Development of Preheating and Power Inverting Systems for Lithium-Ion Batteries

By

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Abstract

A novel short-circuit self-heating (SCSH) control system was developed in this thesis to achieve the preheating of lithium-ion (Li-ion) batteries operated in extremely cold weather ($< -30^{\circ}\text{C}$). The proposed system relies on the internal resistance of batteries and the short circuit current to heat up batteries using Joule heating. Experiments show that the SCSH control system can heat up the commercial Panasonic 18650 Li-ion batteries from -30°C to 0°C in 43 seconds, with less than 5 percent of the battery capacity consumed. The proposed heating system outperformed both external convective air heating and alternating current (AC) heating, in terms of heating time and energy consumption. Furthermore, a DC to AC battery power inverter was developed to implement the AC heating and to make the battery pack available for household appliances. This inverter employs a microcontroller using the direct pulse width modulation (DPWM) technique. The inverter achieves power output at various frequencies through programming, without changing the design of the circuit board. The optimal frequency ratio can be obtained theoretically, validated through MATLAB simulation, and was further examined through experimentation. The selected frequency ratio enables the DPWM signals to stimulate the designed inverter to produce high quality sinusoidal voltage.

Keywords: short-circuit self-heating; Lithium-ion batteries; direct pulse width modulation technique; frequency ratio.

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Nomenclature

A_n	Fourier coefficients
B_n	Fourier coefficients
D_k	the k^{th} output pulse's duty cycle value
D	duty cycle ratio
f_{PWM}	frequency of PWM signals, Hz
$f_{sinusoidal}$	sinusoidal output frequency, Hz
i_a	output current, A
m	mass of battery, kg
M	amplitude modulation ratio
N	frequency ratio
N_s	turn ratio of primary winding and secondary winding
Q	energy needed for battery heat up, J
Q_B	battery capacity, mAh
R_C	conventional coulomb resistance of battery, Ω
R_{OV}	charge-transfer resistance of battery, Ω
T	period of sinusoidal output waveform, s
T_k	time interval of pulse-widths of the k^{th} PWM section
T_s	period of each PWM signal, s
t_{dt}	dead time, s
t_{off}	falling time of MOSFET, s
t_{on}	rising time of MOSFET, s

$u(t)$	desired output voltage, V
U_D	DC input voltage, V
U_m	peak value of the desired output voltage, V
U_O :	output voltage when battery connects load, V
U_I	battery internal voltage, V
U_{out}	output voltage of inverter, V
u_{err}	pulsating voltage errors caused by dead-time effect, V
V_{FB}	feedback control voltage, V

Greek symbols

α_k	angle at the center of the k^{th} PWM signal, rad
Δu_{err}	output pulsating voltage errors, V
θ_s	angular width, rad
θ_k	angular width of the k^{th} PWM section, rad
$\theta_{k(on)}$	starting angular of PWM signal, rad
$\theta_{k(off)}$	ending angular of PWM signal, rad
τ	duration of output pulsating voltage error, s
ω	fundamental angular frequency, rad/s
ω_1	angular frequency of output waveform, rad/s

Acronyms

AC	alternating current
DC	direct current
DPWM	direct pulse width modulation

EV	electric vehicle
HEV	hybrid electric vehicle
MSW	modified-sine-wave
NiMH	nickel-metal hydride
PCB	printed circuit board
PHEV	plug in hybrid electric vehicle
PSW	pure-sine-wave
PWM	pulse width modulation
SCSH	short-circuit self-heating
SOC	state-of-charges
SPWM	sinusoidal pulse width modulation
THD	total harmonic distortion

Chapter 1. Introduction

1.1 Overview

Lithium-ion (Li-ion) batteries have become the most promising energy storage technology and are widely employed in many applications, e.g., portable devices, electric vehicles. Li-ion batteries can also be used to power household appliances after converting the DC voltage into AC voltage. However, Li-ion batteries experience substantially degraded performance under cold weather ($< -30^{\circ}\text{C}$), due to severe power retention loss and capacity degradation. Preheating Li-ion batteries to a battery-friendly temperature is essential for electrical vehicles (EV) in cold weather countries such as Canada. Therefore, a battery preheating system is indispensable for battery systems to achieve desirable performance and life cycles.

Conventional preheating techniques for Li-ion batteries include external heating, such as jacket heating and air/liquid heating, internal heating such as mutual pulse heating [1], and sinusoidal alternating current (AC) heating [2]. Generally, the external heating method requires a long time to warm up a large battery pack, because the external excess heat must penetrate the thickness of the entire battery to reach the core [3]. Studies also show that the external heating method can lead to a non-uniform temperature distribution inside battery packs, however, internal heating can achieve a more uniform temperature distribution [4,5]. The external heating method usually has a low efficiency due to the loss of energy to the environment while heating [6]. For internal heating, such as the AC heating method, although the preheating time can be controlled within a few minutes, it leads to severe battery degradation after long-term usage [7]. Accordingly, a

feasible and practical fast pre-heating technique is highly desirable, especially for electric vehicles (EV).

Besides providing a suitable operating temperature for the battery pack, a power inverter needs to be developed in addition to the heating system to ensure the usage of large size battery packs for appliances powered by alternate current. The power inverter can make the Li-ion batteries have wider applications in daily life and industry, other than portable devices and electric vehicles.

To date, most of the battery backup power inverters available in the market are modified-sine-wave (MSW) inverters, which provide the benefit of low price, but cannot drive the majority of household appliances. Fortunately, there is a portion of pure-sine-wave (PSW) power inverters, which can provide sinusoidal AC voltage that is identical to household grid AC power and is able to power most household appliances. However, most PSW inverters employ the sinusoidal pulse width modulation (SPWM) technique, which requires a complicated control circuit platform. Additionally, the SPWM-based power inverter cannot output AC voltages with variable frequencies and magnitudes for different countries and different applications without changing the hardware circuit design. From the manufacturers' perspectives, a PSW inverter with an adjustable output for applications with different power requirements is crucial for big profit and lower production cost.

In general, a short circuit will lead to overheating, and perhaps even the explosion of Li-ion batteries due to the uncontrollable high short circuit current. On the other hand, if the short circuit current can be well controlled, it will be an ultra-fast heating method without detriment to Li-ion batteries.

1.2 Objective and thesis organization

In this thesis, a novel internal short-circuit self-heating (SCSH) control system needs to be developed to control short-circuiting in batteries for ultra-fast heating purpose, which relies on the internal resistance of the battery and the short circuit current to heat up the battery using Joule heating. The control system needs to ensure the short circuit current is in the safe range when batteries are short-circuited and batteries reach the desired temperature.

In addition, a DC-AC battery power inverter needs to be developed to make the battery pack available for household appliances and to implement the conventional AC heating method. The developed inverter needs to output sinusoidal AC voltage with adjustable frequencies through programming the algorithms without changing the hardware circuit, which is manufactures' preference.

This thesis is organized as follows: Chapter 2 describes the internal structure of the Li-ion battery, the degraded performance of Li-ion batteries at cold temperature and its relevant causes, battery preheating methods, and the SPWM and DPWM techniques used for the DC-AC power inverter. In Chapter 3, the proposed SCSH control system was tested in preheating 18650 Li-ion batteries, and its performance was further compared with both external convective air heating and AC heating methods. Chapter 4 illustrates the detailed technique of the DC-AC power inverter, including the calculation of the optimal frequency ratio, the hardware implementation of the DPWM technique, the design of the inverter's power circuit, and the experimental and simulation results of the DC-AC power inverter. Finally, the conclusion and future work are provided in Chapter 5.

1.3 List of contributions

The contributions of this thesis are as follows. First, a short-circuit self-heating (SCSH) control system was proposed. Experiments were carried out to preheat NCR18650B Li-ion batteries from -30°C to 0°C with the SCSH control system. Preheating time and energy consumption of batteries using SCSH were analyzed. Second, external convective air heating and AC heating methods were implemented to preheat NCR18650B Li-ion batteries, and the performance of both heating methods are illustrated. To achieve the AC heating, a microcontroller-based DC-AC power inverter which can output sinusoidal AC (4 V 60 Hz) to heat up the battery in cold temperature was designed and constructed. Third, an optimal frequency ratio in the DPWM technique was obtained, with which the microcontroller-based power inverter can convert the DC voltage from the battery pack into high quality sinusoidal AC (110 V 60 Hz) with reduced harmonic contents, enabling the Li-ion batteries to have a wider range of application in household products and industrial devices.

