

# TI Designs: TIDA-00998

## Energy Harvesting and Fault Indicator Subsystem for Overhead Fault Indicators Reference Design



### Description

Fault indicators are used on overhead transmission lines for monitoring power cables. Their primary task is to detect fault conditions and indicate using LEDs.

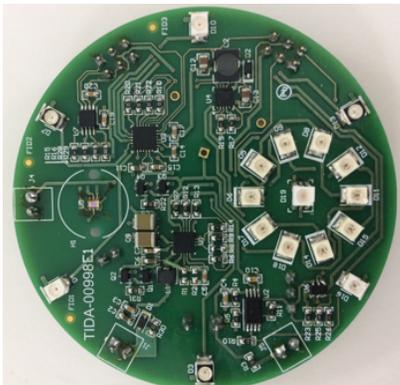
A key challenge for fault indicators is in managing energy storage and consumption so that they last for an extended period of time when the line is down and startup the end equipment quickly. This TI Design shows multiple architectures for extending primary battery life using a secondary battery or supercapacitor with energy harvested from a current transformer (CT) or solar cells. Optimal power management is done using efficient LED drivers to drive series or parallel strings of LEDs to control intensity for uniform 360° visibility.

### Resources

|                            |                |
|----------------------------|----------------|
| <a href="#">TIDA-00998</a> | Design Folder  |
| <a href="#">bq25505</a>    | Product Folder |
| <a href="#">LP55231</a>    | Product Folder |
| <a href="#">LM3509</a>     | Product Folder |
| <a href="#">OPT3001</a>    | Product Folder |
| <a href="#">TPS2113A</a>   | Product Folder |
| <a href="#">PCA9306</a>    | Product Folder |
| <a href="#">TPS61021</a>   | Product Folder |
| <a href="#">TIDA-00807</a> | Tool Folder    |



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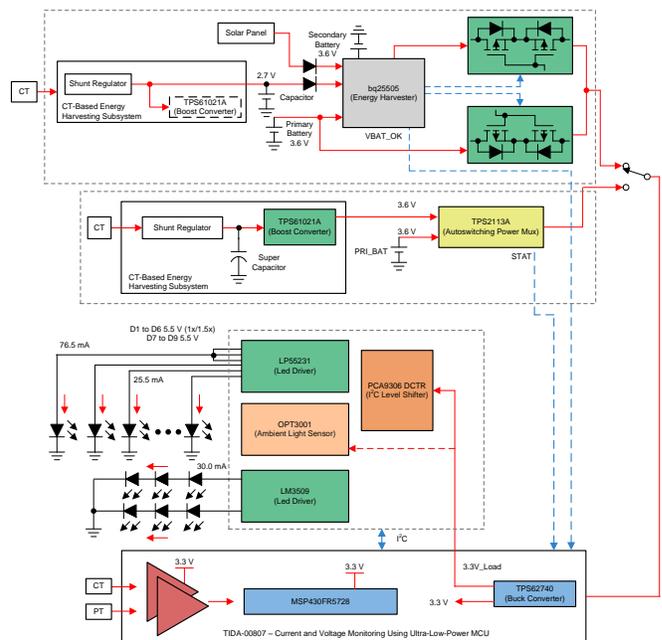


### Features

- Energy Harvesting and Power Management:
  - Solar Energy Harvesting to Charge Li-Ion Battery; Autoswitching Between Primary (Non-Rechargeable) and Secondary (Rechargeable) Storage Elements to Power LED Driver and TIDA-00807
  - Interface to CT-Based Energy Harvesting Subsystem for Load Current Harvesting to Charge Supercapacitor; Power Mux to Autoswitch Between Supercapacitor and Primary Battery
- HMI—High Intensity LED:
  - Drives up to Six Independent LEDs and Three Channels Paralleled to Drive High-Current LED Using LP55231
  - Drives LEDs Connected in String Using LM3509
  - Three-Level LED Intensity Control Based on Ambient Light Level Sensed by OPT3001
  - Light Sensor and LED Drivers Interfaced Using I<sup>2</sup>C (Can Connect to J2 of TIDA-00807)

### Applications

- Overhead Fault Indicators
- Overhead Fault Passage Indicators





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## 1 System Description

Fault indicators are end equipments that indicate the passage of fault currents when installed on transmission lines. By installing a fault indicator, operating costs and service interruptions can be reduced by identifying the section of cable that has failed. At the same time, fault indicators can increase safety and reduce equipment damage by reducing the need for hazardous fault chasing procedures. To provide the greatest benefit, the fault indicator must indicate reliably when a fault current passes through the cable to which the fault indicator is mounted. Misapplication or improper selection of the fault indicator can reduce reliability. The fault indicator must adapt to the electrical network characteristics and be visible to allow maintenance teams to quickly detect faulty network sections.

Once the system recovers from the fault, fault indicators use load current or voltage to reset to a normal state from a fault state. Features like eliminating false tripping by ignoring inrush currents caused by reclosing operations of protective devices on the system is necessary to increase reliable operation.

Various power sources that are used to power overhead fault indicators include the following:

- **Primary battery**—Overhead fault indicators (OHFIs) typically use a non-rechargeable (primary) high capacity (15 to 20 Ah) battery. Lithium or Lithium-Ion based cells are used with a long shelf life (> 10 years) for increasing operating life of an OHFI. A fault indicator indicates the end of life of the primary battery using an additional LED (or by some other means), so that the user can replace battery for continuous operation.
- **Load current**—These fault indicators use part of the load current to automatically reset and to maintain the energy required to respond to fault. In addition to energy harvested from the load current, it also has a supercapacitor or small primary battery for powering the fault indicator during a fault condition.
- **Solar panel**—Energy harvested from solar panel mounted on the OHFI is used to power the system. It typically uses an additional small primary battery as backup.

One of the purposes of fault indicators is to be able to view the fault status from long distance (> 50 m). Fault indicators provide a visual or remote indication of fault in the section of the overhead line that has failed by various means. These indicators include:

- **LED**—An OHFI uses a single or multiple LEDs for indicating fault. They are typically using either red, amber, or both for indicating a permanent or temporary fault. Fault indication should have uniform visibility in all directions (360° visibility). Controlling the intensity of the LED would also increase the visibility during daylight and lesser power consumption during low light ambient conditions.

## 1.1 Key System Specifications

The key parameters for OHFIs are the number of flashing hours and the power source. The main challenge is to increase the life of end equipment by using a low ampere-hour (Ah) battery. When the fault occurs, the OHFI indicates the fault by flashing LEDs until the fault resets or a maximum up to 24 hours depending on type of fault. When the primary battery is used as a power source, flashing hours are limited by the Ah rating of the battery. The main parameter is to extend the life of the end equipment by using a small Ah battery. A higher Ah battery is necessary to increase the number of flashing hours, or the operating life of the OHFI.

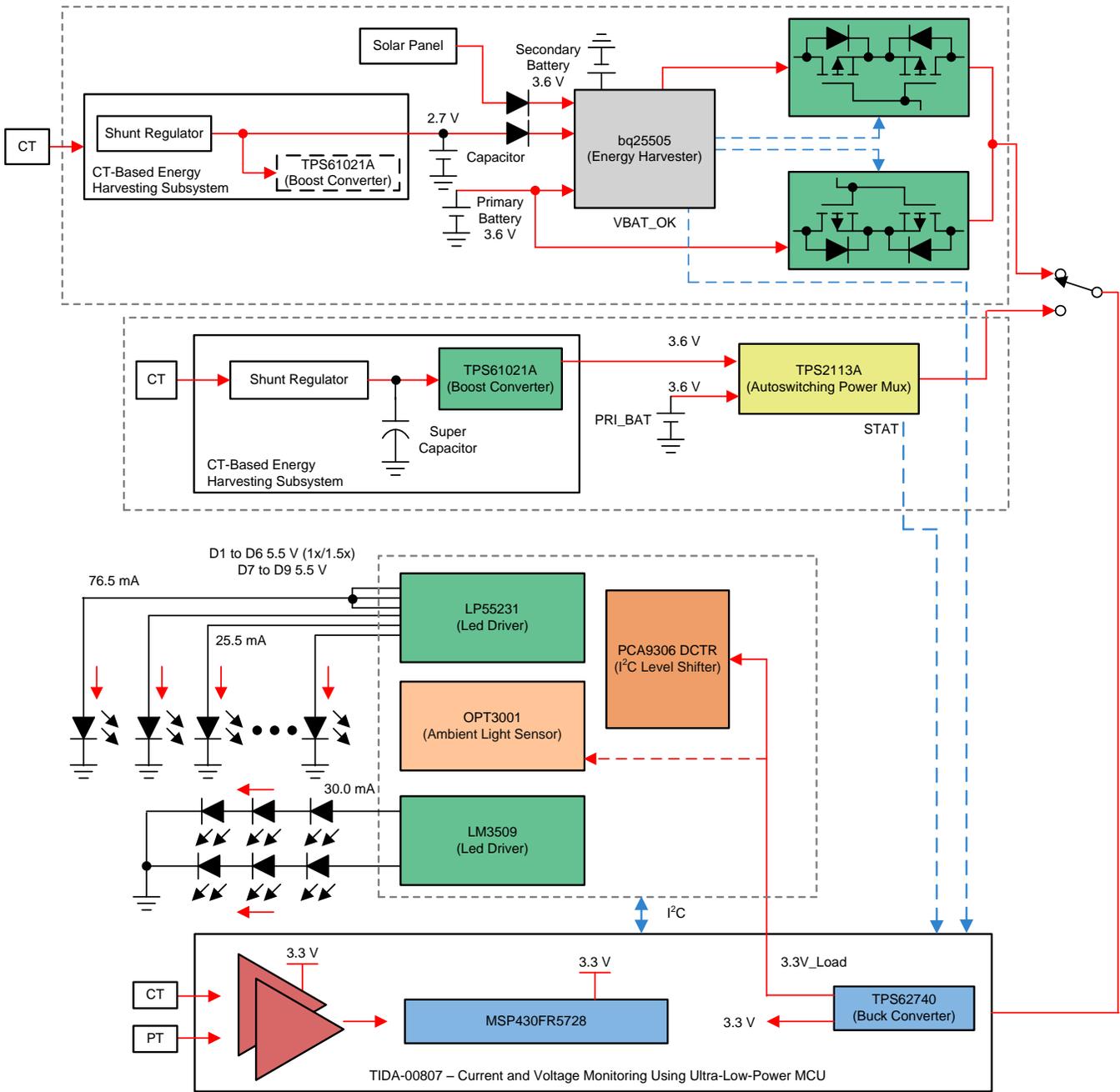
This can be addressed by energy harvesting. CTs or solar cells are used to harvest energy and charge the rechargeable battery or supercapacitor. Once the battery is charged, it supports a definite number of flashing hours. Hence, a smaller rechargeable battery can be used to support a definite number of flashing hours for every charge. In this TI Design, two power architectures are implemented to harvest energy from the CT or solar cells. See [Section 3](#) for more details.

**Table 1. Key System Specifications**

| PARAMETERS                           | DESCRIPTION  |
|--------------------------------------|--|
| Energy harvesting input              | Solar: Low-power and high-efficient energy harvester to harvest energy from voltage source as low as 0.5 V             |
|                                      | CT: Operating range 9 to 100 mA (CT secondary current)   |
| Energy harvesting output             | Secondary (rechargeable) battery: To charge a 3.6-V 1-Ah battery.  |
|                                      | Supercapacitor: 2.7 V 10F  |
| Power mux                            | Autoswitches between primary battery and CT-based energy harvesting subsystem to maintain minimum of 3.3 V to the load |
| LED indication                       | Option 1: Six bright LEDs, two groups of three each of Red/Amber/White color with a minimum current rating of 20 mA    |
|                                      | Option 2: Single bright red LED, with a minimum current rating of 75 mA  |
|                                      | Option 3: 10 bright Red LEDs, two groups of five connected in a string with a minimum current rating of 30 mA          |
| LED intensity control                | Light sensing to control the intensity of LEDs in three steps  |
| Interface                            | I <sup>2</sup> C interface: To interface LED drivers and ambient light sensor to MSP430FR5739 LaunchPad™               |
|                                      | I <sup>2</sup> C level translator: 2-bit bidirectional translator for interfacing MCU and TIDA-00998                   |
| Muxing primary and secondary battery | Two pairs of two P-Ch FET of –20V V <sub>DS</sub> connected in back-to-back configuration driven by bq25505            |

## 2 System Overview

### 2.1 Block Diagram



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**Figure 1. TIDA-00998 Block Diagram**

The TIDA-00998 block diagram contains the following sections:

- [Energy Harvesting Architecture 1: Using Either CT or Solar Input](#)
- [Energy Harvesting Architecture 2: Using CT and Supercapacitor](#)
- [LED Indication and I2C Interface](#)

## 2.2 Highlighted Products

This reference design features the bq25505, LP55231, LM3509, OPT3001, and TPS2113 devices. For more information on each of these devices, see their respective product folders at [www.TI.com](http://www.TI.com).

