TI Designs：TIDA-01556
适用于低功耗太阳能电池充电的最大功率点跟踪算法参考设计

TEXAS INSTRUMENTS

说明

此参考设计是一种基本最大功率点跟踪算法的软件实施，适用于采用太阳能电池板输入的单节电池充电系统。此设计借助充电器的集成功能，完全通过基于 I²C 的简易控制方案来达到最大充电电流，因此无需额外的电路和复杂的固件。

资源

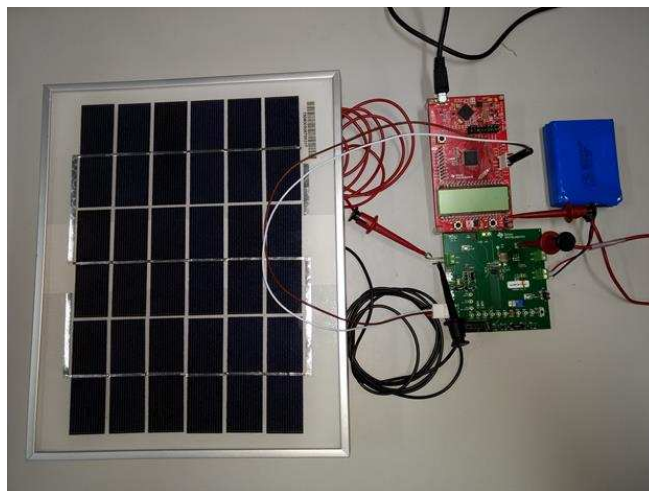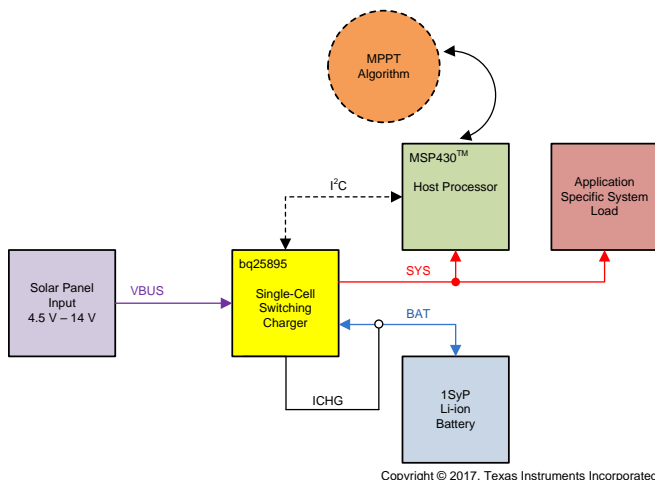|	
TIDA-01556	设计文件夹
bq25895	产品文件夹
MSP430FR4133	产品文件夹

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特性

- 集成式 7 位 ADC 可监控输入电压、电池电压和充电电流
- 具有 100mV 分辨率的可调节输入电压限制
- 具有高充电效率，2A 时为 93%，3A 时为 91%
- 宽输入电压工作范围：3.9V 至 14V
- 具有集成反向阻断 FET，可提供太阳能输入保护
- 针对开路电压的输入高阻抗模式

应用

- 电动自行车
- IP 网络摄像机
- 移动电源解决方案

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1　System Description

This reference design is a software implementation of a simple MPPT algorithm for a single-cell Li-ion battery charging system with a solar panel input. To maximize the output power of the solar panel, a tracking algorithm must have the ability to monitor input power and adjust load impedance, which typically requires extra circuitry and complex firmware.

In this simple algorithm, the bq25895 single-cell switching charger is used along with the MSP430FR4133 microcontroller (MCU) to support the software control. Using the charger's integrated analog-to-digital converter (ADC) and an input power management control loop, input and output power are measured, and the load as seen by the solar panel is dynamically adjusted. Using only I²C communication with the charger, the MCU can monitor and select the peak power point that maximizes the battery charging current.

1.1　Key System Specifications

The bq25895 has an operating input range between 3.9 V and 14 V, which allows for solar panels with typical open circuit voltage ratings of up to 12 V. The charger also has an integrated 7-bit ADC that can measure the input voltage with 100 mV and charging current with 50 mA of precision. The adjustable input voltage dynamic power management loop (V_{IN}DPM) can be configured in 100-mV steps, which enables the software to regulate the input operating voltage. High impedance (HIZ) mode will disable internal biasing and the buck converter—essentially unloading a solar input source. This software uses these elements along with high-charging efficiency to manipulate the load impedance seen at the input and maximize the battery charging current.

2   System Overview

2.1   Block Diagram

图 1 shows the block diagram of the TIDA-01556 reference design.

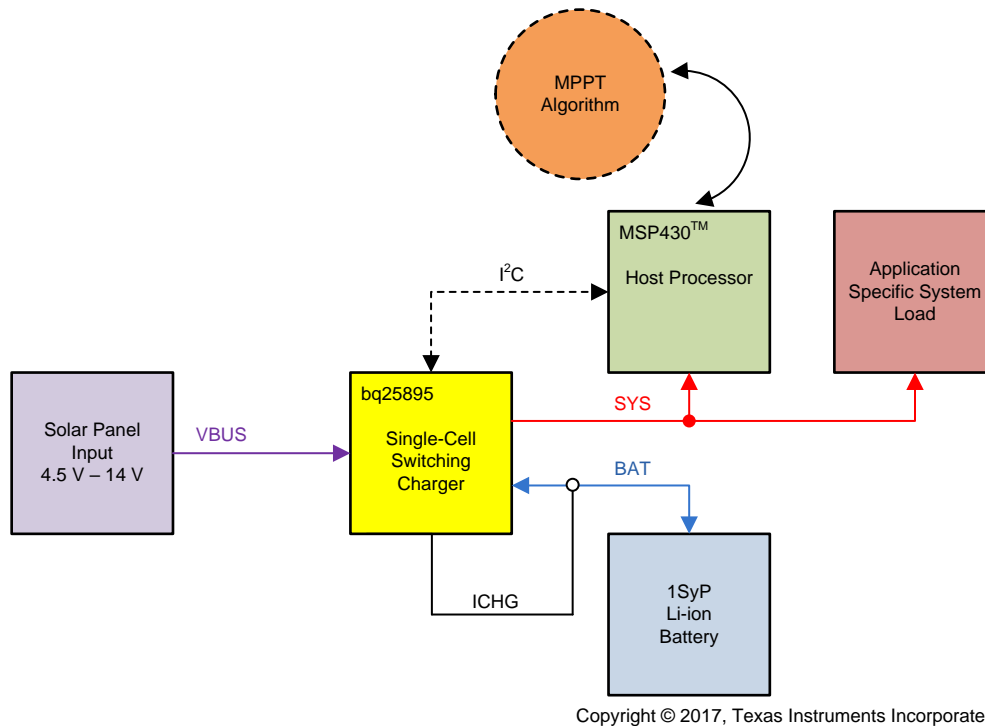Copyright © 2017, Texas Instruments Incorporated

