Design Guide: TIDA-050042

1-6s, up to 1.5A Li-ion Battery Charger Reference Design with Switching Constant Current Source

Description

This reference design demonstrates a cost-optimized onboard battery charger solution for mid-end or low-end vacuum robots, which has up to 1.5-A charging current capability with small layout area, providing ±3% charging voltage accuracy and ±3% charging current accuracy. The design achieves a stable and smooth Pre-Charging to CC (Constant Current) and CC to CV (Constant Voltage) charging profile and has been evaluated with a 4S2P Li-Ion battery pack.

Resources

TIDA-050042	Design Folder
TPS92200	Product Folder
TLV9002	Product Folder
TLV7021	Product Folder
TVS3300	Product Folder

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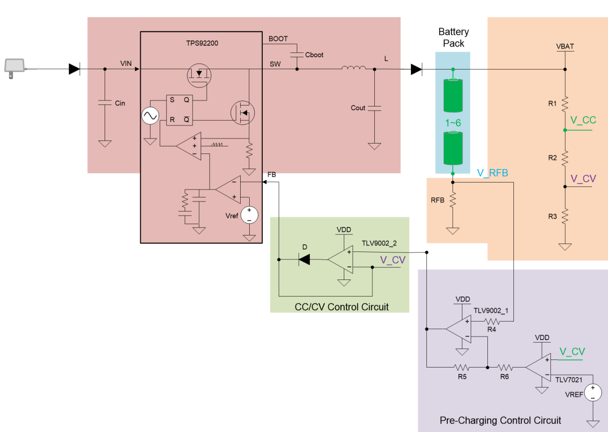
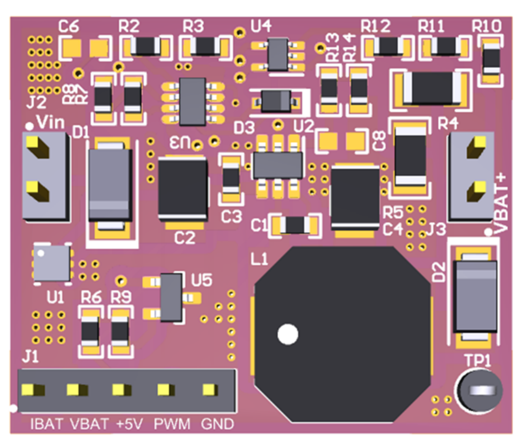
Features

- Widely support from 4-V to 30-V input voltage range (1 - 6s Li-ion battery charger solution)
- Up to 1.5A maximum charging current
- Pure hardware configurable 3-stage charging with external circuits
  - Pre-Charging, CC, and CV
  - CC and CV
- Pure analog control topology
  - Implement of pre-charge stage with simple analog circuit
  - Achieve smooth and stable CC -> CV transition with internal compensation and simple control logic

Applications

- Vacuum robot
- Cordless vacuum cleaner
- Humanoid





1 System Description

A vacuum robot, also called a robotic vacuum cleaner, which has been around for about 23 years, is getting more intelligent and automatic. There is an expectation that robots can do a full cleaning cycle before needing to charge again. With more features added in a vacuum robot, such as mopping, audio interaction, navigating thick carpet, and climbing higher thresholds, the power requirement for a full cleaning cycle is increasing, so the battery capacity is becoming bigger, typically from 2600 mAh to 5200 mAh.

Meanwhile, this also increases the requirements for the battery charger. The following items list the general requirements for an onboard charger, which means the charger circuit is implemented on the main board of the robot, which is widely used for almost all brands of vacuum robots worldwide:

- High-charging current
- Cost effective
- Small size
- High-charging voltage accuracy
- High-charging current accuracy
- Easy to design

Most onboard charging is achieved with the discrete solutions. The most reprehensive one is the asynchronous buck topology charger that uses the system micro controller (MCU) as the digital controller. Figure 1-1 shows the block diagram of this solution.

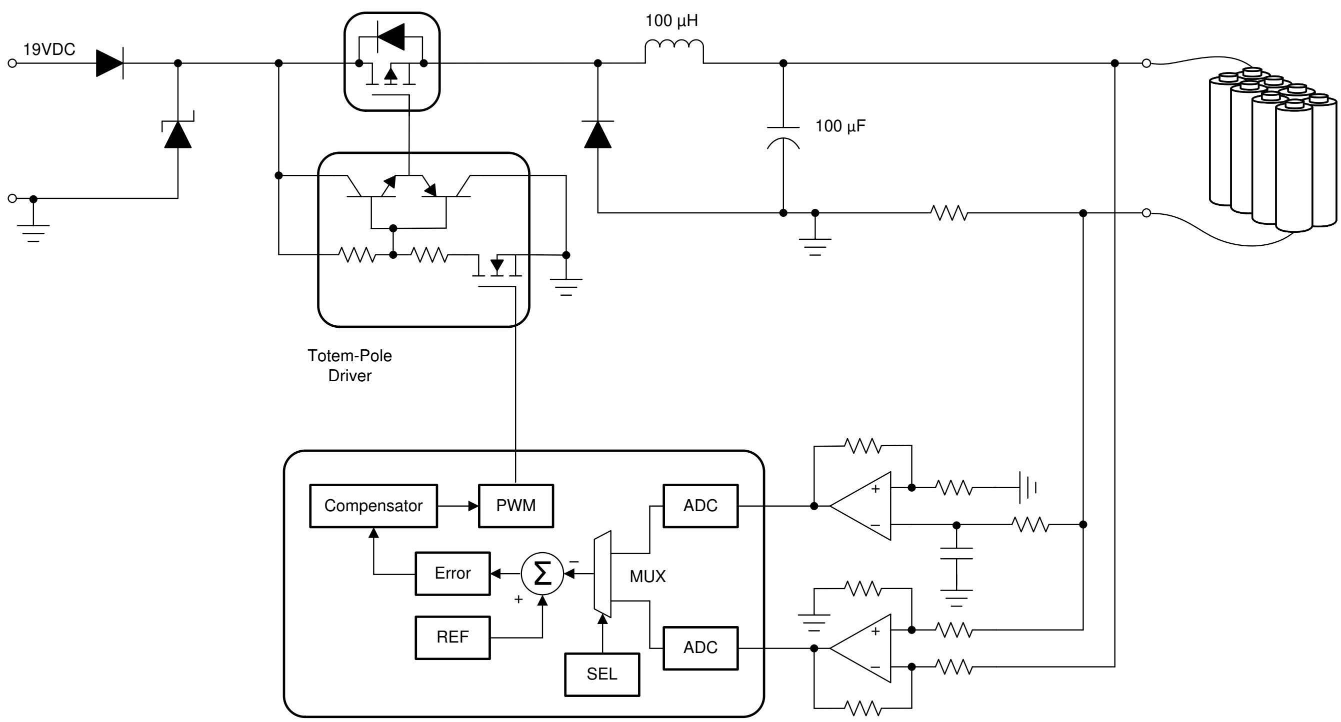


Figure 1-1. Asynchronous Buck Topology Charger Controlled by System MCU

This solution is a digital-controlled, switch-mode power supply (SMPS); *digital control* means sampling feedback information and closing the loop numerically, the error amplifier is replaced with an analog to digital converter (ADC) and a digital filter, the compensator uses digital-signal processing techniques to construct the control effort for the PWM.