Chapter 2. Background and literature review

2.1 Background

Li-ion batteries have emerged as one of the fastest growing and most promising power sources in recent years due to their superiority such as lighter weight, no memory effect, lower self-discharge rate and longer lifespan [4–6], when compared to other rechargeable batteries. Owing to these benefits, Li-ion battery technology has been widely used in portable and hand-held electronic devices [11], such as notebook computers, cell phones, digital cameras, etc. Li-ion batteries are especially suitable for electric vehicles (EV), plug in hybrid electric vehicles (PHEV) and hybrid electric vehicles (HEV) [5–11], because they have greatly increased specific energy and energy density in comparison with other rechargeable batteries [17,18]. For example, nickel-metal hydride (NiMH) batteries, which have dominated the HEV market, have a nominal specific energy and energy density of 75 Wh/kg and 240Wh/L, respectively [21]. In contrast, Panasonic® 18650 Li-ion batteries can achieve 243 Wh/kg and 676 Wh/L, *i.e.* nearly 3 times the specific energy and energy density of the NiMH batteries.

Figure 2.1 shows the schematic illustration of an electrochemical cell inside a Li-ion battery. The positive and negative electrodes are separated by porous film, a separator, that allows lithium ion transfer but prevents electrodes from contact. An electrolyte is composed of an organic solvent and dissolved lithium salt that provides the medium for Li-ion transport. During the course of discharge, Li-ions de-intercalate from the anode, pass through the electrolyte and the separator, and intercalate into the cathode. Simultaneously, the electrons spontaneously leave the oxidized negative electrode and

flow through the external circuit in the opposite direction of the current. On charging, the process is reversed when an external voltage is applied to the battery. The li-ions shuttle between two host electrodes (anode and cathode) during the charge-discharge process, empowering the conversion of chemical energy into electrical energy and storage of electrochemical energy within the battery [22].

Figure 2.1. Schematic illustration of an electrochemical cell [23].

2.2 Battery performance in cold environments

The Li-ion battery is very sensitive to temperature [21], and the performance of Li-ion batteries is degraded at subzero temperatures, resulting in significant losses in capacity, life cycle, power and specific energy [22,23]. Rugh *et al.* [26] pointed out that the relative resistance and relative capacity of Li-ion batteries show worsening characteristics as temperature decreases, with resistance sharply spiking around -40°C and capacity also demonstrating a steep drop off after freezing.

Figure 2.2. (a) Li-ion battery resistance increases with decreasing temperature; (b) Li-ion battery capacity decreases with decreasing temperature [26].

It is well established that the increased cell impedance will cause a decrease in the cell discharge voltage [27]. Therefore, a decrease in the cell energy and specific energy will occur due to the capacity loss and decrease in the cell discharge voltage.

Sit *et al.* conducted comparative investigations of commercial Li-ion batteries from various manufacturers. It was found that the decrease in cell discharge energy and specific energy ranges from 17 to 35% at -20°C , from 43 to 76% at -30°C , and from 78 to 100% at -40°C , respectively, compared with what was obtained at room temperature [28].

The poor performance of Li-ion batteries at low temperature is attributed to significantly slow Li-ion diffusion in the carbon anode, and poor charge transfer at the electrode/electrolyte interface [27]. This can lead to significant plating on the negative electrode during the charging process, and cause irreversible capacity loss from electrolyte reduction [29].

It has also been suggested that the poor performance of Li-ion batteries at low temperatures is due to the increase of the viscosity of the electrolyte, reduced Li-ion mobility, and the high charge-transfer resistance [26–29].

Therefore, the preheating of Li-ion batteries to a normal operating temperature before use is crucial to achieve acceptable power and energy performance, and prolongs battery life.

2.3 Battery preheating techniques and temperature distributions

Different preheating strategies have been researched in previous studies, which are generally classified into two categories: external heating systems and internal heating systems.

The external heating system warms the batteries through transferring heat from battery surfaces to the entire battery to achieve the heating effect. For example, Pesaran *et al.* [4,6] investigated three external preheating methods, including jacket heating, convective heating, and liquid flow heating.

Alternatively, internal heating warms the batteries internally by utilizing the batteries' internal resistance. For instance, Stuart and Hande [2] proposed an internal heating method that uses the alternating current to warm up batteries via internal Joule heating. Ji *et al.* [1] evaluated a mutual pulse heating strategy, in which the whole battery pack is divided into two groups with equal capacity, and the two groups charge or discharge for heating purposes through controlled alternative pulse signals.

Vlahinos *et al* [4] have investigated the performance of different preheating methods for heating HEV batteries in cold temperatures (-40°C) by performing thermal analysis.

The parametric 3-D transient thermal finite element model of a battery pack was built and analyzed. Figure 2.3 and Figure 2.4 show half of the finite element model.

Figure 2.3. Temperature distribution of the battery pack with internal heating for 10 minutes [4].

Figure 2.4. Temperature distribution of the battery pack with external jacket heating for 10 minutes [4].

It can be seen that the internal heating method can achieve more uniform temperature distributions than external heating methods, and cannot find any hot spots inside the battery pack.

2.4 Li-ion battery sourced DC-AC power inverter

Li-ion batteries can be connected in different series and/or parallel combinations to achieve the desired battery pack which can provide the required capacity and voltage. The pack also needs to connect with inverter control systems and protection electronics to convert battery DC voltage into conventional household AC voltage. This allows the use of electronic devices when AC power is not available, and improves the portability of the system. It also comes in handy for consumers in places where an electric grid is inaccessible.

The waveforms of AC output from battery back-up power inverters are generally classified into two types: modified sine wave and pure sine wave. Most commercially available inverters are of the modified sine wave type [34]. A modified sine wave is more of a square wave than a sine wave, which has some drawbacks, as not all devices work properly on a modified sine wave. The modified sine wave units have many harmonics, which can damage sensitive equipment such as laser printers, laptop computers, power tools, and medical equipment. Pure sine wave inverters, on the other hand, are able to output conventional household AC voltage, which has good performance for the smooth operation of electrical appliances. Particularly, they allow for inductive loads to run faster and quieter, due to low harmonic distortion.

Figure 2.5. Modified sine wave and pure sine wave [35].

Most PSW inverters employ either the sinusoidal pulse width modulation (SPWM) technique, or the direct pulse width modulation (DPWM) technique.

2.4.1 Sinusoidal pulse width modulation (SPWM) technique

The SPWM schemes are mostly employed in industrial applications of pure sine wave inverters [34,36]. They produce a good quality sinusoidal voltage waveform of desired fundamental frequency and magnitude, with reduced harmonics, from an H-Bridge inverter [37–39].

In SPWM, a sinusoidal reference voltage waveform is compared with high frequency triangular carrier voltage waveforms. A series of constant amplitude rectangular pulses with different duty cycles in each period could be obtained by the instantaneous intersections of two waves, which determine the switching instants of the switches in the H-Bridge inverter [39–41]. The fundamental frequency and the amplitude of the inverter's AC output voltage are directly related to the sinusoidal reference voltage

waveform [43]. However, unexpected distortion of the inverter's AC output waveforms will decline the fundamental amplitude and introduce unexpected low order harmonic components.

2.4.2 Direct pulse width modulation (DPWM) technique

Y.H. Kim *et al.* [44] proposed a microcontroller-based Direct Pulse Width Modulation (DPWM) technique for DC-AC power inverters. The DPWM technique is characterized by producing constant amplitude rectangular pulses with varying duty cycles for each period directly from the microcontroller. The DPWM technique replaces the conventional SPWM method with the use of a microcontroller, which requires a simple digital platform for implementation. The microcontroller platform reduces the size of the control circuit, and makes it easier to generate varying PWM signals by changing the real-time control algorithms.

The pulse width in each PWM pulse wave is determined by making the area underneath the PWM signal (shaded area) equal to the area under the desired output sinusoidal waveform in the same interval [44], as depicted in Figure 2.6. The PWM pulse trains can be generated directly by the microcontroller, and this technique is called DPWM [45].

Figure 2.6. Output waveform with the DPWM technique.

Given that the desired output voltage of the inverter is a sinusoidal waveform as [44]:

$$u(t) = U_m \sin \omega t \quad (2.1)$$

where, $u(t)$ is the desired output voltage at any time t , U_m and ω are the peak value of the desired output voltage and fundamental angular frequency, respectively.

The positive half period of the desired sine wave output in Figure 2.6(a) is equally divided into N intervals, where N is defined as the ratio of the PWM frequency over twice the sinusoidal output frequency, $N = f_{PWM}/2f_{sinusoidal}$, or simply, the number of pulses in a half cycle. The span of each interval is T_s . As shown in Figure 2.6(b), assigning U_D for a certain time and zero for the rest in each interval will result in the area under the assigned U_D to be equal to the area below the sinewave in the corresponding interval in

Figure 2.6(a). Thus, a sine wave in Figure 2.6(a) is represented by a series of unequal width rectangular pulses with constant amplitude U_D in Figure 2.6(b).