### 2.2.1 bq25505

The bq25505 is specifically designed to effectively extract microwatts ( $\mu\text{W}$ ) to milliwatts ( $\text{mW}$ ) of power generated from a variety of DC energy harvesting, high-impedance sources like photovoltaic (solar) or thermal electric generators (TEGs) without collapsing those sources. Once the VSTOR voltage is above VSTOR\_CHGEN (1.8 V typical), the boost charger can effectively extract power from low voltage output harvesters such as TEGs or single- or dual-cell solar panels outputting voltages down to  $V_{\text{IN(DC)}}$  (100 mV minimum). When starting from  $V_{\text{STOR}} = V_{\text{BAT}} < 100 \text{ mV}$ , the cold start circuit needs a least  $V_{\text{IN(CS)}}$ , 330 mV typical, to charge VSTOR up to 1.8 V.

Key features of this device include:

- Ultra-low power with high-efficiency DC-DC boost charger:
  - Cold-start voltage:  $V_{\text{IN}} \geq 330 \text{ mV}$
  - Continuous energy harvesting from input sources as low as 100 mV
  - Ultra-low quiescent current of 325 nA
  - Input voltage regulation prevents collapsing high-impedance input sources
  - Ship mode with  $< 5 \text{ nA}$  from battery
- Energy can be stored to rechargeable Li-Ion batteries, thin-film batteries, supercapacitors, or conventional capacitors
- User programmable overvoltage level and internally set undervoltage
- Battery-Good output flag:
  - Programmable threshold and hysteresis
  - Warn attached MCUs of pending loss of power
  - Can be used to enable or disable system loads
- Integrated MPPT for optimal energy extraction from a variety of energy harvesters
- Gate drivers for primary (non-rechargeable) and secondary (rechargeable) storage element multiplexing

For more information, see the [bq25505 product page](#).

### 2.2.2 LP55231

The LP55231 is a 9-channel LED driver designed to produce lighting effects for mobile devices. A high-efficiency charge pump enables LED driving over full Li-Ion battery voltage range. The device is equipped with an internal program memory, which allows operation without processor control.

Key features of this device include:

- Three independent program execution engines, nine programmable outputs with 25.5-mA full-scale current, 8-bit current setting resolution and 12-bit PWM control resolution
- Adaptive high-efficiency 1x/1.5x fractional charge pump, efficiency up to 94%
- LED drive efficiency up to 93%
- Charge pump with soft start overcurrent and short-circuit protection
- Built-in LED test
- 200-nA typical standby current
- Automatic power save mode; IVDD = 10  $\mu$ A (typical)
- Two-wire I<sup>2</sup>C-compatible control interface
- Flexible instruction set
- Large SRAM program memory
- Small application circuit
- Source (high-side) drivers
- Architecture supports color control

For more information, see the [LP55231 product page](#).

### 2.2.3 LM3509

The LM3509 current mode boost converter offers two separate outputs. The first output (MAIN) is a constant current sink for driving series white LEDs. The second output (SUB/FB) is configurable as a constant current sink for series white LED bias, or as a feedback pin to set a constant output voltage for powering OLED panels.

Key features of this device include:

- Integrated OLED display power supply and LED driver
- Drives up to 10 LEDs at 30 mA
- Drives up to 5 LEDs at 20 mA and delivers up to 21 V at 40 mA
- Over 90% efficient
- 32 exponential dimming steps
- 0.15% accurate current matching between strings
- Internal soft-start limits inrush current
- True shutdown isolation for LEDs
- Wide 2.7- to 5.5-V input voltage range
- 21-V overvoltage protection
- 1.27-MHz fixed frequency operation
- Low profile 10-pin WSON package (3 x 3 x 0.8 mm)
- General purpose I/O
- Active low hardware reset

For more information, see the [LM3509 product page](#).

## 2.2.4 OPT3001

The OPT3001 is a sensor that measures the intensity of visible light. The spectral response of the sensor tightly matches the photopic response of the human eye and includes significant infrared rejection.

The OPT3001 is a single-chip lux meter, measuring the intensity of light as visible by the human eye. The precision spectral response and strong IR rejection of the device enables the OPT3001 to accurately meter the intensity of light as seen by the human eye regardless of light source. The strong IR rejection also aids in maintaining high accuracy when an industrial design calls for mounting the sensor under dark glass for aesthetics.

Key features of this device include:

- Precision optical filtering to match human eye: Rejects > 99% (typ) of IR
- Automatic full-scale setting feature simplifies software and ensures proper configuration
- Measurements: 0.01 lux to 83k lux
- 23-bit effective dynamic range with automatic gain ranging
- 12 binary-weighted full-scale range settings: < 0.2% (typ) matching between ranges
- Low operating current: 1.8  $\mu$ A (typ)
- Operating temperature range:  $-40^{\circ}\text{C}$  to  $85^{\circ}\text{C}$
- Wide power-supply range: 1.6 to 3.6 V
- 5.5-V tolerant I/O
- Flexible interrupt system

For more information, see the [OPT3001 product page](#).

## 2.2.5 TPS2113A

The TPS2113A enables seamless transition between two power supplies (such as a battery and a wall adapter), each operating at 2.8 to 5.5 V and delivering up to 2 A, depending on package. It includes extensive protection circuitry, including user-programmable current limiting, thermal protection, inrush current control, seamless supply transition, cross-conduction blocking, and reverse-conduction blocking. These features greatly simplify designing power multiplexer applications.

Key features of this device include:

- Two-input, one-output power multiplexer with low  $R_{\text{DS(on)}}$  switches: 84 m $\Omega$  typ (TPS2113A), 120 m $\Omega$  typ (TPS2112A)
- Reverse and cross-conduction blocking
- Wide operating voltage: 2.8 to 5.5 V
- Low standby current: 0.5  $\mu$ A typ
- Low operating current: 55  $\mu$ A typ
- Adjustable current limit
- Controlled output voltage transition time: Limits inrush current and minimizes output voltage hold-up capacitance
- CMOS- and TTL-compatible control inputs
- Auto-switching operating mode
- Thermal shutdown

For more information, see the [TPS2113A product page](#).

### 2.2.6 PCA9306

The PCA9306 device is a dual bidirectional I<sup>2</sup>C and SMBus voltage-level translator with an enable (EN) input, and is operational from 1.2- to 3.3-V VREF1 and 1.8- to 5.5-V VREF2. The PCA9306 device allows bidirectional voltage translations between 1.2 and 5 V without the use of a direction pin. The low ON-state resistance (RON) of the switch allows connections to be made with minimal propagation delay.

Key features of this device include:

- 2-bit bidirectional translator for SDA and SCL lines in mixed-mode I<sup>2</sup>C applications
- Less than 1.5-ns maximum propagation delay to accommodate standard-mode and fast-mode I<sup>2</sup>C devices and multiple masters
- Provides bidirectional voltage translation with no direction pin
- Low 3.5-Ω ON-state resistance between input and output ports provides less signal distortion

For more information, see the [PCA9306 product page](#).

### 2.2.7 TPS61021A

The TPS61021A provides a power supply solution for portable or smart devices powered by alkaline, NiMH, Li-Mn, or Li-ion batteries. The TPS61021A is capable of outputting 3.3-V voltage and 1.5-A current from a battery discharged to as low as 1.8 V. Being capable of operating with a 0.5-V input voltage enables the TPS61021A to extend the battery run time.

Key features of this device include:

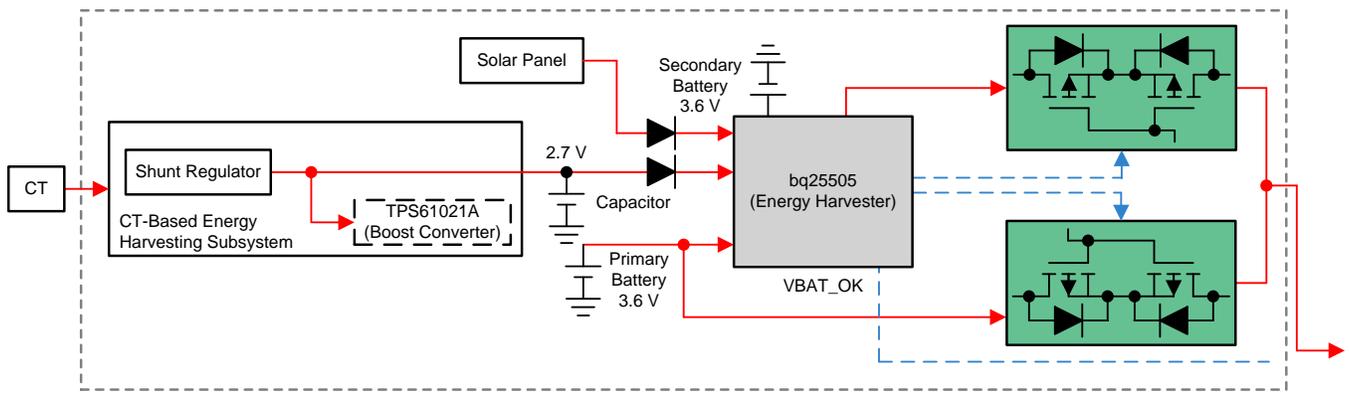
- Input voltage range: 0.5 to 4.4 V
- 0.9-V minimum input voltage for startup
- Output voltage setting range: 1.8 to 4.0 V
- 91% efficiency at  $V_{IN} = 2.4$  V,  $V_{OUT} = 3.3$  V, and  $I_{OUT} = 1.5$  A
- 17-μA typical quiescent current

For more information, see the [TPS61021A product page](#).

### 3 System Design Theory

As described in Section 1, OHFI can be powered using solar energy or by harvesting load current. Two power architectures are demonstrated in this TI Design. In the first architecture, either a CT or solar cell can be used for harvesting energy. The second architecture is only for harvesting energy for the CT, which is a more popular method in the industry. Storage elements and voltage levels are optimized for the both options in this TI Design.

#### 3.1 Energy Harvesting Architecture 1: Using Either CT or Solar Input



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**Figure 2. Architecture With CT or Solar Input Using bq25505**

In this architecture, energy is harvested either using a CT or solar cells. Energy can be harvested from the minimum load current using the CT. With a solar input, the availability of energy can often be sporadic or time-varying. An energy harvester should be able to harvest energy from very low input voltages. The bq25505 with a built-in boost controller and MPPT can harvest energy from as low as 80 mV.

The energy harvesting systems typically need some type of energy storage element, such as a rechargeable battery, supercapacitor, or conventional capacitor. Selecting an energy storage element depends on the operating voltage range of the load connected at the output. If a supercapacitor is used, it should be followed by a boost converter to completely use the energy stored in the supercapacitor. Because the bq25505 output can be directly connected to the load, the rechargeable battery with a 3.6-V nominal voltage is used as an energy storage element. A full-charge voltage at 4.2 V and low voltage under a fully discharged condition at 3.3 V ensures all the energy stored in the battery is used when connected to the LED driver and the TIDA-00807 design. The minimum voltage required for the TIDA-00807 is 3.3 V. CT secondary is connected to the CT-based energy harvesting subsystem. The shunt regulator output (2.7 V) is fed to the bq25505 to charge the secondary battery. Solar cells can be directly connected to the bq25505. Either of these inputs can be connected in the TIDA-00998 design.

### 3.1.1 bq25505 Configuration

**NOTE:** Wherever applicable, the nearest available resistor values are chosen in this TI Design.

A fault indicator should be capable of extending the primary battery life by operating most of the time using energy harvested from an alternate power source. To achieve this, power management of the bq25505 should be configured appropriately. This includes setting an appropriate voltage range condition where the load is receiving energy from the secondary (rechargeable) battery (VBAT\_SEC) instead of from the primary (non-rechargeable) battery (VBAT\_PRI). VBAT\_OK\_PROG indicates when the secondary battery has discharged to an unacceptable amount. When this occurs, the load will start receiving energy from the backup battery and enable the secondary battery to recharge. The desired voltage levels are given in the following equations:

$$VBAT_{OV} = \frac{3}{2} VBIAS \left( 1 + \frac{R_{OV2}}{R_{OV1}} \right) = 4.2 \text{ V} \quad (1)$$

$$VBAT\_OK\_PROG = VBIAS \left( 1 + \frac{R_{OK2}}{R_{OK1}} \right) = 3.3 \text{ V} \quad (2)$$

$$VBAT\_OK\_HYST = VBIAS \left( 1 + \frac{R_{OK2} + R_{OK3}}{R_{OK1}} \right) = 3.6 \text{ V} \quad (3)$$

$$RSUM_{OV} = R_{OV1} + R_{OV2} = 13 \text{ M}\Omega \quad (4)$$

$$R_{OK1} + R_{OK2} + R_{OK3} = 13 \text{ M}\Omega \quad (5)$$

$$R_{OV1} (R8) = \frac{3}{2} \times \frac{RSUM_{OV} \times VBIAS}{VBAT_{OV}} = \frac{3}{2} \times \frac{13 \text{ M}\Omega \times 1.21 \text{ V}}{4.2 \text{ V}} = 5.61 \text{ M}\Omega \rightarrow 5.62 \text{ M}\Omega \quad (6)$$