The following items list several pros and cons of this solution:

- Limited switching frequency due to limited ADC sampling rate and Nyquist-Shannon sampling theorem, typically from 50 kHz to 100 kHz

- Large value of inductor and output capacitor needed to meet the strict output voltage regulation requirement, and large size to occupy board area
- Low efficiency due to the asynchronous buck topology and low thermal performance especially affected by the power dissipation of the free-wheeling diode
- Complex digital-signal processing techniques to achieve a stable closed loop and keep multiple MCU resources occupied, such as memory, PWM, ALU, ADC, the charging voltage accuracy depends on the accuracy of the reference voltage for ADC, and the charging voltage accuracy is around ±3%.

This reference design has developed a competitive solution between above discrete solution and full integrated solution.

1.1 Key System Specifications

Table 1-1 shows the typical requirement and system specification of the ion board charger.

Table 1-1. Key System Specifications

PARAMETER	SPECIFICATIONS
Input voltage range	17 V to 30 V
Number of cells in series	4S
Charge current	Up to 1.5A
Charge voltage accuracy	<=±3%
Charge current accuracy	<=±3%
Charge voltage ripple	±0.023%
Efficiency	> 90%, up to 95%
PCB size	3.0 cm × 2.5 cm

2 System Overview

2.1 Block Diagram

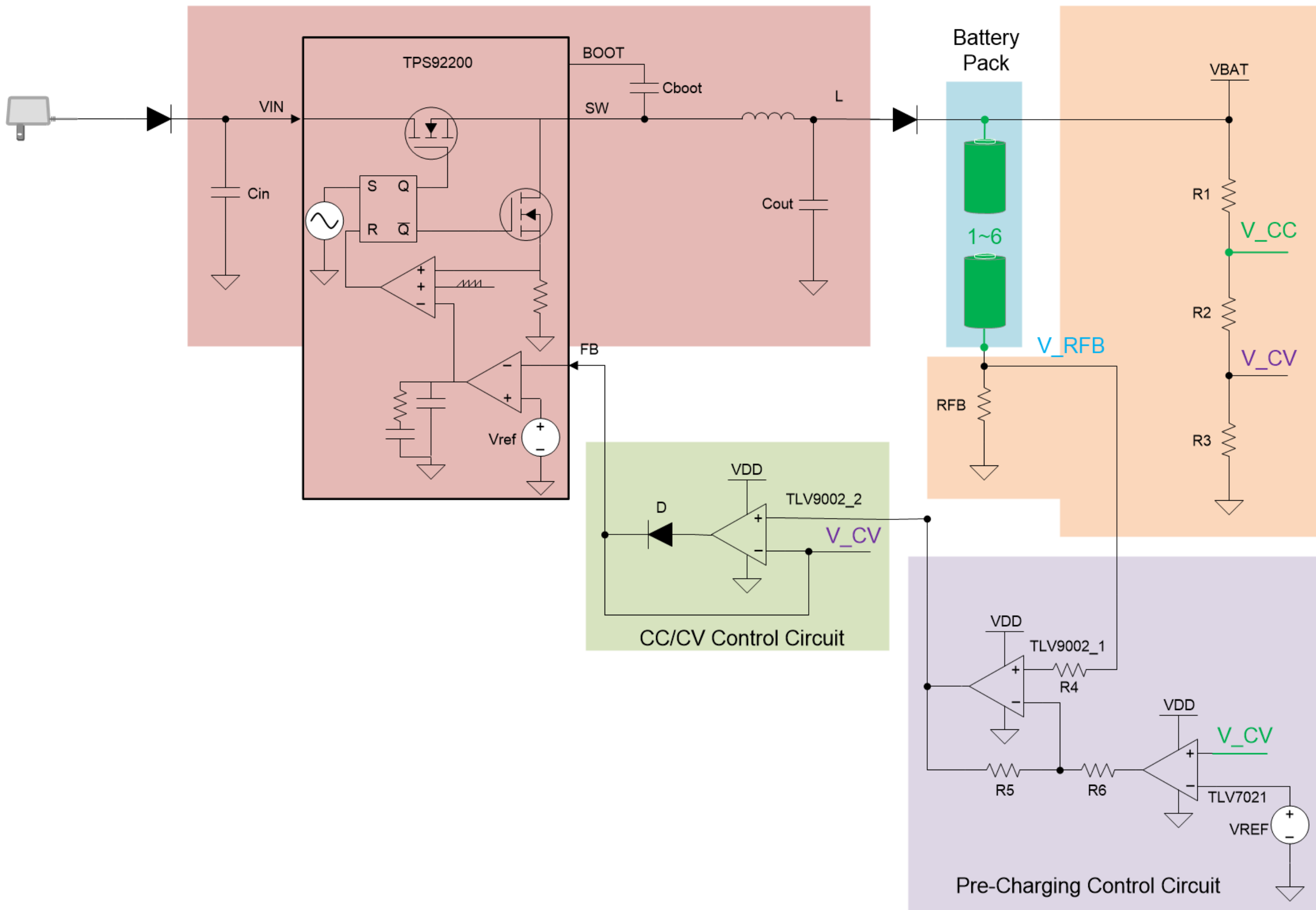


Figure 2-1. TIDA-050042 Block Diagram

2.2 Design Considerations

This reference design attempts to optimize the system BOM cost and charge current capacity by trading-off the charge voltage accuracy. This solution achieves a battery charger based on a synchronous buck converter - the TPS92200 device integrates two switching FETs, internal loop compensation, and employs the SOT-23 package achieving high power density and offering a small footprint on the PCB. The analog control eliminates the MCU resources and software workload, which is easier to implement and accelerate the design cycle. This solution achieves a simple charging profile - constant voltage stage and constant current stage using the TLV9002 device which contributes high current-sensing accuracy and TLV7021 device which is used to switch between Pre-Charging and Constant Current charging process.

