

Controller Board to Convert a Power Supply Into Real-Time Programmable CC-CV Source



TI Designs

The TIDA-00703 is a digital feedback controller board that converts analog power supplies into a real-time configurable constant-voltage constant-current (CC-CV) source with dynamically variable output for performing complex battery charging profiles or driving CC-CV loads.

This reference design replaces the traditional analog feedback with a digital feedback. The presence of an MCU in the feedback loop gives rise to real-time monitoring and configuration capability along with an ability to implement non-linear control behavior.

Design Resources

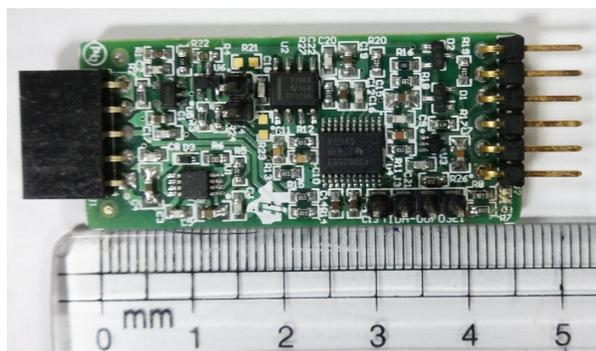
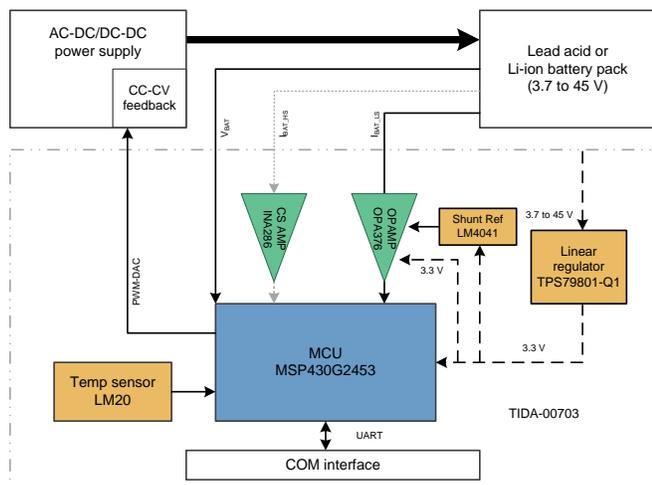
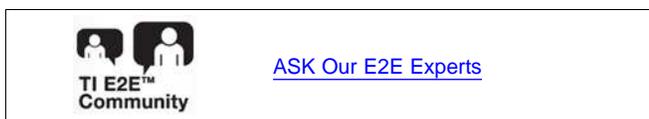
TIDA-00703	Design Folder
TIDA-00355	Tools Folder
MSP430G2453	Product Folder
OPA376	Product Folder
INA286	Product Folder
LM4041	Product Folder
LM20	Product Folder
TPS79801-Q1	Product Folder

Design Features

- Converts Existing Analog Feedback to Digital Feedback
- Adds Real-Time Configurability to Power Stage for Changing Output Voltage and Current
- Can be Programmed to Control Power Stages for Wide Range of Output Voltage and Current
- Low Standby Power Consumption of Less Than 2 mA
- Option for High-Side and Low-Side Current Sensing
- SoC Estimation of Battery When Used to Control Power Supply as Battery Charger
- Provides Redundant Protections for Overcurrent, Overvoltage, and Over-Temperature
- Tested and Validated With TIDA-00355 Power Stage

Featured Applications

- Battery Chargers
- LED Drivers
- Programmable Power Supplies
- Uninterruptible Power Supplies (UPS)
- Power Banks and Power Tools



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1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SYMBOL	TEST CONDITIONS	MIN	NOM	MAX	UNIT
INPUT CONDITIONS						
Input voltage	V_{AUX}		4	5	50	VDC
No load power	P_{NL}	5-V DC Nominal		12		mW
Nominal power	$P_{NOMINAL}$	5-V DC Nominal		40		mW
OUTPUT CONDITIONS						
Output voltage regulation					0.3	%
Output current regulation					1	%
Output voltage ripple				20	50	mV
Charging profile supported						
SYSTEM CHARACTERISTICS						
Protections		Output overvoltage				
		Output overcurrent				
		Thermal shutdown				
Operating ambient		Open frame	0	25	60	°C
Dimensions		Length x Breadth x Height	47 x 20 x 5			mm

2 System Description

Applications that work from AC input mains, like offline battery chargers and LED drivers, typically employ an AC-DC converter for converting the AC mains voltage into a CV-CC DC supply.

Typically, these systems implement voltage and current feedback loops, which regulate the output to a fixed output voltage and maximum output current. These feedback loops compare voltage and current feedbacks with a set reference to generate an error signal, which is passed through a Type 2 or Type 3 error amplifier network and then fed to the power stage controller through an optocoupler.

A host of new features can be added by replacing the analog feedback loop with a digital feedback loop. The significant feature of a digital feedback loop is the ability to dynamically configure and control the output voltage and current.

In applications such as battery chargers, the use of a digital feedback loop provides an option to implement a multi-stage battery charging profile, where the voltage and current set points vary according to the different stages of the profile.

Another key advantage of a digital feedback is that it aids to implement complex control features such as changing the gain or behavior of the error amplifier under different operating conditions.

In addition, presence of an MCU in the feedback provides flexibility to implement a lot of user-defined features. One such feature that has been implemented in this system is the ability to calculate the SoC of the battery when used in a battery charging system. The estimation of the SoC is based on a combination of coulomb counting and open circuit voltage technique. The estimated SoC using this reference design can be used in systems where a high accuracy of SoC estimation may not be required.

3 Block Diagram

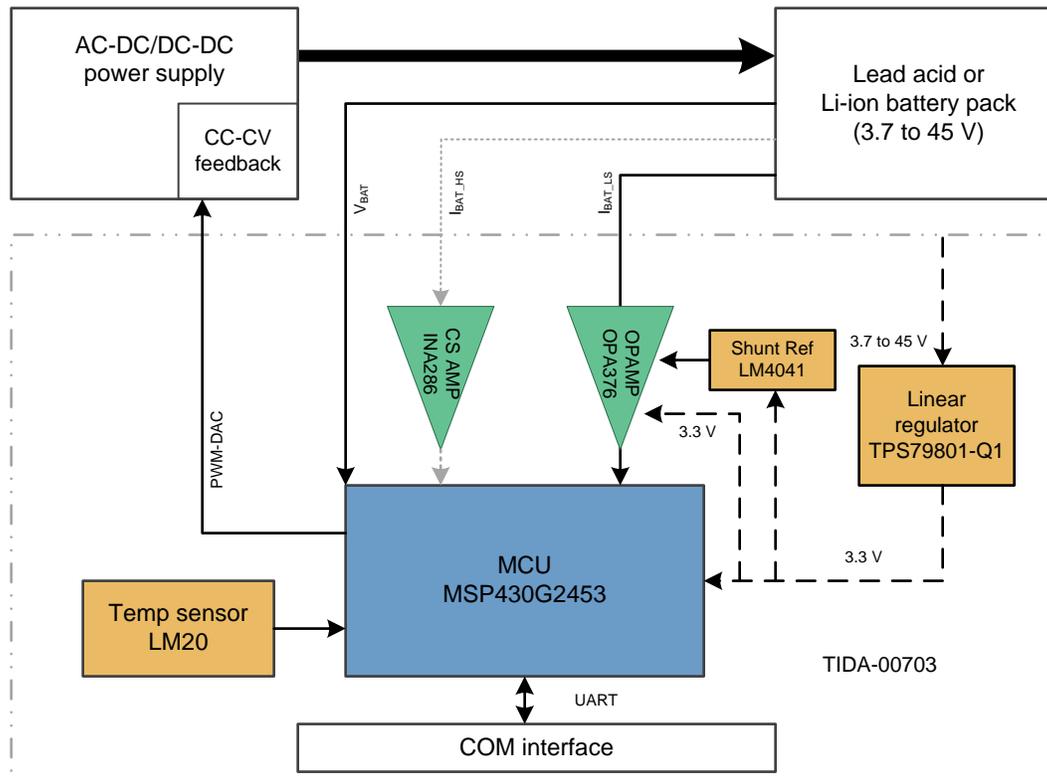


Figure 1. Block Diagram of TIDA-00703

Figure 1 shows the block diagram of the TIDA-00703 board. The TIDA-00703 board consists of an MSP430™ MCU, a precision op-amp OPA376 for low-side current sensing, and an optional dedicated current sensing op-amp INA286 for high-side current sensing. The LM4041 generates a precision reference voltage for use by the current sensing circuit. The LM20 temperature sensor is used for measuring the board temperature. The onboard high-voltage linear regulator TPS79801-Q1 can be optionally used for providing auxiliary power to the TIDA-00703.

The UART interface of the MSP430 is exposed through a connector and is used to connect to a computer through any serial communication utility like HyperTerminal®. It is used to control, monitor, and debug the TIDA-00703 in real time. Alternatively, the UART interface can be connected to an external RS-485 driver through the onboard connector.

3.1 Highlighted Products and Key Advantages

Key features for selecting the devices for this reference design are elucidated in the following subsections. Find the complete details of the highlighted devices in their respective product datasheets.

3.1.1 MSP430G2553

The Texas Instruments MSP430 family of ultra-low-power microcontrollers consists of several devices featuring different sets of peripherals targeted for various applications. The MSP430G2x13 and MSP430G2x53 series are ultra-low-power mixed signal microcontrollers with built-in 16-bit timers, up to 24 I/O capacitive-touch enabled pins, a versatile analog comparator, and built-in communication capability using the Universal Serial Communication Interface (USCI). In addition the MSP430G2x53 family members have a 10-bit analog-to-digital (A/D) converter.

In the TIDA-00703, the MSP430G2553 runs the control algorithms for implementing the digital feedback controller. It runs the PID loops and supports the communication interface for implementing real-time configurability. It was chosen for the following reasons:

- A 10-bit ADC with built-in data transfer controller (DTC)
- 16-bit timer that can generate high-frequency PWM with sufficient resolution
- UART capability for supporting serial communication to a host computer or controller

3.1.2 OPA376

The OPA376 family of low-noise operational amplifiers with e-trim offers outstanding DC precision and AC performance. The OPA376 is single op-amp with rail-to-rail input and output, low offset (25- μ V max), and an ability to operate with common mode voltages up to 100 mV below the ground. Low noise (7.5 nV/ \sqrt Hz), a quiescent current of 950 μ A max, and a bandwidth of 5.5 MHz make this part a good fit for our application.

In the TIDA-00703, the OPA376 is used for low side bi-directional current sensing, where low offset voltage is important in minimizing the current sense resistor value.

3.1.3 INA286

The IN28x family of voltage output current shunt monitors can sense the voltage drop across current sense resistor with common-mode input voltage, anywhere from -14 to 80 V, independent of the supply voltage. With a CMRR of close to 140 dB, maximum offset voltage of \pm 20 μ V, and zero drift architecture, the INA28x family can minimize the size of the sense resistor used for measuring the current under high common-mode voltage conditions.

The INA286 has a fixed gain of 100 V/V. Along with the family features, the IN286 is a good choice of high-side current sensing for this application.

3.1.4 LM4041-N 1.2

The LM4041-N is a precision voltage reference that gives a fixed 1.2-V reference voltage. The LM4041-N's advanced design eliminates the need for an external stabilizing capacitor while ensuring stability with any capacitive load, thus making the LM4041-N easy to use. Bandgap reference temperature drift curvature correction and low dynamic impedance ensure stable reverse breakdown voltage accuracy over a wide range of operating temperatures and currents.