Figure 2.6 shows the way of generating PWM pulse patterns with the DPWM technique. The duration of each interval is $T_s = T/(2N)$, and the corresponding angular width is $\theta_s = \omega T_s = 2\pi f T_s = \pi/N$. The boundaries of the k^{th} section are $(k-1)T_s$ and kT_s , respectively. The angle at the center of the k^{th} section, α_k , can be expressed as:

$$\alpha_k = \omega t_k = \omega \left(kT_s - \frac{1}{2}T_s \right) = \omega(2k-1)T/4N \quad (2.2)$$

where T is the period of sinusoidal output.

Referring to Figure 2.6(a), the area under the sinewave in the k^{th} section can be calculated as [46]:

$$\int_{(k-1)T_s}^{kT_s} U_m \sin(\omega t) dt = \frac{U_m}{\omega} [\cos \omega(k-1)T_s - \cos \omega kT_s] \quad (2.3)$$

If the inverter DC input voltage is given as U_D , the time interval of pulse-widths of the k^{th} PWM section is T_k , and the corresponding angular width is θ_k , as shown in Figure 2.6(b), then the shaded area of the k^{th} output pulse is $U_D \times T_k$, where $T_k = \theta_k / \omega$. Thus the k^{th} output pulse's duty cycle value is defined as $D_k = T_k/T_s$.

Applying the DPWM method, the sinusoidal voltage is converted into pulse widths voltage by the following equation,

$$\begin{aligned} U_D T_k &= \int_{(k-1)T_s}^{kT_s} U_m \sin(\omega t) dt = \frac{U_m}{\omega} [\cos \omega(k-1)T_s - \cos \omega kT_s] \\ &= \frac{U_m}{\omega} 2 \sin \left(\frac{1}{2} \omega T_s \right) \sin \left(\omega kT_s - \frac{1}{2} \omega T_s \right) \end{aligned} \quad (2.4)$$

where $k=1,2,3, \dots, 2N$.

Substitute Equation 2.2 into Equation 2.4, then Equation 2.4 can be rewritten as:

$$U_D T_k = U_D \frac{\theta_k}{\omega} = \frac{2}{\omega} \sin\left(\frac{1}{2} \omega T_s\right) U_m \sin \alpha_k \quad (2.5)$$

Since $T_s = T/2N$, usually N is large enough to ensure that $T_s \ll T, T_s/T \ll 1$,

Thus,

$$\sin\left(\frac{1}{2} \omega T_s\right) = \sin\left(\frac{1}{2} \times 2\pi f \cdot T_s\right) = \sin\left(\pi \cdot \frac{T_s}{T}\right) \approx \pi \frac{T_s}{T} \quad (2.6)$$

Then, Equation 6 becomes: $U_D T_k = U_D \theta_k / \omega = 2\pi T_s U_m \sin \alpha_k / \omega T = T_s U_m \sin \alpha_k$

$$\frac{T_k}{T_s} U_D = \frac{\theta_k}{\theta_s} U_D = U_m \sin \alpha_k \quad (2.7)$$

Then, the expression of the k^{th} pulse's duty cycle ratio, D_k , can be depicted as:

$$D_k = \frac{T_k}{T_s} = \frac{\theta_k}{\theta_s} = \frac{U_m}{U_D} \sin \alpha_k \quad (2.8)$$

where U_m/U_D is called amplitude modulation ratio M , which is defined as the ratio of the maximum value of desired output voltage to the DC supply voltage value. Substitute M and Equation 2.2 into Equation 2.8, and D_k can be written as:

$$D_k = M \sin[\omega(2k - 1)T/4N] \quad (2.9)$$

Once the frequency ratio N and the frequency of desired sinusoidal output waveform are specified, a series of duty cycle values can be determined through Equation 2.9. The distinct duty cycle ratios in each period are the foundation of the DPWM techniques. The duty cycle values can be easily programmed into the microcontroller's register in a form of lookup table, which is clocked at an appropriate frequency to generate the width-modulated pulses in real time. These pulses can drive the inverter circuit to generate sinusoidal output waveforms.

As can be seen from Figure 2.6, DPWM signals have a quarter-wave symmetry. Therefore, only half of duty cycle ratios need to be calculated due to this symmetry in Equation 2.9. Another advantage of applying the symmetric PWM signals is that fewer

harmonics will be introduced than these of asymmetric PWM signals when the output is connected to the inductance loads [47].

Chapter 3. Li-ion battery preheating

3.1 Overview

This chapter illustrates the SCSH technique and its control system. Although the SCSH control system is simple in design, it is technically difficult to control the short circuit current as the current increases rapidly after the battery is short-circuited, especially when the battery is at its activation status. A PWM signal technique involving diminishing duty cycles generated by the microcontroller was developed to keep current in the safe range.

From experiments on Panasonic 18650 Li-ion batteries, the SCSH method is far superior to the external convective air heating and AC heating methods, in terms of heating time and energy consumption.

Chapter 3 is organized in the following way: Section 3.2 describes the SCSH technique and the configuration of Li-ion batteries for experiments. Section 3.3 demonstrates the external convective air heating method and AC heating method, as well as the experimental setup for these two methods. Section 3.4 gives a detailed description of experiment results of three heating methods and makes comparisons between them.

3.2 Short-Circuit Self-Heating (SCSH) technique

3.2.1 Battery resistance and self-heating

The electric model for most types of batteries is shown in Figure 3.1, where U_I represents battery internal voltage, and U_O is output voltage when the battery is connected to the load [2]. When the battery is short-circuited, U_O becomes 0, and U_I works as the power source for internal self-heating.

Figure 3.1. Battery equivalent electrical model [2].

R_C is the conventional Coulomb resistance, which is composed of bulk resistance and surface layer resistance; R_{OV} is charge-transfer resistance, which represents the extra energy that must be supplied to get charge into or out of U_O . R_{OV} increases significantly as the ambient temperature has subzero values [1]. At a sufficiently low temperature, R_{OV} becomes very large, which limits the dramatic increase of the internal current of batteries

after they are short-circuited. The detrimental effects of the short circuit are thus avoided. A large amount of internal heat is generated when the short circuit current passes through the battery resistance, which can quickly warm up the batteries. The short circuit current increases dramatically after the battery temperature reaches the threshold. The control system designed herein will cut off the short circuit once the current exceeds a preset limit to avoid damage to the battery.

3.2.2 SCSH control system design

(a)

Figure 3.2. The SCSH control system: (a) schematic of control system; (b) equivalent circuit of control system.

Figure 3.2(a) schematically shows the SCSH control system. Figure 3.2(b) simplified shows the control circuit. A MOSFET and a hall-effect-based current sensor ACS758 are connected in series with the battery. The MOSFET is controlled by both battery temperature and short circuit current, which are sensed by the DS18B20 (temperature sensor) and ACS758, respectively. Once the battery temperature or short circuit current reaches the preset value, the microcontroller outputs high level signals to turn off the MOSFET. The short circuit is therefore cut off, and short circuit current is well-controlled.

The microcontroller outputs low level signals to turn on the MOSFET to start the SCSH. When the MOSFET is turned on, the battery is short-circuited for self-heating. Electrons flow through the anode, cathode and electrolyte, which generate substantial Joule heat, and the entire battery is quickly warmed up. At the initial stage of preheating,

short circuit current increases slowly, due to the gradual decrease of R_{OV} . The microcontroller outputs a 100 percent duty-cycle PWM signal to turn off the MOSFET once the short circuit current reaches the preset cutoff value. At this point, the short circuit current becomes zero, and the MOSFET will be turned on again to continue the SCSH. However, as shown in Figure 3.3, at this time, the short circuit current of the battery will exceed 30 A in 58 μ s. The ON and OFF status of the MOSFET are determined by the sampled current from the ACS758. There is a response time for transmitting the sampled current value to the microcontroller, processing the current signal and outputting the PWM signals to control the MOSFET. The minimal response time for STM8S103K3 is around 1 ms, which is much longer than 58 μ s. In other words, the short circuit current can reach an extremely high value before the MOSFET is turned off in 1 ms, which will damage the battery or SCSH control board, especially for large battery packs. As a result, a technique of PWM signals with diminishing duty cycles was developed to overcome this challenge. The frequency of the PWM signals is 10 kHz.

Figure 3.3. Current change when the battery is short-circuited after the initial cut off.

