TI Designs: TIDA-01385

Energy Harvesting From Current Transformer With Supercapacitor for Fault Indicator Reference Design

Description

The TIDA-01385 design introduces a circuit to harvest energy from a current transformer for the system load of a fault indicator while storing the extra energy in a 2.7-V supercapacitor. A primary Li/SOCl2 battery is used as backup power to extend the operating time of the fault indicator after the power grid fails. With an input current from 3 mA to 2 A, this TI Design provides a stable 3.6 V to the system load within 2 seconds after the current transformer is connected.

Resources

TIDA-01385	Design Folder
TPS61021A	Product Folder
TLV3492	Product Folder
ATL431A	Product Folder
CSD13202Q2	Product Folder
CSD25310Q2	Product Folder
TIDA-00998	Design Folder

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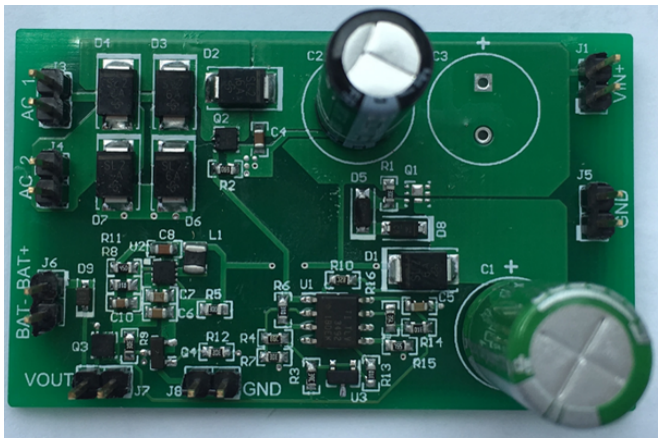
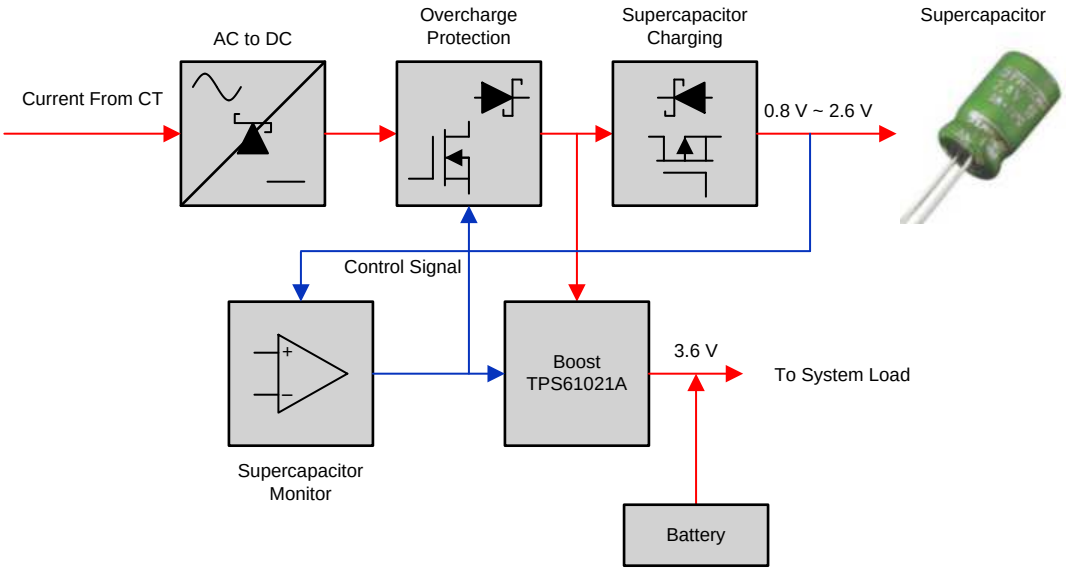
Features

- Harvests Energy From Current Transformer
- Automatic Charging Supercapacitor With Extra Energy
- Provides Stable Output Voltage Within 2 Seconds
- Supercapacitor Full Charged Protection
- Ultra-low Input Boost Converter for Using Maximum Supercapacitor Stored Energy

Applications

- Fault Indicators





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1 System Description

A fault indicator is a device used in electric power distribution networks to detect and indicate fault conditions. The fault indicators reduce operating costs and service interruptions by providing information on the section of the network that has failed. To quickly identify the fault type and location, the latest fault indicator is required to record the operating data of the power networks, which is sent to the data concentrator with low-power wireless communication when necessary.

