Dual Active Bridge Converter with AC Heating Capability for Lithium-ion Batteries in Electric Vehicles

Yuta Sasama
Department of Electrical and Electronic Engineering
Ibaraki University
Ibaraki, Japan
20nm624r@vc.ibaraki.ac.jp

Ryuichi Igarashi
Department of Electrical and Electronic Engineering
Ibaraki University
Ibaraki, Japan
18nn607n@vc.ibaraki.ac.jp

Masatoshi Uno
Department of Electrical and Electronic Engineering
Ibaraki University
Ibaraki, Japan
masatoshi.uno.ee@vc.ibaraki.ac.jp

Abstract—Lithium-ion batteries in electric vehicles need to be adequately heated at low temperatures to avoid the decrease in discharge capacity. AC heating techniques utilizing Joule heat generated by the internal resistance of batteries have been proposed. Although these techniques achieve higher heating efficiency and uniform heating, an ac heating inverter is separately necessary to produce the ac current, likely resulting in increased system complexity and cost. This paper proposes a dual active bridge (DAB) converter integrating an inverter for ac heating in electric vehicles. The proposed converter is derived by sharing two legs of both converters, achieving the simplified system and low-cost. Experimental results of a prototype with a charge-discharge power rating of 300 W demonstrated that in addition to the bidirectional power flow, the proposed converter heated up the twelve-cell battery from −11℃ to 0℃ within 10 min.

Keywords—AC heating, dual active bridge (DAB) converter, internal resistance, lithium-ion battery, low temperature.

I. INTRODUCTION

In recent years, the electric vehicles (EVs) with zero carbon emission have drawn attention due to raising awareness of environmental issues. EVs are equipped with lithium-ion batteries (LIBs) with the advantages of high energy density and long life as their energy sources. However, the practical use at low temperatures faces a severe problem of increased internal resistance. Fig. 1 exemplifies the discharge characteristics of the LIB with the C/3 rate at four temperatures. The increased internal resistance under the subzero temperature condition significantly decreases the discharging voltage and time. The reduced discharging voltage and time result in a shortened driving distance, and therefore heating LIBs is necessary in cold areas.

A variety of heating methods have been proposed and are roughly divided into the external and internal heating techniques [1]–[3]. The LIB system using the external heating technique, such as electric heating wire with air or liquid as a heating medium, is illustrated in Fig. 2. This technique leads to the heat diffusion or nonuniform temperature distribution due to heat conduction and convection, resulting in the low heating efficiency or premature deterioration of LIBs.

To resolve these problems, internal heating techniques have been proposed [1]. Internal heating techniques utilize the Joule heat generated by current flowing through an internal resistance of LIBs. Compared with the external heating, the internal heating techniques achieve high heating efficiency thanks to the lack of heat conduction and convection process. Since the heat is generated from inside the LIB, the entire LIB can be heated uniformly.

Internal heating techniques can be classified into dc heating and ac heating. The difference between two methods in current

Fig. 1. Discharge characteristics of the LIB with C/3 rate at four temperatures.

Fig. 2. LIB system using external heating techniques.

Fig. 3. Current flow directions at LIB using internal heating techniques.
The LIB system using the ac heating technique is illustrated in Fig. 4. This LIB system requires the inverter to generate the ac current in addition to the bidirectional converter that charge or discharge the LIB. The inverter includes multiple switching elements, and therefore the ac heating technique results in increased system complexity and cost [7].

In this paper, the bidirectional converter with ac heating capability is proposed. The proposed converter is derived from integration the dual active bridge (DAB) converter and ac heating inverter with sharing legs. Fig. 5 shows the LIB system using the proposed converter. The integration of two converters reduces the total switch count, achieving the simplified system and low-cost.

This paper is organized as follows. Section II introduces the proposed converter and its major features. Section III presents the detailed operation analysis and mathematical modeling for the ac heating current. The experimental verification using the prototype with a charge-discharge power rating of 300 W will be presented in Section IV.

II. PROPOSED CONVERTER

A. Key Elements for Proposed Converter

The topology using the series-resonant inverter, shown in Fig. 6(a), has been proposed as ac heating inverters for LIBs [6], [8]. This circuit consists of two legs of Q1H-Q2L and Q3H-Q4L, two resonant tanks C1-L1 and C2-L2, and a battery divided into V_batt and V_bat. Resonant tanks are connected between the midpoint of V_batt-V_bat, Q1H-Q2L leg, and Q3H-Q4L leg.