As shown in Figure 3.4, the technique of PWM signals with diminishing duty cycles works in the following way. The microcontroller outputs a 100 percent duty-cycle PWM signal to turn off the MOSFET immediately after the sensed short circuit current reaches the cutoff value for the first time. The duty cycle value of the PWM signals will diminish by 2 percent from 100 percent, and this duty cycle value remains the same in the following PWM cycles until the microcontroller finishes processing the current signal from the ACS758. The duty cycle of the PWM signal becomes 100 percent again to turn off the MOSFET once the detected short circuit current reaches the cutoff value, otherwise, the duty cycle value of the PWM signals will diminish by 2 percent in the following cycles. In this way, the short circuit current increases slowly by following the diminishing duty cycles. The duty cycles of the PWM signal will repeat as stated in the previous steps until the battery reaches the desired temperature sensed by the DS18B20, and the short circuit will eventually be cut off. The flowchart of the algorithm is shown below in Figure 3.5.

Figure 3.4 PWM signals with diminishing duty cycles.

This technique can effectively keep the short circuit current in the safe range by turning the MOSEFT on/off in high frequency with diminishing duty cycle values. The battery temperature can increase quickly in this high frequency short circuit process.

The microcontroller outputs PWM signals with diminishing duty cycles only after the short circuit is shut down by achieving the cutoff current for the first time. The PWM signals with diminishing duty cycles are not needed at the initial stage of SCSH, since the short circuit current increases slowly.

The battery will function properly in both charges and discharges, as the internal temperature reaches or exceeds 0°C which enables the electrochemical interface to generate high power [48]. Therefore, the cutoff temperature for the battery pre-heating system is set to 0°C , which also indicates the completion of the self-heating process. The MOSFET remains off while the battery operates at an above-zero temperature.

Figure 3.5. Flowchart of algorithm.

3.2.3 SCSH control PCB

Because the SCSH technique is an internal heating method, the battery heating process will be similar whether for one battery or a battery pack [49]. The maximum tolerated current value of the SCSH control PCB is 65 A. The battery pack designed in this work is composed of 21 batteries, which are organized in a 7S3P (7 in series and 3 in parallel) configuration. For simplicity, one Li-ion 18650 battery was used with the largest cutoff current set to 20 A in the SCSH experiments.

The SCSH control PCB, as shown in Figure 3.6, is small (55 mm $\times$ 80 mm) and simple in design.

Batteries will be damaged by overheating during SCSH process if the microcontroller, ACS758 or MOSFET fail to work properly. Therefore, a circuit breaker or fuse needs to be installed for large battery packs' SCSH with the control PCB.

Figure 3.6. Photograph of SCSH control PCB.

3.3 Conventional battery heating methods

Two conventional battery heating strategies were proposed and evaluated: external convective air heating and AC heating.

3.3.1 External convective air heating

The external convective heating strategy uses air for heating. Ambient air is heated by a heater and circulated around the batteries to achieve the heating purpose. The experimental setup of the external convective air heating for the battery pack is shown in Figure 3.7.

Figure 3.7. Photograph of the air heating device.

Figure 3.7 shows the arrangement of three rows of seven 18650 batteries spaced 2.5 mm apart in the transverse and longitudinal directions. Special baffles are designed to decrease airflow maldistribution and direct the air over the channel. Plastic sleeve

connectors are used to hold the batteries in place. The detailed specifications of the experimental setup are given in Table 1.

Table 1. Specifications and parameters of the air heating system.

Length of battery pack	140 mm		Length of the channel	175 mm
Width of battery pack	60 mm		Width of the channel	60 mm
Height of battery pack	65 mm		Height of the channel	65 mm
Space between each battery	2.5 mm		Distance between the outlet of blower and battery pack	20 mm
Diameter of blower	46 mm		Air flow rate of the blower	12 m s ⁻¹
Air temperature in the outlet	50°C			

3.3.2 Alternating current (AC) heating

It has been proven that the sinusoidal alternating current (AC) can heat up the battery directly via Joule heating [2], although it appears that the low-temperature charging at a high rate will damage cell capacity and cause increased cell impedance [29]. To test its heating performance, a microcontroller-based power inverter was designed and built to implement the AC heating method. The experiment was carried out to test the efficiency of AC 60 Hz on heating lithium batteries at cold temperatures. To avoid damaging batteries by over-voltage charging during the AC heating, the output voltage of AC 60 Hz inverter is well-controlled to ensure the voltage limit of the batteries is not surpassed.

Figure 3.8. Schematic of AC 60 Hz inverter for heating batteries. (a) DPWM signals control circuit; (b) gate drive circuit; (c) inverter circuit.

Figure 3.8 shows the schematic of the microcontroller-based AC 60 Hz inverter, which can be configured to output AC 60Hz to heat up the Li-ion battery. This schematic will be described in detail in the Chapter 4 of this thesis.

Experiments were carried out on the 18650 Li-ion battery with the state-of-charge (SOC) at 75%, which was verified to be able to offer the fastest AC heating [2]. SOC is defined as $SOC = \text{actual } Q / \text{maximum } Q \times 100\%$, where Q is the battery capacity.

During the test, the Li-ion battery was heated from an initial temperature of -30°C . The heating process was terminated when battery temperature reaches 0°C , which are sensed by the K-type thermocouple. Similar to the SCSH method, for simplicity's sake, only one battery was used for AC heating test.

Figure 3.9. Photograph of the AC inverter.

The AC inverter has a larger size (145 mm $\times$ 225 mm) than SCSH control PCB and is much more expensive to manufacture.

3.4 Experiment setups and results

All the experimental tests in this work were performed with new commercially available Li-ion 18650 batteries (Panasonic NCR18650B). The specifications of the experimental batteries and the parameters of the components inside the battery are listed in Table 2. Before experimental tests, batteries are conditioned at room temperature (20°C) by cycling 5 times using ESI[®] battery analyzer (PCBA 5010-4) with a cutoff voltage of 2.6 V and 4.2 V during discharging and charging, respectively. During the conditioning stage of batteries, the maximum galvanostatic charging and discharging currents are 0.5 C with the cutoff current of C/50 during the potentiostatic stage of the charging process.

K-type thermocouples with TC-08 data logger were used to acquire the temperatures, the resolution of the thermocouples is 0.025°C, and the accuracy is $\pm 0.5^\circ\text{C}$. The thermocouples are calibrated with the mixture of ice and water at room temperature before using.

Most types of Li-ion batteries cannot output any energy in cold winter (around -30°C), therefore, the initial temperature of the tested batteries is set to -30°C.

Table 2. Specification of the commercial Li-ion 18650 battery.

Property	Values		Property	Values
Capacity (Ah)	Min. 3.25 Typ. 3.35		Diameter (mm)	18.06±0.03
Charging voltage (V)	4.2		Height (mm)	65±0.03
Energy density	243 Wh kg ⁻¹		Charging	CC-CV, Std. 1625 mA, 4.20V, 4.0 hrs
Nominal voltage (V)	3.6-3.7		Max. discharge rate (C)	2
Weight (g)	48.5		T.op (positive side)	Flat top
Model	NCR18650B			

3.4.1 SCSH method

3.4.1.1 SCSH setup

For the SCSH method test, experiments were conducted on one Li-ion battery with different cutoff currents to determine the effects of SCSH current on the preheating of the Li-ion battery at cold temperatures. The battery was connected to the SCSH control board with 10 mΩ wire, fortunately this resistance will become negligibly small at the ambient temperature of -30°C. Both the temperature sensor (DS18B20) and the K-type thermocouple were attached at the surface of the battery. DS18B20 is used to control the SCSH PCB until the battery reaches the desired temperature, and the K-type thermocouple is used for recording the temperature change of the battery during the SCSH process. Both the SCSH control PCB and the battery were placed inside a freezer

at the temperature of -30°C for 3 hours before the preheating test, and then the control PCB was powered by a DC power supply to start SCSH. The battery stayed inside the freezer during the whole SCSH process.

3.4.1.2 SCSH results

Figure 3.10. SCSH heating time with different cutoff currents: (a) 10 A cutoff current; (b) 15 A cutoff current; (c) 20 A cutoff current.

Figure 3.10 shows the battery surface temperature curves during the SCSH preheating process under different cutoff currents. As can be seen, the 18650 Li-ion battery can be heated from -30°C to 0°C in 43 s at a 20 A cutoff current with the SCSH method, which is faster than that of 10 A and 15 A tests. The short circuit currents are well controlled under the preset cutoff value, which can effectively prevent the SCSH control board and battery from damage.