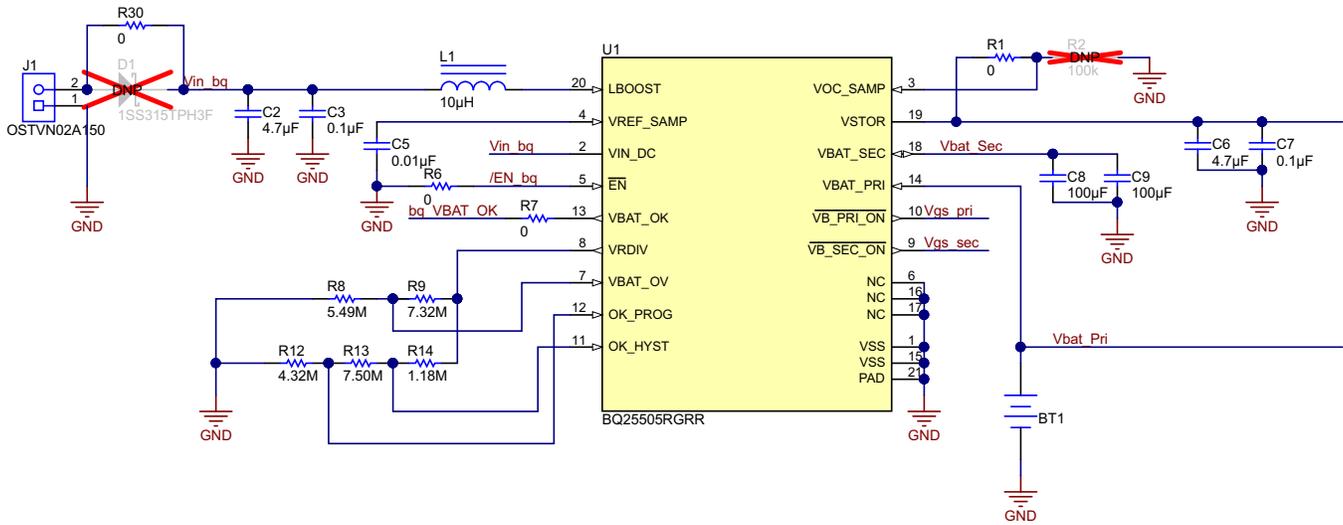
$$R_{OV2} (R9) = RSUM_{OV} - R_{OV1} = 13 \text{ M}\Omega - 5.61 \text{ M}\Omega = 7.38 \text{ M}\Omega \rightarrow 7.32 \text{ M}\Omega \quad (7)$$

$$R_{OK1} (R12) = \frac{VBIAS \times RSUM_{OK}}{VBAT_{OK\_HYST}} = \left( \frac{1.21 \text{ V}}{3.63 \text{ V}} \right) \times 13 \text{ M}\Omega = 4.369 \text{ M}\Omega \rightarrow 4.32 \text{ M}\Omega \quad (8)$$

$$R_{OK2} (R13) = \left( \frac{VBAT\_OK}{VBIAS} - 1 \right) \times R_{OK1} = \left( \frac{3.3}{1.21} - 1 \right) \times 4.32 \text{ M}\Omega = 7.462 \text{ M}\Omega \rightarrow 7.5 \text{ M}\Omega, \text{ then} \quad (9)$$

$$R_{OK3} (R14) = RSUM_{OK} - R_{OK1} - R_{OK2} = 13 \text{ M}\Omega - 7.5 \text{ M}\Omega - 4.32 \text{ M}\Omega = 1.18 \text{ M}\Omega \quad (10)$$

After rounding off to the nearest values, VBAT\_OV, VBAT\_OK\_PROG, and VBAT\_OK\_HYST are at 4.18 V, 3.311 V, and 3.641 V, respectively.



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Figure 3. bq25505 Configuration for Li-Ion Battery Charging With Solar Input

### 3.1.1.1 Maximum Power Point Tracking for Charging Secondary Battery

A solar panel MPP varies with the amount of light on the panel and with temperature. The MPP is listed by the harvesting source manufacturer as a percentage of its open circuit (OC) voltage. Therefore, the bq25505 implements a programmable maximum power point tracking (MPPT) sampling network to optimize the transfer of power into the device. In this TI Design, VSTOR is connected to VBAT\_SEC to give an 80% MPPT.

### 3.1.1.2 Push-Pull Multiplexer Drivers

There are two push-pull drivers intended to multiplex between a primary non-rechargeable connected at VBAT\_PRI and secondary storage element connected on VBAT\_SEC based on the VBAT\_OK signal. When the VBAT\_OK signal goes high, indicating that the secondary rechargeable battery at VBAT\_SEC is above the VBAT\_OK\_HYST threshold, the VB\_PRI\_ON output goes high followed by the VB\_SEC\_ON signal going low in order to connect VBAT\_SEC to the system output. When VBAT\_OK goes low, indicating that the secondary rechargeable battery at VBAT\_SEC is below the VBAT\_OK threshold, the VB\_SEC\_ON output goes high followed by the VB\_PRI\_ON signal going low in order to connect VBAT\_PRI to the system.

### 3.1.2 Solar Panel Selection

The rating of the solar cell required is proportional to the rating of the energy storage element and limited by the rating of the bq25505. The cycle-by-cycle current limit of the bq25505 charger is typically 230 mA (average of 125 mA) and the maximum input voltage is 5.1 V.

In this TI Design, the SLMD121H04L from IXYS, which is a monocrystalline solar cell, is used with a typical operating MPP voltage of 2.0 V and 44.6 mA. It has its maximum peak power of 89.2 mW. To increase the battery charging current, two of them are connected in parallel.

### 3.2 Energy Harvesting Architecture 2: Using CT and Supercapacitor

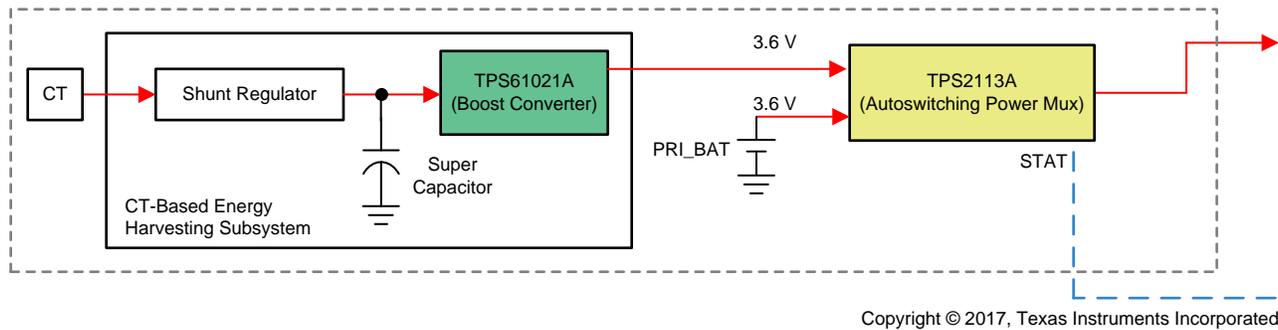


Figure 4. Architecture With CT Input Using TPS61021A and TPS2113A

This architecture is suitable for systems with only CT as an energy harvesting source. The CT input is connected to the CT-based energy harvesting subsystem. A supercapacitor is used as the energy storage element in this architecture. The shunt regulator charges the supercapacitor at 2.7 V. The TPS61021A boosts the supercapacitor voltage to 3.6 V. The TPS2113A connects output to the TPS61021A or a primary battery depending on the voltage levels and VNS configuration. The STAT pin indicates the status of the primary battery.

#### 3.2.1 TPS2113A Configuration

In this TI Design, the power mux TPS2113A is used to autoswitch between the supercapacitor and primary battery to the supply load. OUT connects to IN1 if VSNS is greater than 0.8 V; otherwise, OUT connects to the higher of IN1 and IN2. When the IN1 drops below 3.6V, output is switched to primary battery connected to IN2. The TPS2113A has internal hysteresis of 60 mV for autoswitching between two input power sources.

$$VSNS = 3.6 \text{ V} \times \frac{R_5}{R_4 + R_5} = 0.8 \text{ V} \tag{11}$$

R4 and R5 resistors are chosen as 3.48M and 1.00M using Equation 11.

The output current limit ( $I_{LIM}$ ) is set using an external resistor ( $R_{ILIM}$ ) connected to ground at Pin 4 ( $I_{LIM}$ ) using Equation 12.  $R_{ILIM}$  is chosen as 499  $\Omega$  to set the current limit to 1 A in this TI Design.

$$R_{ILIM} = \frac{500}{I_{LIM}} \tag{12}$$

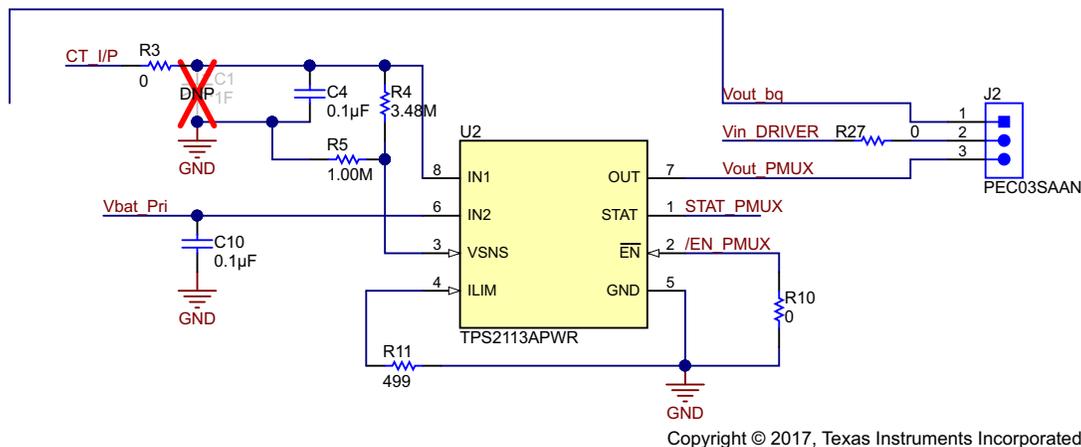
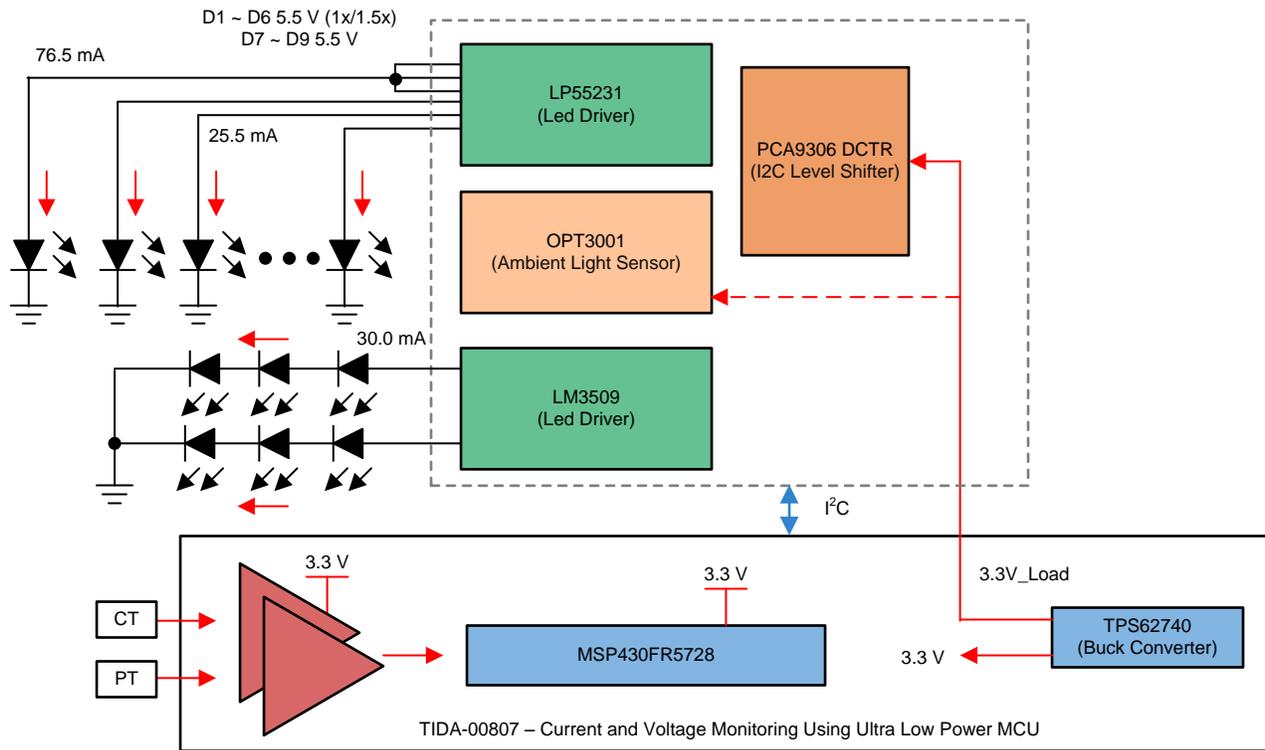