2.3 Highlighted Products

The following subsections detail the highlighted products used in this reference design, including the key features for their selection. See their respective product data sheets for complete details on any highlighted device.

2.3.1 TPS92200

The TPS92200 device is a 1.5-A synchronous buck LED driver with 30-V maximum input voltage. By integrating the high-side and low-side NMOS switches, the TPS92200 device provides high power density with high efficiency in an ultra-small solution size. The TPS92200 device uses peak-current-mode control and full internal compensation to provide high transient response performance over a wide range of operating conditions.

Due to the constant current characters of the LED driver, it can also been used to implement a competitive charger solution. 4 V to 30 V supply voltage range is very popular for 1s to 6s Li-ion battery applications with the general AC-DC adaptors or USB power supply.

Flexible dimming method can help to provide kinds of battery charger solutions which includes digital charger solution with less external components and pure-hardware solutions with a little external components.

For safety and protection the TPS92200 devices implement full protections include LED open, LED+ short to GND, LED short, sense resistor open and short, and device thermal protection. Those protections also enhance the safety of the battery packs.

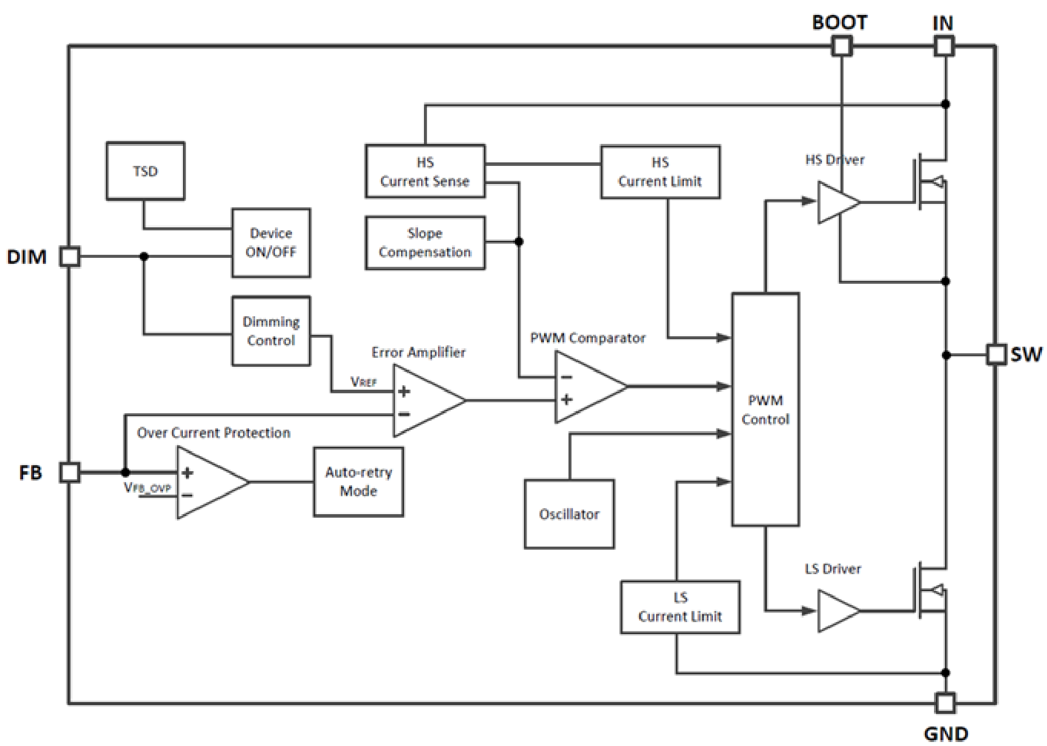


Figure 2-2. TPS92200 Functional Block Diagram

2.4 System Design Theory

To achieve the simplified charging profile, the battery charger should have pre-constant charging control (Pre-CC), constant current (CC) control and constant voltage (CV) control. The TPS92200 device implements a constant-frequency, peak current mode control to improve line and load transients. The optimized internal compensation network minimizes the external component counts and simplified the constant voltage loop design.

2.4.1 Pre-Charging Control

To achieve pre-constant current control, the design needs to set the pre-charging voltage threshold.