The power supply for the fault indicator is an energy harvesting device with the primary battery as backup. The energy harvesting devices could be the current transformer (CT) or solar cell. Because the energy from a CT varies with the current through the power lines or from solar cell changes with sunlight condition, an energy buffer such as a supercapacitor or rechargeable battery is required to provide stable power supply. The primary battery should be long shelf life (>10 year) lithium or lithium-ion based cells, such as a Li/SOCl2 battery, considering the long lifetime of the fault indicator.

This reference design introduces a circuit to harvest energy from a CT to charge a supercapacitor and provide stable power for the system load. The backup primary battery is the Li/SOCl2. For another reference design about energy harvesting in this application field, see the TIDA-00998 design.

1.1 Key System Specifications

Table 1 summarizes the key specifications for the TIDA-01385 design. The supercapacitor capacity can be selected based on real requirement without impacting the performance of the reference design.

Table 1. Key System Specifications

PARAMETER	DESCRIPTION
CT input current	CT secondary peak current range of 3 mA to 2 A
Supercapacitor backup time	100 seconds with a 10-F capacitance and 50-mA load current
Output voltage	3.6 V when powered from the CT and supercapacitor
	3 to 3.3 V when powered from the primary battery
Output voltage startup time	2 seconds (typical)

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2 System Overview

2.1 Block Diagram

The block diagram of the TIDA-01385 is shown in Figure 1. The power input is from the secondary side of the CT. The maximum input current of the CT should be lower than 2 A. The minimum input current depends on the system load requirement. Normally it should be higher than 3 mA.

The function of the each block is as follows:

- The AC to DC is a full-bridge rectifier, transferring the AC input current into DC current.
- The overcharge protection circuit shorts the current from the CT to ground when the supercapacitor is fully charged. The circuit becomes inactive and the current charges the supercapacitor again if the supercapacitor voltage is lower than a voltage threshold.
- The supercapacitor charging circuit charges the supercapacitor only when the input voltage is higher than 1.6 V, which is high enough for the operation of the TPS61021A. So all the energy from the CT can be used for the system load even if the supercapacitor voltage is zero.
- The supercapacitor monitor circuit controls the protection circuit to prevent the supercapacitor from overcharge.
- The boost converter TPS61021A boosts the low input voltage to 3.6 V for the system load. The 3.6-V voltage can prevent the battery from discharge during normal operating condition.
- The battery is a Li/SOCl2 battery and connected to a 3.6-V power rail through a Schottky diode in series. The battery can support system load when the power grid fails and the supercapacitor is out of charge.