The LM4041-N 1.2 is used to provide a precise reference voltage to offset the output of the low-side current sensing circuit based on the OPA376.

3.1.5 LM20

The LM20 is a precision analog output CMOS integrated-circuit temperature sensor that operates over -55°C to 130°C . It operates with a supply voltages ranging from 2.7 to 5.5 V with quiescent currents less than $10\ \mu\text{A}$.

In the TIDA-00703 application, it is used for measuring temperature compensation for use in battery profile corrections.

3.1.6 TPS79801-Q1

The TPS79801-Q1 is a 50-V high-voltage micro-power low-dropout linear regulator. It is capable of supplying a 50-mA output current with a dropout voltage of only 300 mV. With a low operating current of $40\ \mu\text{A}$ and $1\ \mu\text{A}$ in shutdown, this device is suitable for high-voltage input systems where low standby current is also important. The TPS79801-Q1 has an adjustable output voltage and is used in the TIDA-00703 to provide a regulated 3-V output for all the components on the board.

4 System Design Theory

The TIDA-00703 reference design a digital feedback controller that is capable of controlling the operation of an AC/DC or DC/DC power stage that work with an error amplifier based feedback network.

The TIDA-00703 is independent of the power stage's topology and is suitable for applications where traditional analog feedback error amplifiers have been used. The digital feedback controller can control the working of the power stage through the Feedback/Comp pin of the power stage's controller.

Figure 2 and Figure 3 compare block diagrams of a system with traditional analog feedback and a modified system with digital feedback.

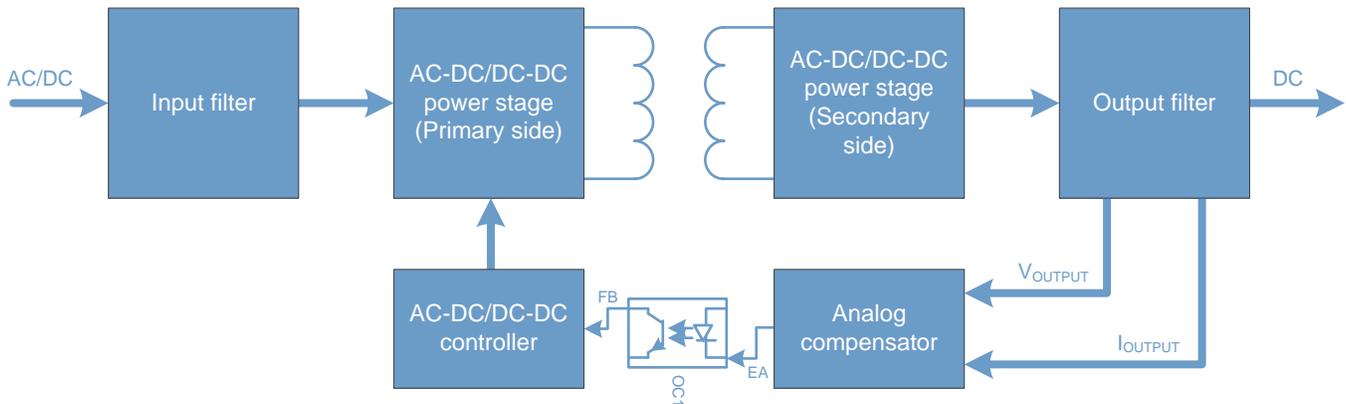


Figure 2. Block Diagram of Power Stage With Analog Feedback

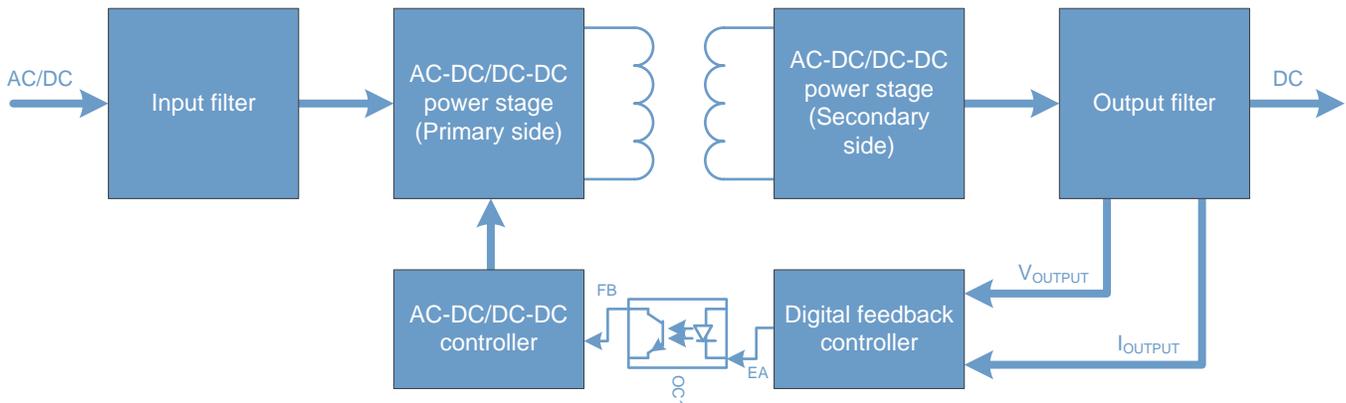


Figure 3. Block Diagram of Power Stage With Digital Feedback

For example, if the power stage were to be a flyback converter based on UCC28700, by controlling the current being drawn from the FB pin the peak current through the switching MOSFET could be controlled, thereby controlling the output voltage and current. If the power stage was an HB-LLC converter based on the UCC25600, by controlling the power drawn from the RT pin of the HB-LLC Controller, the switching frequency of the HB-LLC power stage can be controlled, thereby controlling the output voltage and current.

The core of the TIDA-00703 is the MSP430 MCU. It measures the output voltage and current and generates the error signal necessary to control the working of the power stage to regulate the output voltage and current to the set limits.

The measured output voltage and current error is first passed through configurable digital PID filters present in the control firmware running on the MSP430. It then generates the required error signal to be fed to the power stage's controller. The digital error signal generated from the MCU is in the form of a PWM signal, which is then passed through a simple RC filter network. The RC network filters the PWM to generate an equivalent analog error signal that can be directly fed to the power stage controller.

Compared to the traditional analog feedback control, the major advantage in using a digital feedback controller comes from the following features:

- The ability to change the operating output voltage and current (set points) in real time.
- The system's closed loop performance can be improved using non-linear control methods.
- Different set of gains for the error amplifier stage can be used under different operating conditions like transient, steady stage, and so on.
- The ability to implement complex output profiles like the ones required for battery charging where the output voltage and current limits need to be varied during the various stages of charging.
- Inherent debug and monitoring capability due to the presence of an MCU.

One of the additional features implemented in the TIDA-00703 is the ability to measure the SoC of the battery when used to control a battery charger power supply.

The battery SoC estimation is implemented as a combination of coulomb counting with open circuit voltage compensation. The coulomb counting method of SoC estimation works by integrating the current flowing in and out of the battery. In order to do this, an accurate estimation of the current flowing into and out of the battery is required.

The TIDA-00703 provides for high-side and low-side current sensing.

Overall, the use of a digital feedback controller offers a lot of flexibility, adaptiveness, and configurability to existing and new AC/DC or DC/DC SMPS.

4.1 Hardware Design and Component Selection Criteria

The following sections describe the various sections in the TIDA-00703 keeping the design goals in view.

4.1.1 Low-Side Current Sense

The low-side current sense circuit is used for sensing bi-directional current, which is both battery charging and discharging current.

The output of the low-side current sense circuit is connected to the ADC pin of the MSP430. The voltage range that can be sensed at this pin is between 0 to 2.5 V (internal V_{REF} of the MSP430 ADC).

In order to sense the bi-directional current, the output of the low-side current sense amplifier circuit needs to be level shifted close to 1.225 V so that maximum dynamic range for sensing both positive and negative current is available.

The low-side current sense amplifier circuit is shown in Figure 4.

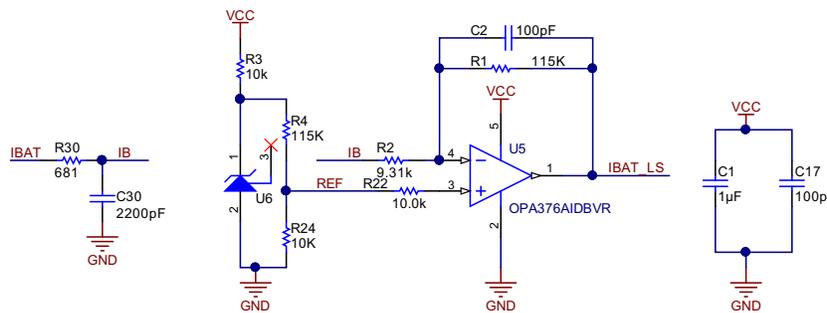


Figure 4. Low-Side Current Sense Amplifier Section

The offset in the output voltage is created using the U6 LM4041 reference voltage generator. The IBAT net is taken across the current sense resistor from the power stage board. When the battery is charging, IBAT is positive with reference to GND and when the battery is getting discharged, the IBAT is negative with reference to GND.

The OPA376 based amplifier is used in the inverting amplifier configuration. The voltage on IBAT can vary from -100 to 100 mV. The calculations for the various components are shown in Equation 1 and Equation 2.

At no load, the output of the low-side current sensing amplifier should be $V_{LCS(noload)} = 1.225$ V. Since the maximum output voltage of the low-side current sense circuit should be less than $V_{LCS(max)} = 2.5$ V, the maximum amplification can be given as

$$I_{GAIN} = \frac{V_{LCS(max)} - V_{LCS(noload)}}{100 \text{ mV}} \quad (1)$$

$$I_{GAIN} = 12.25$$

This design chose a value of $I_{GAIN} = 11.5$ to have a safety margin.

By fixing the value of R22 = 10 K, the value of the resistor R1 can be calculated as 115 K. The value of the resistor at the inverting input of the op-amp is split into two to add an additional low-pass filter stage to attenuate the switching noise from the current sense signal on the power stage board. It is possible that the value of the resistor R30 can be made 0, if sufficient filtering is present in the power stage itself.

In order to fix $V_{LCS(noload)} = 1.225\text{ V}$, the following calculations are performed.

The LM4041 provides a reference voltage of 1.225 V. It is passed through a potential divider network comprising of R24 and R4 to form the REF signal. Since the OPA376 amplifier circuit appears as a non-inverting amplifier to the REF signal, the gain of the circuit will be $(1 + I_{GAIN})$.

Therefore,

$$V_{LCS(noload)} = REF \times (1 + I_{GAIN}) \tag{2}$$

$$REF = \frac{V_{LCS(noload)}}{1 + I_{GAIN}}$$

$$REF = \frac{1.225}{12.5} = 0.1\text{ V}$$

In order to get $g = 0.1\text{ V}$, the values of R4 and R24 are chosen as 115 K and 10 K, respectively.

4.1.2 High-Side Current Sense

The INA286 current shunt monitor is used for performing high-side current sense. The +IN and -IN pins need to be connected across the high-side current sense resistor on the power stage board.

The output offset is required, as in the case of the low-side current sensing. This can be done internally in the INA286 by connecting the REF2 pin to the V_{REF} signal. Figure 5 shows the high-side current sense amplification circuit.