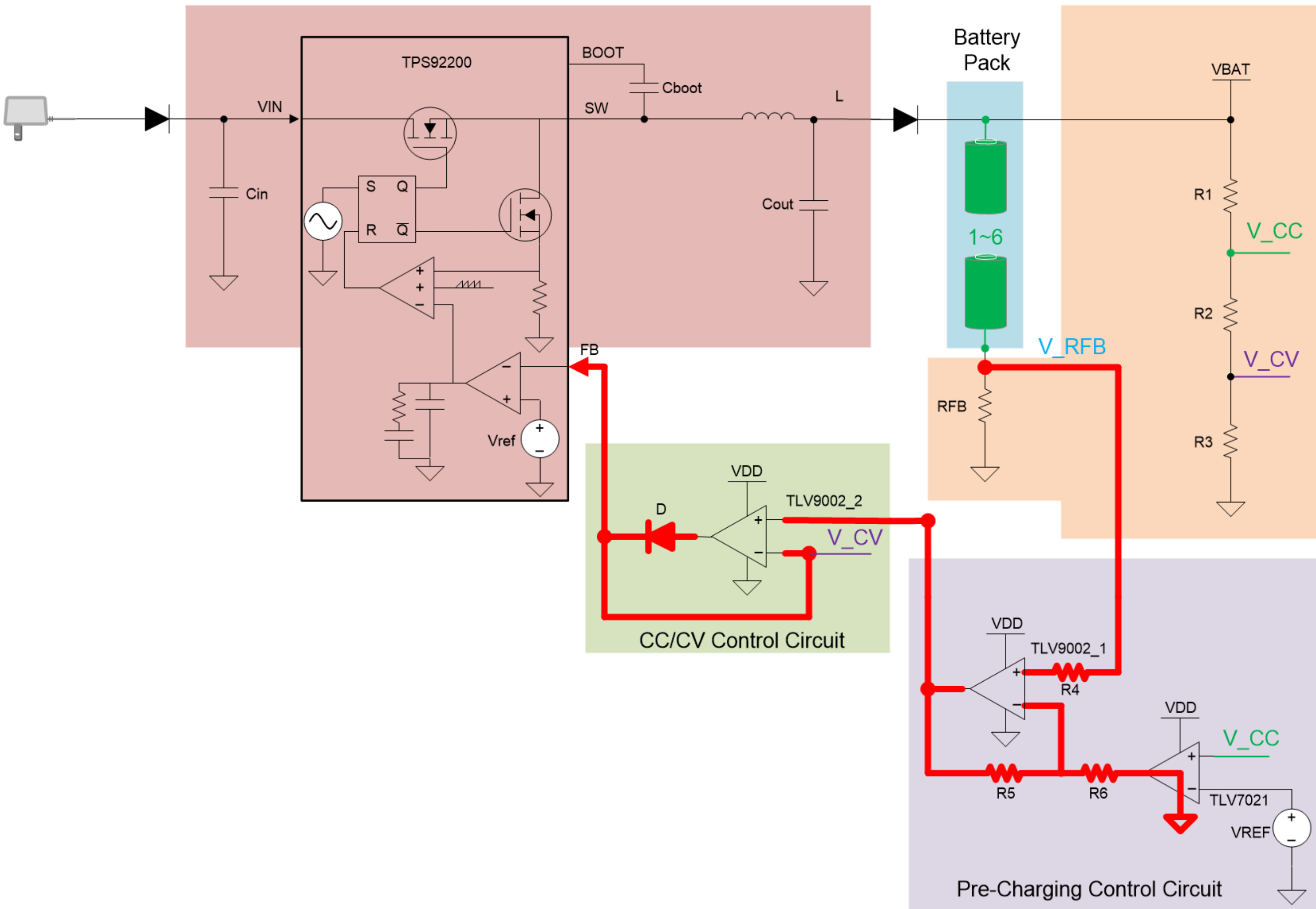


Figure 2-3. Pre-Charging Control

VREF can come from the voltage divider or a constant voltage source, like TL431. R1, R2 and R3 are used to detect the battery voltage, when the battery voltage meets the Equation 1, it enters into Pre-charging mode shown in Figure 2-3.

$$V\_CC = VBAT * \frac{R1}{R1 + R2 + R3} \leq VREF \quad (1)$$

For the Pre-Charging mode, TLV7021 outputs low and TLV9002_1 amplifiers the sensed voltage form the RFB with the gain shown in Equation 2.

$$\text{Gain} = 1 + \frac{R5}{R6} \quad (2)$$

Since the battery is not fully charged, battery sensed voltage V_CV meets Equation 3 which lead to TLV9002_2 output high and schottky diode conducts to the close loop path.

$$\text{V\_CV} = \text{VBAT} * \frac{R1 + R2}{R1 + R2 + R3} < Vref \quad (3)$$

- Where is the internal reference of TPS92200, 99mV (typ).

The charging current under Pre-Charging mode is calculated with Equation 4.

$$I_{out} = \frac{Vref}{Gain * RFB} \quad (4)$$

Pre-Charging mode ends up when the V_CC approaches to VREF.

2.4.2 Constant Current Control

When V_CC is higher than VREF, comparator TLV7021 output open and TLV9002_1 works like a buffer that does not amplify the V_RFB. TLV9002_2 also works under close loop as shown in Figure 2-4.

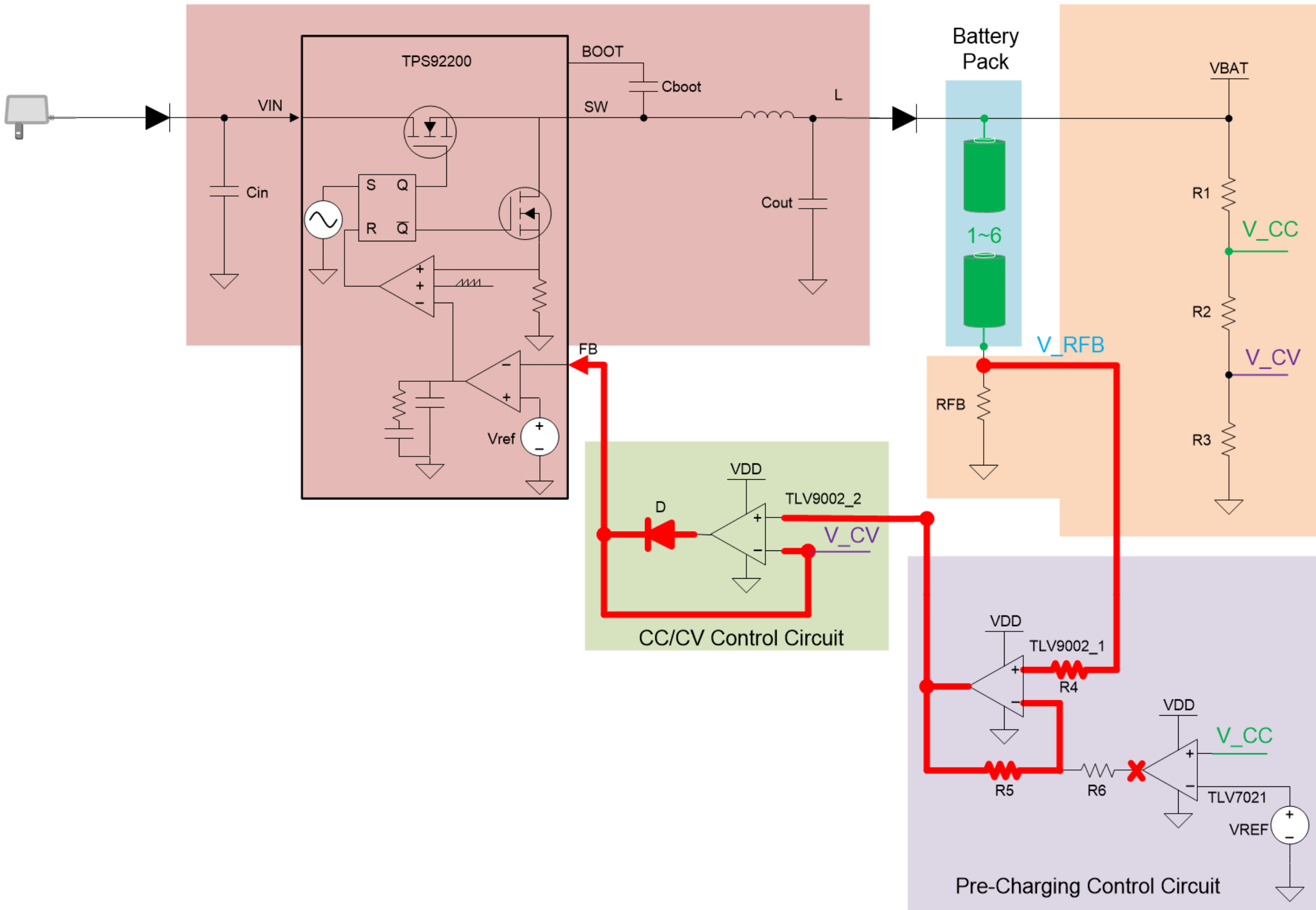


Figure 2-4. Constant Current Control Design

The charging current under constant current mode is calculated with Equation 5.

$$I_{out} = \frac{Vref}{RFB} \quad (5)$$

Constant current mode ends up when the V_CV approaches to Vref.