Figure 5. TPS2113A Configuration

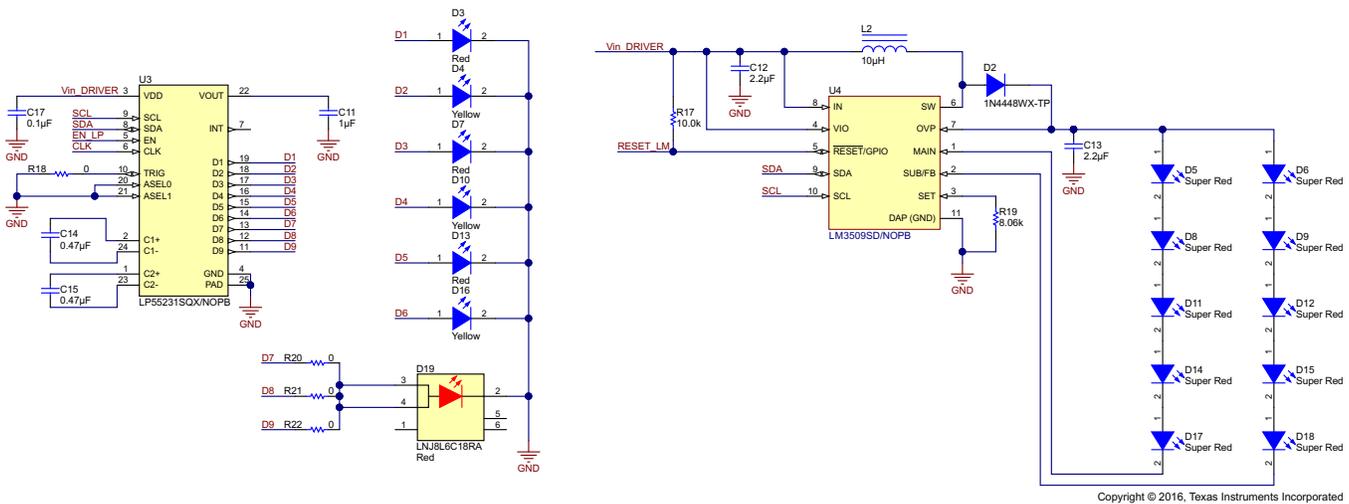
### 3.3 LED Indication and I<sup>2</sup>C Interface



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Figure 6. LED Fault Indication and TIDA-00807 Interface

The key parameters in choosing the LED driver for this application are the low quiescent current and peak efficiency to enhance the battery operating life. Two LED drivers are demonstrated in this TI Design. The first one is LP55231, which is a nine-channel parallel LED driver. The second one is LM3509 with an integrated boost switch for series connected LEDs. These are controlled and configured through I<sup>2</sup>C bus. For high efficiency, these are powered from the TPS62740 output in the TIDA-00807 design. Either of the two outputs from the power stage is connected to the TIDA-00807 using connector J2. The TPS62740 in the TIDA-00807 design regulates the output voltage to 3.3 V.



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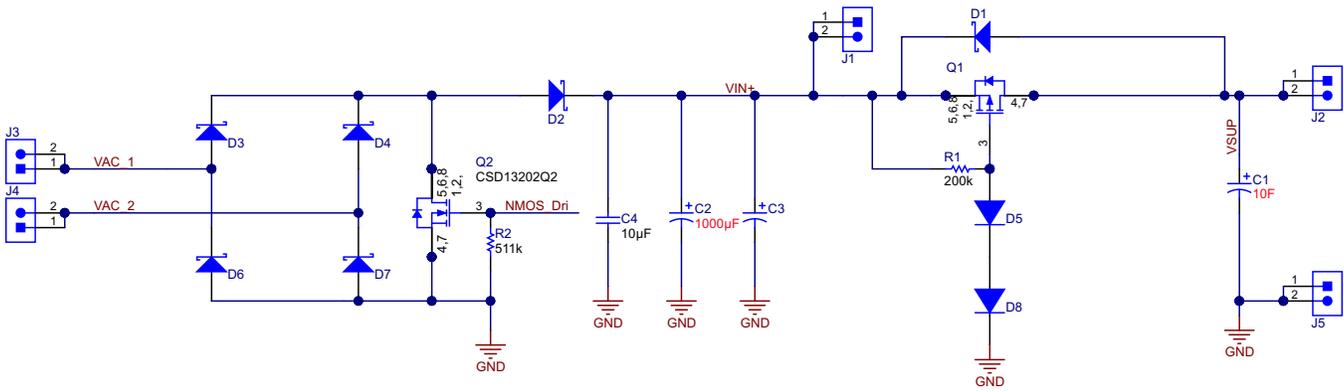
Figure 7. LP55231 and LM3509 Configuration

### 3.4 CT-Based Energy Harvesting Subsystem (TIDA-00998\_CT\_EHS)

The major functionality of this board is to shunt regulate the CT secondary to 2.5 V to charge the supercapacitor and boost the supercapacitor voltage to 3.6 V using the TPS61021A. For evaluating Power Architecture 1, J2 is connected to J1-2 of the TIDA-00998 board. For evaluating Power Architecture 2, J7 is connected to J5-1 of the TIDA-00998 board. The minimum CT secondary required to startup the analog front-end (TIDA-00807) and LED driver in 3 seconds is 9 mA. To startup the analog front-end (TIDA-00807) for the CT secondary current for less than 9 mA, additional control is required from the MCU to connect or disconnect the supercapacitor based on the CT secondary current.

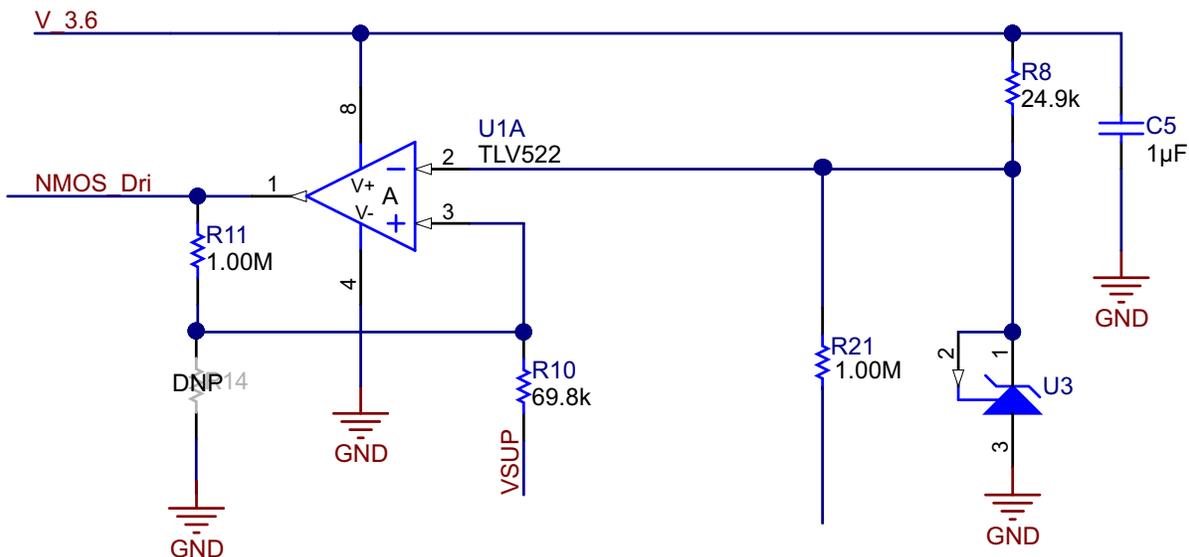
#### 3.4.1 Shunt Regulator

The CT secondary is connected to J3 and J4. Q2 acts as a shunt switch to regulate the supercapacitor voltage to 2.5 V. The TLV522 op amp is used for regulation by comparing supercapacitor voltage and reference generated by the ATL431.



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Figure 8. Shunt Regulating FET and Supercapacitor Charging

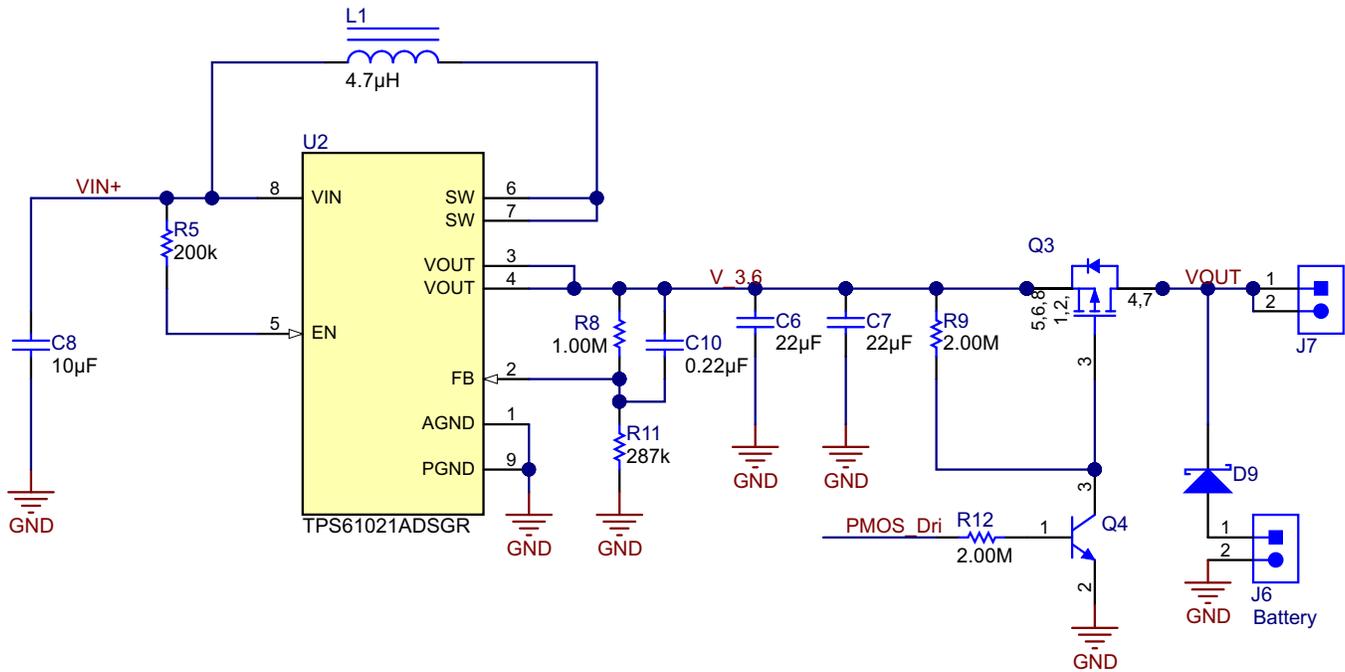


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Figure 9. 2.5-V Shunt Regulation Control

### 3.4.2 TPS61021A (Boost Converter With Integrated Switch)

In this TI Design, the TPS61021A is used to boost the supercapacitor voltage to 3.6 V. The TPS61021A is capable of outputting 3.3-V voltage and 1.5-A current from a battery discharged to as low as 1.8 V. Operating with a 0.5-V input voltage, the TPS61021A can extend the battery run time. In this design, due to voltage drop due to diode D1 (Figure 8), the minimum voltage at supercapacitor (VSUP) to boost is 0.69V.



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Figure 10. TPS61021A Boost Converter Configuration

### 3.4.3 Supercapacitor Backup Time Estimation

A 10F 2.5-V capacitor is used in this TI Design. The leakage current of the supercapacitor is 30 µA and an ESR of 75 mΩ. The TIDA-00807 board requires 15 µA at 3.6 V in standby mode.

$$\text{Energy stored in supercapacitor, } E_S = \frac{1}{2} \times C \times (V_1^2 - V_2^2) = \frac{1}{2} \times 10 \times (2.5^2 - 0.69^2) = 28.87 \text{ J} \quad (13)$$

$$\text{Power loss due to leakage current of supercapacitor, } P_{LK} = \frac{1}{2} \times (V_1 + V_2) \times I_{LKG} = \frac{1}{2} \times (2.5 + 0.69) \times 30 \mu = 47.85 \mu\text{W} \quad (14)$$

$$\text{Standby power consumption of TIDA-00807, } P_{LOAD} = \frac{V_{LOAD} \times I_{STANDBY}}{\eta_{TPS61021}} = \frac{3.6 \times 15 \mu}{60\%} = 90 \mu\text{W} \quad (15)$$

$$\text{Power loss due to ESR of supercap, } P_{ESR} = \left( \frac{P_{LOAD}}{\frac{1}{2} \times (V_1 + V_2)} \right)^2 \times \text{ESR}_{\text{SUPERCAP}} = \left( \frac{90 \mu\text{W}}{\frac{1}{2} \times (2.5 + 0.69)} \right)^2 \times 0.075 = 238.79 \text{ pW} \quad (16)$$

$$\text{Total backup time, } t = \frac{E_S}{P_{LK} + P_{LOAD} + P_{ESR}} = \frac{28.87 \text{ J}}{(43.5 \mu\text{W} + 90 \mu\text{W} + 238.79 \text{ pW}) \times 3600} = 56.41 \text{ hrs} \quad (17)$$

## 4 Getting Started Hardware and Software

### 4.1 Hardware

This section provides information on integrating various boards for testing functional and performance of this TI Design.