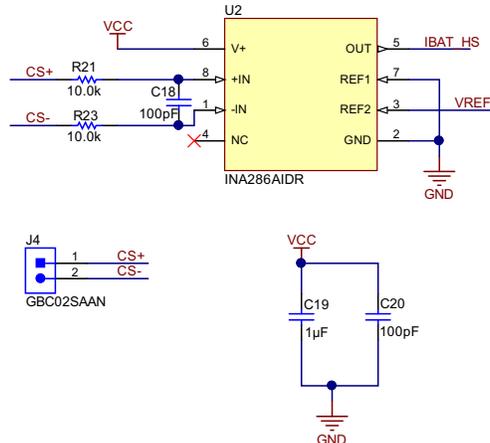


Figure 5. High-Side Current Sense Amplifier Section

The INA286 has a fixed gain of 100 V/V. So the maximum differential voltage that can be sensed in this design will be 12 mV. Take care while dimensioning the high-side sense resistor on the power stage board so that the maximum differential voltage stays within the $\pm 10\text{-mV}$ range to have some margin for corrections.

4.1.3 Microcontroller

Figure 6 shows the MSP430G2553 section of the TIDA-00703 schematic. The MSP430G2553 interacts with the other components of the TIDA-00703 through a set of peripherals.



Figure 6. Microcontroller Section

It takes the analog input for the battery voltage, low-side battery current, high-side battery current, and temperature. These can be seen as the nets VBAT, IBAT_LS, IBAT_HS, and VTEMP, respectively.

The most important output from the MSP430G2553 MCU in the TIDA-00703 board is the PWM output.

The MSP430G2553's TIMER A is used to generate a PWM output at 40 kHz. This PWM is converted into an analog signal by passing through a two stage RC filter formed by the resistors and capacitors R12, R13, C10, and C11 with a corner frequency of around 3.4 kHz. This filtered PWM signal is used to control the current through the optocoupler on the power stage board, thereby controlling the operation (regulating the output) of the power stage.

Since Timer A is working at 16 MHz in order to have sufficient resolution on the duty cycle control, the PWM frequency was chosen as 40 kHz.

4.1.4 Serial Communication Interface

The TIDA-00703 reference design has a 6-pin berg strip connector J2 for serial communication interface.

The connector J2 exposes the USCI pins of the MSP430G2553. These can connect to the computer or an external motherboard through the RS-232/RS-485 or the USB port using a suitable driver. Figure 7 shows picture schematic of the connector.

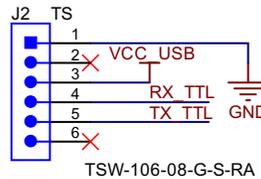


Figure 7. UART Connector

The TIDA-00703 supports a serial interface in the firmware for data logging or monitoring and also for configuring a few of the parameters that can be dynamically changed. A TTL-USB converter cable like the TTL-232R-3V3 can be used to directly connect the TIDA-00703 to the computer using the USB board. This interface has been extensively used in the validating and obtaining results on the TIDA-00703.

4.1.5 Power Stage Board Interface Connector

The TIDA-00703 is interfaced to the power stage board using the power stage interface connector J1. Figure 8 shows this connector.

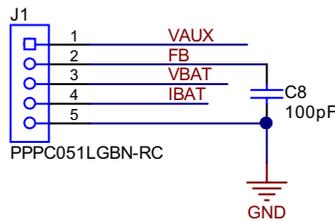


Figure 8. Connector for Interfacing With Power Stage

The output voltage, current, and the auxiliary power supply from the power board can be connected to the TIDA-00703 board through this connector. The feedback control signal generated by the TIDA-00703 board (FB) is exposed through this connector. This feedback control signal is the filtered PWM output and has to be connected to the optocoupler on the power stage board.

4.2 Firmware

The major component of the digital feedback control is implemented by the MSP430 MCU. The firmware running on the MSP430 implements the PID control loop for controlling the operation of the power stage. Apart from this it also runs a Master Profile Control loop, which implements the multi stage charging profile for Lead Acid and Lithium Ion batteries and also the CC/CV reference control for powering CC/CV loads.

Figure 9 shows the peripheral blocks in the MSP430 that play an important role in this reference design as well as their interaction with other components in the TIDA-00703.

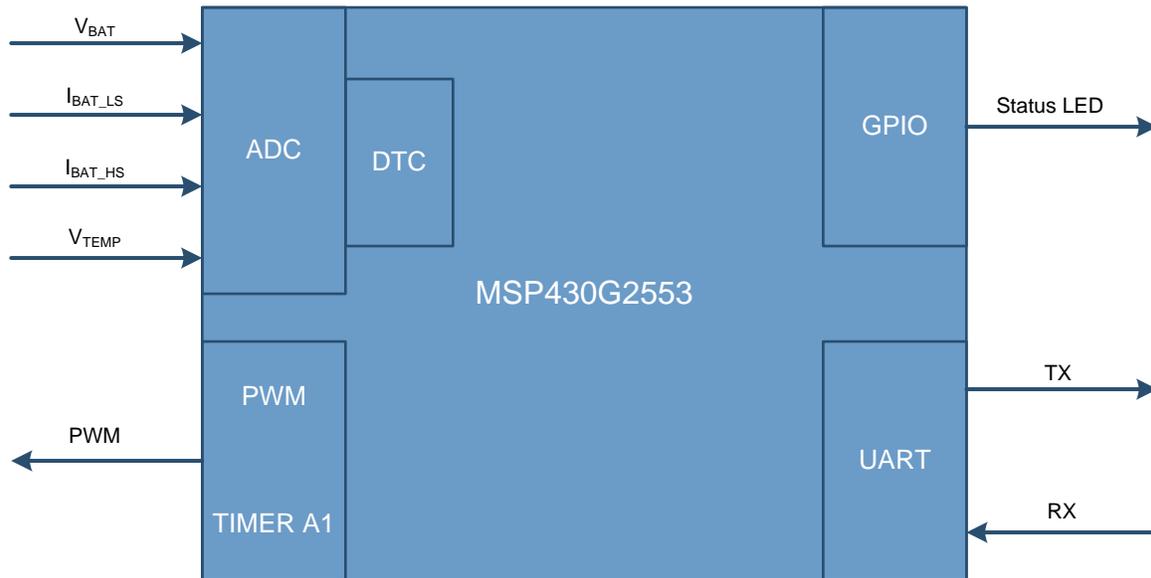


Figure 9. Block Diagram Depicting MCU's Interaction With System

The 10-bit SAR ADC in the MSP430G2553 is configured to work in Repeated Sequence of Channels Mode. It samples and converts the battery voltage, low-side battery current, high-side battery current, and the temperature. The results of the ADC are handled through the DTC, which stores the conversion results directly in the configured memory locations.

The TIMER A1 is configured to generate a PWM output at 40 kHz. This PWM is filtered (converted to analog) by passing through a second-order RC low-pass filter and is given as the control output from the TIDA-00703 board to the power stage.

The USCI is configured to operate in UART mode. The UART is used to interface the TIDA-00703 to a computer or another master board. This interface can be used to debug (log) as well as configure the operation of the TIDA-00703 board in real time.

A couple of GPIO's on the MSP430G2553 are used for status LED indications.

The main control loop (PID loop) takes the feedback from the ADC signals and calculates the duty cycle of the PWM output from TIMER A1. This loop is executed once every 200 μ s.

The firmware running on the MSP430 has the following major sections:

- Constant Voltage and Current Error PID Loop
- Master Control Loop
- Serial Interface Utility
- SoC Estimator (for battery charger applications)

4.2.1 Constant Voltage and Current Error PID Loop

As the name suggests, the Constant Voltage and Current Error PID loop implements the functionality to perform closed loop control of the power stage board.

The PID loop is invoked once every 200 μ s. It obtains the filtered ADC values for output voltage and current and compares it with the reference output voltage and current. The resultant error is passed through a PID controller.

The output of the PID controller is the duty cycle for the PWM generated through TIMER A1.

The gains for the PID controller are configurable through the serial interface. This allows the user to fine tune the controller for different power stages. Once the gains are fixed, they can be updated in the firmware.

4.2.2 Master Profiler Loop

The firmware running on the MSP430 can be configured to operate in one of three predefined profiles:

- LI-Ion charging profile
- Lead acid charging profile
- CC-CV profile

The Li-Ion charging profile and the lead acid charging profile are used when the system is configured as a battery charger. Because the battery charging profiles are different for the two chemistries, the appropriate profile setting needs to be selected in the firmware.

The CC-CV profile is used for operating the power stage in a constant voltage and constant current regulation mode. This is used to power resistive, LED, or other miscellaneous loads.

The master control loop is invoked once every 10 ms and is responsible for setting the voltage and current reference values to which the Constant Voltage and Current Error PID loop regulates the power stage. When operating in the first two predefined profiles, this loop sets the output voltage and current reference values depending on the current state of the battery charging.

If the power stage is not used as a battery charger, select the CC-CV profile as the operating profile. In this mode, the Master Profile loop plays no significant role, and the user has the freedom to dynamically change the output voltage and current operating point through the serial interface.

Find information about how to select the required profile in the firmware, change the settings, and interact with the TIDA-00703 using the serial interface in [Section 6](#).

4.2.3 Serial Interface Utility

The serial interface utility module is responsible for managing the UART based debug and monitoring interface in the TIDA-00703 reference design. This module is responsible for generating log information (output voltage, current, SoC) as well as act as a command interface for the user to update certain parameters like output voltage and current that can control the operation of the power stage in real time.

[Section 6](#) provides screenshots to demonstrate using the serial interface utility.

4.2.4 SoC Estimator

The SoC estimator firmware module is responsible for calculating the SoC of the battery when the TIDA-00703 is used to control the power stage as a battery charger. It uses a combination of open circuit voltage and coulomb counting methods to calculate the current SoC of the battery.

The battery voltage and battery current are measured once every 10 ms. This information is used to estimate the SoC of the battery.

In the absence of a dedicated battery SoC monitoring IC on the TIDA-00703 board, this module estimates the SoC with a reasonable accuracy.

Inside the firmware running on the MSP430G2453, these modules are implemented as part of the main loop, TIMER A1, and UART interrupt handler routines. The flowcharts depicting the program execution flow is shown in [Figure 10](#) and [Figure 11](#).