2.4.3 Constant Voltage Control

A cost effective and simplified way to switching CC control and CV control is using one diode to achieve the OR logic function. Figure 2-5 shows the block diagram of this implementation.

With the charging process, VBAT will increase and when the V_CV equals to Vref, TPS92200 will enter status state. Output current will drop and TLV9002_2 output low, schottky diode will be blocked and V_CV will be regulated directly which lead to the constant voltage control like the traditional DC-DC converter.

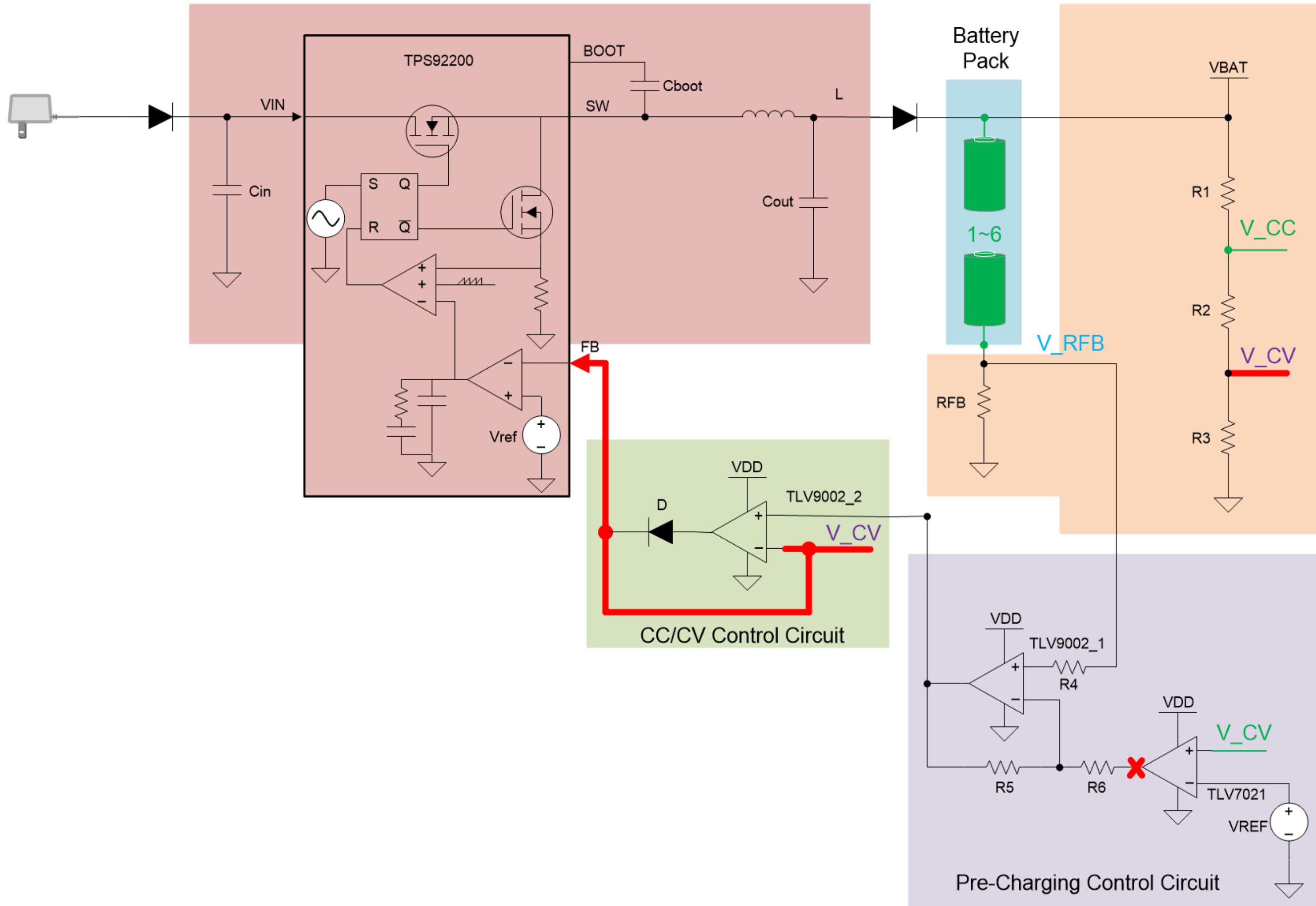


Figure 2-5. Constant Voltage Control

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware

Figure 3-1 shows the overview of the PCB for the TIDA-050042 design, which features:

- Two-terminal input for power supply (J2): This pin is used to connect the DC supply from the pre-stage AC/DC output voltage.
- Two-terminal output for output voltage (J3): This pin is used as the output of this charger and to connect to the battery.
- Six-terminal connector (J1): The connector is used for the external communication interface, the pin definition from left to right is: IBAT, VBAT, +5 V, PWM, and GND. The IBAT pin is the output of the current-sensing circuit, the VBAT is the output of voltage sensing circuit, and the +5 V is the power supply for the op amp and comparator. The PWM pin is optional and is used to adjust the output current.