#### 4.1.1 TIDA-00998 Board Connections

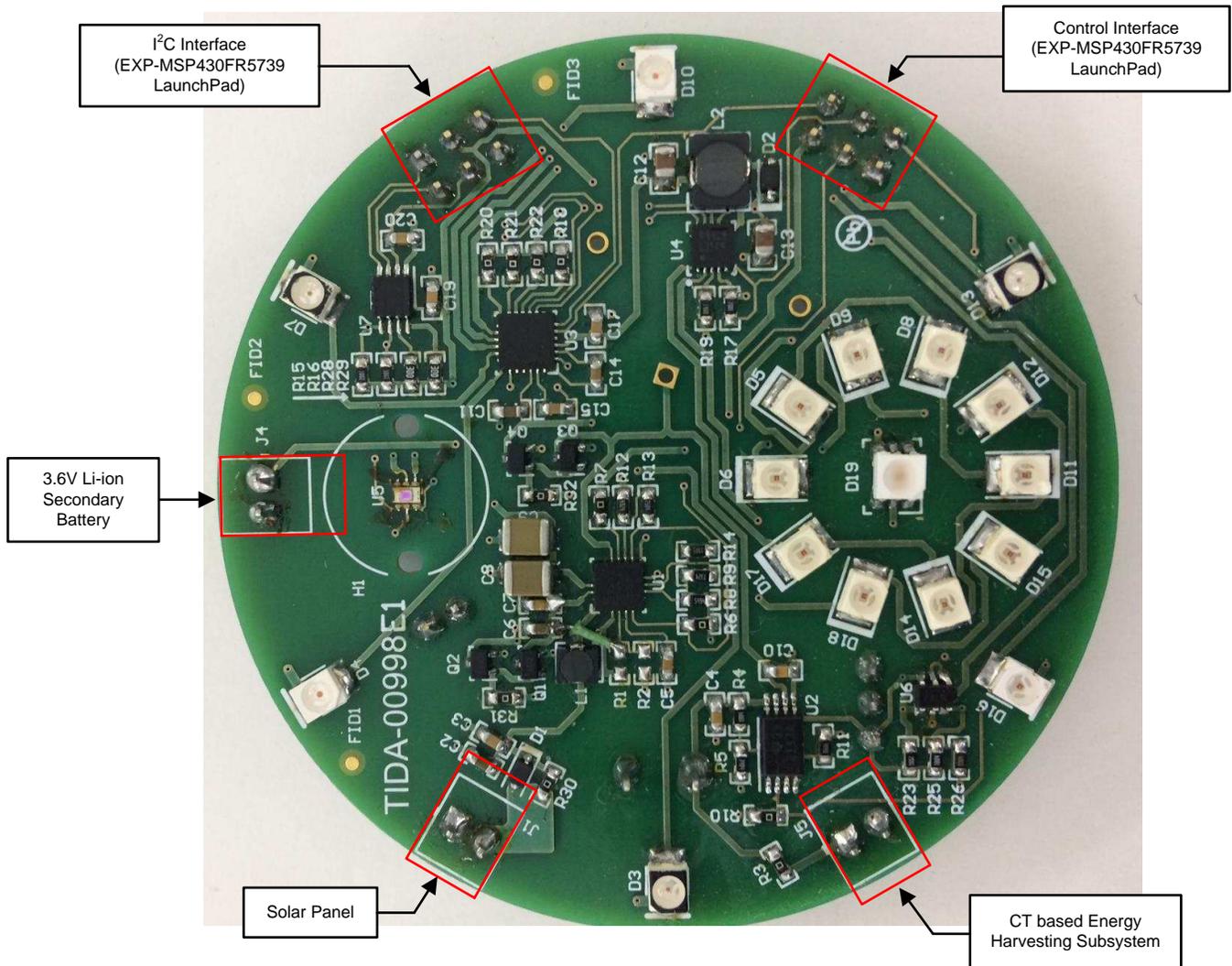
[Table 2](#) provides information on pin connections to the TIDA-00998 design.

**Table 2. TIDA-00998 Connections**

| <b>FUNCTIONS</b>                           | <b>INPUT</b>               | <b>SIGNAL NAME</b> | <b>PINS</b> |
|--|----------------------------|--------------------|-------------|
| bq25505 solar cell input                   | Power                      | VIN_BQ             | J1-2        |
|  |                            | GND                | J1-1        |
| Secondary battery                          | Power                      | VBAT_SEC           | J4-1        |
|  |                            | GND                | J4-2        |
| Primary battery                            | Power                      | VBAT_PRI           | BAT+        |
|  |                            | GND                | GND         |
| CT-based energy harvesting subsystem input | Power                      | CT_I/P             | J5-1        |
|  |                            | GND                | J5-2        |
| HOST interface                             | I <sup>2</sup> C interface | SDA1               | J3-1        |
|  |                            | SCL1               | J3-2        |
|  |                            | CLK                | J3-5        |
|  |                            | GND                | J3-6        |
| Enable/Status signals                      | Signal                     | bq_VBAT_OK         | J6-5        |
|  |                            | /EN_bq             | J6-3        |
|  |                            | /EN_PMUX           | J6-2        |
|  |                            | /EN_LP             | J6-6        |
|  |                            | STAT_PMUX          | J6-1        |

### 4.1.2 TIDA-00998 Interface to CT-Based Energy Harvesting Subsystem and EXP-MSP430FR5739 LaunchPad

Figure 11 provides information on the setup used for functional and performance testing of the TIDA-00998 design.



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**Figure 11. TIDA-00998 Hardware Interface Diagram**

### 4.1.3 MSP-EXP430FR5739 LaunchPad

For functional and performance testing, the MSP-EXP430FR5739 LaunchPad is used in this TI Design. P1.6 and P1.7 are configured as SDA and SDL for communicating with LED drivers. Connect 10K pullup resistors between VCC and P1.6, P1.7.

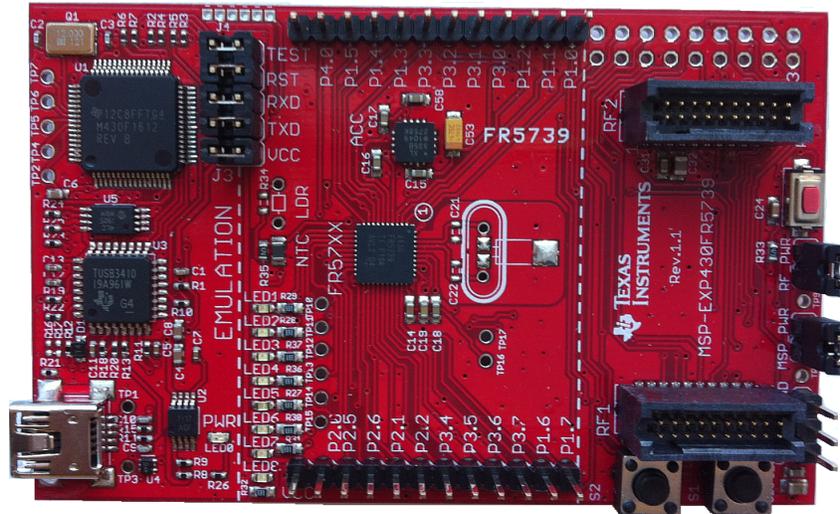


Figure 12. MSP-EXP430FR5739 LaunchPad

Table 3. LaunchPad Connections

| FUNCTION                   | SIGNAL NAME | PINS |
|----------------------------|-------------|------|
| I <sup>2</sup> C interface | SDA1        | P1-6 |
|                            | SCL1        | P1-7 |
| LP55231 Enable signal      | /EN_LP      | VCC  |
|                            | Ground      | GND  |

For more information, see the [MSP-EXP430FR5739 product page](#).

## 4.2 Getting Started Software

### 4.2.1 I<sup>2</sup>C Address Settings

The I<sup>2</sup>C addresses for the devices are listed in [Table 4](#).

**Table 4. I<sup>2</sup>C Address Settings**

| SERIAL NO | DEVICE  | ADDRESS |
|-----------|---------|---------|
| 1         | LP55231 | 0x32    |
| 2         | LM3509  | 0x36    |
| 3         | OPT3001 | 0x44    |

### 4.2.2 LP55231 Register Settings

- Default register settings:
  - Charge pump—Misc. register [0x36] Bits [4:3] is set to "0-0" to disable the charge pump
  - Clock selection—Misc. register [0x36] Bits [1:0] is set to "1-1" to disable the charge pump
  - Output enable—Output ON/OFF control registers [0x04,0x05] is set with all 1's to enable all the outputs
  - Chip enable—Register [0x00] Bit[6] is set with 1 to enable the device
  - Current setting—All the current control registers [0x26 – 0x2E] is set with "100" to give a 10-mA current with each LED
  - PWM registers—All the PWM registers with [0x16 – 0x1E] is set with 0xFF to provide a 100% duty cycle
- Enable or Disable mode registers:
  - Enable—CMD\_LP55231\_ON is used to enable the LP55231 LEDs. The latest configured LEDs will turn ON with default register settings and latest current configured.
  - Disable—CMD\_LP55231\_OFF command is used to disable the LP55231 by setting the chip enable register [0x00] with Bit [6] as "0"
- Individual channel ON and OFF control:
  - CMD\_LP55231\_LED\_CTRL command—Controls the LED that is turned on in the LP55231. The selected LEDs will turn ON with the current set and the others will be OFF
  - PWM registers [0x16 – 0x1E]—Set to "0x00" to turn off the LEDs that are not selected
- Current control:
  - CMD\_LP55231\_SET\_CURRENT—Sets the current for the individual LEDs in the LP55231. The parameter for this command is directly used to the current registers [0x26 – 0x2E] to give the current of "Parameter-Value / 10 – (mA)"
- Flashing control:
  - CMD\_LP55231\_BLINK is used to blink or flash the LEDs selected. Blinking is done by turning ON and OFF alternatively the selected LEDs
  - PWM registers [0x16 – 0x1E] is used to turn ON and OFF selected LEDs

### 4.2.3 LM3509 Register Settings

- Default register settings:
  - The GP register of LM3509 is maintained as same as the default register setting other than Enable Control
    - Unison Mode—Disabled: This bit is set to zero
    - Rate of Change—RMP0, RMP1: Both bits are set to zero to provide the timing of 51  $\mu$ s/step
    - OLED Mode—This mode is disabled by setting this bit to zero
    - ENM, ENS—By default, both LED branches are enabled by setting these bits to "1"
    - Current—The default current value is set with  $\approx$  10 mA
- Enable/Disable mode:
  - GP Register [0x00] Bits [1:0]—Enables or disables the LED branches. Setting these bits to 1 enables the LED and setting it to 0 disables the LED
- Individual channel ON and OFF control:
  - CMD\_LM3509\_LED\_CTRL command controls which LED branch should be turned ON. The branch with respect the corresponding bit turns ON the LEDs with the current set
- Current control:
  - CMD\_LM3509\_SET\_CURRENT controls the current of the LED branch in the LM3509. Both branches will be set with the current mentioned. Register [0xA0, 0xB0] is set with the value given to set the current
- Flashing control:
  - CMD\_LM3509\_BLINK blinks or flashes the LED branches selected. Blinking is done by turning ON and OFF alternatively the selected LED branch. To turn ON and OFF Enable bits in the GP register "0x10 Bits [1:0]" is used

### 4.2.4 OPT3001 Register Settings

- Default register settings:
  - Corresponding bits for the following configuration is configured in register [0x01]:
    - Conversion time: Set to 100 ms
    - Mode of conversion: Continuous conversion
    - Range: Auto range
- Enable or Disable mode:
  - CMD\_OPT3001\_ON/ CMD\_OPT3001\_OFF command enables or disables the OPT3001. Conversion mode bits of the configuration register [0x01] is set to zero to disable the OPT3001.
- Reading intensity:
  - When the OPT3001 is enabled every  $\approx$  200 ms, a light intensity is measured. The read value is converted into an equivalent lux value and printed in the UART terminal.
  - Use Equation 3 from the [OPT3001 datasheet](#) to convert the register data into an equivalent lux value
- Current control versus ambient light intensity:
  - CMD\_ENABLE\_AUTO\_MODE sets the functionality of the TIDA-00998 board in auto mode. In this mode, ambient light intensity is measured from the OPT3001 and the current for the LM3509 and LP55231 is set according to [Table 5](#)
  - Only the latest selected LEDs will glow with this configured current value

### 4.2.5 LED Current Setting Based on Ambient Light Intensity

Table 5 shows the current setting for LP55231 and LM3509 based on ambient light intensity (Lux value) reading by the OPT3001. Current through the LED is lower for low ambient light and higher for high ambient light.

Table 5. Intensity versus Set Current

| SERIAL NO | LUX VALUE      | CURRENT SET    |
|-----------|----------------|----------------|
| 1         | Lux < 50       | LM3509: 5 mA   |
|           |                | LP55231: 10mA  |
| 2         | 50 < Lux < 700 | LM3509: 15 mA  |
|           |                | LP55231: 15 mA |
| 3         | 700 > Lux      | LM3509: 30 mA  |
|           |                | LP55231: 20 mA |

### 4.2.6 Commands for LED Control

The following subsections detail the UART interface to the TIDA-00998 design. The default setting in the firmware for the LP55231 is ON and LM3509 is OFF. See Section 4.2.6.2 for a command list to control the LP55231, LM3509, and OPT3001 using the UART interface.

#### 4.2.6.1 Serial Communication

Once the firmware to the MSP430™ LaunchPad is loaded, use the application UART terminal to send the commands to control or configure the LED drivers connected to the LaunchPad "Hercules", a serial terminal used for validation. Figure 13 shows the settings for the terminal.