It is noteworthy that the battery surface temperature continues to rise gradually after the circuit is cut off at 0°C owing to large amounts of heat generated inside the battery during the SCSH process.

Some heating time and battery capacity energy consumption are required for Li-ion batteries to be heated up with the SCSH method from -30°C to 0°C . Experiments were also conducted to check the battery voltage and the discharged capacity after each SCSH process to determine the capacity consumed for the SCSH preheating.

Figure 3.11. Battery voltage and discharge capacity curve.

Table 3. Voltage of battery before each SCSH activation.

SCSH cycles	1 th	2 th	3 th	4 th	5 th
Voltage before SCSH	4.17 V	4.104 V	4.054 V	4.001 V	3.948 V

The voltage of the battery before each SCSH for 5 cycles are shown in Table 3. After checking the consumed capacity in Figure 3.11 based on the data in Table 3, it can be seen that the battery still has high voltage and capacity after the SCSH. Each heating cycle consumes less than 5 percent of battery capacity, which suggests that considerable battery energy still can be left for operating after the heating process.

Another feature of the SCSH is that the battery can offer a great amount of energy after preheating. Experiments have been carried out on the Li-ion battery to compare the discharge performance of the battery at -30°C with SCSH and without SCSH, which are further compared with that of a conventional Li-ion battery discharged at room temperature, as shown in Figure 3.12, in which the batteries are discharged in 1 C rate with a cutoff voltage of 3 V.

It can be observed below that the battery tested at -30°C without SCSH cannot output any energy. The conventional Li-ion battery can discharge around 3000 mAh at room temperature, and Li-ion battery at -30°C with SCSH can discharge around 2500 mAh. The readily available high-power capability after the SCSH makes the heating method possible for a wide variety of applications where high battery power is critically needed.

Figure 3.12. Battery discharge ability at different conditions.

3.4.2 External convective air heating

3.4.2.1 Setup of external convective air heating method

The experiment devices are shown in Figure 3.7. An 800 W fan heater (hair dryer) was selected to preheat the battery pack. According to Figure 2.4, the lowest temperature with external heating method will occur in the center of the battery. A hole was drilled in the center of anode of one battery in the 7th row to measure the internal temperature. Four K-type thermocouples were utilized to measure temperature changes: three were attached at the surface of the 1st, 4th, 7th row batteries, one was placed at the center of the 7th row battery. The battery pack was placed inside the freezer at a temperature of -30°C for 3 hours before the preheating test, and then they were moved out of the freezer to the room temperature to conduct the experiment. The heating process was terminated when the internal temperature of the 7th row battery reached 0°C.

3.4.2.2 Results of external convective air heating method

Figure 3.13. Battery pack temperature during the external convective air heating.

Figure 3.13 shows the temperature curves of batteries during the external convective air heating. The temperature curves have three stages. Stage A: battery pack is still in the fridge; Stage B: battery pack is in the channel before heating; Stage C: battery pack heating process (starts at 75 s). The internal temperature of the last row batteries reaches 0°C at 186 s, which gives a total heating time of 111 s. The power consumption of the hair dryer during the preheating process is 88800 J, which is equivalent to 10.36 percent of the total energy of the pack. However, this heating method shall consume more energy and take longer time for battery heating if it is carried out in -30°C, since the inlet air temperature will be lower.

The external convective air heating method has several disadvantages. First, the battery pack does not have a uniform temperature distribution. As shown in Figure 3.13, the batteries in the first row of the pack have the maximum surface temperature, and the

coldest temperatures are found at the last row due to the decrease of air temperature in the direction of the flow. The maximum temperature difference in the pack is around 40°C, and there is a 10°C temperature difference between the battery core and the outer surface, which means that some batteries in the pack will be overheated in this process. Second, because this method applies heat to the external surface of the battery, there will be a significant amount of heat lost to the environment during the preheating period. Third, this strategy requires additional devices, such as a heater, a flow loop and a fan for air flowing, which increases system cost and complexity. Last, this heating method is not suitable for larger batteries, because the low thermal conductivity of the cell will lead to a slow temperature increase in the battery center.

3.4.3 Alternating current (AC) heating

3.4.3.1 Setup of alternating current (AC) heating method

The AC inverter in Figure 3.9 can output AC 4 V 60 Hz to warm batteries through charging. The inverter can be powered by battery pack or DC power supply. In this work, a DC power supply was selected to power the inverter and record the energy consumption during the heating process. The inverter was connected to one battery with 10 mΩ wire, and one K-type thermocouple was attached to the surface of the battery. Prior to the preheating test, battery was placed inside the freezer at a temperature of -30°C for 3 hours. During the whole heating preheating process, the inverter was placed in the room temperature and the battery stayed inside the freezer.

3.4.3.2 Results of alternating current (AC) heating method

The temperature curves of the battery heated through the AC 4 V 60 Hz external power is illustrated in Figure 3.14. The results show that it took 550 s to warm up the battery from -30°C to 0°C . The corresponding energy consumption in this heating process is 3740 J, which accounts for 9.62 percent of one battery's capacity. The high energy consumption is expected from the energy consumption of the power inverter itself and the heat loss from the battery during the long heating process.

Figure 3.14. Effect of AC heating on 18650 lithium battery.

However, the AC heating method was found to have a significant effect on battery aging [49], and relevant research shows that battery capacity fades, and impedance progressively increases after long-term AC heating [7]. Moreover, the AC 60 Hz inverter

is large and heavy, which would be an unsuitable choice for on-board purposes and could be used as an off-board heater.

3.4.4 Uncertainties in the experiments

There may exist some discrepancies in the experiment results by inappropriate operation and uncertainties of measurements. To minimize the uncertainties of measurement, it is necessary to ensure that the K-type thermocouples and freezer are well calibrated from the manufacturer, and remain good accuracy within their lifespan. Before each heating test, the thermocouples still need to be calibrated with the mixture of ice and water at room temperature. The internal temperature of the freezer will be verified with the accurate thermocouples.

Measures that need to be taken to get the accurate results from each preheating experiment. For SCSH test, the thermocouple and DS18B20 should have good contact with battery surface by thick foam tapes, which can effectively prevent the readings of the thermocouple for battery surface temperature from being affected by the cold ambient temperature. However, the preheating time of SCSH can be variable even though the measurement is accuracy. The preheating time is primarily determined by the internal resistance of the battery, as well as the resistance of the connected wires. Due to different internal resistance of individual cells and different resistance of connected wires, it would be reasonable to get a slight different preheating time for SCSH test. Besides, the voltage of the tested battery can also influence the preheating time, the battery with higher voltage has a shorter preheating time.

For external convective air heating test, the thermocouple should be placed at the leeward side of battery surface, and covered by insulated tape, to avoid the inaccurate measurement caused by the hot air flow. To get the accurate internal temperature of the battery, the thermocouple should be placed in the center of battery core through the small drill hole, then the hole needs to be sealed by sealant. However, the heating effects can be mitigated with narrower longitudinal spacing and wider transverse spacing between battery cells.

For AC heating test, the thermocouple should be attached at the battery surface as the SCSH test. The frequency of AC voltage can influence the preheating time. The higher frequencies contribute to the faster heating effect.

3.4.5 Discussion

To summarize, the SCSH method, and the other two conventional heating strategies were evaluated on the aspects of energy consumption, heating time, and compactness. The tested results are shown in Table 4.

Table 4. Summary of the tested results of three heating systems.

Heating method	SCSH	Convective air heating	AC heating
Heating time (s)	43	111*	550
Energy consumed	5%	10.36%	9.62%

*Experiment was carried out at ambient room temperature.

Among the three methods, the SCSH method takes the least time for heating. Additionally, the external air heating method should take longer time and consume more energy if tested at -30°C , since the inlet air temperature would be lower.

From the compactness perspective, the SCSH strategy does not require additional heating systems or complex circuit components, which enables low cost and high reliability. This compactness allows on-board heating for battery packs. Comparatively, the inverter for AC heating method is larger and heavier, and thus can be only used for off-board heating purposes. The external convective air heating method requires space between cells, which lowers the energy density of the system and increases the difficulty of assembly.

In terms of energy consumption, the SCSH approach consumes the least amount of battery capacity among the three methods. To sum up, the SCSH method is the most effective, efficient, economic, and lightweight design among the tested heating systems.