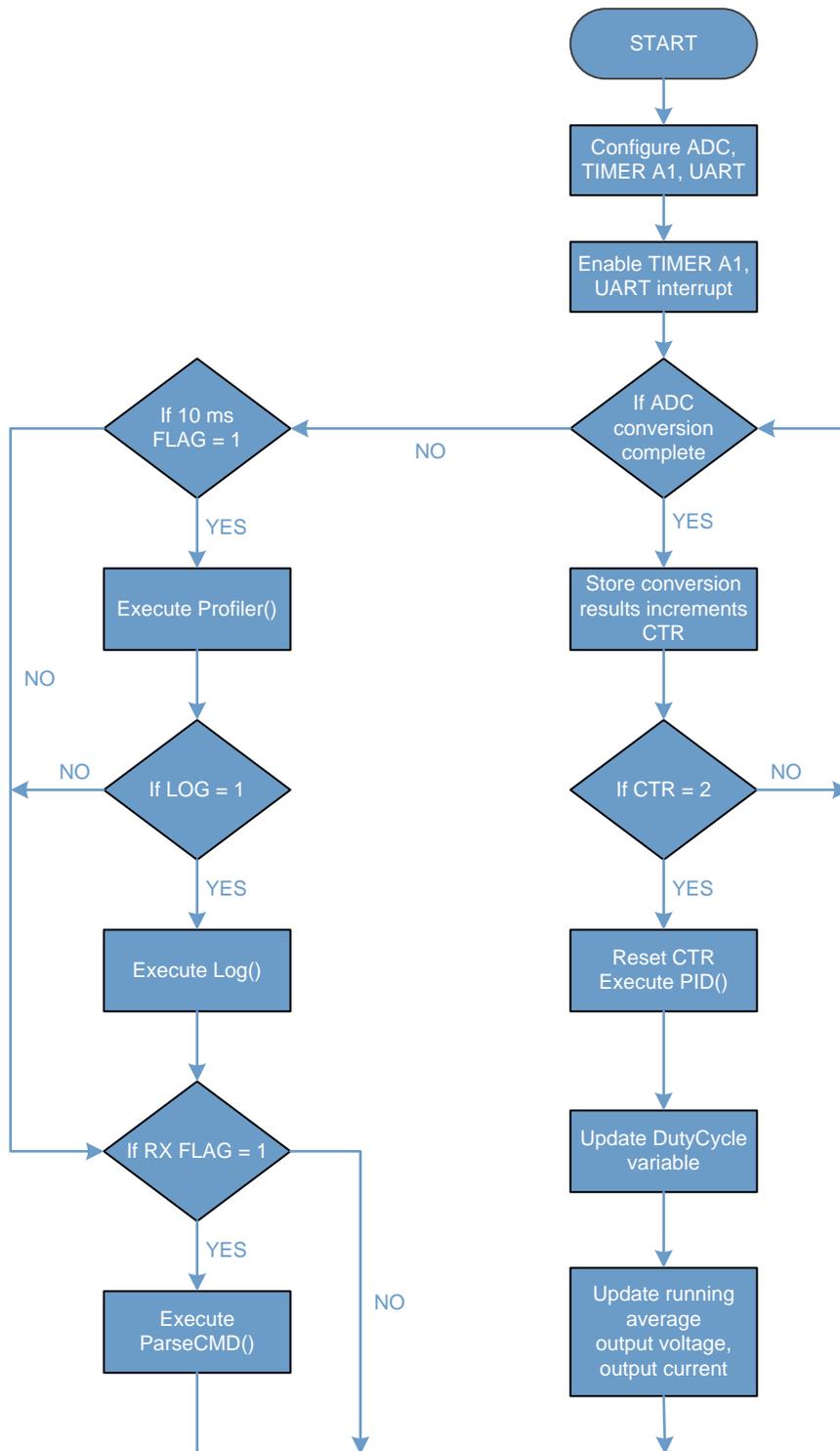


Figure 10. Flowchart of Main Control Loop

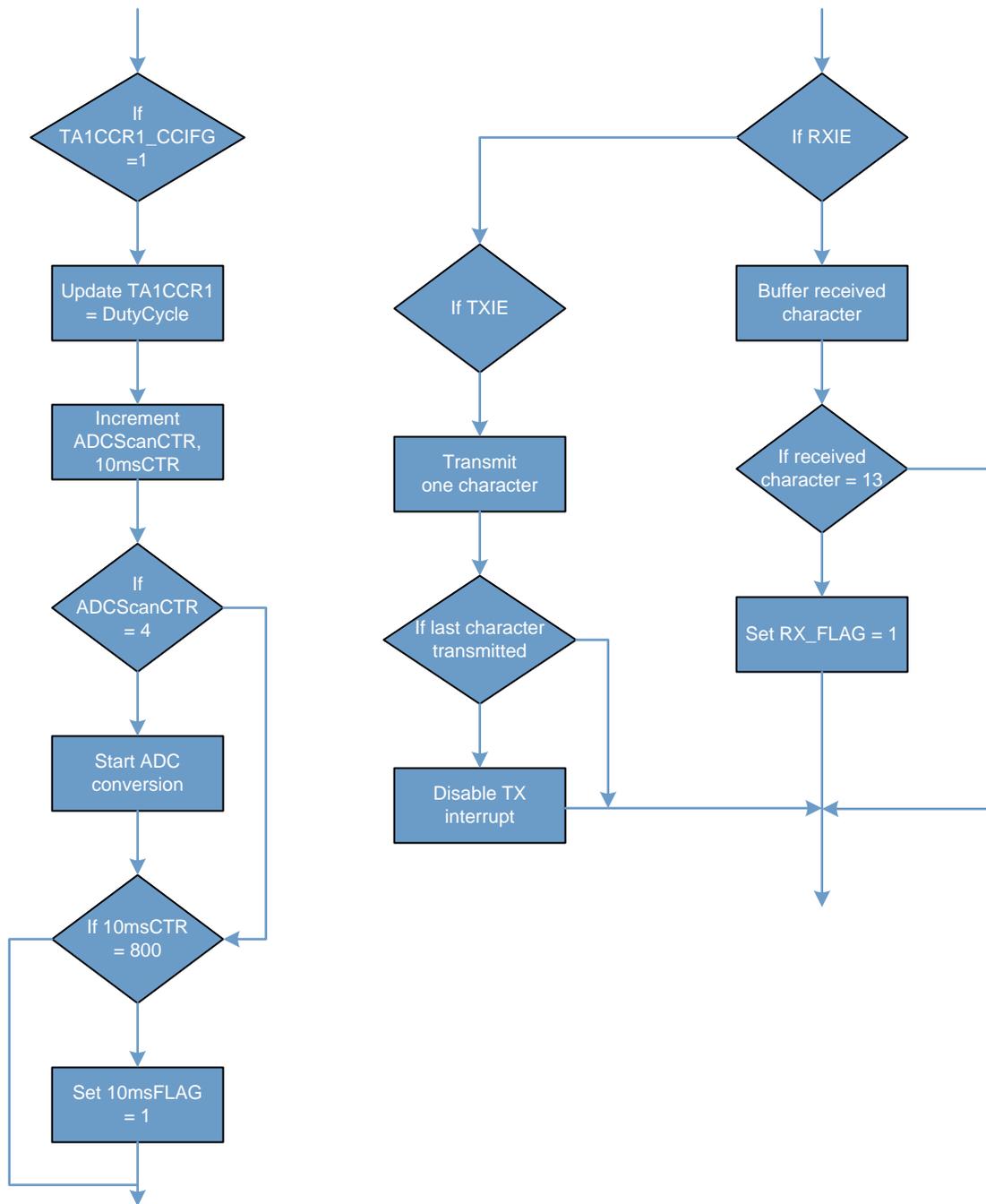


Figure 11. Flowchart of Interrupt Routines

5 Getting Started Hardware

The functional and performance testing of the TIDA-00703 design was done by using the TIDA-00355 design as the power stage. The TIDA-00355 is a 400-W PFC and HB-LLC reference design for providing up to 44 V and 9 A to a Li-ion battery pack.

The testing and validation is done for two different kinds of loads a 8-cell Li-ion battery pack and a resistive load.

The TIDA-00703 reference design is mounted on to the TIDA-00355 board using the connector J1. [Figure 12](#) shows the TIDA-00703 mounted on the TIDA-00355.

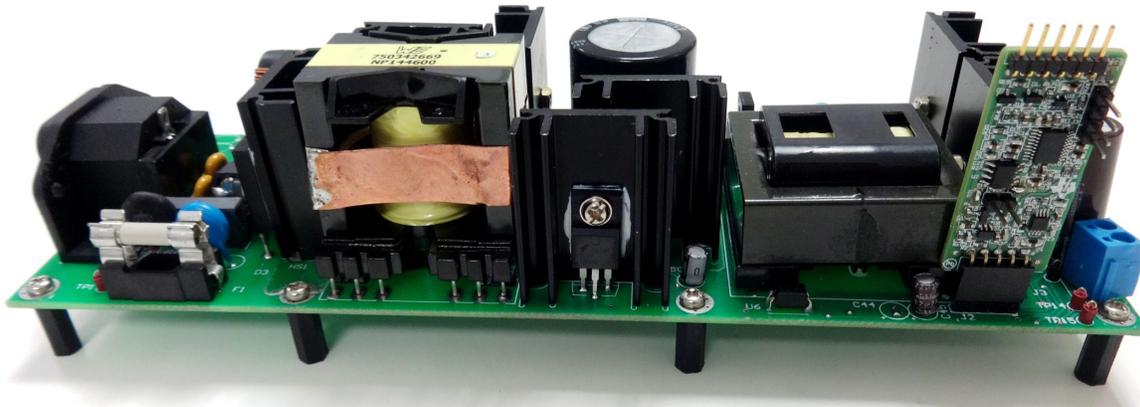


Figure 12. Mounting TIDA-00703 on TIDA-00355

The TIDA-00703 can be connected to a PC or laptop using the USB port. Connector J2 on the TIDA-00703 provides a serial interface connection to the onboard MSP430G2453. By inserting a TTL-USB converter cable like the TTL-232R-3V3, the TIDA-00703 can be monitored from the PC or laptop through a serial utility like the HyperTerminal. [Figure 13](#) shows how to connect the TTL-232R-3V3 cable to the TIDA-00703.

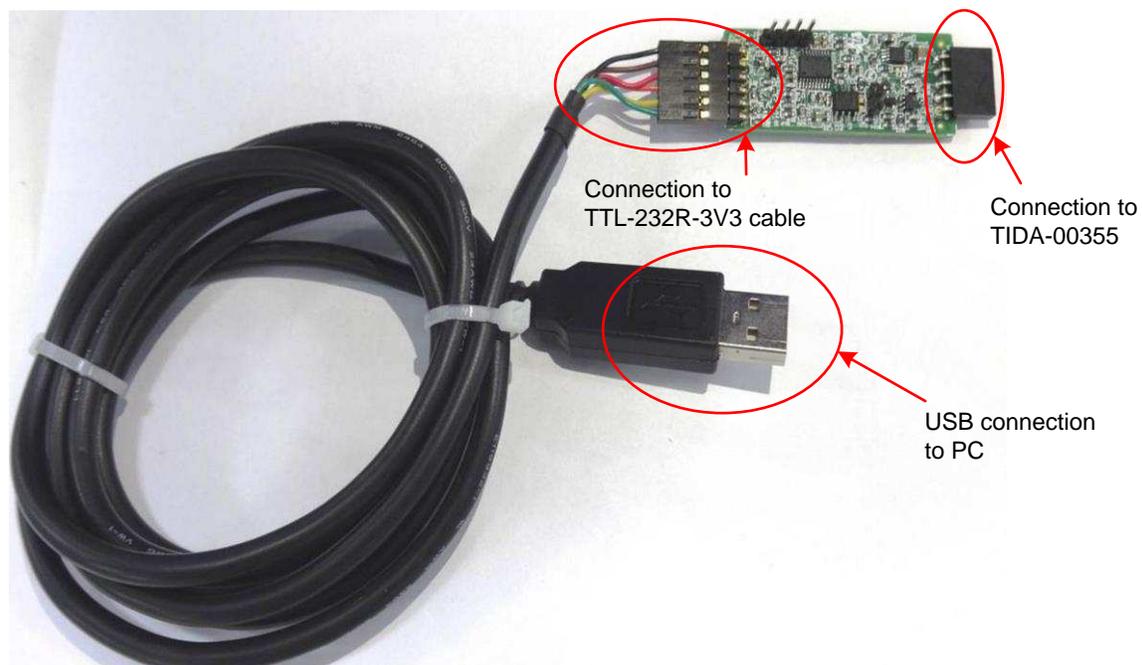


Figure 13. Connecting TIDA-00703 to PC

Find more details on this in [Section 6](#).