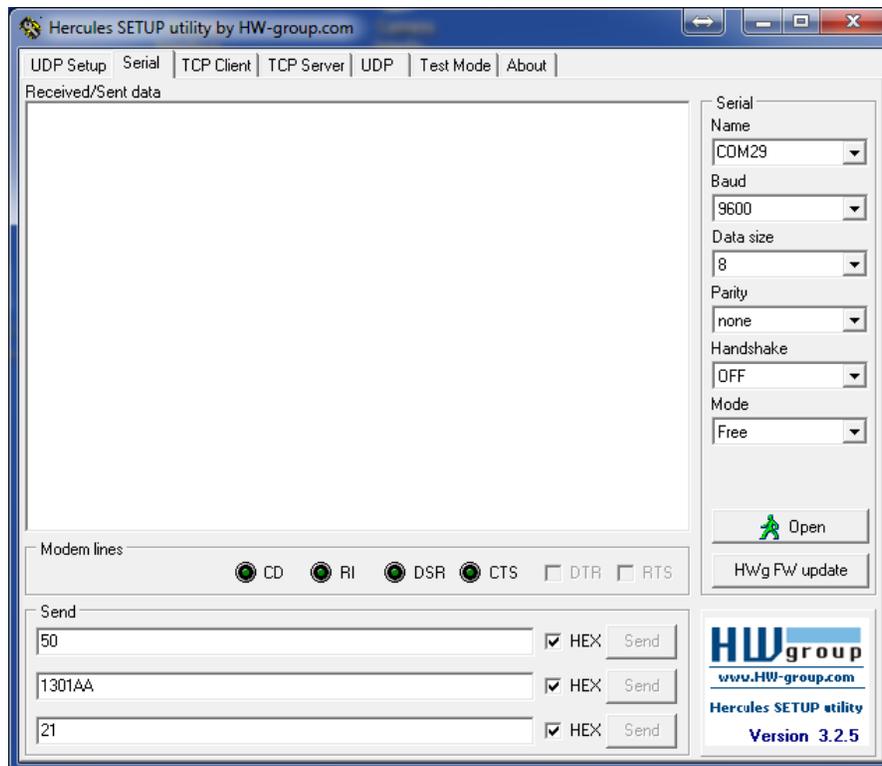


Figure 13. Hercules User Interface for Serial Communication

#### 4.2.6.2 Command List to Control or Configure LED Drivers

Table 6 lists commands to control or configure the LED drivers.

**Table 6. Command List to Control LP55231**

| SERIAL NO | COMMAND                 |      | PARAMETERS                                | DESCRIPTION  |
|-----------|-------------------------|------|---|--|
| 1         | CMD_LP55231_OFF         | 0x10 | —   | Turns off LP55231 and blinking                                       |
| 2         | CMD_LP55231_ON          | 0x11 | —   | Turns on LP55231 with selected LEDs (initially all will be selected) |
| 3         | CMD_LP55231_BLINK       | 0x12 | —   | Blinks the LEDs selected   |
| 4         | CMD_LP55231_LED_CTRL    | 0x13 | 2 bytes; Bit position high means light ON | Selects the LEDs to turn ON or blink based on bit position           |
| 5         | CMD_LP55231_SET_CURRENT | 0x14 | 1 byte; Current value                     | Set the current register for all the LEDs with given value           |

**Table 7. Command List to Control LM3509**

| SERIAL NO | COMMAND                |      | PARAMETERS                         | DESCRIPTION   |
|-----------|------------------------|------|------------------------------------|---|
| 1         | CMD_LP3509_OFF         | 0x20 | —                                  | Turns off LM3509 and blinking                                       |
| 2         | CMD_LP3509_ON          | 0x21 | —                                  | Turns on LM3509 with selected LEDs (initially all will be selected) |
| 3         | CMD_LP3509_BLINK       | 0x22 | —                                  | Blinks the LEDs selected  |
| 4         | CMD_LM3509_LED_CTRL    | 0x23 | 1 byte; BIT0 - Main; BIT1 - SUB    | Selects the LEDs to turn ON or blink based on bit position          |
| 5         | CMD_LM3509_SET_CURRENT | 0x24 | 1 byte; Current value (LSB 5 bits) | Sets the current register for all the LEDs with given value         |

**Table 8. Command List to Control OPT3001**

| SERIAL NO | COMMAND                  |      | PARAMETERS | DESCRIPTION  |
|-----------|--------------------------|------|------------|--|
| 1         | CMD_OPT3001_OFF          | 0x30 | —          | Turns of OPT3001   |
| 2         | CMD_OPT3001_ON           | 0x31 | —          | Measures LUX value and prints in UART  |
| 3         | CMD_TURNOFF_ALL          | 0x50 | —          | Turn of all (LP55231, LM3509, OPT3001)   |
| 4         | CMD_LP55231_LM3509_BLINK | 0x51 | —          | Blink both LM3509 and LP55231 with selected LEDs   |
| 5         | CMD_ENABLE_AUTO_MODE     | 0x52 | —          | Enables setting the current for LP55231, LM3509 based on intensity. Note: Light value will be measured in an interval of 5 sec approximately |
| 6         | CMD_DISABLE_AUTO_MODE    | 0x53 | —          | Disables setting the current for LP55231, LM3509 based on intensity  |

## 5 Testing and Results

The following equipment is used to test the TIDA-00998 design:

- Keithley 2450 source meter
- Tektronix MSO 2024B mixed signal oscilloscope
- Agilent E3631 DC power supply
- Agilent 34401A 6½ digit multimeter
- PTS3.3C
- Electronic Load - KIKUSUI PLZ164WA
- CT AC1020 or equivalent

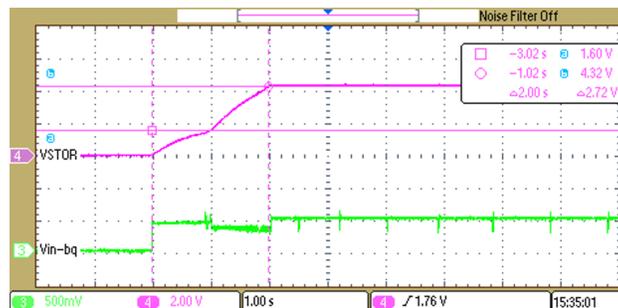
### 5.1 Energy Harvesting—Either CT or Solar Input Using bq25505

#### 5.1.1 Cold Start Operation

To test the bq25505 cold start operation:

1. Connect the bq25505 input to a DC current source of 5 mA at an open circuit voltage of 500 mV without connecting any energy storage element at VBAT\_SEC.
2. Verify the input voltage and voltage at the VSTOR pin.

Cold start is verified at a 500-mV DC input in this TI Design. After the voltage at the VSTOR pin reaches 1.8 V from 0 V at startup, the bq25505 boosts the input voltage to 4.2 V.



**Figure 14. bq25505 Cold Boot Operation**

#### 5.1.2 MPPT Operation

The peak efficiency of the solar cell SLMD121H04L is at 80% of its open circuit voltage. Hence, bq25505 is configured to track 80% of the input open circuit voltage. The peak open circuit voltage is 2.5 V (max) at 1000 W/m<sup>2</sup> irradiance. The minimum open circuit voltage is 1.7 V at 2 W/m<sup>2</sup> irradiance. Programmable DC source with current limit is used to simulate the solar input for this test.

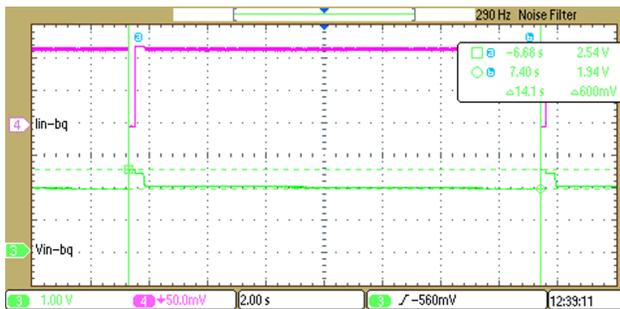
To test the bq25505 MPPT operation:

1. Connect a rechargeable battery to VBAT\_SEC.
2. Apply 3.6-V DC to VBAT\_PRI.
3. Apply 2.5-V DC at a 120-mA current limit to the bq25505 input (J1 connector).
4. Record the bq25505 input voltage (VIN\_BQ) and current.
5. Record the VBAT\_SEC voltage (VBAT\_SEC) and current.
6. Repeat Steps 1 to 5 at the 3-V, 2.5-V, and 2-V input.
7. Repeat Steps 1 to 6 at 100-mA and 50-mA input current limits.

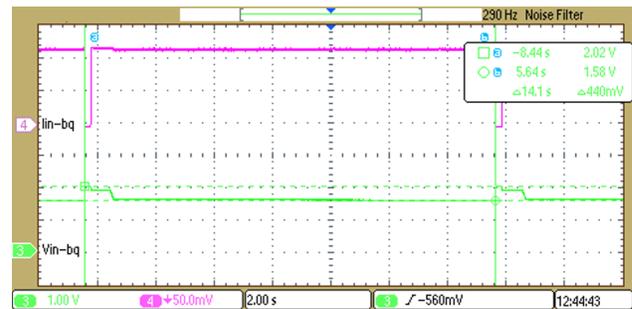
The bq25505 is configured for a tracking input at 80% of open circuit voltage is captured at 2-V and 2.5-V inputs. The minimum efficiency of charging at a 2-V 120-mA input current is 80%.

**Table 9. MPPT Verification**

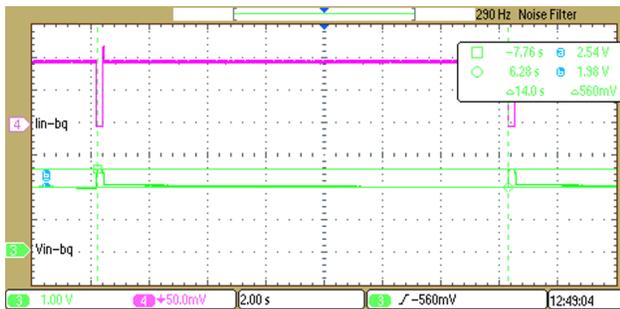
| SERIAL NO | DC INPUT                   |                            |                        | BATTERY     |              | EFFICIENCY |
|-----------|----------------------------|----------------------------|------------------------|-------------|--------------|------------|
|           | V <sub>IN_BQ(OC)</sub> (V) | I <sub>IN_LIMIT</sub> (mA) | V <sub>IN_BQ</sub> (V) | VOLTAGE (V) | CURRENT (mA) |            |
| 1         | 2.5                        | 120                        | 2.385                  | 4.101       | 57.101       | 81.82%     |
| 2         | 2.0                        | 120                        | 1.727                  | 4.087       | 40.500       | 79.87%     |
| 3         | 2.5                        | 100                        | 2.118                  | 4.082       | 43.260       | 83.37%     |
| 4         | 2.0                        | 100                        | 1.723                  | 4.070       | 34.240       | 80.88%     |
| 5         | 2.5                        | 50                         | 2.058                  | 4.055       | 22.070       | 86.97%     |
| 6         | 2.0                        | 50                         | 1.664                  | 4.048       | 17.330       | 84.32%     |



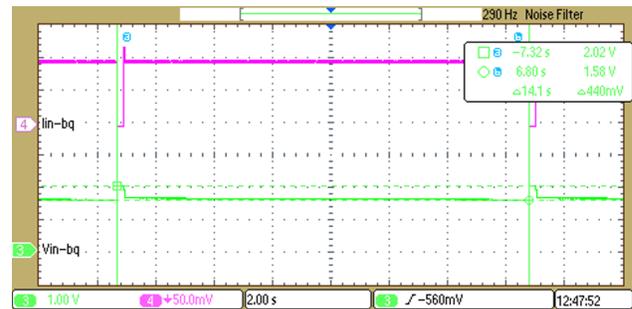
**Figure 15. Vin\_bq = 2.5 V at 120 mA**



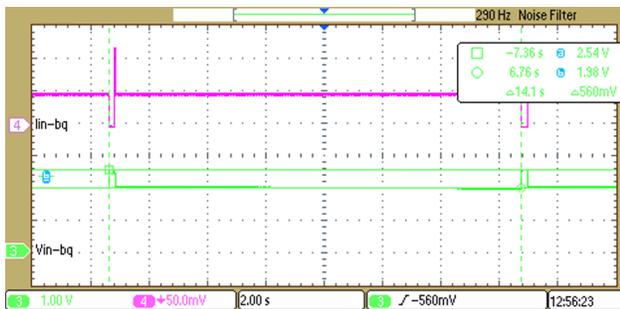
**Figure 16. Vin\_bq = 2.0 V at 120 mA**



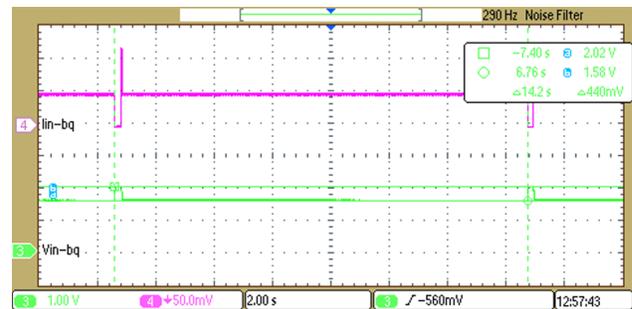
**Figure 17. Vin\_bq = 2.5 V at 100 mA**



**Figure 18. Vin\_bq = 2.0 V at 100 mA**



**Figure 19. Vin\_bq = 2.5 V at 50 mA**



**Figure 20. Vin\_bq = 2.0 V at 50 mA**

### 5.1.3 Autoswitching Operation

The typical voltage for a lithium-ion single-cell battery that is rechargeable is 3.6 V. The battery voltage for fully charged and fully discharged conditions are 4.2 V and 3.3 V, respectively. Hence, bq25505 is configured to switch the load to the primary battery when the rechargeable battery voltage drops to 3.3 V. With a hysteresis of 0.3 V, the load is switched back to rechargeable battery at 3.6 V when charged. The VBAT\_OK pin goes high when the load is connected to rechargeable battery, or low indicating the battery good condition.