图 1. TIDA-01556 Block Diagram

2.2   Design Considerations

Due to the control scheme of this algorithm (described in 节 2.4.4), several considerations must be made to ensure proper algorithm functionality. First, the battery voltage level must be large enough for the charger to be above the pre-charge threshold and low enough to avoid the constant voltage (CV) mode of charging. Both pre-charge and CV modes of operation prevent the charge current from moving linearly with input power. Secondly, the system load must be low (less than 100 mA) and constant (±50-mA variation) during the sampling period in order to avoid inaccuracies in tracking. To maximize power, the charger must never be in supplement mode operation where the battery discharges current into the system. Other internal clamps must be neglected through either the charge current setting or the input current limit (I_{IN}DPM) setting, which avoids limiting charge current or input power respectively.

2.3   Highlighted Products

2.3.1   bq25895

The bq25895 device has the following key features:

- Integrated 7-bit ADC for system monitoring (voltage, temperature, charge current)
    - Measure input voltage with 100-mV resolution and charging current with 50-mA resolution
    - Burst and one-second continuous sampling modes with 10-ms typical conversion rate
- Adjustable V_{IN}DPM thresholds to regulate input voltage for unknown input current capability

- – Supports range from 3.9 V to 14 V in 100-mV steps
- High-efficiency 5-A, 1.5-MHz switched-mode buck charge
  - – 93% charge efficiency at 2-A and 91% charge efficiency at 3-A charge current
  - – Optimized for high-voltage inputs (9 V to 12 V)
- Resistance compensation (IRCOMP) to maximize input power without overloading adapters
- Narrow VDC (NVDC) power path management
  - – Instant-on works with no battery or deeply discharged battery
  - – Ideal diode operation in battery supplement mode
- BATFET control to support ship mode, wake up, and full system reset

2.3.2   MSP430FR4133

The MSP430FR4133 device has the following key features:

- Embedded MCU
  - – 16-bit RISC architecture up to 16 MHz
  - – Wide supply voltage range from 1.8 V to 3.6 V
- Optimized low-power modes (at 3 V)
  - – Active mode: 126 µA/MHz
  - – Standby mode <1 µA with real-time clock (RTC) counter and liquid crystal display (LCD)
  - – Shutdown (LPM4.5): 15 nA
- Low-power ferroelectric RAM (FRAM)
  - – Up to 15.5 KB of nonvolatile memory
  - – Built-in error correction code (ECC)
  - – Configurable write protection
  - – Unified memory of program, constants, and storage
- Enhanced serial communications
  - – Enhanced USCI A (eUSCI_A) supports UART, IrDA, and SPI
  - – Enhanced USCI B (eUSCI_B) supports SPI and I²C

2.4   System Design Theory

2.4.1   Solar Panel Power Point Tracking

Most energy harvesting input sources provide varying amounts of power depending on the fluctuation of their driving disturbances. Additionally, differences in material properties, electrical connections, and circuit construction can cause variation in the characteristic IV curve of similar devices from the same manufacturer. For solar panels, disturbances come in the form of irradiance and temperature. Looking at the IV curve of a typical panel, changes in sunlight affect the short circuit current while changes in temperature cause the open circuit voltage to shift. All of these parameters inherently affect the power

characteristic of a solar panel during a given instance of conditions. Thus, at different operating points, there is different power output from the solar panel. This characteristic is a departure from a typical power design that can be developed around a regulated input source at a certain operating point, such as one found from a AC-DC wall adapter. Moreover, a given power design can suffer from inconsistent regulation or charging performance when the input source power varies.

As such, most designs using a solar panel as the input source use a control scheme to track the panel along the characteristic power curve under an instance of environmental conditions and across different panel manufacturers. In these so-called *maximum power point trackers*, the power converter manipulates the operating point of the panel to vary the load impedance on the panel to maximize the input power at all times. While they do not guarantee a fixed regulation point, MPPTs do provide a means to maximize panel efficiency, and ultimately, output power.

2.4.2 MPPT Algorithms

There are three common implementations of power point tracker. The first and simplest tracker is the fractional open circuit voltage (FOCV) method. This control is based primarily on the assumption that the maximum power point of a solar panel under any given condition is at an operating point equal to a fixed ratio of the open circuit voltage. The voltage ratio selected for designs using this tracker are chosen anywhere between 70% and 80%. A benefit to this method is the simplicity in circuit or software design, which generally only requires some voltage divided reference. This method is suitable for most single solar cell applications; however, the method suffers from poor tracking and low efficiency when considering solar panels. These devices incorporate strings of parallel and series cells that have complex power curves and stray from the ratiometric assumption under uneven irradiance and temperature distributions across the panel.