5.1 Test Conditions

For input, the power supply source (V_{IN}) must range from 85- to 270-V AC. Set the input current limit of the input AC source to 2.5 A.

For output, use an electronic variable load or a variable resistive load, which must be rated for ≥ 50 V and must vary the load current from 0 mA to 10 A.

5.2 Equipment Needed

- Isolated AC source
- Single-phase power analyzer
- Digital oscilloscope
- Multi-meters
- Electronic or resistive load
- TIDA-00355 reference design

5.3 Modifications for TIDA-00355

1. Remove resistor R45.
2. Change resistor R40 to 133K
3. Change capacitor C40 to 220 nF
4. Change resistor R21 to 631 Ω

5.4 Procedure

1. Connect the TIDA-00703 and TIDA-00355 using the J1 on TIDA-00703 and J2 on TIDA-00355. Align Pin 1 on both the connectors to insert in the correct position.
2. For real-time monitoring and debugging, connect the TTL-USB cable to connector J2 on the TIDA-00703. Connect the other end to a PC or laptop.
3. Connect the electronic load to the TIDA-00355 connector J3 with the correct polarity.
4. Configure the electronic load in CR mode and initially set a resistance of 100 Ω and a minimum voltage of 25 V at the output.
5. Power on the TIDA-00355 board by connecting to the AC supply. Set the AC supply voltage to a minimum of 175-V AC.
6. The TIDA-00355's output will start regulating at 32 V (CV mode) if the default firmware settings are used.
7. Slowly decrease the load resistance to increase the output current. When the load current touches 5 A, the load voltage starts decreasing and load current remains constant in 5 A.
8. Observe the switching waveforms and other output waveforms in both CV and CC regions.

6 Getting Started Firmware

6.1 Programming Connector

Figure 14 shows the MSP430G2453 Spy-Bi-Wire™ interface on the TIDA-00703 board. The connector J3 can be used for programming the MSP430G2453 using a MSP430 LaunchPad™ or the MSP-FET430UIF Programmer.

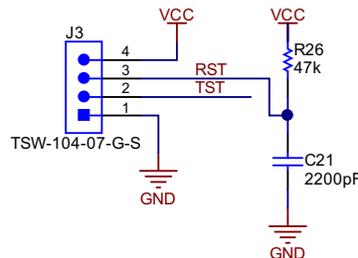


Figure 14. MSP430 Programming Connector on TIDA-00703

6.2 Configurations in Firmware

The firmware running the MSP430G2453 allows for configuring certain parameters of the system. These configurations include the voltage and current settings and also choosing one of the three pre-defined profiles.

If the current selected profile is either the Li-ion charging profile or the lead acid battery charging profile, then settings such as maximum battery voltage and current can only be changed through the settings in the *DigitalFeedbackConfiguration.h* file, compiling the firmware, and flashing it on to the MSP430 through the Spy-Bi-Wire interface.

A small code snippet of the *DigitalFeedbackConfiguration.h* file is shown as a screenshot in Figure 15.

```

DigitalFeedbackConfiguration.h
1 /*
2  * DigitalFeedbackConfiguration.h
3  *
4  * Created on: Dec 9, 2015
5  * Author: a0132467
6  */
7
8 #ifndef DIGITALFEEDBACKCONFIGURATION_H_
9 #define DIGITALFEEDBACKCONFIGURATION_H_
10
11
12 #define PROFILE      1      /*1-for LI-ION, 2 -for Lead ACID, 3 -for CC CV*/
13
14
15 //For PRFOLE 1
16
17 #define LIION_MAX_V      780  //Max CV voltage
18
19 #define LIION_MAX_I      200  //Max Charging Current
20
21 #define LIION_TERMINATION_I      20  //Min Charging Current for termination
22
23 #define LIION_RECONNECT_V      760  //Voltage at which charging re-starts
24
25
26 //For PRFOLE 2
27
28 #define LEADACID_MAX_V      668  //Max CV voltage
29

```

Figure 15. Firmware Configuration File

The various gains of the PID loops can also be configured through this file.

If the current selected profile is the CC-CV profile, then the voltage and current can be changed dynamically while the system is working. This can be done using the serial communication interface. More details on this in [Section 6.4](#).

6.3 Setting Current and Voltage Limits in Firmware

The reference voltage of the ADC in the MSP430G2453 is set to 2.5 V. Because the ADC in the MSP430G2453 has a 10-bit resolution, the maximum value is limited to 1023. On the power stage board, while dimensioning the potential divider network for output voltage sensing and the current sense resistor for current sensing, limit the maximum voltage at the ADC input to be less than 2.5 V.

For the current sense resistor, take into account the gain of the current sense amplification stage. For the low-side current sense amplifier, the gain is 11.5, and for the high-side current sense amplifier, the gain is 100.

Once the output voltage potential divider and the current sense resistor are determined, then calculate and enter the limits for the desired voltage and current regulation points in the *DigitalFeedbackConfiguration.h* file.

6.4 Connecting to HyperTerminal for Log

As described, the TIDA-00703 can be connected to a PC or laptop using a TTL-USB cable. The TTL-USB cable will appear as a COM port on the PC or laptop. By using a serial utility like the HyperTerminal or Tera Term, the user will be able to connect to the TIDA-00703 for monitoring and configuration purposes.

[Figure 16](#) shows the TTL-USB cable enumerating as a COM port. This can be seen in the Device Manger window after connecting the cable to the PC or laptop.

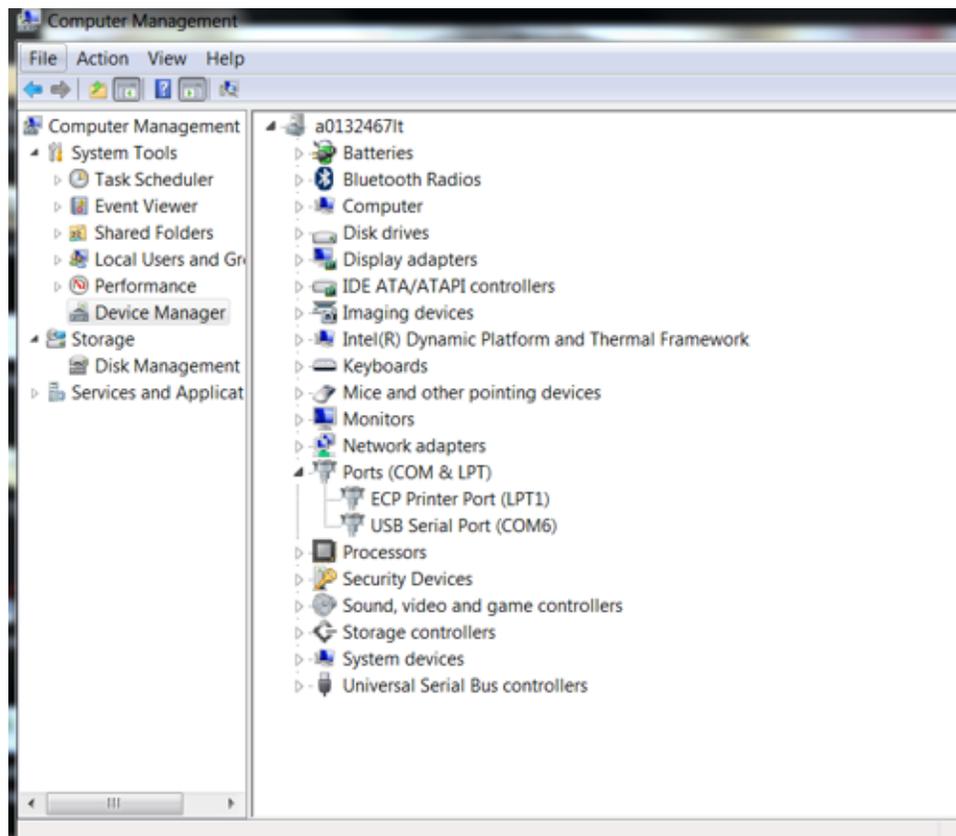


Figure 16. Device Manager Screenshot Showing the USB Serial Port

Configure the serial utility (HyperTerminal or Tera Term) to use the following settings:

- Baud rate: 115200
- Parity: None
- Data: 8-bit
- Stop bit: 1 bit
- Flow control: None

Figure 17 shows this configuration in Tera Term.

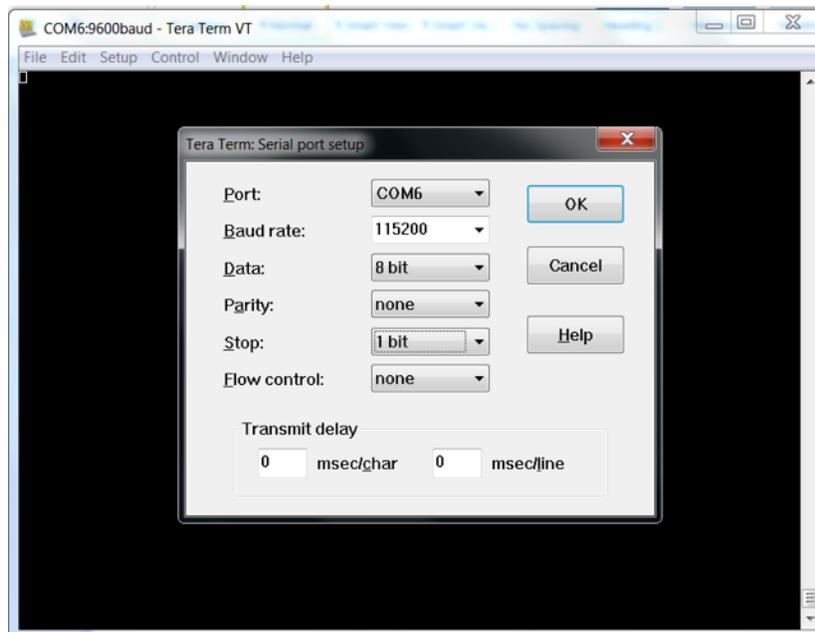


Figure 17. UART Settings to Use

7 Test Results

Testing and validation is done for two different kinds of loads. The first test is conducted using an 8-cell Li-ion Battery Pack. This test is performed to verify the battery charging profile and charging voltage and charging current accuracy. The second test is performed on resistive loads. This test is performed to verify the regulation accuracy, ripple, and transient response in both CC and CV regions.

If the SoC estimation feature of the TIDA-00703 needs to be tested, a slight modification to the test setup has to be performed. The change required is shown in [Figure 22](#).