To test the bq25505 autoswitching operation:

1. Apply 3.6-V DC at VBAT\_PRI.
2. Connect an external DC source at VSTOR and vary the voltage from 3 to 4.2 V and decrease to 3 V.
3. Verify the VBAT\_PRI, VSTOR, and VOUT\_BQ voltages.

The bq25505 output is switching to VSTOR at 3.6 V while the rechargeable battery is charging and switching to the primary battery at 3.3 V while the rechargeable battery is discharging. The VBAT\_OK pin goes low when the output is powered from the primary battery.

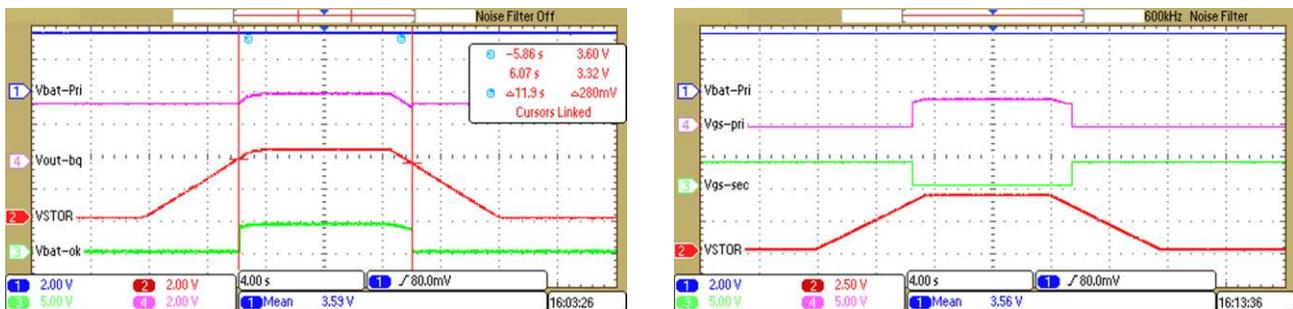
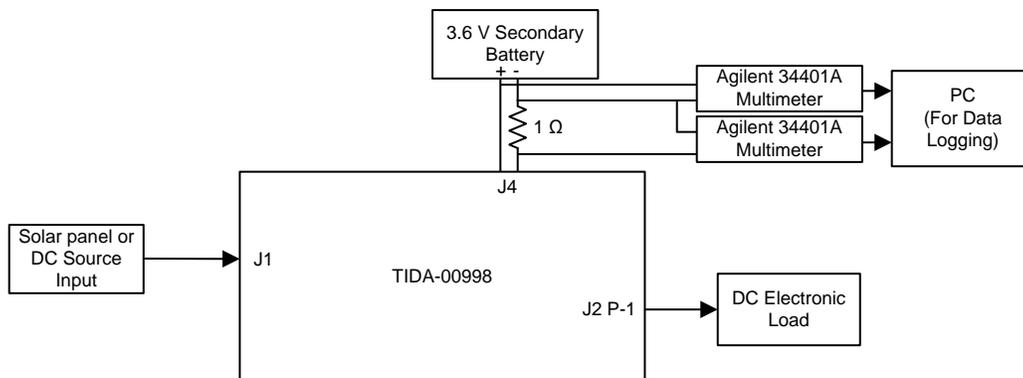


Figure 21. Autoswitching Between VSTOR and VBAT\_PRI

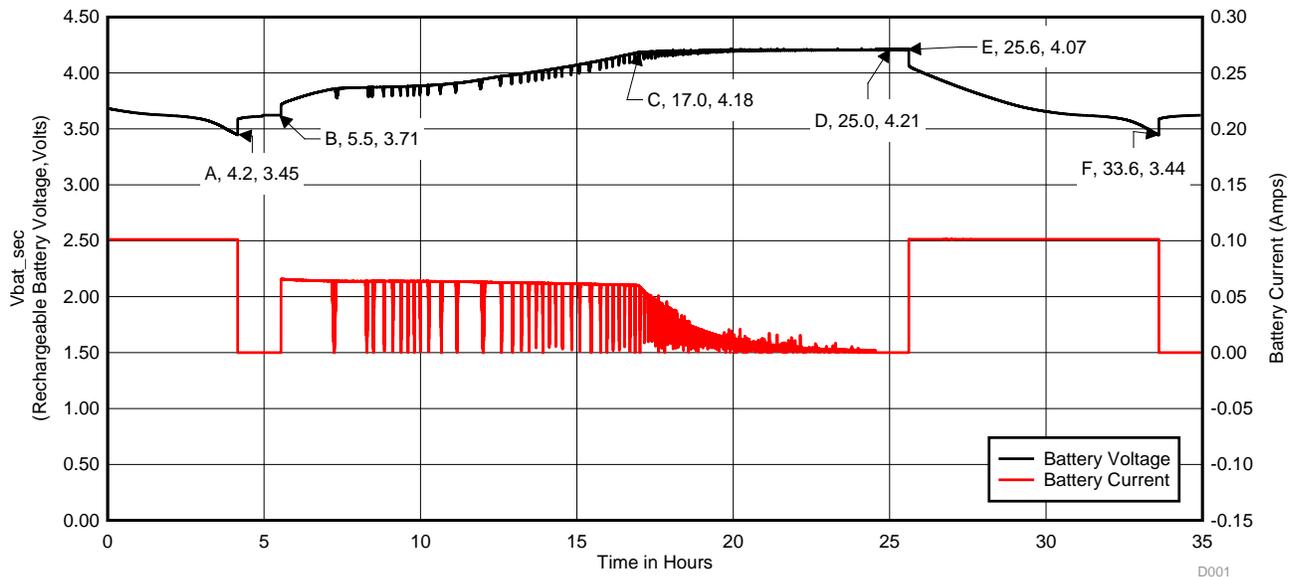
### 5.1.4 Li-Ion Battery Charging and Discharging

One complete cycle of charge and discharge is captured in this test. The battery voltage for fully charged and fully discharged conditions is 4.2 V and 3.3 V, respectively. The input to the bq25505 for a charging battery is 2.5 V, 120 mA. Once the battery is charged completely, it is discharged at a 100-mA constant current load to check the backup time. The bq25505 is configured to switch to the primary battery when the VSTOR voltage drops to 3.3 V. The maximum resistance between VBAT\_SEC and VSTOR of the bq25505 is 1.5 Ω. At a 100-mA load current, the VBAT\_SEC voltage at which load is switched to the primary battery is 3.3 V + (0.1 × 1.5) = 3.45 V.



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Figure 22. Test Setup for Battery Charging and Discharging



**Figure 23. Battery Charging and Discharging**

shows the charge and discharge cycle of the rechargeable battery using bq25505. At time  $t = 0$  hrs, the battery is discharging at a 100-mA constant current load. At  $t = 4.2$  hrs (Point A), when the VBAT\_SEC drops to 3.45 V, the load is switched to the primary battery. At  $t = 5.5$  hrs (Point B), the battery is getting charged at  $\approx 65$  mA of current. At  $t = 17$  hrs (Point C), VBAT\_SEC is at 4.18 V, reaching 65% of its total charge capacity. At  $t = 25$  hrs (Point D), the battery is completely charged. The total charge time from Point B to Point D is about 19.5 hrs. Assuming a peak sunny period of around 6 to 7 hrs in a day, it takes about 3 days to completely charge the battery. At  $t = 25.6$  hrs (Point E), the battery is discharged at a 100-mA constant current load. At  $t = 33.6$  hrs (Point F), the output load is switched to the primary battery, making the backup time at 8 hrs.

Extrapolating this data at a 1-mA load, the backup time is at minimum  $8 \times (100 \text{ mA} / 1 \text{ mA}) = 800$  hrs ( $\approx 33$  days) due to lower battery impedance at a lighter load discharge.

## 5.2 Energy Harvesting—CT Input

### 5.2.1 Start-up at 9-mA CT Secondary Current

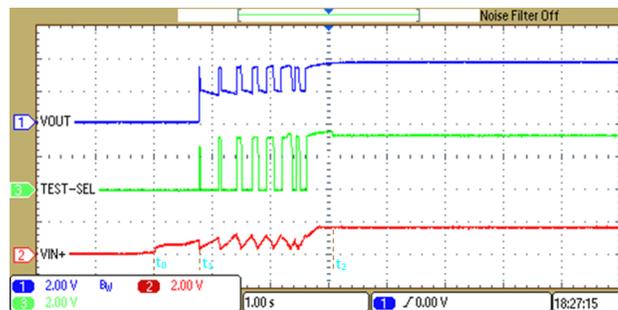
For the TIDA-00807 design during this test, JP2 is short to power the MCU, and the load switch of the TPS62740 (U10) should be in the off position.

1. Connect the CT-AC1020 (three primary turns) secondary to the CT-based energy harvesting subsystem at J3 and J4.
2. Connect the CT-based energy harvesting subsystem to the TIDA-00998 and TIDA-00807 boards as shown in [Table 10](#).

**Table 10. Test Setup Hardware Connections**

| BOARD      | FROM      | TO        |
|------------|-----------|-----------|
| AC1020     | Secondary | J3, J4    |
| TIDA-00807 | J5-1      | J7 (VOUT) |
|            | J5-2      | J8 (GND)  |
| TIDA-00998 | J2-2      | J7 (VOUT) |
|            | J5-2      | J8 (GND)  |

3. Apply a 5-A 50-Hz RMS current at the CT primary using PTS3.3C.
4. Measure  $V_{OUT}$  (CT-based energy harvesting subsystem),  $V_{in+}$  (CT-based energy harvesting subsystem), and TEST\_SEL (TIDA-00807).



**Figure 24. MCU (TIDA-00807) Wakeup at 9-mA CT Secondary Current**

At time  $t_0 = 0$  sec, CT is powered. As discussed in [Section 3.4.1](#), the voltage in  $V_{in+}$  is regulated to 2.5 V by the shunt regulator. At time  $t_1 = 0.8$  sec, voltage across  $V_{in+}$  reaches to 0.9 V, turning on the TPS61021 (boost converter with a 0.5-V ultra-low input voltage), which boosts the  $V_{in+}$  to 3.6 V. From time  $t_1$  to  $t_2$ , the MCU (of the TIDA-00807 design) and TPS61021 turns on and off before settling at time  $t_2 = 3.05$  sec.

### 5.2.2 CT-Based Energy Harvesting Subsystem—Supercapacitor Charging and Discharge

As discussed in [Section 3.4](#), the CT-based energy harvesting subsystem is used to harvest the energy using the CT. CT secondary is connected to the J3 and J4 connectors. The shunt regulator regulates the supercapacitor voltage to 2.5 V. On startup when the voltage across C3 (Vin+) reaches 0.9 V, the TPS61021 starts boost operating and boost the output voltage (V<sub>OUT</sub>) to 3.6 V.

Based on [Equation 13](#) to [Equation 17](#), a 10F supercapacitor can support 700 μA of load for 1.8 hours. Practical testing at 700uA of load at 3.6V given 1.7hours backup time. The difference between estimated and actual values is due to variation in leakage current and ESR of capacitor.

### 5.2.3 Power Mux Autoswitching Operation

To test the power mux autoswitching operation:

1. Apply 3.6-V DC at VBAT\_PRI.
2. Connect an external DC source at VIN\_CT and vary the voltage from 0 to 4.2 V and vice versa.
3. Verify VBAT\_PRI, VIN\_CT, VOUT\_PMUX, and STAT pin voltages.

Power mux switches to the primary battery when the CT input is dropped to 3.44 V and switches back to the CT input at 3.6 V. The STAT pin goes high when the output is fed from the primary battery.