Chapter 4. Microcontroller-based DC-AC power inverters

4.1 Overview

A DC to AC battery backup inverter was developed to make the battery pack available for household appliances, as well as carry out the AC heating method on Li-ion batteries. This inverter employs the PIC16F883 microcontroller to apply the DPWM technique to drive the inverter circuit. The power inverter can achieve AC sinusoidal voltage with various frequencies through programming, without changing the design of the circuit board. The optimal frequency ratio in the DPWM technique was theoretically obtained. It was validated through the MATLAB[®] simulation and was examined through further experimentation. The optimal frequency ratio enables DPWM signals to stimulate the designed inverter to output sinusoidal voltage waveforms with an acceptable THD value. The THD is an index used to evaluate the performance of output waveforms. This index shows the ratio of the sum of all harmonic components to the fundamental frequency [50], which is defined as $THD = \sqrt{\sum_{n=2}^{\infty} U_n^2} / U_1$, where n is the order of harmonic components, U_n is the voltage of the n^{th} harmonic, U_1 is the voltage of the fundamental frequency.

This chapter proceeds as per the following outline. Section 4.2 describes the selection method for the optimal frequency ratio in the DPWM technique; Section 4.3 subsequently presents the MATLAB simulation of the DPWM technique with the selected optimal frequency ratio, compared to two different frequency ratios. Section 4.4 provides details on hardware implementation of the DPWM technique and hardware

circuit construction of the inverter. Finally, Section 4.5 illustrates the results of hardware experiments and compares them with simulation results.

4.2 Selection of optimal frequency ratio in the DPWM technique

Frequency ratio, the number of PWM pulses in a half cycle of a sinusoidal waveform, is a key parameter in the DPWM technique. It determines the quality of output voltage. A proper frequency ratio shall be selected, especially after introducing dead time into DPWM driving signals.

4.2.1 Harmonic analysis of the DPWM output waveform without considering dead time

The output voltage U_{out} in Figure 2.6(b) can be expressed in the form of a Fourier series as follows,

$$U_{out} = \sum_{n=1,3,\dots}^{\infty} A_n \sin n\omega t + \sum_{n=1,3,\dots}^{\infty} B_n \cos n\omega t \quad (4.1)$$

where n is the harmonic order, A_n and B_n are the Fourier coefficients [51]:

$$A_n = \frac{2U_D}{\pi} \sum_{k=1}^{2N} \int_{\theta_{k(on)}}^{\theta_{k(off)}} \sin n\omega t d(\omega t) = \frac{2U_D}{n\pi} \sum_{k=1}^{2N} [\cos n\theta_{k(on)} - \cos n\theta_{k(off)}]$$

$$B_n = \frac{2U_D}{\pi} \sum_{k=1}^{2N} \int_{\theta_{k(on)}}^{\theta_{k(off)}} \cos n\omega t d(\omega t) = \frac{2U_D}{n\pi} \sum_{k=1}^{2N} [\sin n\theta_{k(off)} - \sin n\theta_{k(on)}]$$

where $\theta_{k(on)}$ 、 $\theta_{k(off)}$ can be expressed in terms of N according to Figure 2.6,

$$\theta_{k(on)} = \alpha_k - \frac{\theta_k}{2} = \frac{\pi(2k-1)}{2N} - \frac{U_m}{2U_D} \left(\cos \frac{k-1}{N} \pi - \cos \frac{k}{N} \pi \right)$$

$$\theta_{k(off)} = \alpha_k + \frac{\theta_k}{2} = \frac{\pi(2k-1)}{2N} + \frac{U_m}{2U_D} \left(\cos \frac{k-1}{N} \pi - \cos \frac{k}{N} \pi \right)$$

Figure 4.1 show the harmonic contents as a percentage of the fundamental component (50/60 Hz) in the DPWM output waveforms for different frequency ratios, N . Harmonic distribution (the amplitude of different harmonic contents), is used to evaluate the performance of various modulation strategies, which is defined as $\sqrt{(A_n^2 + B_n^2)/(A_1^2 + B_1^2)}$, $n=1, 3, 5, \dots$. The harmonic order, n , is ratio of the frequency of harmonic contents to the fundamental component.

Figure 4.1. Harmonic distribution of DPWM output waveforms with different frequency ratios.

According to Equation 4.1, the harmonic spectrums of the DPWM output waveform with different frequency ratios $N = 12, 24, 36, 48, 50$, are shown in Figure 4.1. As can be seen above, the output waveform contains many harmonic contents in addition to the fundamental frequency. Low order harmonic components disappear as frequency ratio increases, and the order of the dominant harmonic of output voltage is around frequency ratio, N [52]. This implies that PWM frequency should be kept high enough to raise the order of dominant harmonic that can be easily filtered out using an appropriate low pass filter. Nevertheless, from a practical point of view, increasing the PWM frequency will result in higher switching losses since the switching frequency of MOSFETs increases. It is important to note that in order to put all MOSFETs in inactive status to avoid shoot-through, dead time needs to be inserted into DPWM signals. However, the additional dead time will introduce low order harmonics, which will be exemplified in Section 4.2.2. Hence, an optimal frequency ratio should be selected, such that switching losses are at a minimal level while minimizing the total harmonic distortion (THD) after injecting dead time into DPWM signals [53].

4.2.2 Selection of optimal frequency ratio while considering the effects of dead time

Adding dead time will introduce harmonic components in the output of the power inverter. This corresponding THD value is proportional to the frequency ratio. However, according to Figure 4.1, the frequency ratio should be kept high enough to eliminate the low order harmonic components in the DPWM output waveform. Consequently, the optimal frequency ratio should be relatively high to make the filter smaller. Even after

considering effects of dead time, an acceptably low THD value in output voltage must be achieved.

4.2.2.1 Spectrum analysis of DPWM signals after inserting dead time

To avoid shoot-through between the DC source and the ground in the inverter circuit, dead time is injected to the DPWM gate drive signals to prevent both MOSFETs in each leg of the H-Bridge inverter from conducting simultaneously [54]. The dead-time effect will result in output voltage errors, and the accumulated voltage errors can degrade the quality of the output voltage. For instance, dead time would cause distortion of the output waveform by introducing low order harmonic components [55], and reducing the magnitude of the fundamental output voltage [56].

Figure 4.2. Leg-A of the H-Bridge inverter circuit.

The dead-time effect is associated with both the duration of dead time and the direction of the output current i_a within each period of output voltage. The output current, i_a , changes its direction every half-cycle of the output waveform [57].

Figure 4.3. PWM driving signals of MOSFETs in leg-A.

Figure 4.3 shows the gate drive PWM signal pairs, Q1G and Q2G, for MOSFETs in leg-A of the H-Bridge inverter in Figure 4.2. The dead time is inserted prior to the rising edges of the PWM pulses, and both MOSFETs Q1 and Q2 cease to conduct during this dead time. The output current must conduct through the reverse recovery diodes QD1 or QD2 during the dead time.

The output voltage is delayed by the dead time as shown in Figure 4.3. The voltage errors (shaded area) consist of commutation dead time error, the switching rise time error and fall time error [56]. Actual inverter output voltage can be considered as the result of the ideal voltage combined with voltage errors.

The output pulsating voltage errors in one period of output voltage can be represented by the following expression [55],

$$u_{err} = \begin{cases} -N(\tau_1 - \tau_2)U_D & i_a > 0 \\ N(\tau_1 - \tau_2)U_D & i_a < 0 \end{cases} \quad (4.2)$$

where $\tau_1 = t_{dt} + t_{on}$, $\tau_2 = t_{off}$, t_{dt} is dead time, t_{on} and t_{off} are the rising time and falling time of MOSFET respectively. N is the frequency ratio.

The number of positive and negative pulsating voltage errors caused by dead-time effect in one period of sinusoidal output are both N . And these pulsating voltage errors can be considered as a periodical pulsating function, with pulse width, τ , amplitude, U_D , and period T , the same as the period of sinusoidal output voltage.

The total harmonic distortion (THD) caused by the dead time can be expressed by the following expression [53],

$$\text{THD} \approx \frac{2\sqrt{2}N}{MT} \sqrt{(t_{dt} + t_{on} + t_{off})^2 - \frac{2}{\pi^2}(t_{dt} + t_{on} - t_{off})^2} \quad (4.3)$$

Equation 4.3 is the THD value for harmonic components caused by dead-time effect [53], which is proportional to frequency ratio N . However, the THD value for DPWM output waveform without considering dead-time effect is inversely proportional to frequency ratio N . Overall, the THD value of DPWM output waveforms with dead-time effect taken into consideration is non-linear with frequency ratio N . Fortunately, harmonic components caused by DPWM output waveforms without considering dead-time effect can be significantly eliminated by selecting a proper filter. Therefore, the THD value in Equation 4.3 can be used as the criteria to select the optimal frequency ratio.