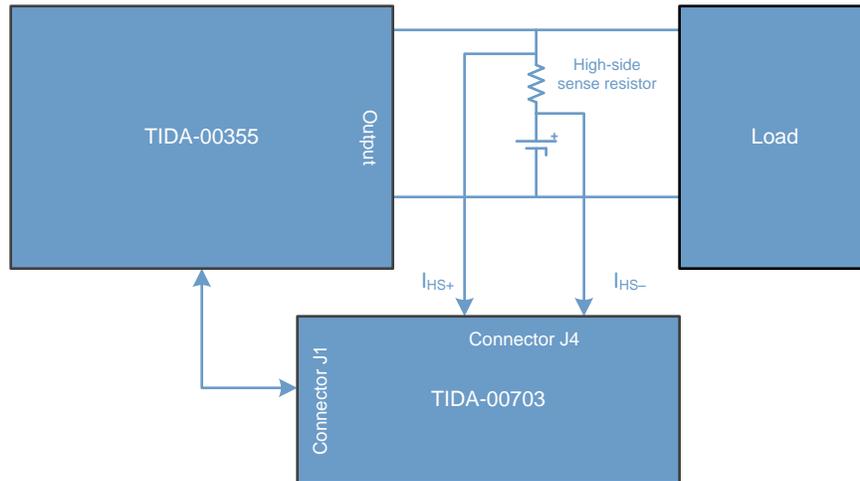


Figure 22. Test Setup to Estimate SoC

7.1 Performance Data

Table 2. Voltage Regulation With a Battery Load in the Constant Voltage Region

V_{SET} (V)	V_{OUT} (V)	V_{OUT_RIPPLE} (V)	$V_{OUT_REGULATION}$ (%)	V_{OUT_RIPPLE} (%)
25	25.15	0.13	0.60	0.52
27	27.12	0.12	0.44	0.44
29	29.09	0.12	0.31	0.41
31	31.06	0.13	0.19	0.42
33	33.08	0.14	0.24	0.42

Table 3. Current Regulation With a Battery Load in the Constant Current Region

I_{SET} (A)	I_{OUT} (A)	I_{OUT_RIPPLE} (A)	$I_{OUT_REGULATION}$ (%)	I_{OUT_RIPPLE} (%)
3	3.05	0.18	1.67	6.00
4	4.04	0.21	1.00	5.25
5	5.02	0.22	0.40	4.40
6	6.04	0.26	0.67	4.33

Table 4. Voltage Regulation With a Resistive Load in the Constant Voltage Region

V_{SET} (V)	V_{OUT} (V)	I_{OUT} (A)	$V_{OUT_REGULATION}$ (%)	V_{OUT_RIPPLE} (%)
25	24.92	2.0	-0.32	2.01
25	24.88	2.5	-0.48	2.31
25	24.97	3.0	-0.12	1.20
25	24.96	3.5	-0.16	1.08
25	25.03	4.0	0.12	1.40
25	25.03	4.5	0.13	1.58
25	25.02	5.0	0.11	1.78
30	30.09	2.0	0.30	0.76
30	30.10	2.5	0.33	0.96
30	30.08	3.0	0.27	1.00
30	30.07	3.5	0.23	1.19
30	30.04	4.0	0.13	1.57
30	30.04	4.5	0.13	1.91
30	30.06	5.0	0.20	1.70
35	35.42	2.0	1.21	0.85
35	35.42	2.5	1.20	1.16
35	35.42	3.0	1.20	1.23
35	35.41	3.5	1.17	1.21
35	35.43	4.0	1.23	1.28
35	35.42	4.5	1.20	1.27
35	35.42	5.0	1.20	1.24

Table 5. Current Regulation With a Resistive Load in the Constant Current Region

I_{SET} (A)	I_{OUT} (A)	V_{OUT} (V)	$I_{OUT_REGULATION}$ (%)	I_{OUT_RIPPLE} (%)
3	3.089	30	2.97	3.42
3	3.110	28	3.67	3.59
3	3.090	26	3.00	3.90
3	3.090	24	3.00	3.87
3	3.100	22	3.33	3.82
4	3.965	30	-0.88	3.78
4	3.955	28	-1.13	3.67
4	3.950	26	-1.25	3.92
4	3.940	24	-1.50	4.05
4	3.949	22	-1.28	4.10
5	5.060	30	1.20	3.35
5	5.050	28	1.00	3.07
5	5.050	26	1.00	3.23
5	5.050	24	1.00	3.26
5	5.040	22	0.80	3.27
6	6.080	30	3.37	1.33
6	6.084	28	3.30	1.40
6	6.082	26	3.21	1.37
6	6.091	24	3.04	1.52
6	6.095	22	3.36	1.58