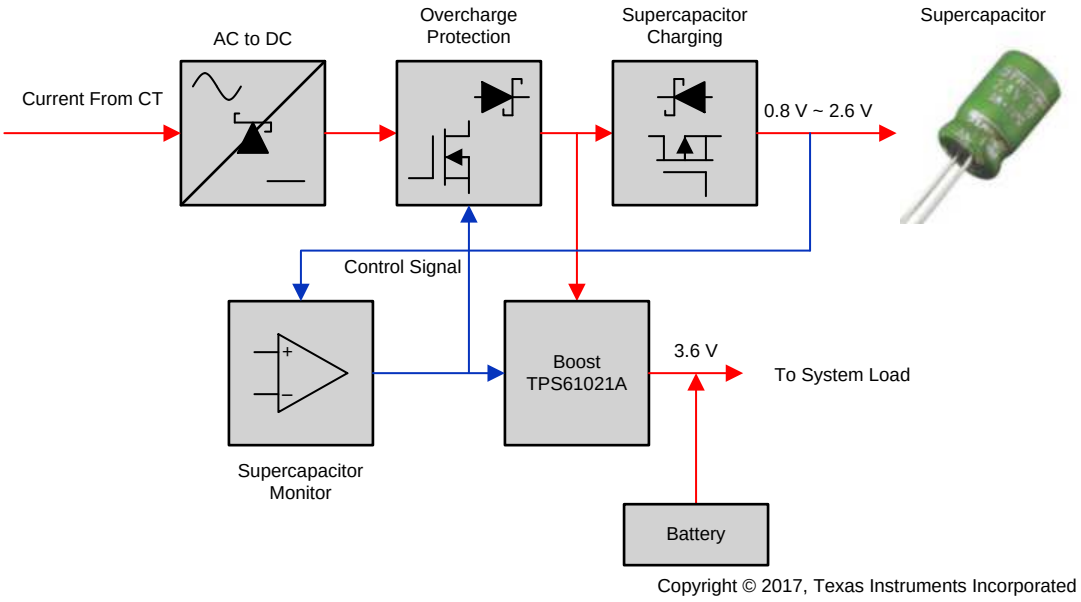

Figure 1. Block Diagram of TIDA-01385

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2.2 Highlighted Products

The reference design features the TPS61021A, TLV3492, ATL431, CSD13202Q2, and CSD25310Q2. The following subsections briefly summarize the key performance of each device. To find more details about each device, see their respective datasheets at TI.com.

2.2.1 TPS61021A

The TPS61021A is an ultra-low input voltage device. The device can operate with an input voltage between 0.5 and 4.4 V after it finishes startup from a 0.9-V input voltage. The wide input voltage range makes it suitable in the application that is powered by the signal-cell supercapacitor. Other key features of this device include:

- 17-µA typical quiescent current
- PFM operation mode at light load
- Output overvoltage protection
- Output short-circuit protection
- 2-mm×2-mm WSON package
- True disconnection between input and output during shutdown

2.2.2 TLV3492

The TLV3492 is a 1.8-V, nano-power, dual push-pull comparator. The small power consumption helps to minimize the power loss of the reference design. The push-pull output can reduce the external components to drive the MOSFET. Other key features of this device include:

- Very low supply current: 0.8 µA (typical)
- Input common-mode range: 200-mV beyond supply rails
- Supply voltage: 1.8 to 5.5 V
- High speed: 6 µs
- Push-pull CMOS output stage

2.2.3 ATL431

The ATL431 is an adjustable, three-terminal shunt regulator with low quiescent current. The device is offered in two grades, with initial tolerances (at 25°C) of 0.5%, 1%, for the B and A grade, respectively. The reference design selects the grade device ATL431A. Other key features of this device include:

- Adjustable regulated output: 2.5 to 36 V
- Very-low operating current
- Internally compensated for stability
- Extended cathode current range: 35 µA to 100 mA

2.2.4 CSD13202Q2 and CSD25310Q2

The CSD13202Q2 is a 12-V N-Channel power MOSFET. Its continue drain current is up to 14 A. Its gate-to-source threshold voltage is typically 0.8 V and the drain-to-source on-resistance is only 9.1 mR at a 2.5-V driving voltage.

The CSD25310Q2 is a 20-V P-Channel power MOSFET. The gate-to-source threshold voltage of this device is typically 0.85 V. The drain-to-source on-resistance is 27 mR at a 2.5-V driving voltage. The device has low thermal resistance and up to 150°C maximum operating junction temperature.

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2.3 System Design Theory

The entire schematic of the TIDA-01385 can be found in the TIDA-01385 design folder. The following subsections explain the behavior of each subcircuit.

2.3.1 Rectifier and Overcharge Protection

The circuit shown in Figure 2 is used for rectifying the AC to input DC voltage and protecting the supercapacitor from overcharge. The full-bridge rectifier is composed of four Schottky diodes. The current capability of the Schottky diodes should be higher than maximum input current, which is 2 A in this reference design. The maximum voltage rating of diode must be higher than 5 V.