The second is the perturb and observe (PO) method of tracking. This control scheme involves disturbing the panel operating voltage and monitoring the change in output power. The delta between the previous disturbance's power and the current power then determines the direction in which to move the operating point—always towards the maximum power. This algorithm is more involved both in hardware and software than FOCV as sensors are required to measure power, a controller to adjust dynamically adjust power point, and a state machine to track power and make decisions. Due to the method of tracking, PO can potentially capture the MPP very accurately, but oftentimes the controller can oscillate around the power point depending on step size. This method can altogether miss the power point if local maxima are found along the power curve during the sweep.

The third common MPPT algorithm is the incremental conductance (IC) method. This method, similar to PO, is a so-called *hill climbing* tracker, which means the method attempts to move the operating point towards the MPP. The IC method differs from the PO method in that it uses the relation that the change in panel power with respect to voltage is positive to the left of the MPP and negative to the right. Using this, IC monitors the instantaneous conductance of the panel to the relative change in conductance and varies the input voltage accordingly. While this implementation can be very accurate and more stable than PO, the IC tracker can be both complex and costly to implement, typically requiring a processor or MCU to perform the calculations, interpret the sensed values, and rapidly process the decision tree.

2.4.3 Simple Battery Charging MPPT Algorithm

In this design, the tracking principles described in 节 2.4.2 are used to implement an innovative way to find the maximum power point. The principle of this algorithm relies on monitoring the reflected input power from the solar panel in the form of charging current as the input voltage is manipulated. Similar to the PO method, this is a hill-climbing scheme that selects the operating point that grants the highest battery charging current. Essentially, the solar panel is maintained in an overloaded state at varying levels of input voltage, effectively moving the panel power along its characteristic curve. This operation is performed within a certain range of input voltages reminiscent of FOCV to optimize the tracking time, which reduces the effects of inconsistent irradiance patterns. Furthermore, the integrated features of the bq25895 allow feedback and control to be handled by just two devices—the charger and the host controller—minimizing cost and complexity. As such, the software only requires simple reads and writes to the charger's internal registers.

2.4.4 MPPT Algorithm Implementation

The registers involved in the MPPT algorithm measure the input voltage (VBUS) and the charging current (ICHG) and manipulate the V_{IN}DPM threshold. The bq25895 can provide instantaneous information about VBUS and ICHG to within 100 mV and 50 mA, respectively. Additionally, the V_{IN}DPM voltage can be moved in 100-mV steps, which gives precise control of the input operating point. To manipulate these parameters, the MSP430™ MCU universal serial communications interface (eUSCI) module can be easily instantiated to implement the required I²C protocol. 图 2 shows the algorithm flow diagram.
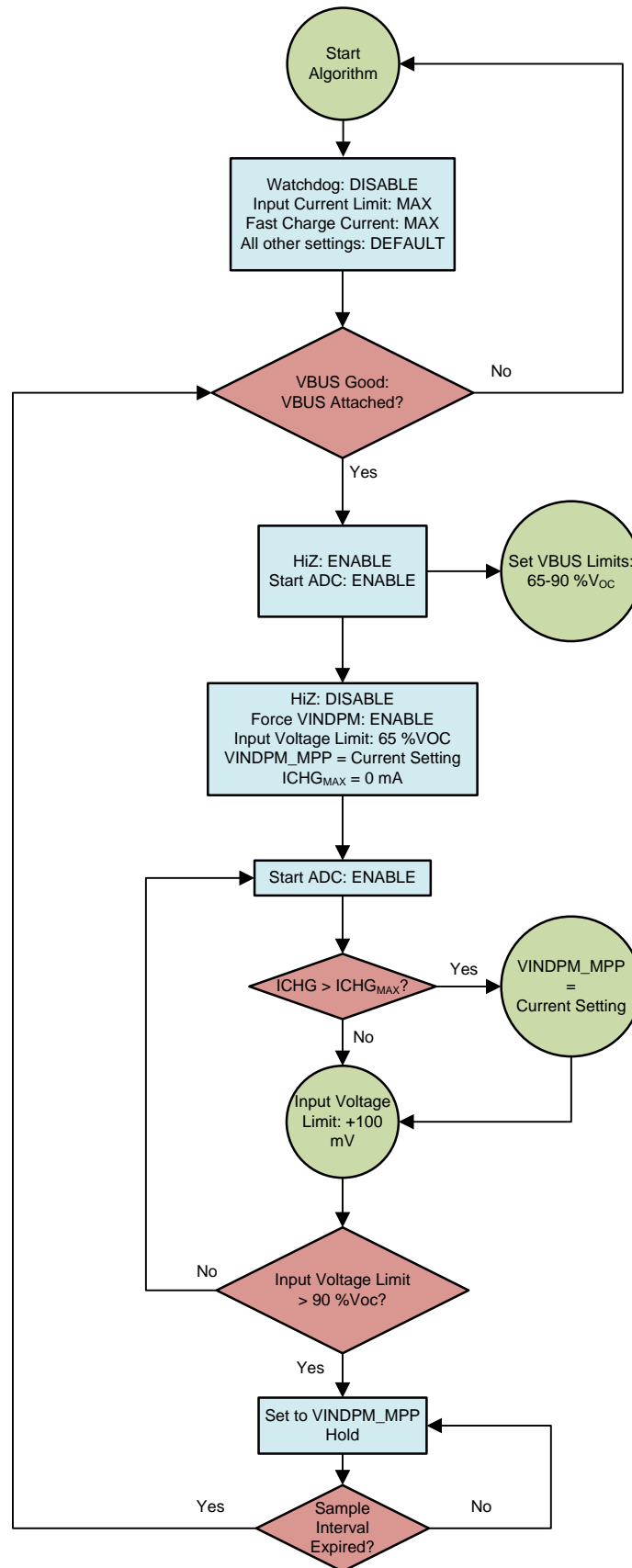
图 **2. MPPT Algorithm Flow Diagram**

The flow diagram has three distinct blocks of operation:

Initialization

- Within Initialization, there are three initial conditions that must be set assuming that I²C communication and port configuration has already been configured. The first setting is to disable the charger watchdog timer. This timer, separate from the MSP430 MCU watchdog, will reset specific parameters on the bq25895 if the timer is not reset every 40 s. The second setting is the $I_{IN}DPM$ parameter, which is set to the highest value provided by the charger (3 A). The third setting is the charge current, which is also set to the maximum of 5.056 A. The aforementioned parameters are set, so the power provided by the panel is in no way clamped by other control loops. The intention is to use only the voltage regulation loop to freely control the solar panel's power point upwards. Afterward, the controller verifies that a panel with sufficient power has been applied to the charger. This is checked with the power good (PG) status bit.