7.2 Performance Curves

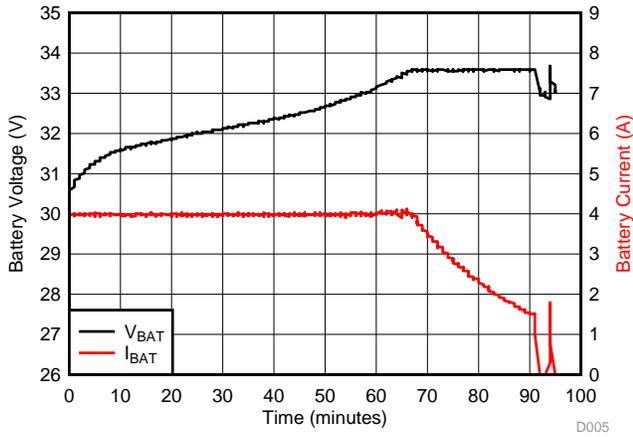


Figure 23. Battery Charging Profile Results for 8-Cell Li-Ion Battery Pack

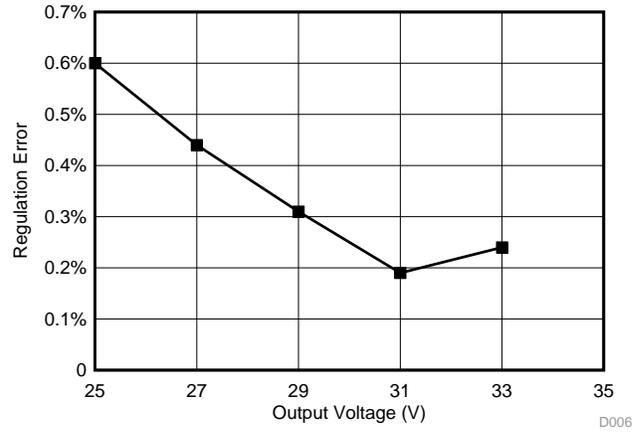


Figure 24. Output Voltage Regulation Error for Battery Load

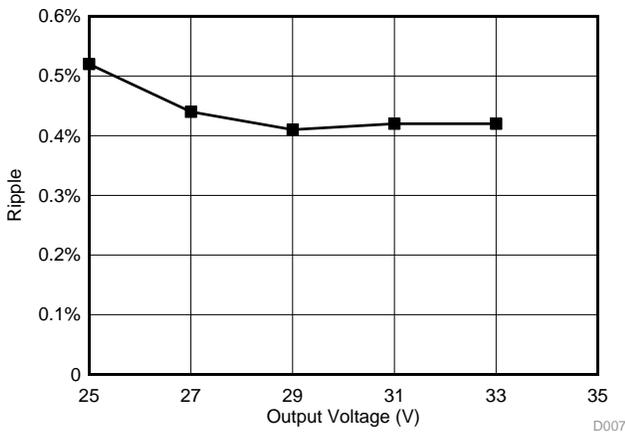


Figure 25. Output Voltage Ripple for Battery Load

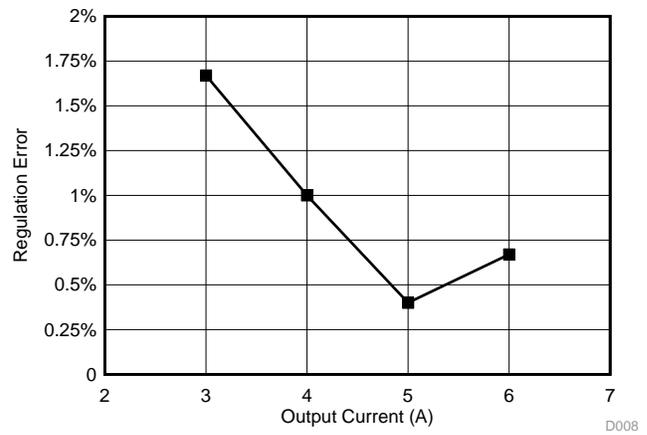


Figure 26. Output Current Regulation Error for Battery Load

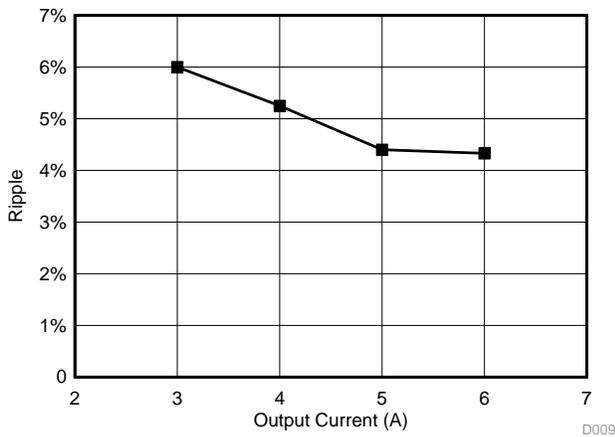


Figure 27. Output Current Ripple for Battery Load

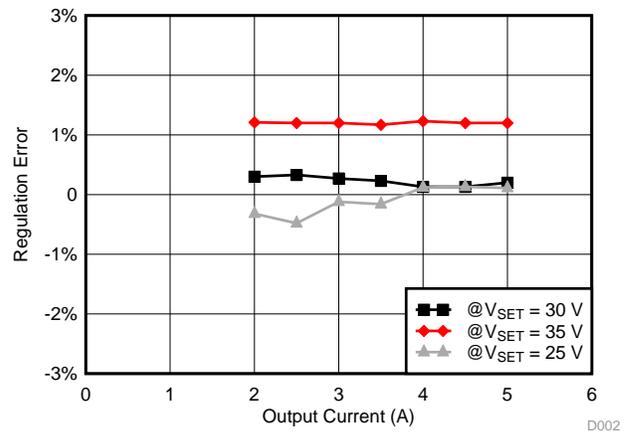


Figure 28. Output Voltage Regulation Error for Resistive Load

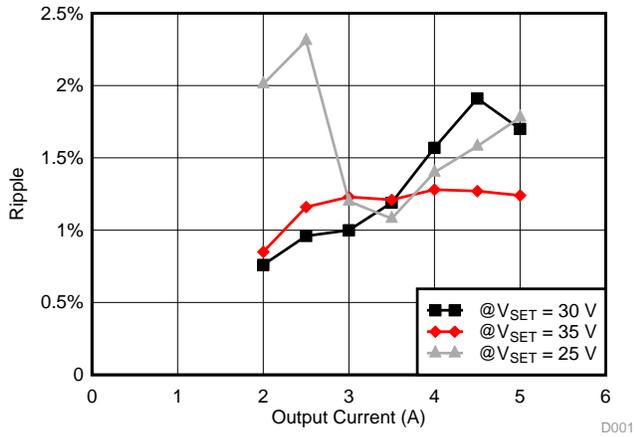


Figure 29. Output Voltage Ripple for Resistive Load

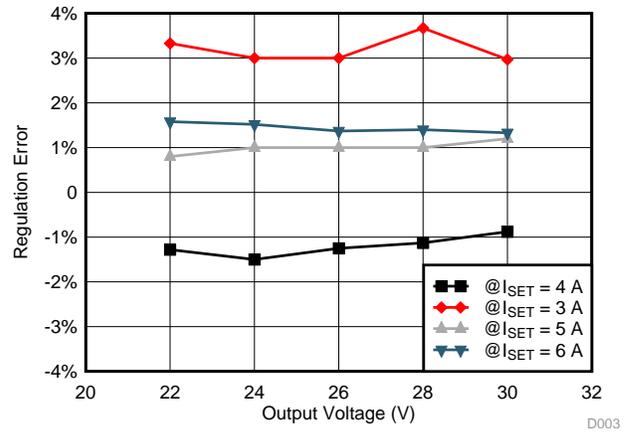


Figure 30. Output Current Regulation Error for Resistive Load

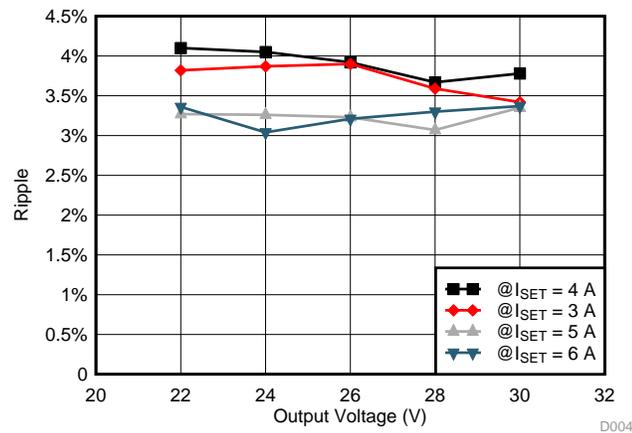


Figure 31. Output Current Ripple for Resistive Load

7.3 Functional Waveforms

7.3.1 Output Voltage Regulation and Ripple in CV Region

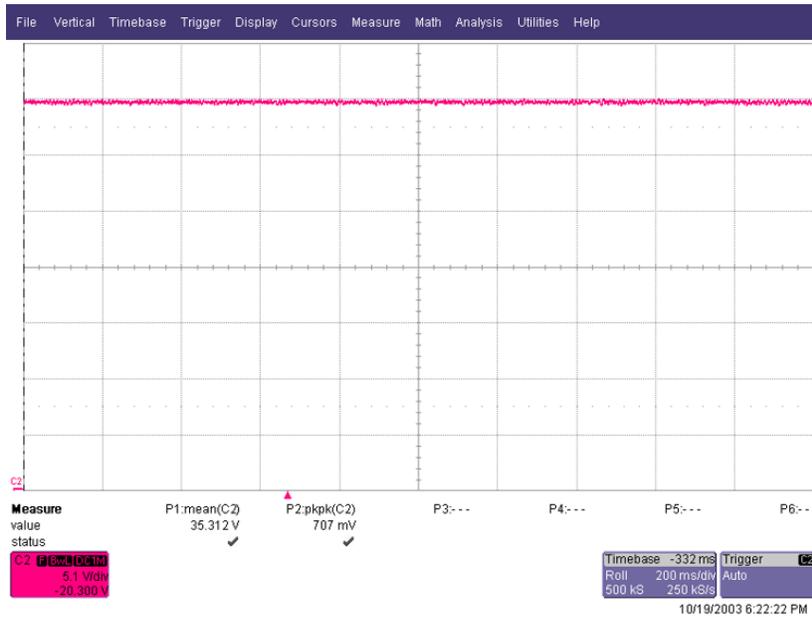


Figure 32. Output Voltage in CV Mode Regulating at 35 V

NOTE: Rose trace: Output voltage, 5 V/div

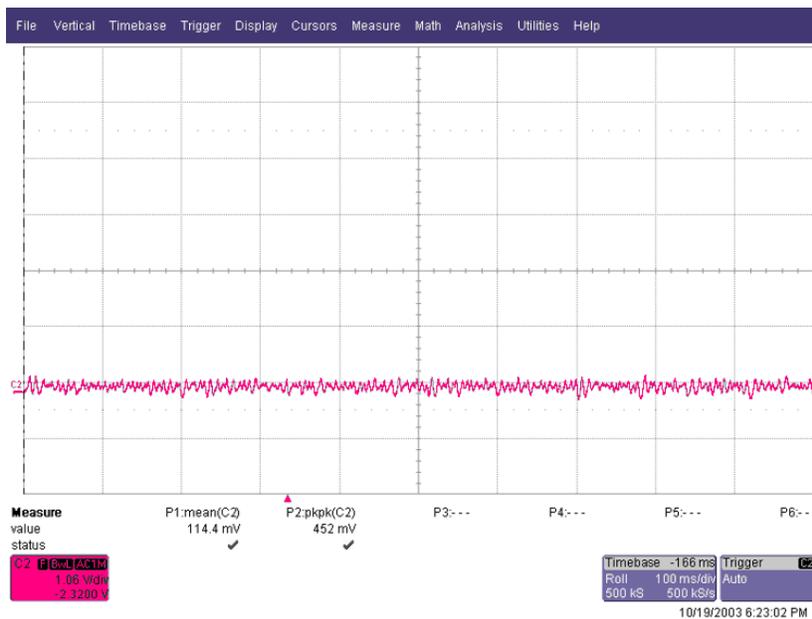


Figure 33. Output Voltage Ripple in CV Mode Regulating at 35 V

NOTE: Rose trace: Output voltage (AC coupled), 1 V/div

7.3.2 Output Current Regulation and Current Ripple in CC Region

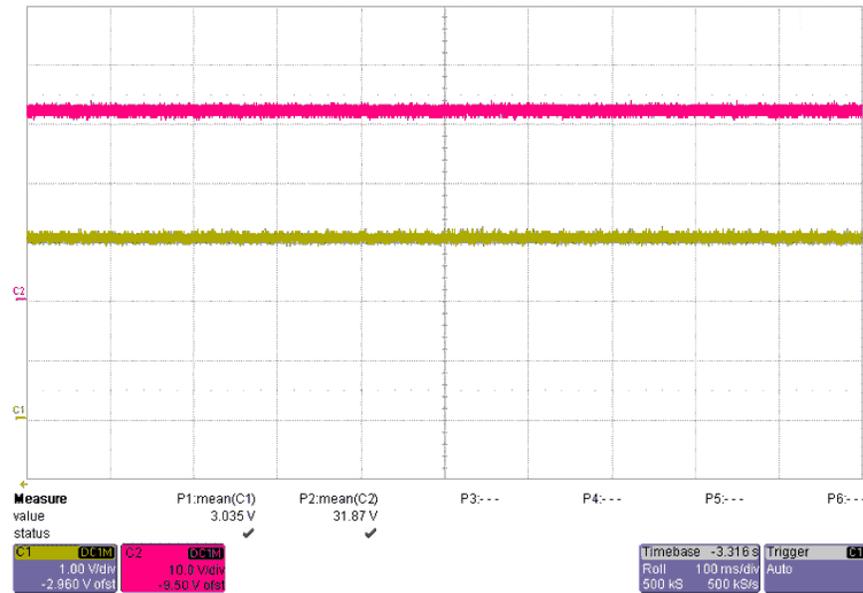


Figure 34. Output Voltage and Current in CC Region

NOTE: Rose trace: Output voltage, 10 V/div; Yellow trace: Output current, 1 A/div



Figure 35. Output Voltage and Current (AC Coupled) in CC Region

NOTE: Rose trace: Output voltage, 10 V/div; Yellow trace: Output current (AC coupled), 200 mA/div

7.3.3 Turn-On Characteristics

The turn-on characteristics when supplying a resistive load is shown in [Figure 36](#).

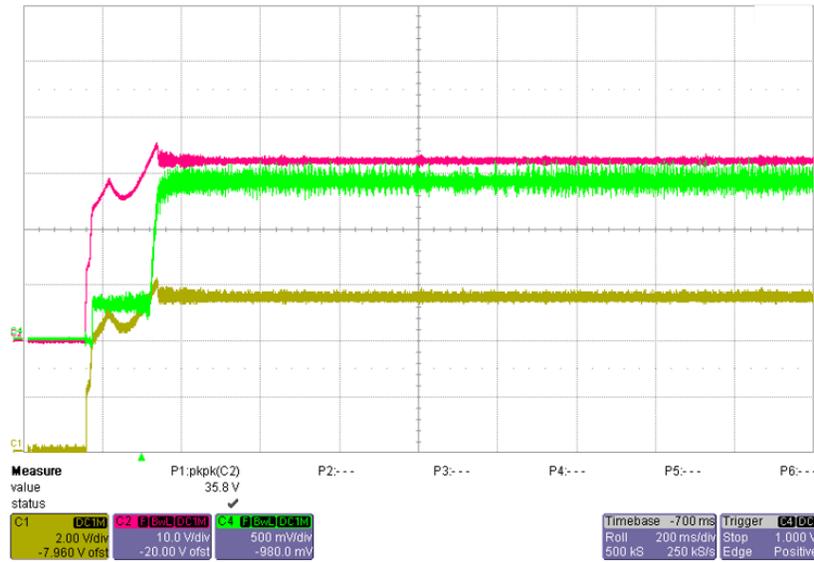


Figure 36. Output Turn ON Waveform for Resistive Load

NOTE: Rose Trace: Output voltage, 10 V/div; Yellow trace: Output current, 2 A/div; Green trace: Digital feedback controller output, 500 mV/div

7.3.4 Controller and Power Stage Response to Step-Load Change

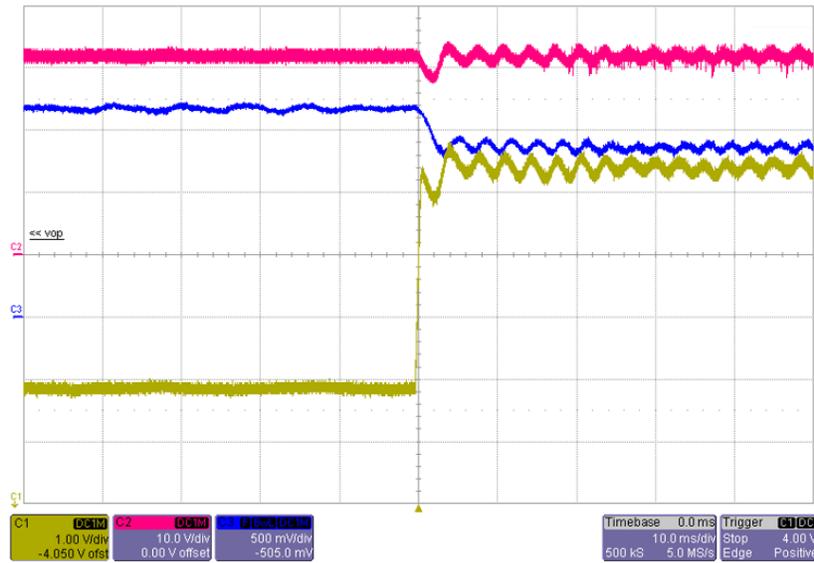


Figure 37. Output Response for Step Change in Load in CV Region

NOTE: Rose Trace: Output voltage, 10 V/div; Yellow trace: Output current, 1 A/div; Blue trace: Digital feedback controller output, 500 mV/div

8 Design Files

8.1 Schematics

To download the schematics, see the design files at TIDA-00703.

