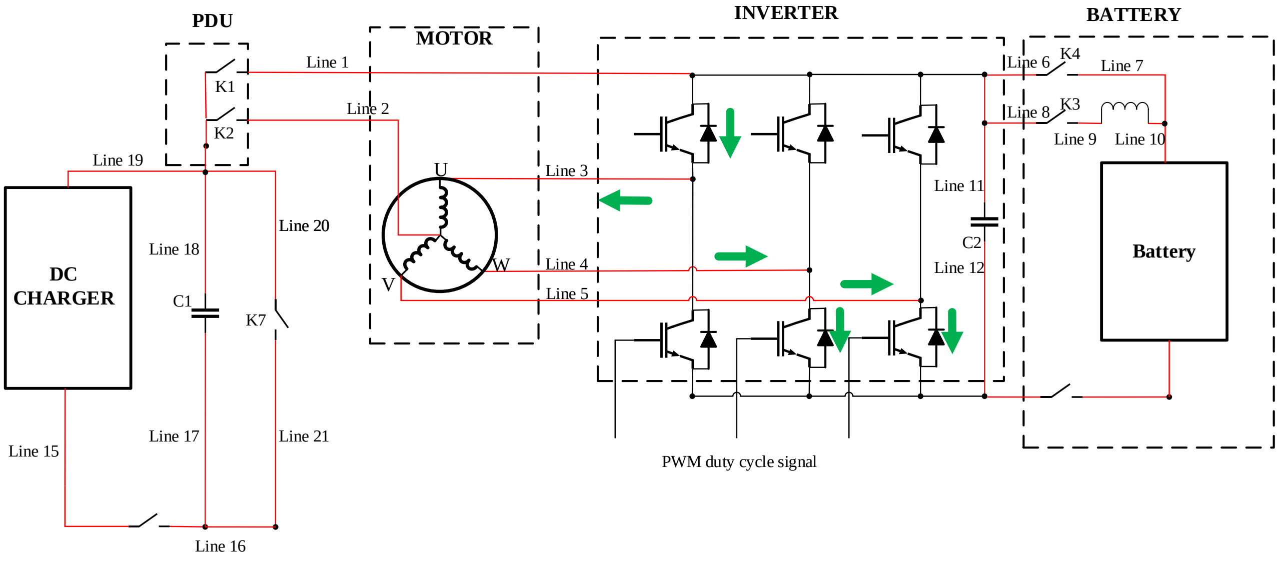

Figure 7: Traditional pulse heating system with charging process of the battery.

Table 1: Parameters of the heating system used in the simulations

Parameter	Symbol	Value
Cell nominal voltage	V_{cell}	480V (140V+340V)
Cell capacity	C_{cell}	200Ah
Inductance of direct axis	L_d	148µH
Inductance of quadrature axis	L_q	478µH
Pole pairs	p	4
Flux linkage	ψ_f	0.0382V·s
Maximum phase current	I_m	100A

In the traditional pulse heating by using electric drive system, the energy is transmitted from the motor and the battery. The battery currents are limited by phase currents, electronic driving parameters, etc. To compare the heating currents between traditional pulse heating method and the proposed method, simulations have been carried out with the same parameters, which is shown in Table 1. It can be clearly seen in Fig. 8 that the maximum battery current with traditional pulse heating method is about 20 A (0.1C). The reason is that the current I_d is equal to the sum of battery current I_{bat} and capacitive current I_c, as shown in Eq. (9). As transient pulse current can be provided by bus capacitance of inverter, the pulse current of battery is relatively low. However, compared with traditional way, the value by using the proposed method can be reached 3 times higher and up to 300 A (1.5C), which proves that the buck and boost circuit is an attractive system to promote the battery currents. In this way, battery 1 can be charged by an increase voltage from battery 2, the relationship of voltage is shown in Eq. (4). Therefore, the voltage and relevant current are controllable. Inversely, the battery 2 can be charged by a decrease voltage form battery 1 with the duty cycle. Owing to the inductance, the current has a response time and increases with time constant. The current close loop is realized when expected value is reached. Therefore, the frequency is limited by the response time and a certain voltage difference is necessary between the batteries. The reason has been explained as follows.

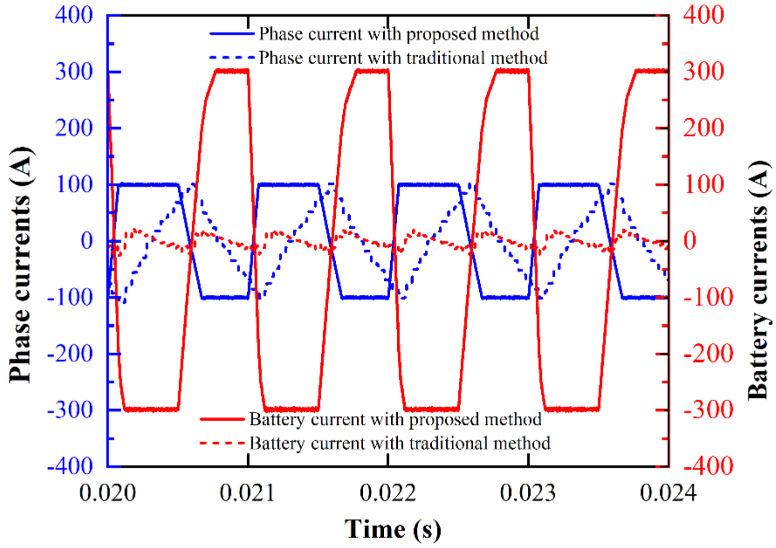

Figure 8: Comparison of heat currents provided by traditional and proposed methods.