The N-type MOSFET Q2 is used to protect the supercapacitor from overcharging. When supercapacitor voltage is lower than setting limit 2.6 V, the Q2 opens, so the current flows through the D2 to power the system load and charge the supercapacitor. After the supercapacitor voltage reach 2.6 V, the Q2 turns on to short the input current into ground. When the supercapacitor is discharged to a setting value of 2.4 V by the load, Q2 opens again.

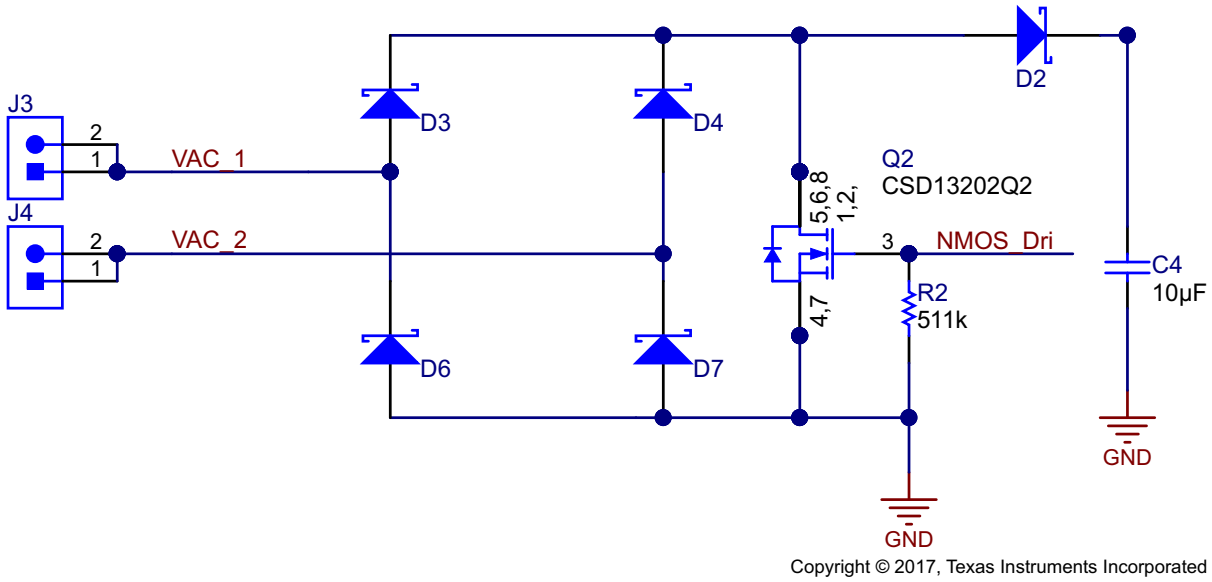

Figure 2. Rectifier and Overcharge Protection

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2.3.2 Supercapacitor Charging

The supercapacitor charging circuit is shown in Figure 3. The function of the circuit is limiting the charging current according to the input voltage VIN+. The minimum voltage to charge the supercapacitor is defined by Equation 1:

$$V_{IN+MIN} = V_{GS_th} + 2 \times V_D \quad (1)$$

Where:

- V_{GS_th} is the gate-to-source threshold voltage of the P-FET Q1
- V_D is the forward voltage of the D5 and D8