Preconditioning

- The Preconditioning section refreshes various parameters for the next iteration of the Tracking loop. This allows the algorithm to account for dynamic changes to the panel's power performance and thus, optimize the speed to locate the MPP. Initially, the open circuit voltage (V_{OC}) of the panel is read by placing the bq25895 in HIZ mode to completely unload the panel from the circuit. Using the ADC's VBUS information, an operating range to search for the MPP is selected at the system designer's discretion. For the purpose of this design implementation, it was assumed that the MPPT of any panel would be located anywhere between 65% and 90% of the V_{OC}, which is partially taken from the FOCV method. After this, inital conditions reset the algorithm through the Tracking phase and locate the new MPPT for the current loop iteration.

Tracking

- The Tracking phase is the heart of this design's MPPT implementation and also the simplest in operation. The loop steps through $V_{IN}DPM$ settings beginning at the 65% V_{OC} point. The loop continually monitors the I_{CHG} ADC value and searches for the operating point that gives the largest charge current. To accommodate cases where successive iterations of the Tracking loop yield the same maximum charge current, a separate counter can be added. In this design, the counter allows the algorithm to select the midpoint between these successive operating voltages. This selection calculation is somewhat arbitrary and can optimized for particular panels or environmental conditions. Once an appropriate $V_{IN}DPM$ is selected, the algorithm sets and holds this threshold until the sample interval timer expires. Again, this is another parameter that is completely definable based on expected variability of irradiance and temperature.

2.4.5 Block Code Description

In *Initialization*, three main functions are created and instantiated. The initialization code block shows that $I_{IN}DPM$ is set to 3000 mA and ICHG is set to 5056 mA, which are both the maximum levels for the bq25895. The algorithm also verifies the PG status to continue through the iteration.

Initialization code block:

```
set_IINDPM(3.000);
set_ICHG(5.056);

while (1){
      while (get_PGSTAT()){
```

These variables can be changed to meet the design constraints.

- *set_IINDPM():* Sets the input current limit for the charger.
- *set_ICHG():* Sets the charging current limit for the charger.
- *get_PGSTAT():* Determines if a valid solar panel was applied.

In *Preconditioning*, there are two functions and a set of variables, as shown in the following preconditioning code block.

Preconditioning code block:

```
set_HIZ(ENABLE);
unsigned char voc = get_VBUS();
set_HIZ(DISABLE);

unsigned char voc_low = VOC_LOW*voc/100 - (100-VOC_LOW)*VBUSV_OFFSET/100;
unsigned char voc_high = VOC_HIGH*voc/100 - (100-VOC_HIGH)*VBUSV_OFFSET/100;

unsigned char ichg_max = 0X0;
unsigned char vindpm_max = 0X0;
```

The variables *voc_low* and *voc_high* represent the search $V_{IN}DPM$ range for the tracker phase. To iterate through the loop, *vindpm_max* is used while *ichg_max* is continually updated with the new, maximum charge current level.

- *set_HIZ():* A boolean passed here disables or enables HIZ mode.

- *get_VBUS():* The ADC starts and measures to gather the panel input voltage.

In *Tracking*, there are two critical functions for the routine to operate. As shown in the following tracking code block, other operations are performed to determine the $V_{IN}DPM$ at the MPP.

Tracking code block:

```
set_VINDPM(i);

unsigned char ichgr = get_ICHGR();

if (ichgr > ichg_max){
    count = 0;
    ichg_max = ichgr;
    vindpm_max = i;

}

else if (ichgr == ichg_max){
    if (i > vindpm_max){
        vindpm_max = i;
        count++;

    }
}

else

}


vindpm_max -= (count/2)*0X01;

set_VINDPM( vindpm_max );
```

After the $V_{IN}DPM$ is changed, and the charge current reading is parsed, the conditional statement updates both the operating point and the value of the max current value. The second conditional statement handles similar ADC reads, allowing the algorithm to implement the aforementioned midpoint selection scheme.

- *get_ICHGR():* The ADC is started and read to measure the panel input voltage.

- *set_VINDPM():* Sets the input voltage regulation threshold, changing the solar panel operating point.

3   Hardware, Software, Testing Requirements, and Test Results

3.1   Required Hardware and Software

For algorithm evaluation purposes, the following devices and software packages are used.

3.1.1   Hardware

- bq25895EVM-664
- MSP430FR4133 LaunchPad™
- Single-cell Li-Ion battery, 4.2-V $V_{BATREG,}$ ≥ 2000-mAh capacity
- 5 W to 10 W, 4.5 V to 12 V solar panel
  - Solarland® SLP005-06U, 5 W, 6 V
- Solar panel model (see 图 3)
  - Keithley™ SourceMeter 24XX—0.15-A, 0.5-A and 1-A current source, 4.5-V and 10-V compliance
  - Farnell® BZX79C15 Zener Diode, 0.5 W
  - R_{Series} = 1.5 Ω, ≥ 1 W
  - R_{Shunt} = 365 Ω
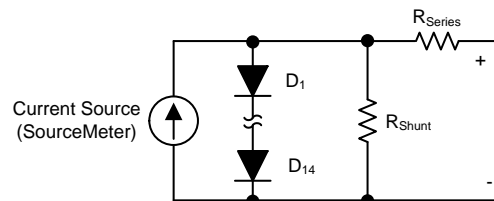
图 3. Solar Panel Model—10 V V_{OC}, 0.5 A and 1.0 A I_{SC}

3.1.2   Software

- Latest version of Code Composer Studio™ (CCS)
- TIDA-01556 software

3.1.2.1   Software Setup

Use the following instructions for the software setup.