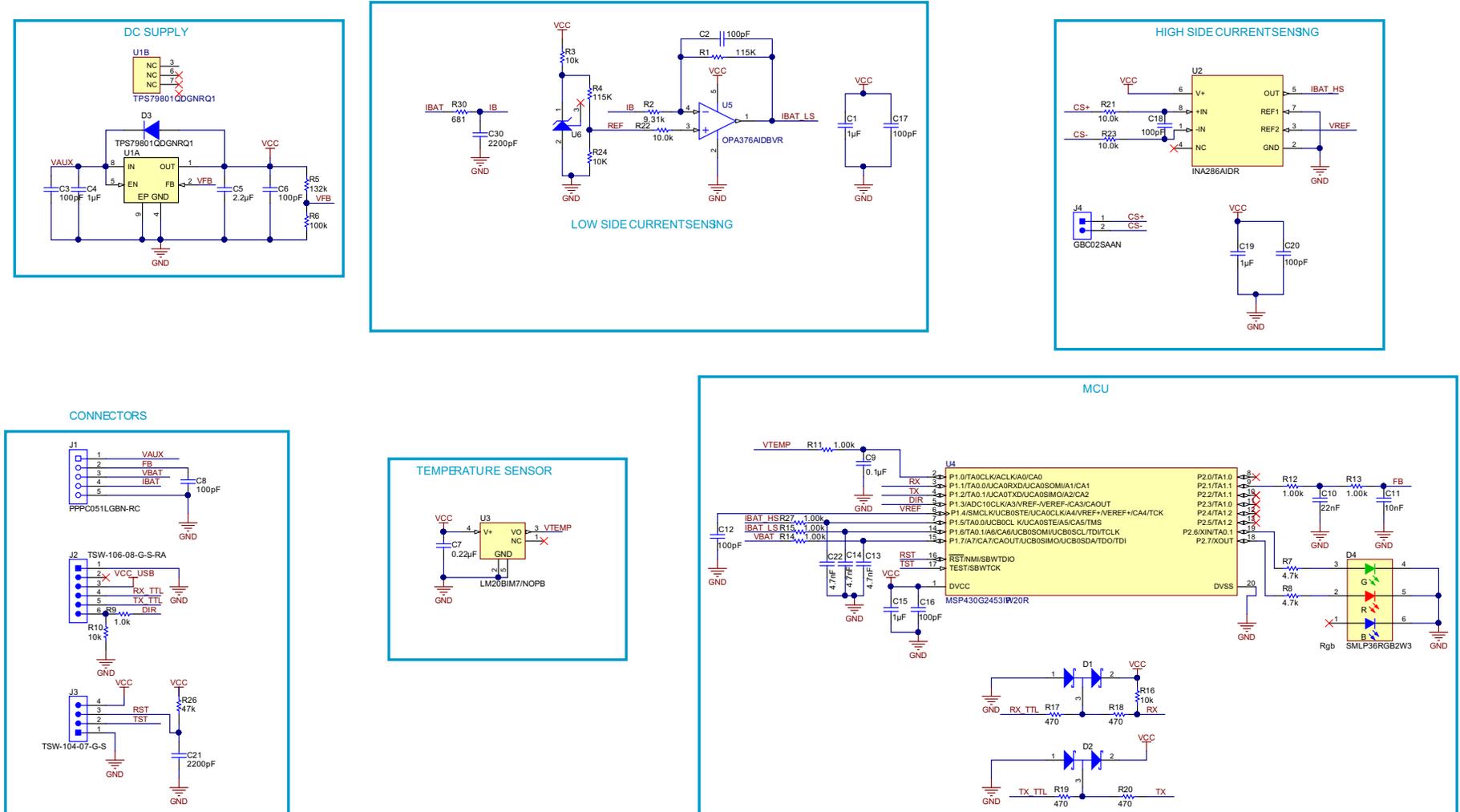


Figure 38. TIDA-00703 Schematic

8.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-00703](#).

Table 6. BOM

QTY	REFERENCE	PART DESCRIPTION	MANUFACTURER	MANUFACTURER PARTNUMBER	NOTE
1	!PCB1	Printed Circuit Board	Any	TIDA-00703	Fitted
1	C1	CAP, CERM, 1 μ F, 6.3 V, +/- 10%, X6S, 0603	MuRata	GRM185C80J105KE26D	Fitted
9	C2, C3, C6, C8, C12, C16, C17, C18, C20	CAP, CERM, 100 pF, 25 V, +/- 10%, X7R, 0603	AVX	06033C101KAT2A	Fitted
1	C4	CAP, CERM, 1 μ F, 50 V, +/- 10%, X7R, 1206	TDK	C3216X7R1H105K	Fitted
1	C5	CAP, CERM, 2.2 μ F, 10 V, +/- 10%, X5R, 0805	AVX	0805ZD225KAT2A	Fitted
1	C7	CAP, CERM, 0.22 μ F, 16 V, +/- 5%, X7R, 0805	AVX	0805YC224JAT2A	Fitted
1	C9	CAP, CERM, 0.1 μ F, 16 V, +/- 5%, X7R, 0603	AVX	0603YC104JAT2A	Fitted
1	C10	CAP, CERM, 0.022 μ F, 50 V, +/- 10%, X7R, 0603	AVX	06035C223KAT2A	Fitted
1	C11	CAP, CERM, 10000 pF, 50 V, +/- 10%, X7R, 0603	AVX	06035C103KAT2A	Fitted
3	C13, C14, C22	CAP, CERM, 4700 pF, 100 V, +/- 5%, X7R, 0603	AVX	06031C472JAT2A	Fitted
1	C15	CAP, CERM, 1 μ F, 10 V, +/- 10%, X7R, 0805	AVX	0805ZC105KAT2A	Fitted
1	C19	CAP, CERM, 1 μ F, 16 V, +/- 10%, X6S, 0805	MuRata	GRM216C81C105KA12D	Fitted
2	C21, C30	CAP, CERM, 2200 pF, 100 V, +/- 5%, X7R, 0603	AVX	06031C222JAT2A	Fitted
2	D1, D2	Diode, Schottky, 30 V, 0.2 A, SOT-23	Diodes Inc.	BAT54S-7-F	Fitted
1	D3	Diode, Switching, 75 V, 0.3 A, SOD-523	Micro Commercial Components	1N4148X-TP	Fitted
1	D4	LED, Rgb, SMD	Rohm	SMLP36RGB2W3	Fitted
2	H1, H2	Bumpon, Hemisphere, 0.44 X 0.20, Clear	3M	SJ-5303 (CLEAR)	Fitted
1	J1	Receptacle, 100mil, 5x1, Gold, R/A, TH	Sullins Connector Solutions	PPPC051LGBN-RC	Fitted
1	J2	Header, 100mil, 6x1, Gold, R/A, TH	Samtec	TSW-106-08-G-S-RA	Fitted
1	J3	Header, 100mil, 4x1, Gold, TH	Samtec	TSW-104-07-G-S	Fitted
1	J4	Header, 2.54 mm, 2x1, Gold, TH	Sullins Connector Solutions	GBC02SAAN	Fitted
2	R1,R4	RES, 115 k, 0.1%, 0.1 W, 0603	Panasonic	ERA-3AEB1153V	Fitted
1	R2	RES, 9.31 k, 1%, 0.1 W, 0603	Panasonic	ERA-3AEB9311V	Fitted
5	R3,R21, R22, R23,R24	RES, 10.0 k, 0.1%, 0.1 W, 0603	Panasonic	ERA-3AEB103V	Fitted
1	R5	RES, 132 k, 0.5%, 0.1 W, 0603	Yageo America	RT0603DRE07132KL	Fitted

Table 6. BOM (continued)

QTY	REFERENCE	PART DESCRIPTION	MANUFACTURER	MANUFACTURER PARTNUMBER	NOTE
1	R6	RES, 100 k, 0.5%, 0.1 W, 0603	Yageo America	RT0603DRE07100KL	Fitted
3	R7, R8, R26	RES, 4.7 k, 5%, 0.1 W, 0603	Vishay-Dale	CRCW06034K70JNEA	Fitted
1	R9	RES, 1.0 k, 5%, 0.1 W, 0603	Vishay-Dale	CRCW06031K00JNEA	Fitted
2	R10, R16	RES, 10 k, 5%, 0.1 W, 0603	Vishay-Dale	CRCW060310K0JNEA	Fitted
6	R11, R12, R13, R14, R15, R27	RES, 1.00 k, 1%, 0.1 W, 0603	Vishay-Dale	CRCW06031K00FKEA	Fitted
4	R17, R18, R19, R20	RES, 470, 5%, 0.1 W, 0603	Vishay-Dale	CRCW0603470RJNEA	Fitted
1	R30	RES, 681, 1%, 0.1 W, 0603	Vishay-Dale	CRCW0603681RFKEA	Fitted
1	U1	Single Output Automotive LDO, 50 mA, Adjustable 1.275 to 28 V Output, 3 to 50 V Input, 8-pin MSOP (DGN), -40 to 125 degC, Green (RoHS & no Sb/Br)	Texas Instruments	TPS79801QDGNRQ1	Fitted
1	U2	High-Accuracy, Wide Common-Mode Range, Bi-Directional CURRENT SHUNT MONITOR Zero-Drift Series, D0008A	Texas Instruments	INA286AIDR	Fitted
1	U3	2.4V, 10µA Temperature Sensor, 5-pin SC-70 Micro SMD, Pb-Free	Texas Instruments	LM20BIM7/NOPB	Fitted
1	U4	16 MHz Mixed Signal Microcontroller with 8 KB Flash, 512 B SRAM and 24 GPIOs, -40 to 85 degC, 20-pin SOP (PW), Green (RoHS & no Sb/Br)	Texas Instruments	MSP430G2553IPW20R	Fitted
1	U5	Precision, Low Noise, Low Iq Operational Amplifier, 2.2 to 5.5 V, -40 to 125 degC, 5-pin SOT23 (DBV0005A), Green (RoHS & no Sb/Br)	Texas Instruments	OPA376AIDBVR	Fitted
1	U6	Precision Micropower Shunt Voltage Reference, 0.1% accuracy, 1.2 V, 15 ppm / degC, 12 mA, -40 to 85 degC, 3-pin SOT-23 (DBZ), Green (RoHS & no Sb/Br)	Texas Instruments	LM4041A12IDBZR	Fitted
2	FID1, FID2	Fiducial mark. There is nothing to buy or mount.	N/A	N/A	Not Fitted

8.3 Layout Guidelines

A careful PCB layout is extremely important in the current sensing and amplification circuit to provide appropriate device operation and design robustness.

8.3.1 Low-Side Current Sense

- Place resistor R30 and capacitor C30 closer to connector J1, pin 4.
- Place resistors R2, R22, and R1 closer to the U5 (OPA376) IC. Their traces should be short.
- Place the voltage reference network formed by U6 (LM4041), R3, R4, and R24 closer to the OPA376 (U5).

8.3.2 Microcontroller

- Place the decoupling capacitors C15 and C16 closer to U4 (MSP430G2453) pin 1.
- Keep the decoupling capacitor C12 as close as possible to the VREF net pin 6.
- Place the second-order filter components R12, C10, R13, and C11 as close as possible to pin 9 to reduce the high-frequency PWM loop length.
- Place the filter components on the ADC lines R27, R15, R14, C22, C14, and C13 close to the U4 ADC pins.

8.3.3 Layout Prints

To download the layout prints, see the design files at [TIDA-00703](#).

8.4 Altium Project

To download the Altium project files, see the design files at [TIDA-00703](#).

8.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-00703](#).

8.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-00703](#).

9 References

1. Texas Instruments, *Digital Loop Exemplified*, Application Report ([SLUA622](#))
2. Texas Instruments, *230-V, 400-W High Efficiency Battery Charger With PFC and LLC for 36-V Power Tools*, TIDA-00355 Design Guide ([TIDU789](#))

10 About the Author

RAMKUMAR S is a Systems Engineer at Texas Instruments, where he is responsible for developing reference design solutions for the industrial segment. Ramkumar brings to this role his diverse experience in analog and digital power supplies design. Ramkumar earned his master of technology (M.Tech) from Indian Institute of Technology, Delhi.

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (December 2015) to A Revision	Page
• Changed from preview page.....	1

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