4.2.2.2 Mathematical calculation for optimal frequency ratio

Figure 4.1 shows that low order harmonics will be eliminated with an increasing frequency ratio, and the dominant harmonic order of output voltage equals the frequency ratio. These low order harmonics can be easily filtered out. However, introducing dead time in PWM signals will cause distortion of the output waveform and the THD value will increase, and thus the quality of output voltage will also decrease. The optimal

frequency ratio should be selected to make sure that the THD is in acceptable range, which is 3%-5% according to the IEEE 519 Standard. The upper bound of N can be determined by Equation 4.4,

$$\frac{2\sqrt{2}N}{MT} \sqrt{(t_{dt} + t_{on} + t_{off})^2 - \frac{2}{\pi^2} (t_{dt} + t_{on} - t_{off})^2} < 3\% \quad (4.4)$$

MOSFET (FDA50N50) was chosen for the AC 60 Hz power inverter's hardware implementation: $t_{off} = 460$ ns, dead time is set to $t_{dt} = 1034$ ns, $t_{dt} + t_{on} = 1254$ ns, $T = 16.67$ ms, $M = 0.8$ [58]. Substitute these parameters into Equation 4.4 to get $N < 84.36$. Thus, 84 is chosen as the optimal frequency ratio. Similarly, the optimal frequency ratio for AC 50 Hz or other frequency can be determined by changing the value of T and the parameters of MOSFET.

In the following sections, the calculated optimal frequency ratio will be verified by simulation and experimentation with the proper filter, together with two other frequency ratios for comparison.

4.3 Choosing the optimal frequency ratio using Simulink

Simulation has been carried out in MATLAB Simulink to analyze the performance of the inverter driven by DPWM signals using different frequency ratios. The MATLAB simulation contains three parts: DPWM signal generation sub system, single phase H-Bridge inverter circuit and THD evaluation of output voltage [59]. The DPWM signals source module generates unipolar switching signals to control four MOSFETs. High DC voltage is supplied to the four MOSFETs, and the frequency of the sinusoidal output is set to 60 Hz.

Figure 4.4. DPWM driving signals for four MOSFETs.

The simulation was built to examine the THD of sinusoidal output waveforms when different frequency ratios are used. The inverter structure in the simulation and the simulation results can be used as guidelines for implementing the hardware circuit.

Figure 4.5. Simulink design of DPWM controlled inverter.

Figure 4.5 shows the diagram of the Simulink simulation. THD evaluation is not shown in this diagram. The MOSFETs' periodic driving signals, as shown in Figure 4.4, are generated from the DPWM generator sub system according to Equation 2.9. After this, the dead time that is simulated from analog RC delay circuits is inserted into the generated pulse trains. The DPWM signals consist of four periodic signals that are used to trigger four MOSFETs. The first two pulse trains are input signals for MOSFET Q1 and Q2, and the second pair of pulse trains are for Q3 and Q4. The DPWM signals generated with three different frequency ratios are applied to the H-Bridge inverter block. The simulation results of three output voltage waveforms with frequency ratio 40, 84, and 120, are shown in Figure 4.6, and the corresponding THD values are calculated. Figure 4.7 shows the corresponding harmonic spectrum of the voltage waveforms. The results show that the output voltage has the lowest THD at 3.69% when the frequency ratio is 84.

Figure 4.6. Output voltage waveforms of the inverter with different frequency ratios N .

Figure 4.7. Spectrum of voltage waveforms.

The simulation results show that output voltage has the desired THD value when frequency ratio N equals 84, which is a good verification of the calculation.

1. Set the PWM period by writing 231 into the PR2 register.

The PWM period is determined by the frequency ratio N and the period of the output sinusoidal waveform, T_{out} , as $T_{PWM} = T_{out}/2N$.

The period of PWM is also specified by the value in the PR2 register [60], which is defined as:

$$T_{PWM} = [(PR2) + 1] \times 4 \times T_{OSC} \times (TMR2 \text{ Prescale Value}) \quad (4.5)$$

The prescale value of TMR2 is set to 3, and the value of PR2 is set to 231.

2. Set the duty cycle of PWM.

The PWM duty cycle is determined by writing a 10-bit value into CCP1L and CCP1CON<5:4> registers. The duty cycle value in $(CCP1L:CCP1CON\langle 5:4 \rangle)$ can be calculated from the following formula,

$$(CCP1L:CCP1CON\langle 5:4 \rangle) = D \times 4(PR2 + 1) \quad (4.6)$$

where D is the duty cycle ratio, which can be calculated from Equation 2.9. Then a sequence of duty cycle values can be obtained from a series of duty cycle ratios, and the duty cycle value sequence will be stored in EEPROM in the form of a look-up table [61].

3. Set the CCP1CON register properly to select the full-bridge enhanced PWM output mode, and configure the polarity of all four PWM output pins as the active-high state.

4. Clear the interrupt flag bit, TMR2IF, and set the TMR2ON bit of the T2CON register to enable Timer2, then a new PWM cycle starts.

Figure 4.9. Simplified Block Diagram of the enhanced PWM mode [60].

The microcontroller can generate DPWM signals with an algorithm according to the following steps:

1. In the full-bridge PWM, the forward mode is selected once the P1M1 bit in the CCP1CON register is set to 0, and the pin P1D is modulated to output PWM signals. P1D starts to output high level after the pre-calculated PWM duty cycle value in (*CCPR1L:CCP1CON* $\langle$ 5:4 $\rangle$) is latched to CCPR1H, and Timer2 starts counting. The output of P1D will change to low level when the value of TMR2 equals to the duty cycle value.
2. One PWM period completes when TMR2 matches the value of PR2. The interrupt flag, TMR2IF, will be generated by CCP1 immediately. Then, a corresponding interrupt subroutine is invoked to change the duty cycle of the next PWM period by latching the next duty cycle value in (*CCPRxL:CCPxCON* $\langle$ 5:4 $\rangle$) to CCPR1H.

3. In the interrupt subroutine, the interrupt counter increases by one when every interrupt occurs and can be used for counting the number of PWM pulses that the P1D or P1B pin outputs. The direction of full-bridge mode is tuned when the preset upper counter bound is achieved.

4. Once the value of the interrupt counter equals the frequency ratio, N , the interrupt counter will be reset to zero and the P1M1 bit will be reversed to “1”. Subsequently, the full-bridge PWM changes to the reverse mode. Pin P1B is modulated to output PWM signals in the next DPWM period while pin P1D is placed in its inactive state. The first PWM duty cycle value in (*CCPR1L: CCP1CON*(5:4)) will be latched to *CCPR1H* again [62].

5. The direction control bit P1M1 is reversed every time when the upper bound of interrupt counter is achieved, so that P1B and P1D can output DPWM signals alternately.

The detailed programming flowchart is shown in Figure 4.10, including a main program and an interrupt subroutine [62].

Figure 4.10. Algorithm structure (a) Flowchart diagram of main program; (b) Flowchart of interrupt subroutine.

4.4.2 Hardware circuit design

After generating DPWM signals with the PIC16F883 microcontroller, hardware circuits composed of boosting circuit, gate drive circuit, and inverter circuit, need to be designed for experimental platform setup.

The boosting circuit can boost low DC voltage to high DC voltage. Once it has DPWM signals from the PIC16F883 microcontroller, the gate drive circuit can drive the

MOSFETs in the inverter circuit to invert the high voltage from the boosting circuit to AC sinusoidal output. Different amplitudes of AC output can be obtained by different low DC input voltages. In this work, DC 24 V from the battery pack is supplied to the power inverter to achieve AC 110 V, 60 Hz.

For the AC heating strategy, the boosting circuit is not implemented, because only low DC voltage is required for the inverter circuit.

4.4.2.1 Boosting circuit design

Figure 4.11. The boosting circuit: (a) schematic of boosting circuit; (b) equivalent circuit of boosting circuit.

The design of boosting circuit is based on open resources [63].

The boosting circuit aims to convert the DC 24 V from the battery pack to AC 24 V, then boost it to AC 190 V via a transformer.

The KA3525A pulse width modulator is employed to output two complementary PWM signals with a maximum of 45% pulse width. This can control two complementary pairs of NPN and PNP transistors. The complementary PWM signals control half-bridge MOSFETs conducting alternately through the push-pull transistors. The AC 24 V input for the transformer is generated by DC 24 V alternating through two primary windings. The transformer can boost AC 24 V to AC 190 V, with the turn ratio of primary winding and secondary winding, $N_s = 3:3:24$. The output voltage of the transformer is rectified by a rectifier bridge to get DC 190 V. Then voltage ripples are removed by capacitors to provide a smooth DC voltage for the inverter circuit. As can be seen in Figure 4.11(a), the output voltage is sensed through a resistive divider and sent back to KA3525A. The PWM width is changed in accordance with this feedback control voltage, V_{FB} , to keep the actual output voltage matched to the desired output value.