1. Install the latest version of CCS from TI.com.
2. Download the .zip file containing the design software and use the import wizard of CCS to import the files.
3. Connect the LaunchPad development kit to the computer using the included USB cable.
4. Build the code in CCS.

3.2 Testing and Results

3.2.1 Test Setup

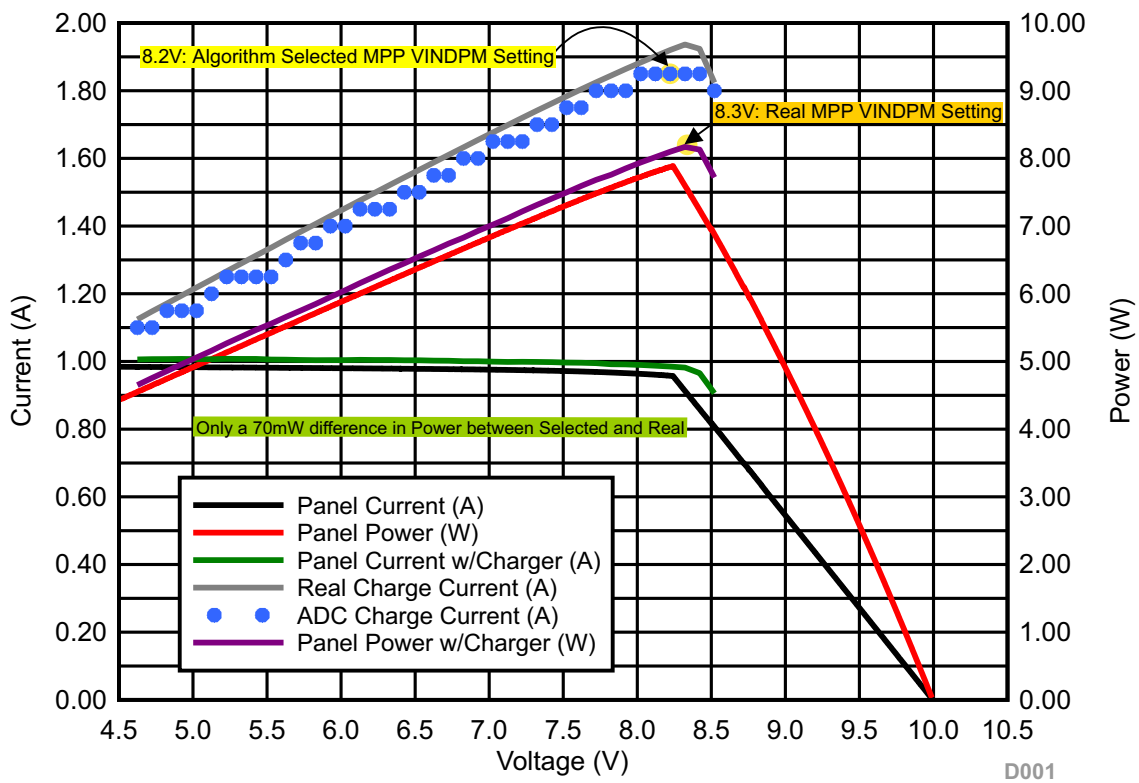#### 3.2.1.1 Test Setup One—Model

Use the following instructions to set up the simulated solar panel model test hardware.

1. Connect the SCL, SDA, and GND lines from the charger board on either connector J7 or J8 to the following pins on the LaunchPad development kit.
   - SCL - P5.3
   - SDA - P5.2
   - GND - Any GND on the LaunchPad development kit
2. Connect a Li-ion cell or a bipolar power supply to terminal J4.
3. Move the jumper on header JP2 between D- and D-/PG.
4. Remove the jumper on header JP1.
5. Add jumper to header JP5 between D- and D+/PSEL.
6. Connect V_{OUT} of solar model to the VBUS and GND of terminal J1.
7. Turn on the Keithley Sourcemeter and run the code on the LaunchPad development kit.

3.2.1.2 Test Setup Two—Outdoor

Use the following instructions to set up the simulated solar panel model test hardware.