This topology is equivalent to two single-phase series-resonant inverters connected in parallel, and therefore is suitable to enhance an ac heating current and to reduce the heating time. This inverter operates with a fixed 50% duty cycle $d$ at a fixed switching frequency $f_s$ without feedback control. Switching losses can be low due to zero current switching (ZCS).

The DAB converter, shown in Fig. 6(b), is identical to a traditional one. The DAB converter achieves bidirectional power flow by manipulating a phase shift (PS) angle between the primary and secondary winding voltages [9]. All switches can be driven in zero voltage switching (ZVS) manner in wide operating ranges.

B. Configuration and Features

Fig. 7 shows the proposed DAB converter. This converter is derived from integrating two converters shown in Fig. 6. In comparison with a conventional system using a bidirectional converter and ac heating inverter separately, not only can the system be simplified by the integration of two converters into a single unit, but also four switches are shared by both converters in the course of the integration, thus reducing the total switch count and cost.

The proposed converter operates either in the ac heating mode or power transfer mode. These two modes are with different principles at a different $f_s$ and are independent of each other. The proposed converter operates with a ZCS and ZVS manner in the ac heating and power transfer mode, respectively, achieving soft-switching operations in both modes.
In the ac heating mode, $f_i$ is a kHz-order. Only primary side switches are driven to generate the ac current $i_{LC}$ by series-resonant tanks. The resonant frequency of the LC tanks $f_i$ is set slightly higher than twice $f_i$ to operate in discontinuous current mode (DCM). Resonant converters operating in the DCM are known to have constant current characteristics, realizing an over-current protection for batteries [10].

In the power transfer mode, on the other hand, $f_i$ is several ten kHz-order. Similar to traditional DAB converters, all switches are driven. In this mode, $f_i$ is set to be rather higher than $f_i$, so that an impedance of LC tanks is high, and therefore, $i_{LC}$ does not flow through LC tanks. The added LC tanks do not affect the power transfer operation, and the proposed converter operates similarly to the traditional one. Section III shows the details of two modes.

### III. OPERATION ANALYSIS

#### A. Operation Modes in AC Heating Mode

Theoretical operation waveforms and current flow directions in the ac heating mode are shown in Figs. 8 and 9, respectively. $i_{batH}$ and $i_{batL}$ are currents flowing through $V_{batH}$ and $V_{batL}$. It should be noted that high-side switches $Q_{1H}$ and $Q_{2H}$ synchronize, and so do low-side switches $Q_{1L}$ and $Q_{2L}$.

**Mode 1** [Fig. 9(a)]: The gating signals for the high-side switches, $v_{gs1H}$ and $v_{gs2H}$, are applied at $t_{LC} = 0$, achieving ZCS turn-on. Voltages of the resonant tanks, $v_{LC1}$ and $v_{LC2}$, equal to $V_{batH}$ and $V_{batL}$, respectively. The primary winding is short-circuited through $Q_{1H}$ and $Q_{2H}$, and its voltage $V_p$ is zero. Gating signals of $v_{gs1H}$ and $v_{gs2H}$ are removed before $i_{LC}$ becomes zero again. Body diodes conduct after $Q_{1H}$ and $Q_{2H}$ turn off, achieving ZVS turn-off.

**Mode 2** [Fig. 9(b)]: This mode begins as $i_{LC}$ reaches zero. The current flows through only the capacitor $C_{ac}$.

**Mode 3** [Fig. 9(c)]: The gating signals for the low-side switches, $v_{gs1L}$ and $v_{gs2L}$, are applied at $t_{LC} = 0$, achieving ZCS turn-on. $v_{LC1}$ and $v_{LC2}$ equal to $V_{batH}$ and $i_{LC}$ flows. The primary winding is short-circuited through $Q_{1L}$ and $Q_{2L}$, and $V_p$ is zero. Gating signals of $v_{gs1L}$ and $v_{gs2L}$ are removed before $i_{LC}$ becomes zero similarly to Mode 1. Body diodes conduct after $Q_{1L}$ and $Q_{2L}$ turn off, achieving ZVS turn-off.