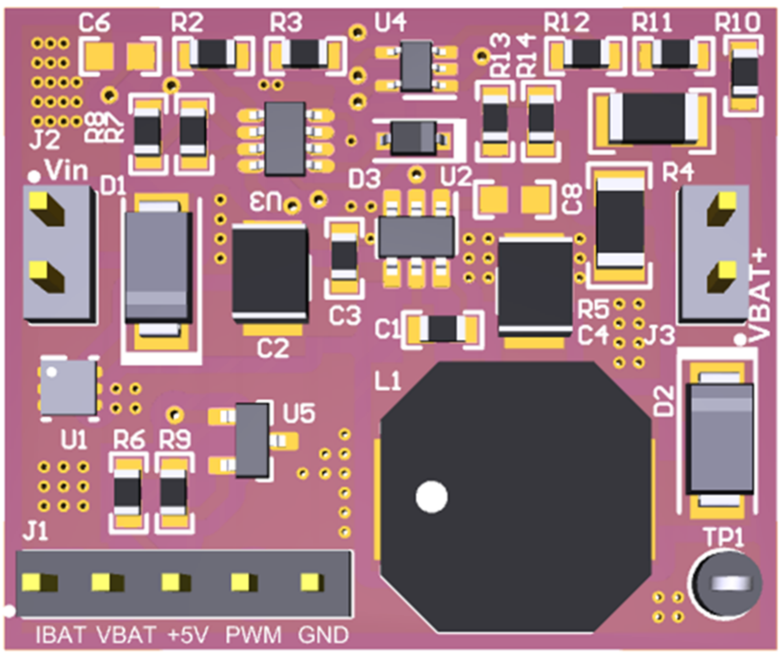


Figure 3-1. TIDA-050042 Printed-Circuit Board

3.2 Testing and Results

3.2.1 Test Setup

Table 3-1. Test Environment List

MATERIALS	USAGE	COMMENTS
DC Source	Power Supply	30-V, 2-A Power source
DC Source	Power Supply	6-V, 1-A Power Source
TIDA-050042 Board	Battery charger board	----
Electronic Load	Battery pack simulation	CC, CV, CR mode
4S2P Li-Ion battery pack	Load	With protection circuit

The following steps show how to set up the test platform in the lab during the test:

1. Ensure the TIDA-050042 board has the right output voltage at no load
2. Connect the electronic load and choose the CV mode to test the constant output current
3. Connect the electronic load and choose the CC mode to test the constant output voltage

3.2.2 Test Results

3.2.2.1 Pre-Charging, CV and CC Mode Steady State

Figure 3-2 shows the steady state of pre-constant current (Pre-CC) mode. Figure 3-3 shows the steady state of constant current (CC) mode and Figure 3-4 shows the steady state of constant voltage (CC) mode. The blue curve (CH4) is the output voltage and the purple curve (CH1) is the switching frequency. The CV mode is tested at the following conditions: output voltage at 16.5 V and the output current at 0.5 A; the CC mode is tested at the following conditions: output voltage at 15 V and output current at 1.0 A.

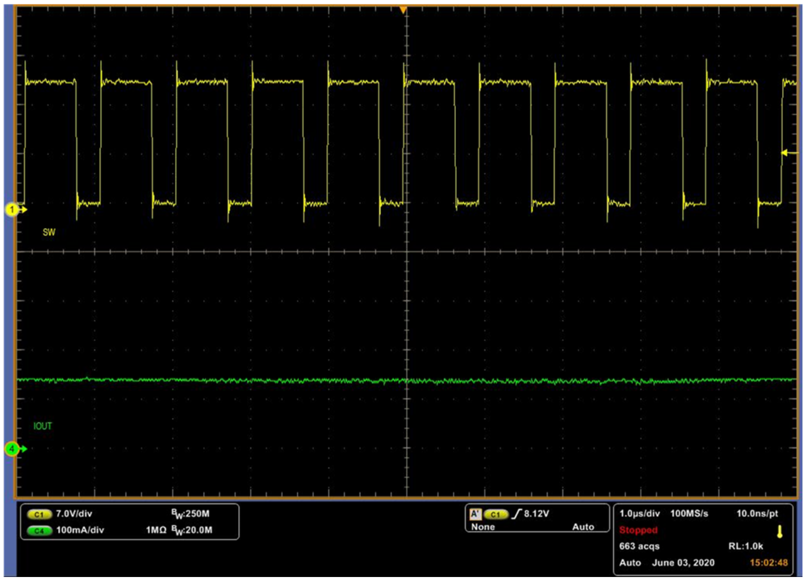


Figure 3-2. Pre-Charging Mode Steady State

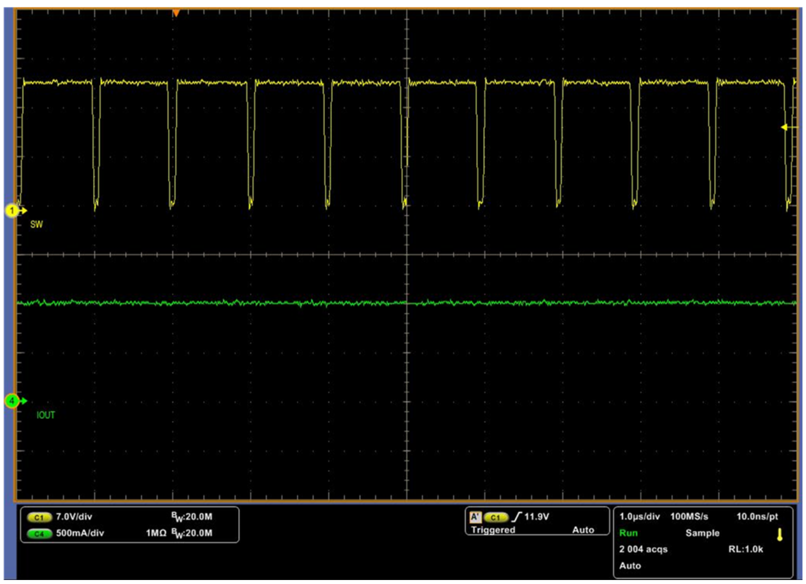


Figure 3-3. CC Mode Steady State

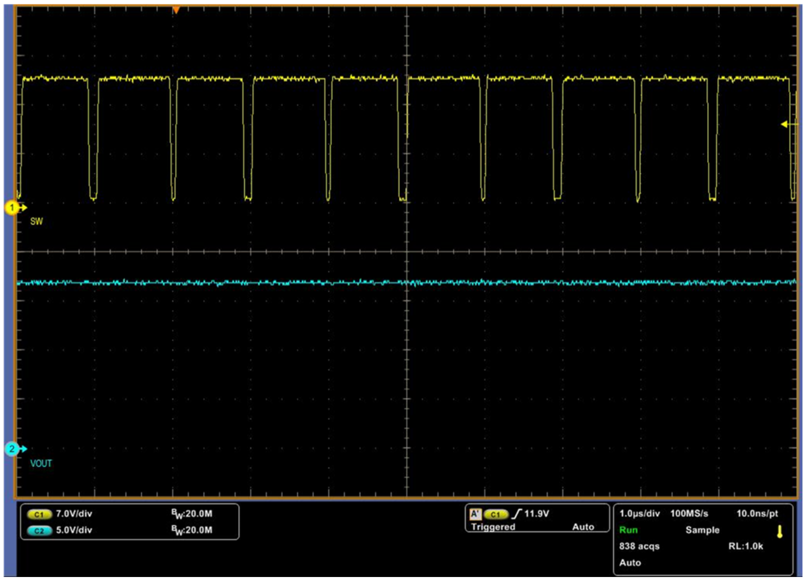


Figure 3-4. CV Mode Steady State

3.2.2.2 CV Voltage Ripple and CC Current Ripple

Figure 3-5 shows the current ripple of CC mode, and Figure 3-6 shows the voltage ripple of CV mode. The output voltage ripple is less than ±20 mV. The output current ripple is tested by measuring the output voltage of the current-sensing circuit, the current ripple is less than ±5 mA.