1. Connect the SCL, SDA, and GND lines from the charger board on either connector J7 or J8 to the following pins on the LaunchPad development kit.
   - SCL - P5.3
   - SDA - P5.2
   - GND - Any GND on the Launchpad
2. Connect a Li-ion cell to terminal J4.
3. Move the jumper on header JP2 between D- and D-/PG.
4. Remove the jumper on header JP1.
5. Add jumper to header Jp5 between D- and D+/PSEL.
6. Connect solar panel output terminals to the VBUS and GND of terminal J1.
7. Run the code on the LaunchPad development kit.
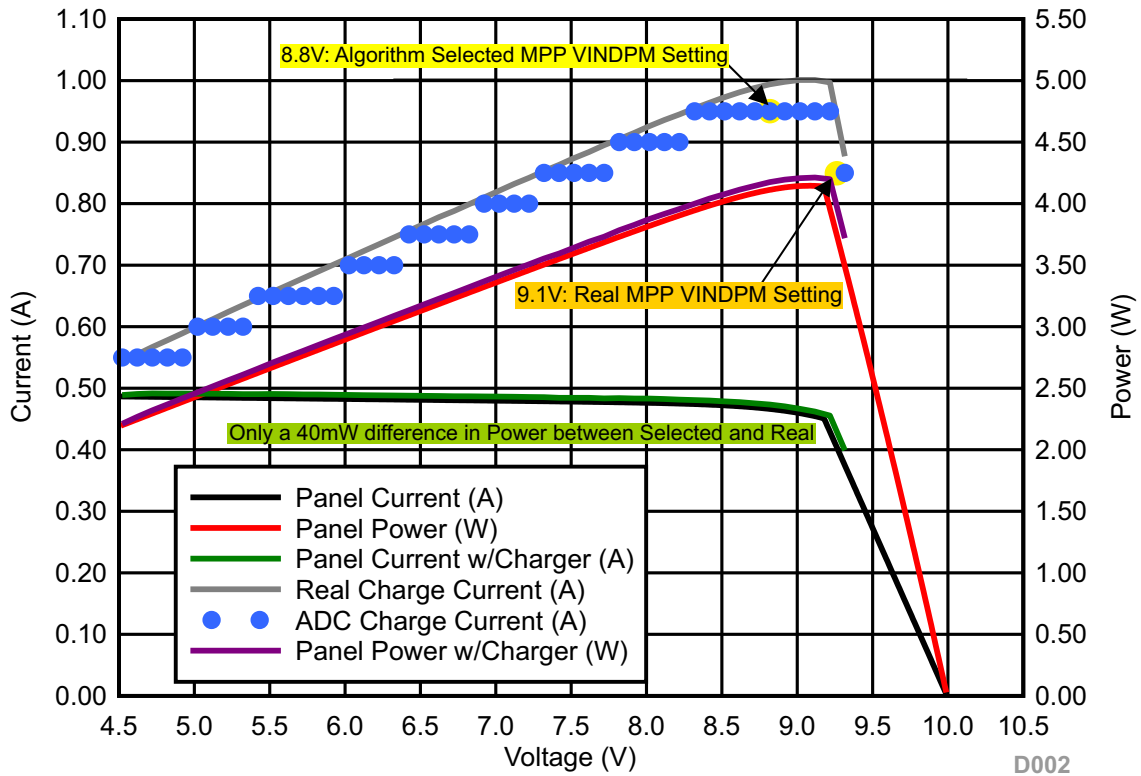
3.2.2 Test Results

3.2.2.1 *Test Setup One—Results*

图 4 and 图 5 show the performance of two different test conditions. One simulates a high irradiance environment with a 1-A short circuit current, and the other is a moderate irradiance at 0.5 A. The optimal $V_{IN}DPM$ in the high irradiance test is 100 mV away from the selected MPP voltage; however, the resulting difference in power between the two operating points is less than 1%. While the medium irradiance test has a seemingly larger gap between the real and selected MPP voltages, the difference in input power is still within 1%. This discrepancy can be attributed to the ADC resolution in combination with the midpoint calculation, which is designed to optimize a particular panel characteristic. Nonetheless for the given granularity, the difference in power is insignificant when considering the low power panels targeted here, and thus, the presented algorithm provides very good MPP tracking accuracy.

(10V V_{OC}, 1A I_{SC}, 3.8V V_{BAT})

图 **4. High Irradiance Simulation—MPPT Performance**

(10V V_{OC}, 0.5A I_{SC}, 3.8V V_{BAT})

图 **5. Moderate Irradiance Simulation—MPPT Performance**

图 6 and 图 7 show the accuracy of the V_{OC} measurement and subsequent boundary determination during the Preconditioning phase of the algorithm.
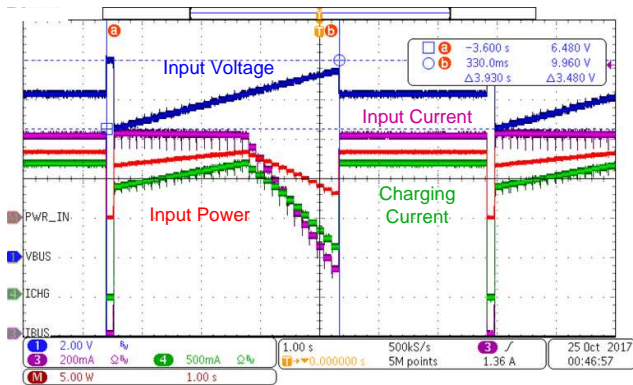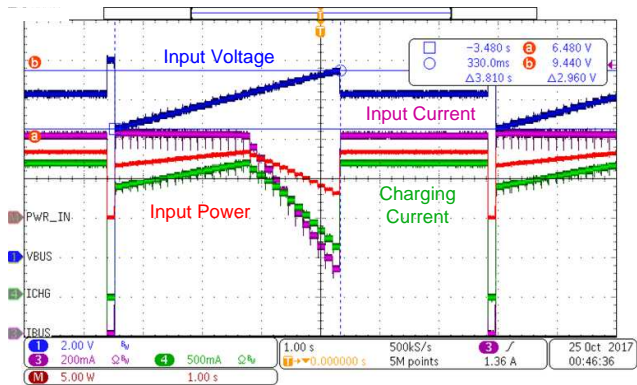