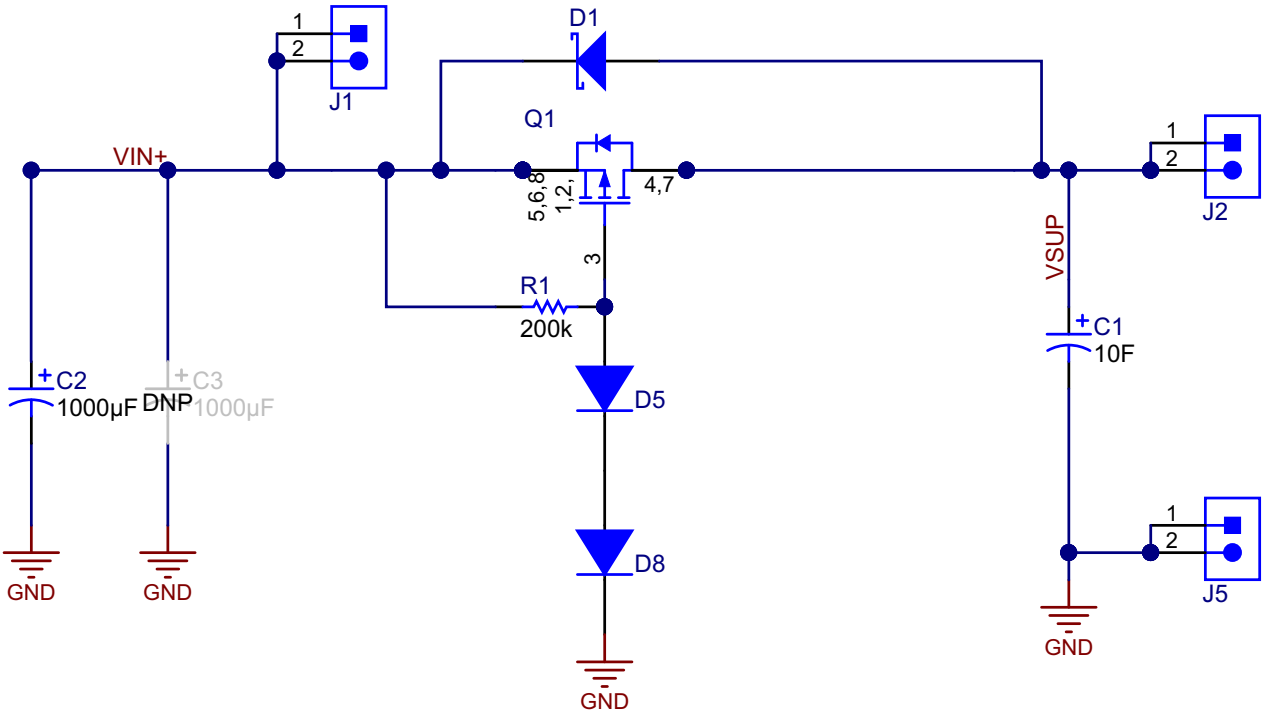

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Figure 3. Schematic of Supercapacitor Charging Circuit

V_{GS_th} increases with the current flowing through the MOSFET channel (I_{DS}). V_{GS_th} is 0.8 V when the P-FET starts to conduct and is approximately 1.3 V when I_{DS} is 2 A. V_D also increases with the forward current. V_D is approximately 0.4 V if several microamps flow through it. Therefore, the minimum voltage to charge the supercapacitor V_{IN+_MIN} is 1.6 V. No current flows through Q1 if VIN+ is lower than 1.6 V.

When input current is 2 A, V_{GS_th} will be approximately 1.3 V, so the VIN+ is 2.1 V even the supercapacitor is 0 V. The power loss in Q1 could reach 4 W at this condition. In the PCB layout, make sure the junction temperature of Q1 is not higher than 150°C for this short period.

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2.3.3 Boost Converter Solution

The schematic of the boost converter solution TPS61021A is shown in Figure 4. Most of the external components are selected based on the suggestion in the datasheet. The feed-forward capacitor C10 can help to extend the startup time of the boost converter. Long startup time reduces the inrush input current. This helps the reference design start up easily when the input current from the CT is weak. However, the feed-forward capacitor impacts the stability of the TPS61021A, so the system load current should be not higher than 50 mA.