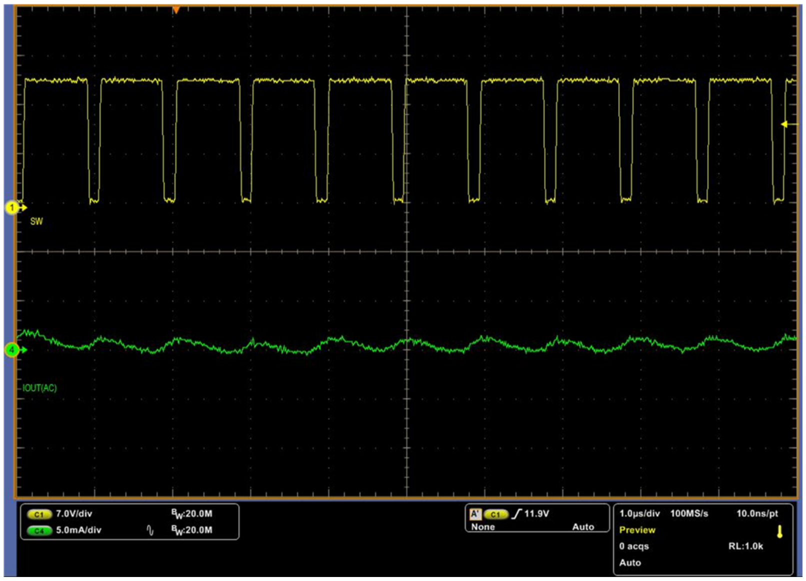


Figure 3-5. CC Mode Current Ripple

Figure 3-6. CV Mode Voltage Ripple

3.2.2.3 Efficiency Test

Figure 3-7 shows the efficiency curve of the battery charger across 0.1A to 1.0A.

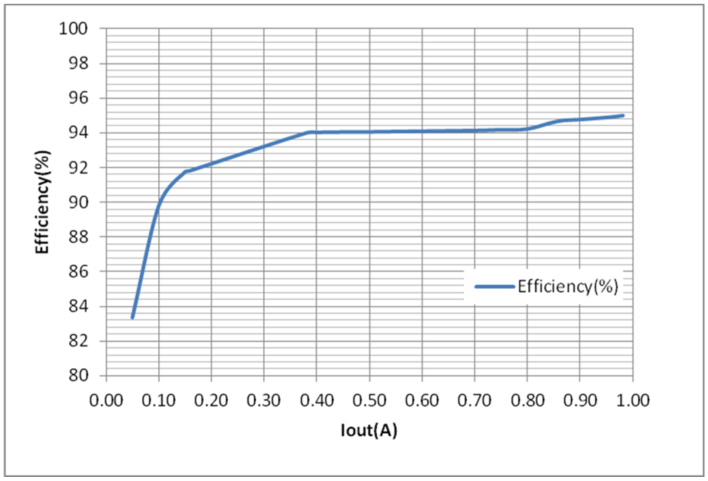


Figure 3-7. Efficiency Versus Output Current

3.2.2.4 Thermal Test

Figure 3-8 shows the thermal image of the board after 10 minutes of continuous running. The maximum temperature observed on the TPS92200 device is 68.7°C.

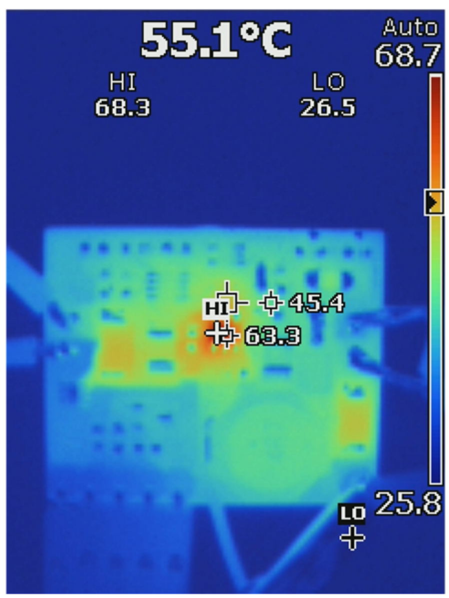


Figure 3-8. Thermal Test

3.2.2.5 Voltage and Current Close Loop Stability

Figure 3-9 shows the voltage close loop stability performance of TIDA-050042 reference design, the gain crossover frequency is 730.92Hz, and the phase margin is 99.9°, which means this control circuit is stable and can provide enough bandwidth.

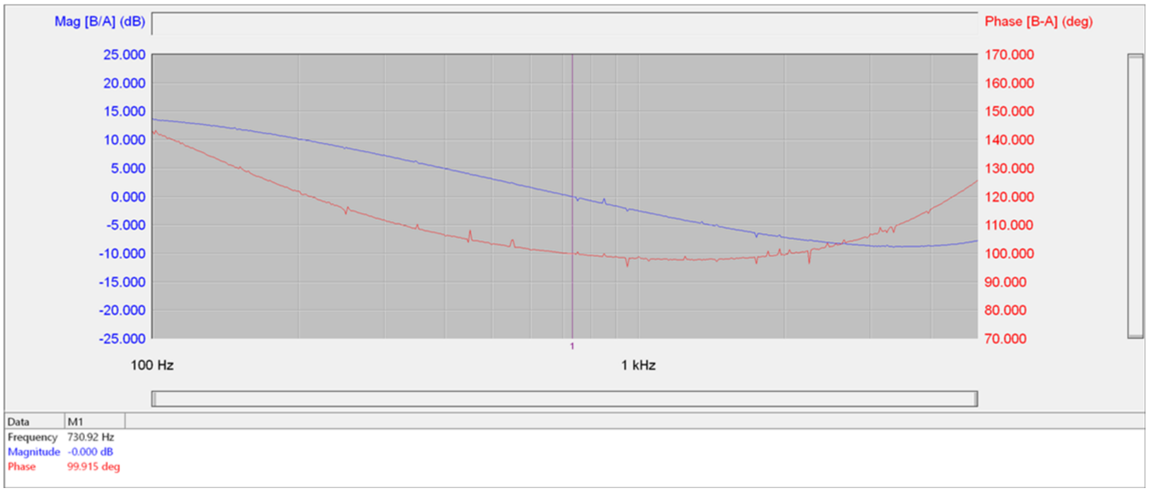


Figure 3-9. Voltage Open Loop Stability

Figure 3-10 shows the current close loop stability performance of TIDA-050042 reference design, the gain crossover frequency is 24.52 kHz, and the phase margin is 90.3°, which means this control circuit is stable and can provide enough bandwidth.