图 **6. Tracking Loop Range—Lower Limit**

图 **7. Tracking Loop Range—Upper Limit**

Looking at 图 8, the total tracking time is 3.93 s, which is reasonably fast. This time is not fixed; time will depend on the sweep range of the algorithm, which is based entirely on the *Preconditioning* limits. Optionally to improve tracking speed, an additional route can be added to the Tracking phase, which allows the algorithm to prematurely exit the sweep once the maximum charge current is located. For this particular sweep range from 6.5 V to 9.5 V (V_{OC} = 10 V), there is a 1.38-s improvement in tracking time without sacrificing tracking accuracy (see 图 9).
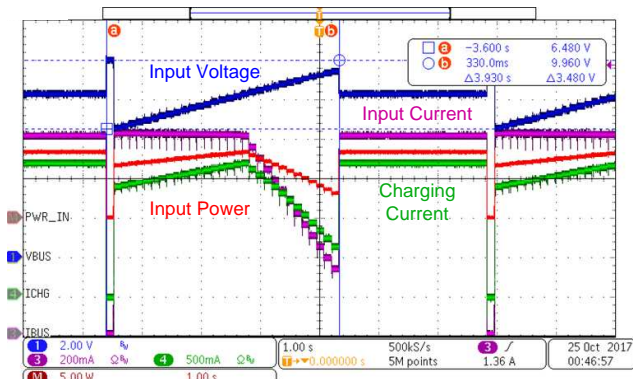
图 8. MPPT Without Tracking Time Optimization
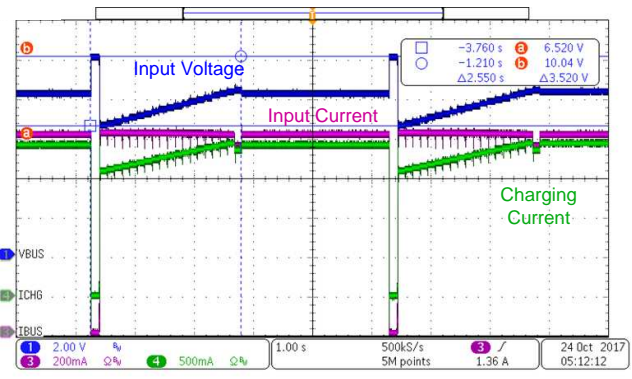
图 9. MPPT With Tracking Time Optimization

Lastly, it is important to note the range of open circuit voltages and short circuit currents that this design can operate under. To give the algorithm adequate headroom to search for the MPP, the minimum V_{OC} is given as 4.5 V. Because this implementation of the algorithm operates between 65% and 95% of this value, and the bq25895's lowest operating voltage (for charging mode) is 3.9 V, the code clamps the lower bound of the Tracking loop to a 3.9 V V_{IN}DPM value. Note that this value must be increased depending on application in order to meet the *Power up REGN Regulation (LDO)* section's requirement of the charger[1].

图 10 and 图 11 show the MPPT performance with a low V_{OC} at 4.5 V. Two points of note here are the clamping voltage at start of the Tracking phase, and the short tracking time due to *Preconditioning* range limits.
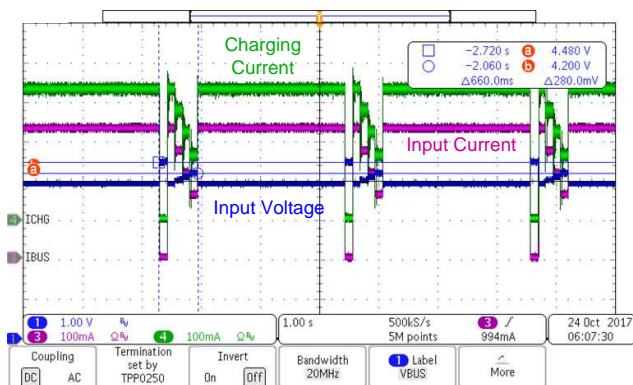

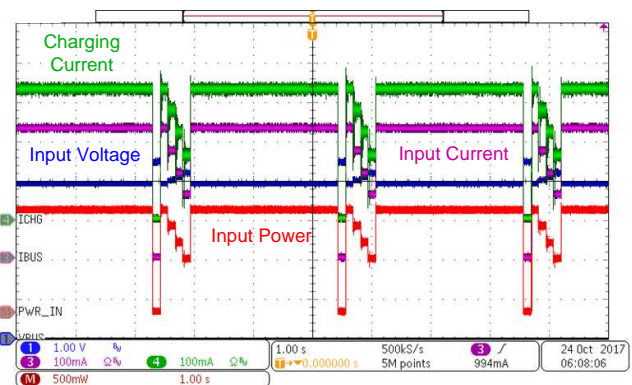图 10. MPPT Range—Low Input Voltage: V_{OC} = 4.5 V, I_{SC} = 0.5 A

图 11. MPPT Range—Low Input Voltage: V_{OC} = 4.5 V, I_{SC} = 0.5 A Showing Input Power

In 图 12 and 图 13 performance of the algorithm at a low panel current is tested. The accuracy of the tracker in selecting the optimal MPP operating voltage degrades slightly due to the midpoint calculation. The number of sample points that show the same maximum ADC charge current increases for lower short circuit currents, moving the midpoint further away from the V_{MPP}. This effect can be mitigated with an improved selection calculation for different voltages that report the same maximum current.
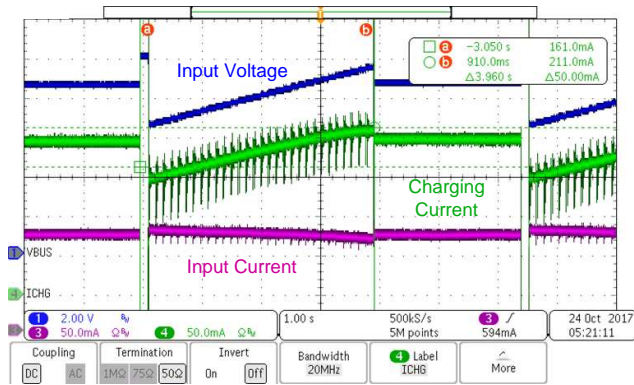