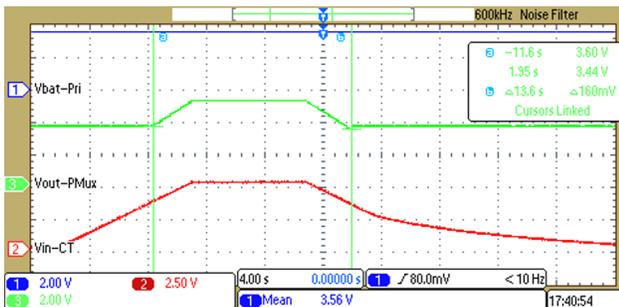


Figure 25. Power Mux Autoswitching Operation

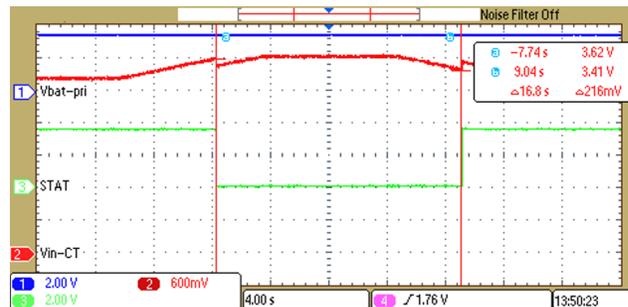


Figure 26. START Pin Verification

### 5.3 Fault Indication

#### 5.3.1 LP55231 Efficiency Powered by 3.6-V Battery

To test the LP55231 efficiency:

1. See [Section 4.1.1](#) to [Section 4.1.3](#) to connect the LaunchPad to the TIDA-00998 board.
2. Apply 3.3-V DC at VIN\_DRIVER using an external DC power supply.
3. Follow the steps in [Section 4.2.2](#) to Enable LP55231 (see [Section 4.2.6](#) for LP55231 control using UART) D1, D3, and D5 channel outputs and set the LED current to 20 mA.
4. Record the input voltage, current, and LED forward voltage and current.
5. Repeat Steps 1 to 4 at 3.6-V, 4-V, and 4.2-V input voltages.
6. Repeat Steps 1 to 5 by enabling D7, D8, and D9 channels only.

**Table 11. LP55231 Efficiency With VAOL-S2WR4 White LED (D1, D3, D5 Enable)**

| SERIAL NO | CURRENT SETTING (mA) | ACTUAL LED CURRENT (mA) | INPUT CURRENT (mA) | INPUT VOLTAGE (V) | V_LED (V) | EFFICIENCY |
|-----------|----------------------|-------------------------|--------------------|-------------------|-----------|------------|
| 1         | 20                   | 19.866                  | 59.690             | 3.3               | 3.113     | 94.19%     |
| 2         | 20                   | 19.947                  | 59.954             | 3.6               | 3.113     | 86.31%     |
| 3         | 20                   | 19.992                  | 60.191             | 4.0               | 3.113     | 77.55%     |
| 4         | 20                   | 20.017                  | 60.306             | 4.2               | 3.113     | 73.81%     |

**Table 12. LP55231 Efficiency With HSMZ-A400-V39M1 Red LED (D1, D3, D5 Enable)**

| SERIAL NO | CURRENT SETTING (mA) | ACTUAL LED CURRENT (mA) | INPUT CURRENT (mA) | INPUT VOLTAGE (V) | V_LED (V) | EFFICIENCY |
|-----------|----------------------|-------------------------|--------------------|-------------------|-----------|------------|
| 1         | 20                   | 19.926                  | 60.868             | 3.0               | 2.271     | 0.7434%    |
| 2         | 20                   | 19.974                  | 61.052             | 3.3               | 2.249     | 0.6689%    |
| 3         | 20                   | 20.015                  | 61.234             | 3.6               | 2.249     | 0.6126%    |
| 4         | 20                   | 20.069                  | 61.470             | 4.0               | 2.253     | 0.5517%    |
| 5         | 20                   | 20.093                  | 61.590             | 4.2               | 2.256     | 0.5257%    |

**Table 13. LP55231 Efficiency With LNJ8L6C18RA Red LED (D7, D8, D9 Enable)**

| SERIAL NO | CURRENT SETTING (mA) | ACTUAL LED CURRENT (mA) | INPUT CURRENT (mA) | INPUT VOLTAGE (V) | V_LED (V) | EFFICIENCY |
|-----------|----------------------|-------------------------|--------------------|-------------------|-----------|------------|
| 1         | 20                   | 19.889                  | 60.817             | 3.3               | 2.038     | 0.6059%    |
| 2         | 20                   | 19.934                  | 60.980             | 3.6               | 2.038     | 0.5552%    |
| 3         | 20                   | 19.985                  | 61.186             | 4.0               | 2.038     | 0.4992%    |
| 4         | 20                   | 20.011                  | 61.287             | 4.2               | 2.038     | 0.4753%    |

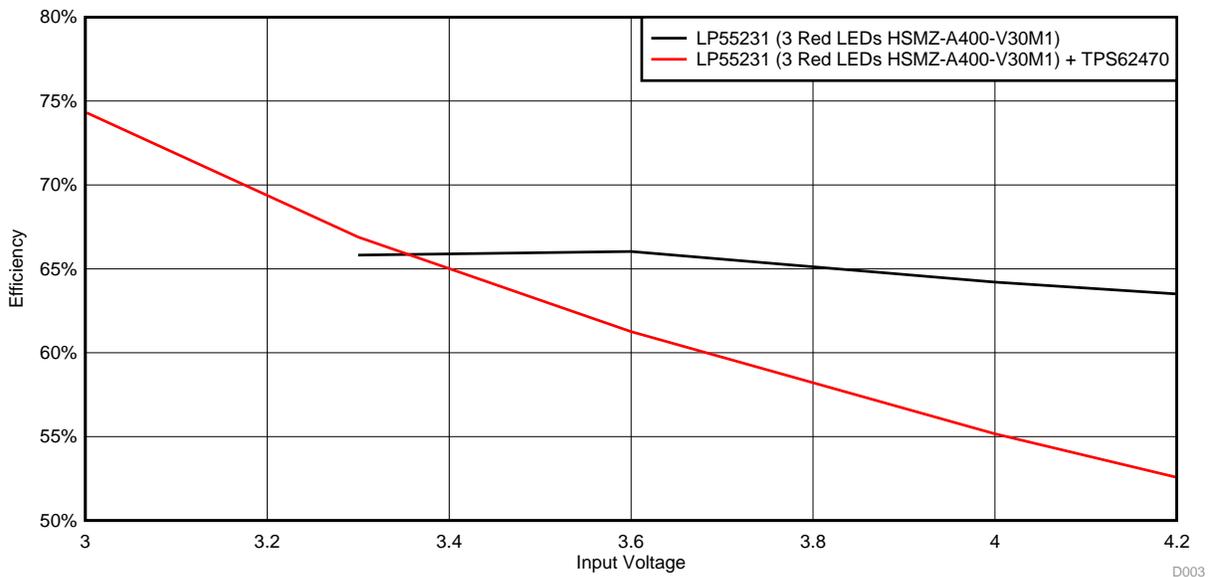
### 5.3.2 LP55231 Efficiency Powered by 3.6-V Battery + TPS62740 (Regulated to 3 V)

To test the LP55231 + TPS62740 efficiency:

1. Remove R49 and R50. Populate R53 and R54 with 0  $\Omega$  to configure the TPS62740 (U10) output to 3 V in the TIDA-00807 design.
2. Connect  $V_{CC}$  (Pin 1 of J1 connector) of the TIDA-00807 to VIN\_DRIVER (Pin 2 of J2 connector) in the TIDA-00998.
3. Apply 3.3 V at J5 Pin 1 of the TIDA-00807 using an external power supply.
4. Follow the steps in [Section 4.2.2](#) to enable LP55231 (see [Section 4.2.6](#) for LP55231 control using UART) D1, D3, and D5 channel outputs and set the LED current to 20 mA.
5. Record the input voltage, current, and LED forward voltage and current.
6. Repeat Steps 1 to 5 at 3.6-V, 4-V, and 4.2-V input voltages.

**Table 14. LP55231 Efficiency With HSMZ-A400-V39M1 Red LED + TPS62740 (D1, D3, D5 Enable)**

| SERIAL NO | CURRENT SETTING (mA) | ACTUAL LED CURRENT (mA) | INPUT CURRENT (mA) | INPUT VOLTAGE (V) | V_LED (V) | EFFICIENCY |
|-----------|----------------------|-------------------------|--------------------|-------------------|-----------|------------|
| 1         | 20                   | 19.918                  | 61.873             | 3.3               | 2.249     | 0.6582%    |
| 2         | 20                   | 19.918                  | 56.532             | 3.6               | 2.249     | 0.6603%    |
| 3         | 20                   | 19.918                  | 52.326             | 4.0               | 2.249     | 0.6421%    |
| 4         | 20                   | 19.918                  | 50.386             | 4.2               | 2.249     | 0.6350%    |



**Figure 27. LP55231 + TPS62740 Efficiency**

The rechargeable battery voltage varies from 3.3 to 4.2 V based on the battery charge level. The efficiency of the LP55231 reduces at higher input voltages. To increase efficiency, the LP22331 is powered from the buck converter TPS62070 in the TIDA-00807 design, which regulates the output voltage to 3 V. At a 4.2-V input voltage, the efficiency of LP55231 + TPS62740 is higher by 10.9%, then driving the LP55231 directly from the bq25505 output.

### 5.3.3 LM3509 Efficiency Powered by 3.6-V Battery

To test the LM3509 efficiency:

1. Follow the steps in [Section 4.1.1](#) to [Section 4.1.3](#) to connect the LaunchPad to the TIDA-00998 board.
2. Apply 3.3-V DC at VIN\_DRIVER using an external DC power supply.
3. Follow the steps in [Section 4.2.3](#) to enable LM3509 (see [Section 4.2.6](#) for LM3509 control using UART) MAIN/SUB channel outputs and set the LED current to 30 mA. Apply 3.3 V at J5 Pin 1 of the TIDA-00807 using an external power supply.
4. Record the input voltage, current, and output voltage and current
5. Record the input voltage, current, and LED forward voltage and current.
6. Repeat [Steps 1 to 4](#) at 3.6-V, 4-V, and 4.2-V input voltages.

**Table 15. LM3509 Efficiency With Only Main Enable**

| SERIAL NO | CURRENT SETTING (mA) | ACTUAL LED CURRENT (mA) | INPUT CURRENT (mA) | INPUT VOLTAGE (V) | V_LED (V) | EFFICIENCY |
|-----------|----------------------|-------------------------|--------------------|-------------------|-----------|------------|
| 1         | 30                   | 29.885                  | 121.16             | 3.3               | 10.79     | 0.8065%    |
| 2         | 30                   | 29.902                  | 109.57             | 3.6               | 10.78     | 0.8172%    |
| 3         | 30                   | 29.893                  | 116.34             | 4.0               | 11.37     | 0.7304%    |
| 4         | 30                   | 29.909                  | 107.56             | 4.2               | 11.33     | 0.7501%    |

**Table 16. LM3509 Efficiency With Only Sub Enable**

| SERIAL NO | CURRENT SETTING (mA) | ACTUAL LED CURRENT (mA) | INPUT CURRENT (mA) | INPUT VOLTAGE (V) | V_LED (V) | EFFICIENCY |
|-----------|----------------------|-------------------------|--------------------|-------------------|-----------|------------|
| 1         | 30                   | 29.765                  | 120.730            | 3.3               | 10.79     | 0.8061%    |
| 2         | 30                   | 29.776                  | 109.110            | 3.6               | 10.78     | 0.8172%    |
| 3         | 30                   | 29.770                  | 115.670            | 4.0               | 11.36     | 0.7309%    |
| 4         | 30                   | 29.779                  | 106.876            | 4.2               | 11.31     | 0.7503%    |

### 5.3.4 LED Intensity Control Verification

In this test, ambient light is varied to check the LED driver current is set as defined in [Section 4.2.5](#). When the ambient light intensity is low, LED current is minimum to decrease the brightness. When the ambient light intensity is high, LED current is maximum to increase the brightness.

**Table 17. LED Intensity Control Verification**

| SERIAL NO | LED DRIVER | DESCRIPTION   | VERIFIED |
|-----------|------------|---|----------|
| 1         | LP55231    | Ambient light: Lux < 50, LED current set to 10 mA       | OK       |
| 2         |            | Ambient light: 50 > Lux < 700, LED current set to 15 mA | OK       |
| 3         |            | Ambient light: 50 > Lux > 700, LED current set to 20 mA | OK       |
| 4         | LM3506     | Ambient light: Lux < 50, LED current set to 5 mA        | OK       |
| 5         |            | Ambient light: 50 > Lux < 700, LED current set to 15 mA | OK       |
| 6         |            | Ambient light: 50 > Lux > 700, LED current set to 30 mA | OK       |

## 6 Design Files

### 6.1 Schematics

To download the schematics, see the design files at [TIDA-00998](#).

### 6.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-00998](#).

### 6.3 Layout Prints

To download the layout prints for each board, see the design files at [TIDA-00998](#).

### 6.4 Altium Project

To download the Altium project files, see the design files at [TIDA-00998](#).

### 6.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-00998](#).

### 6.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-00998](#).

## 7 Software Files

To download the software files, see the design files at [TIDA-00998](#).

## 8 Related Documentation

1. HW Group, [Hercules Setup Utility](http://www.hw-group.com/products/hercules/index_en.html), UART Tool ([http://www.hw-group.com/products/hercules/index\\_en.html](http://www.hw-group.com/products/hercules/index_en.html))

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## Revision History

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

| <b>Changes from Original (April 2017) to A Revision</b> | <b>Page</b> |
|---|-------------|
| • Changed <a href="#">Figure 3</a> .....                | <b>11</b>   |

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