4.4.2.2 Gate drive circuit design

The DPWM signals generated by the PIC18F883 control circuit are applied to the gate of the MOSFET through the gate drive circuit. The gate drive circuit is designed to provide electrical isolation between the control circuit and inverter circuit while maintaining the required gate drive voltage to drive the MOSFETs.

(a)

(b)

Figure 4.12. The drive circuit: (a) schematic of drive circuit; (b) equivalent circuit of drive circuit.

The design of gate drive circuit is based on open resources [64].

The drive circuit is shown in detail in Figure 4.12. The drive circuit employs TLP250 opto-isolators to amplify DPWM signals from the PIC16F883 to trigger the MOSFETs. Opto-isolators can also isolate the PIC16F883 control circuit, which operates at a 5 V level, from the high DC voltage applied for the inverter circuit. The desired DPWM pulse trains generated from the PIC16F883 are transmitted to the logic circuit unit, which is designed to generate two complementary signals from each DPWM signal. TLP250 opto-isolators accept four low-power signals and output the appropriate high-current gate drive for the MOSFETs placed in the inverter circuit [65].

As shown in Figure 4.13, when pin P1D is modulated to output DPWM signals while P1B is placed in its inactive state, pin 3 and pin 4 of CD4081 output two complementary DPWM trains to drive MOSFET Q1 and Q2. Pin 10 of CD4081 outputs high level to keep Q3 ON, and pin 11 of CD4081 remains low level to maintain Q4 OFF

through TLP250. Similarly, P1B is modulated while P1D is in the inactive state.

Figure 4.13. Timing diagram of DPWM signals.

R-C snubber circuits are employed to generate the specific time delay between MOSFETs Q1 and Q2, and Q3 and Q4, to avoid the shoot-through for MOSFETs on one bridge.

The bootstrap supply in the drive circuit is used to drive high side MOSFETs, and is composed of bootstrap diodes and capacitors [42], i.e. C11, C9, C13, C15, as shown on the right side of Figure 4.12(a).

4.4.2.3 Inverter circuit design

The inverter circuit consists of a DC voltage source, four H-Bridge MOSFETs, and an LC passive filter.

Figure 4.14. The H-Bridge inverter circuit: (a) schematic diagram of H-Bridge inverter circuit; (b) equivalent circuit of H-Bridge inverter circuit.

The design of inverter circuit is based on open resources [63].

Figure 4.14 shows the inverter circuit of a full H-Bridge unipolar inverter, where four MOSFETs are employed to convert the DC voltage source into AC voltage [63,64].

As displayed in Figure 4.12(a), the MOSFET pairs Q1 and Q2, and Q3 and Q4 are controlled by the pin P1D and the pin P1B of the PIC16F883, respectively. When pin P1D is modulated and P1B is placed in its inactive state, the negative half cycle of sinusoidal output can be achieved. Similarly, when pin P1B is modulated and P1D is placed in its inactive state, the positive half cycle of sinusoidal output can be obtained, as can be seen in Figure 4.13. Both Q1 and Q3 are high side MOSFET, which means that their drain terminals are connected to high DC input voltage, 190 V. The voltage of the source terminal can float between 0 V and 190 V while the MOSFET is working. The bootstrap supply in Figure 4.12(a) can provide between 12 V and 202 V to the gate terminal of MOSFET to establish the rated collector-to-emitter conduction.

The RCD absorber, which provides an extra path for discharging the voltage surges when MOSFET is off, effectively eliminates voltage spikes induced by the inductor to protect the MOSFETs during their commutations.

Based on the optimal frequency ratio 84, the LC filter circuit is designed and placed at the output of the PWM inverter to filter out most harmonic contents other than those which are fundamental [36].

4.4.3 Prototyping

The implementation of the inverter circuit is shown in Figure 4.15.

Figure 4.16. Driving board of the inverter.

The driving circuit board is composed of the DPWM signals control circuit, the gate drive circuit, and the KA3525A control unit of the boosting circuit, as shown in Figure 4.16. After programming the Microchip PIC16F883 on the driving board, the experimental prototype can be achieved by connecting the driving board with the power board through connectors. The inverter can output AC 110V, 60 Hz sinusoidal waveform after fed by DC 24 V from the battery pack.

4.5 Comparison of the experimental and simulation results

Experiments were carried out with a prototype inverter under similar configurations as the simulation studies. The frequency ratio N is set to 40, 84 and 120, while the frequency of output voltage remains at 60 Hz. Sampled data were collected from a Tektronix DPO 2024B oscilloscope, then analyzed in MATLAB to evaluate the qualities of the generated waveforms by calculating the THD.

Several waveforms were collected from the inverter with different frequency ratios. Output voltage waveforms from the experimental studies are depicted in Figure 4.17. The

corresponding harmonic spectrums of each output voltage waveform are shown in Figure 4.18.

Figure 4.17. Output voltage waveforms under different frequency ratios.

Figure 4.18. Spectrum for output voltage waveforms.

The harmonic analyses show that the THD values are comparable to the simulation results, which can be seen in Table 5. As expected, when the frequency ratio of 84 is selected, the output voltage waveform has the lowest THD value.

Table 5. THD values of simulations and experiments under different frequency ratios.

Frequency ratio	40	84	120
THD of simulation	11.52%	3.69%	4.43%
THD of experiment	12.55%	3.98%	4.78%

There is noticeable agreement when comparing the THD value of voltage waveforms for simulation and experimental results. Table 5 shows a nonlinear relationship between THD value and frequency ratio. Both simulation and experiment results have the lowest THD value when the frequency ratio is set to 84, and have the largest THD value when the frequency ratio equals 40. As can be seen from Equation 4.3, the lowest THD induced by the dead-time effect occurs when the frequency ratio is set to 40. However, low order harmonic components introduced by the DPWM output waveforms without dead time will have a greater contribution to the overall THD value when the frequency ratio is much lower than the optimal one.

As a proper filter is selected to eliminate low order harmonics in DPWM output waveforms for $N = 84$, dead-time effect will determine the overall THD value when the frequency ratio is larger than 84. Since the THD caused by dead-time effect is proportional to the frequency ratio, the measured THD value for frequency ratio 120 is larger than that of 84.

Although simulation results and experiment results have good agreement, there are still some discrepancies between these two results. The THD value in experimental results are slightly larger than that of simulation results. One possible cause is that the physical properties of MOSFETs are not considered in simulation, e.g. turn-on delay time and rise time, turn-off delay time and fall time, which can lead to higher THD values due to a more severe dead-time effect in experiments.

Chapter 5. Conclusion and future work

5.1 Conclusion

The SCSH method described in this thesis was designed to bring battery temperature from subzero temperatures to 0°C, and its performance was compared through experimentation with the two existing conventional heating methods. The SCSH control system can heat up the 18650 Li-ion batteries from -30°C to 0°C in 43 seconds, with less than 5% of the battery capacity consumed. The external convective air heating takes 111 s, is not very efficient and requires spaces between cells, which lowers the energy density of the system and increases the difficulty of assembly. For AC heating, a microcontroller-based DC-AC power inverter was designed and built. The inverter takes 550 s to heat, which is much less efficient than the SCSH method. Comparatively, the benefits of the SCSH method are two-fold. First, low energy consumption and rapid heating can be achieved. Second, the control PCB has a small size and lightweight design, which allows on-board heating for the battery pack.

The battery powered DC to AC power inverter developed in this thesis increases the versatility of battery packs, availing them for a greater number of household appliances. Additionally, the inverter can be used to carry out the AC heating strategy. This inverter employs the microcontroller based DPWM technique at the optimal frequency ratio. The inverter allows for output of high quality AC sinusoidal voltage with adjustable frequencies through programming, without changes to the hardware circuit.

Simulations and experiments were carried out to evaluate the performance of the selected optimal frequency ratios. The simulation results suggest that the DPWM

technique with the optimal frequency ratio is capable of eliminating most harmonic contents of outputs. Low THD sinusoidal waveforms were also obtained in experiments conducted with the PIC16F883 microcontroller based inverter at the optimal frequency ratio.

5.2 Future work

Future work should be conducted in the following subjects:

- (1) A higher current SCSH control board should be designed and built to get higher cutoff current for faster heating for larger battery packs.
- (2) A user-friendly programmable interface should be designed to allow users to configure the power inverter to output the desired magnitude and frequency voltage.
- (3) A battery health management system should be developed to monitor the battery health condition when powering household appliances through inverters.

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