图 12. MPPT Range—Low Input Current: I_{SC} = 0.15 A, V_{OC} = 10 V

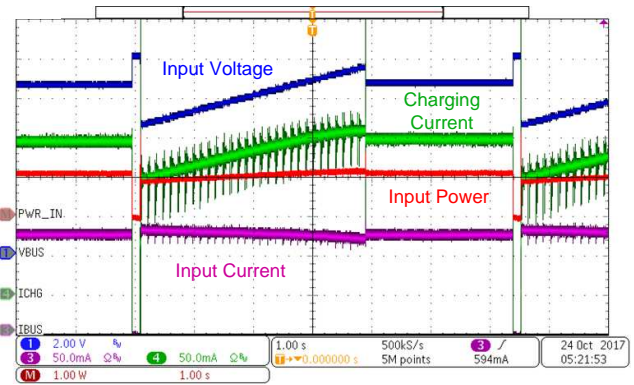图 13. MPPT Range—Low Input Current: I_{SC} = 0.15 A, V_{OC} = 10 V Showing Input Power

3.2.2.2 *Test Setup Two—Results*

With a real solar panel in an outdoor setting, the design code was tested to gauge accuracy under variable irradiance conditions. As seen in 图 14, the variability of direct sunlight due to several factors, such as time of day, cloud light scattering, shading, and angle of irradiance, all create a non-ideal power curve for a real panel. The tracking speed of the algorithm overcomes these non-idealities by attempting to sample and identify the MPPT much faster than the time frame of the dynamic change in light intensity. The charge current reflects the discrete steps in V_{IN}DPM and ADC charge current reading.
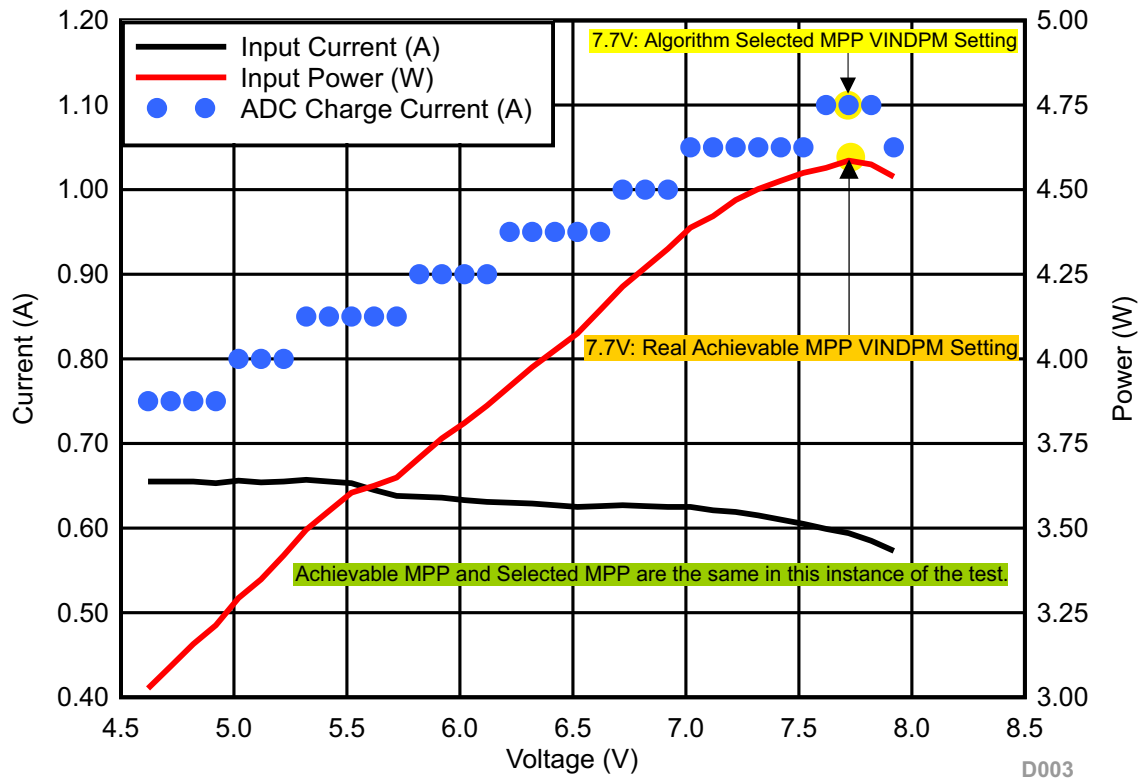

(9.5V_{OC}, 0.65A I_{SC}, 3.1V_{BAT}, 6Ah Battery)

图 **14. Outdoor, Real Solar Panel—MPPT Performance**

4　Software Files

To download the software files, see the design files at TIDA-01556.

5　Related Documentation

1.　Texas Instruments, *bq25895 I²C Controlled Single Cell 5-A Charger with MaxCharge™ for High Input Voltage and Adjustable Voltage 3.1-A Boost Operation Data Sheet*

5.1　商标

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6　Terminology

MPPT — Maximum power point tracking

V_{OC} — Open circuit voltage of a solar panel

I_{SC} — Short circuit current of a solar panel

PO — Perturb and observe MPPT

IC — Incremental conductance MPPT

FOCV — Fractional open circuit voltage MPPT

V_{MPP} — Operating voltage at the maximum power point

V_{BATREG} — Maximum battery regulation voltage. Typically specified by battery manufacturer, this is the maximum voltage a Li-ion or Li-Polymer battery must be charged to and is the regulation voltage for the constant voltage phase of a typical charge cycle.

ADC — Analog-to-digital converter

VBUS — Input voltage pin for the bq25895 single-cell switched mode charger

ICHG — Charge current limit for the bq25895 single-cell switched mode charger

V_{IN}DPM — Input voltage dynamic power management. This is the lower input regulation voltage threshold for the bq25895 single-cell switched mode charger when the input source is overloaded.

I_{IN}DPM — Input current dynamic power management. This is the highest input current threshold for the bq25895 single-cell switched mode charger to prevent the input source from being overloaded.

7　About the Author

JOEL HERNANDEZ is an applications engineer at Texas Instruments supporting single-cell switched-mode charging solutions. Joel earned his Bachelor of Science in Electrical Engineering (BS.EE) from the University of Central Florida.

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