![Fig. 8. Key operation waveforms in ac heating mode.](image)

![Fig. 9. Current flow directions in ac heating mode. (a) Mode 1, (b) Mode 2 and 4, and (c) Mode 3.](image)

![Fig. 10. Equivalent circuits in ac heating mode. (a) Mode 1 and (b) Mode 3.](image)
The equivalent circuit, $R_{eq}$, $L_{eq}$, and $C_{eq}$ (as designated in Fig. 10) are given by

$$R_{eq} = R_L + R_C + R_{on}$$

$$L_{eq} = \frac{1}{\frac{1}{L_{r1}} + \frac{1}{L_{r2}}}$$

$$C_{eq} = C_{r1} + C_{r2}$$

where $R_{on}$ is on resistances of switches, and $R_L$ and $R_C$ are equivalent series resistances of the inductor and capacitor, respectively. The resonant frequency of the RLC series circuit, which consists of $R_{eq}$, $L_{eq}$, and $C_{eq}$, is expressed as

$$f_r = \frac{1}{2\pi\sqrt{L_{eq}C_{eq}}}$$

When $V_{batt}$ and $V_{bat}$ have the same characteristics and $i_{LC}(t)$ evenly splits, $i_{batt}(t)$ and $i_{bat}(t)$ are given by

$$i_{batt}(t) = -i_{bat}(t) = \frac{1}{2}i_{LC}(t)$$

From Fig. 10(a),

$$V_{batt} = -v_{bat} + v_{eq} = (R_{eq} - \frac{1}{2}R_{bat})i_{LC} + L_{eq}\frac{d}{dt}i_{LC} + \frac{1}{C_{eq}}\int i_{LC}dt$$

where $R_{bat}$ is the internal resistance of the battery, and $v_{bat}$, $v_{eq}$, and $v_{ref}$ are voltages of $R_{bat}$, $R_{eq}$, $C_{eq}$, and $L_{eq}$, respectively.

To simplify the analysis, $\gamma$ and $\omega$ are defined as

$$\gamma = \frac{2R_{eq} - R_{bat}}{4L_{eq}}$$

$$\omega = \frac{1}{L_{eq}C_{eq}} - \gamma^2$$

According to (6), $i_{LC}(t)$ in Mode 1 is deduced as

$$i_{LC}(t) = \frac{V_{batt} + v_{eq}(0)}{\omega L_{eq}} \cdot e^{-\gamma t} \cdot \sin \omega t$$

where $v_{eq}(0)$ is the initial value of $v_{eq}$. $\omega$ should be positive for an underdamped oscillation in the current wave, and therefore $C_{eq}$ and $L_{eq}$ have to meet the following requirement.

$$\frac{1}{L_{eq}C_{eq}} - \gamma^2 > 0$$

Similar to (9), $i_{LC}(t)$ in Mode 3 is given by

$$i_{LC}(t) = -\frac{V_{batt} + v_{eq}(0)}{\omega L_{eq}} \cdot e^{-\gamma t} \cdot \sin \omega t$$

According to (9) and (11), the coefficient and $\gamma$ determine the peak value and attenuation, respectively. $I_{batt}$ and $I_{bat}$, the RMS values of $i_{batt}(t)$ and $i_{bat}(t)$, are expressed as

$$I_{batt} = \frac{1}{\sqrt{T_s}} \int_0^{T_s} i_{batt}^2(t) \, dt$$

where $T_s$ is the switching period. The Joule heat, $Q_{batt}$ and $Q_{bat}$, which heat up $V_{batt}$ and $V_{bat}$, can be yield by (12) as

$$Q_{batt} = Q_{bat} = R_{bat} \cdot I_{batt}^2 \cdot t$$

According to (13), the larger the values of $I_{batt}$ and $I_{bat}$, the shorter will be the heating time.

C. Operation Modes in Power Transfer Mode

The power transfer direction from the primary to secondary side is defined as discharging operation, and vice versa. Theoretical operation waveforms in the discharging operation are shown in Fig. 11. $\varphi$ is the PS angle between $Q_{in}$-$Q_{out}$, and $\varphi_d$ is the PS duty cycle ($= \varphi \times 360^\circ$). $d$ is fixed to be 50% to maximize the amount of power transfer, and $T_d$ is assumed short enough to be neglected. $V_{in}$ and $V_{out}$ are defined as

$$V_{in} = V_{batt} + V_{bat}$$

$$V_{out} = \frac{n_1}{n_2} V_{out}$$

As mentioned in the previous section, the proposed converter operates identically to the traditional ones [11]–[13] when $f_s$ is rather higher than $f_i$. The output current of the DAB converter $I_{out}$ can be expressed in the identical form,

$$I_{out} = \frac{2}{T_s} \int_0^{T_s} i_{LC} \, dt$$

$$= \frac{V_{in}}{L_{kg}f_s n_2} \varphi_d (1 - |2\varphi_d|)$$

where $L_{kg}$ is the transformer leakage inductance, and $i_{LC}$ is the current of $L_{kg}$.