Practically, the battery cells in a whole battery are separated into two parts with same capacity. Whenever one part is charging, another part is discharging. Differently, since a boost circuit exists in this work, a certain voltage difference is necessary between the batteries. It is largely due to two reasons: (1) when the voltage difference of battery is small, the voltage difference of two ends of inductance is also relatively low, leading to a slow response current; (2) The battery charging and discharging result in a certain voltage rise and fall, which will further reduce the voltage difference of the inductance. The current of the inductance tends to be 0 when the voltage difference is very small. Therefore, the discharge circuit cannot work normally with small voltage difference between battery cells. However, the thermal consistency of different battery cells encountered challenge owing to the different currents. The non-uniform temperature gradient will deteriorate SOC of the battery cells, resulting the thermal runaway, premature failure of cells [30, 31]. In this circumstance, the thermal of battery with small current can be compensated by sticking the heating film, realizing the thermal consistency.

3.4 Validation by a pre-research experiment

As discussed in Section 3.3, the battery current is mainly related to the phase current. As a consequence, the pre-heating effect is relatively small with regard to a small battery current by using the traditional pulse heating method. For example, the battery current reached a maximum value of 50A with the phase currents of 300A, which proofs the traditional combined module invert is unfavorable for battery pre-heating [4]. On the contrary, battery heating method in this work realizes high pre-heating rate due to the energy storage and release of the motor coil, together through the electricity transfer between different battery modules. In this way, one battery current is related to the sum of phase currents and another battery current is proportionally. Therefore, the battery current is relatively high.

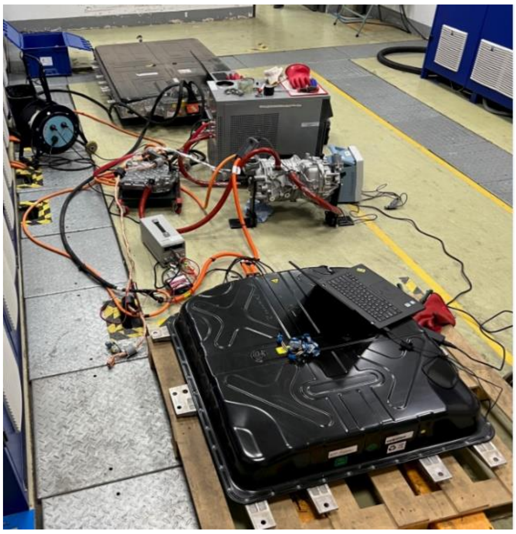

Figure 9: The test equipment with two battery cells with 200Ah capacity.

To validate the proposed method, a pre-research experiment has been carried out, as shown in Fig. 9. 200V voltage difference exists between the batteries (340V and 140V). The results have been shown in Fig. 10 that about 200A of maximum battery current has been realized, which proves the feasibility of the proposed method. In our future work, a 800V driving system will be carried out to verify the high RMS of battery current and heating rate.

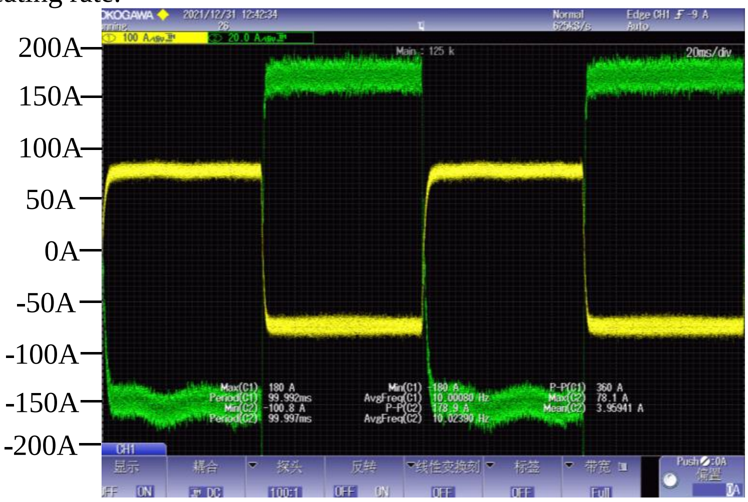

Figure 10: The test equipment with two battery cells with 200Ah capacity.

Conclusions

A self-internal heating system with the existing circuit, in which the cells were rearranged into two modules and some relays were added, was proposed to promote heating rate for batteries. With this configuration, buck and boost operation modes were achieved. The conclusion can be summarized as following:

(1) A refined circuitry topology is compatible with the existing electrical architecture. With this circuit, electricity transfer between the cells can be realized through a motor.

(2) A certain voltage difference is necessary between the batteries, forming the boost circuit in the system. With the buck and boost circuit, a high pulse current of the batteries has been achieved.

(3) The rapid, efficient, and harmless battery heating method is realized by using the proposed circuitry topology, which enables high battery current and low cost with the existing circuit.

(4) Relevant heating rate experiments with 800V system by using the proposed refined circuitry topology will be carried out in the future work.

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Presenter Biography

Dongcui Wang was graduated from Harbin Institute of Technology (2007.09 - 2009.07), and majored in mechanical and electronic engineering. As the chief of MCU and the head of electronic power department in Shanghai E-Propulsion Auto-Technology company (SEAT) at present, he has rich experience in software, hardware design and system development. Up to now, he has developed a large number of motor controllers for new-energy mass production projects in SEAT for SAIC MOTOR, such as hybrid vehicles of e550/eRX5 and electric vehicles of ERX5/EI5/ER6/Marvel, etc.