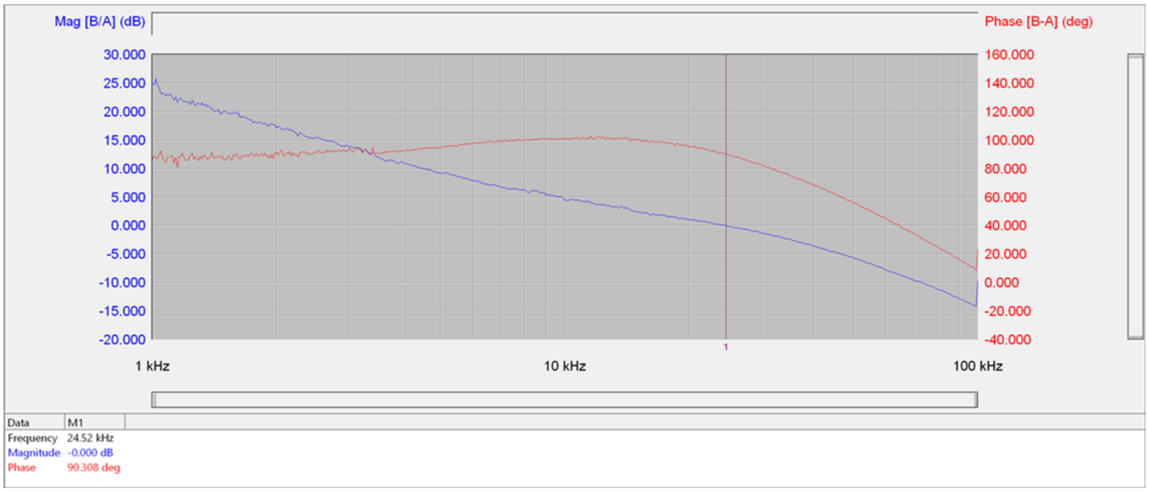


Figure 3-10. Current Open Loop Stability

3.2.2.6 Charging Profile

Figure 3-11 shows the charging profile of this solution, the load is using a 4S2P battery pack with protection circuit.

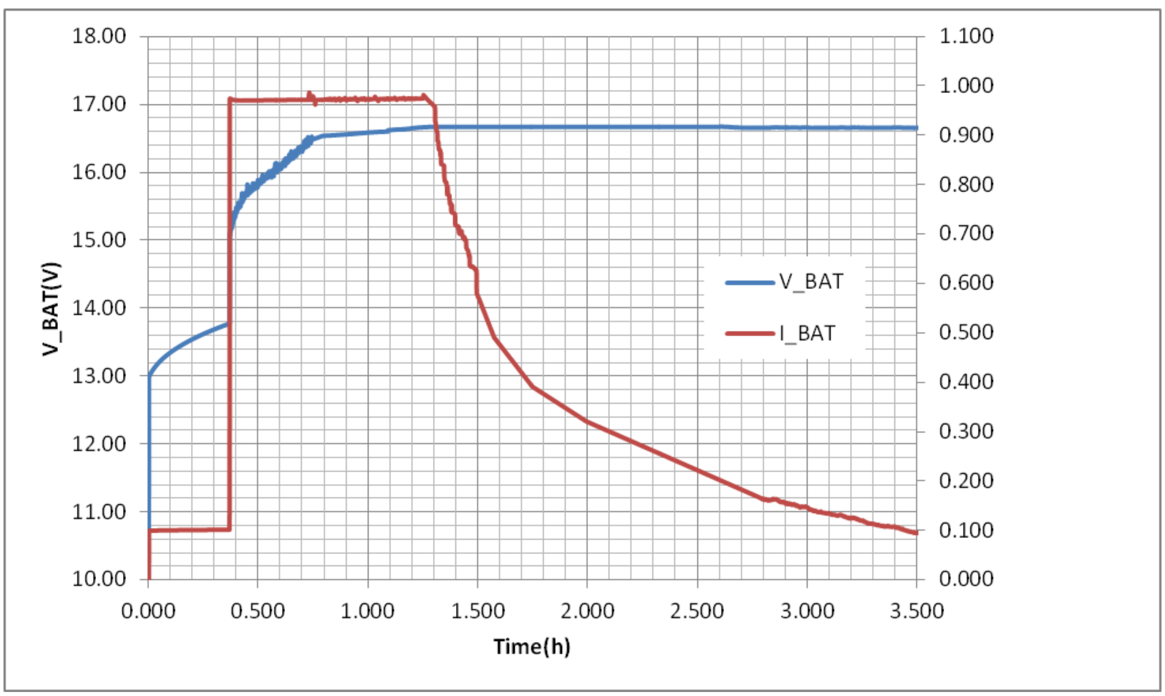


Figure 3-11. Charging Profile

The charging profile consists of Pre-CC mode, CC mode and CV mode, the transformation between Pre-CC to CC and CC to CV is smooth and stable.

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-050042.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-050042.

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-050042.

4.4 Altium Project

To download the Altium Designer® project files, see the design files at TIDA-050042.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-050042.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-050042.

5 Software Files

To download the software files, see the design files at TIDA-050042.

6 Related Documentation

1. Texas Instruments, *TPS92200 4 V to 30 V Input Voltage, 1.5A Output Current Synchronous Buck LED Driver With Flexible Dimming Options Data Sheet*
2. Texas Instruments, *TLV900x Low-Power, RRIO, 1-MHz Operational Amplifier for Cost-Sensitive Systems Data Sheet*
3. Texas Instruments, *TVS3300 33-V Flat-Clamp Surge Protection Device Data Sheet*
4. Texas Instruments, *Low Power, Small Size Comparator with Open-drain Output Data Sheet*

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7 About the Author

Sean Zhou is an application engineer at Texas Instruments, responsible for supporting and developing reference design solutions with LED drivers for various applications.

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