The output power $P_{out}$ is given by

$$P_{out} = I_{out} \cdot V_{out}$$

$$= \frac{V_{in} V_{out} n_1}{L_{kg} f_s n_2} \varphi_d (1 - |2\varphi_d|)$$

Therefore, $I_{out}$ and $P_{out}$ can be controlled by manipulating $\varphi_d$.

IV. EXPERIMENTAL RESULTS

A. Prototype

A prototype with a charge-discharge power rating of 300 W was designed for a LIB consisting of twelve cells connected in series, as shown in Fig. 12, and its component values are listed in Table I. $V_{in}$ and $V_{out}$ were 48 V and 200 V, $f_s$ was set to be 2.5 kHz and 50 kHz in the ac heating mode and power transfer mode, respectively. $f_i$ was 3.4 kHz to achieve the DCM operation in the ac heating mode, as mentioned in section II-B.
B. LIB Heating

Fig. 13 shows the experimental platform using the thermostatic chamber for LIB heating. The initial LIB temperature was set to be $-11^\circ C$. Fig. 14 shows measured key operation waveforms in the ac heating mode. These waveforms agreed well with the theoretical ones shown in Fig. 8, verifying the DCM operation of the prototype.

Fig. 15 shows the temperature evolution of the LIB. The LIB temperature rose to $0^\circ C$ within 10 min. Fig. 16 shows the temperature distributions of the LIB before and after heating. Fig. 16(b) shows that the LIB temperature was uneven. The result implies that the heat radiation was not even by convection in the thermostatic chamber, and the unevenness was not caused by the ac heating operation.

C. Power Transfer

The power transfer test was conducted using a dc power supply and an electric load instead of the LIB. Large-capacity electrolytic capacitors were connected to the midpoint between resonant tanks and batteries. To investigate the impact of resonant tanks, power conversion efficiencies of the DAB converter alone were also measured by removing resonant tanks.

Fig. 17 shows the measured key operation waveforms at 300 W in the power transfer mode. These waveforms agreed well with the theoretical ones shown in Fig. 11, verifying the operation of the prototype. $i_{LC}$ was considerably smaller than $i_{Lkg}$, demonstrating the power transfer without the current flowing through resonant tanks.

Fig. 18 shows drain-source and gate-source voltages of $Q_{1H}$-$Q_{2L}$ and $Q_{3H}$-$Q_{4L}$, $v_{ds}$ and $v_{gs}$, at 300 W in the discharge operation. $v_{gs}$ was applied after $v_{ds}$ declined to zero, verifying ZVS turn-on. Although only some waveforms are shown due to space limitations, ZVS turn-on for all switches were achieved in both discharging and charging operation.

Fig. 19 shows measured characteristics of $P_{out}$ as a function of $\phi_L$. $P_{out}$ reached a rated power of 300 W at $\phi_L = 0.167$, and the measured characteristics agreed well with the theoretical ones. These results demonstrated the direction of power transfer and the amount of output power could be controlled by manipulating $\phi_L$.

Fig. 20 shows the measured power conversion efficiencies in the discharging operation. The efficiency of the traditional DAB converter was 90.7% at 300 W, while that of the proposed one was 90.4%. This result verifies the impact of the added resonant tank on the power conversion efficiency of the proposed DAB converter was very minor.
from −11℃ demonstrated that the prototype could heat the twelve-cell LIB for the ac current were conducted. The experimental verification transfer mode. The converter operates either in the ac heating mode or the power
achieving the simplified system and low-cost. The proposed converter is derived from the integration of two converters with sharing switches, capability for LIBs in EVs. The proposed converter is derived

This paper has proposed the DAB converter with ac heating capability for LIBs in EVs. The proposed converter is derived from the integration of two converters with sharing switches, achieving the simplified system and low-cost. The proposed converter operates either in the ac heating mode or the power transfer mode.

The detailed operation analysis and mathematical modeling for the ac current were conducted. The experimental verification demonstrated that the prototype could heat the twelve-cell LIB from −11℃ to 0℃ within 10 min by ac heating, in addition to the bidirectional power flow by the DAB converters.

REFERENCES