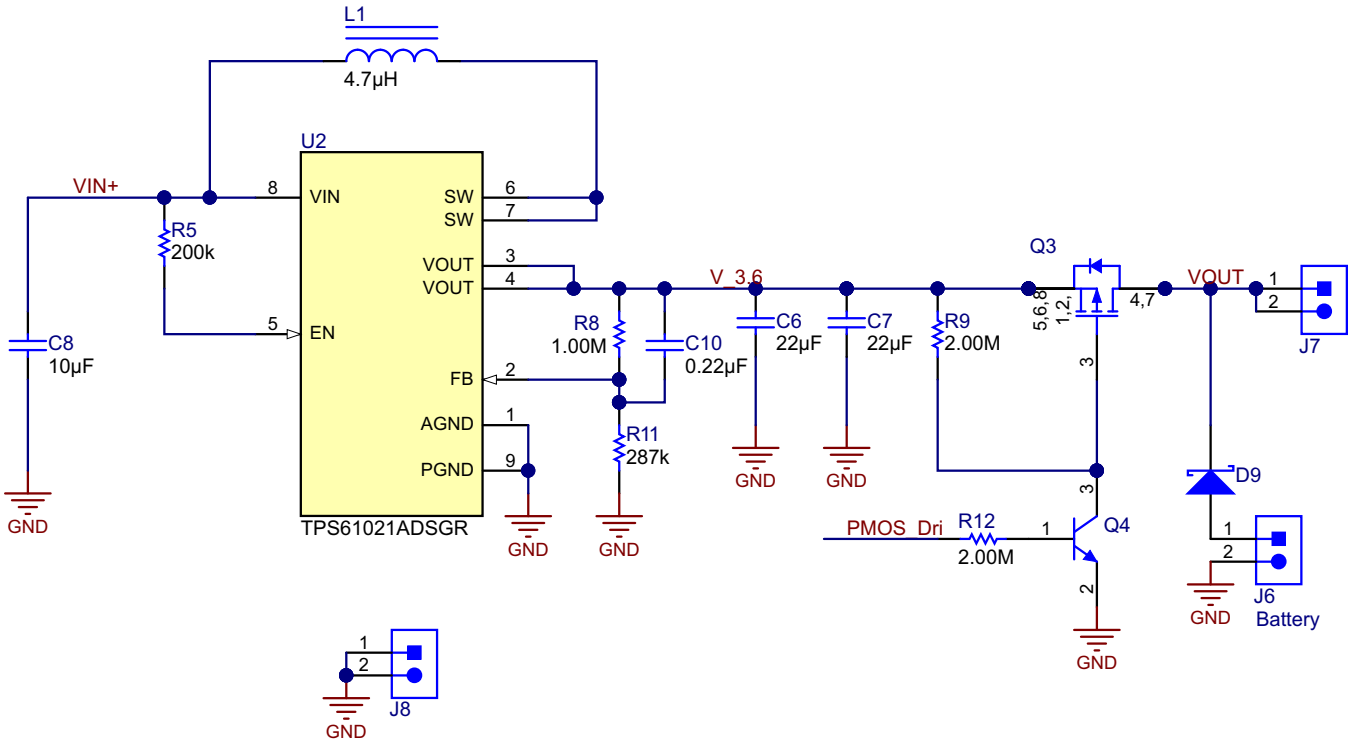

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Figure 4. Schematic of Boost Converter Solution

The P-type MOSFET Q3 and NPN transistor Q4 in Figure 4 closes only when the output voltage of the TPS61021A is higher than 3.3 V. This function is designed to prevent the system loads from operating at a low-voltage condition. Some system loads may consume large current when the voltage is closed to their minimum operating voltage. The large current requirement could cause the startup of the circuit to fail if the input current of the CT is weak. Depending on the performance in real applications, this function can be removed.

The 3.6-V primary battery is connected VOUT rail through a Schottky diode. No current flows out of the battery when the boost converter is working. After the power lines fail and the supercapacitor is out of charge, the Schottky diode starts to conduct and maintain the VOUT voltage at 3.3 V to about 3 V, which is related to the load condition. The Schottky diode can be replaced by a power multiplexer such as TPS211xA family devices for better performance. See Section 3.2 of the TIDA-00998 design guide for more information (TIDUCL5).

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2.3.4 Supercapacitor Protection Circuit

Figure 5 shows the schematic for the supercapacitor protection and system load starting voltage. U3 is a shunt regulator with low quiescent current that provides a 2.5-V reference voltage. U1A is used to drive the Q2 and control the supercapacitor voltage. U1B is used to control the voltage to turn on Q3.

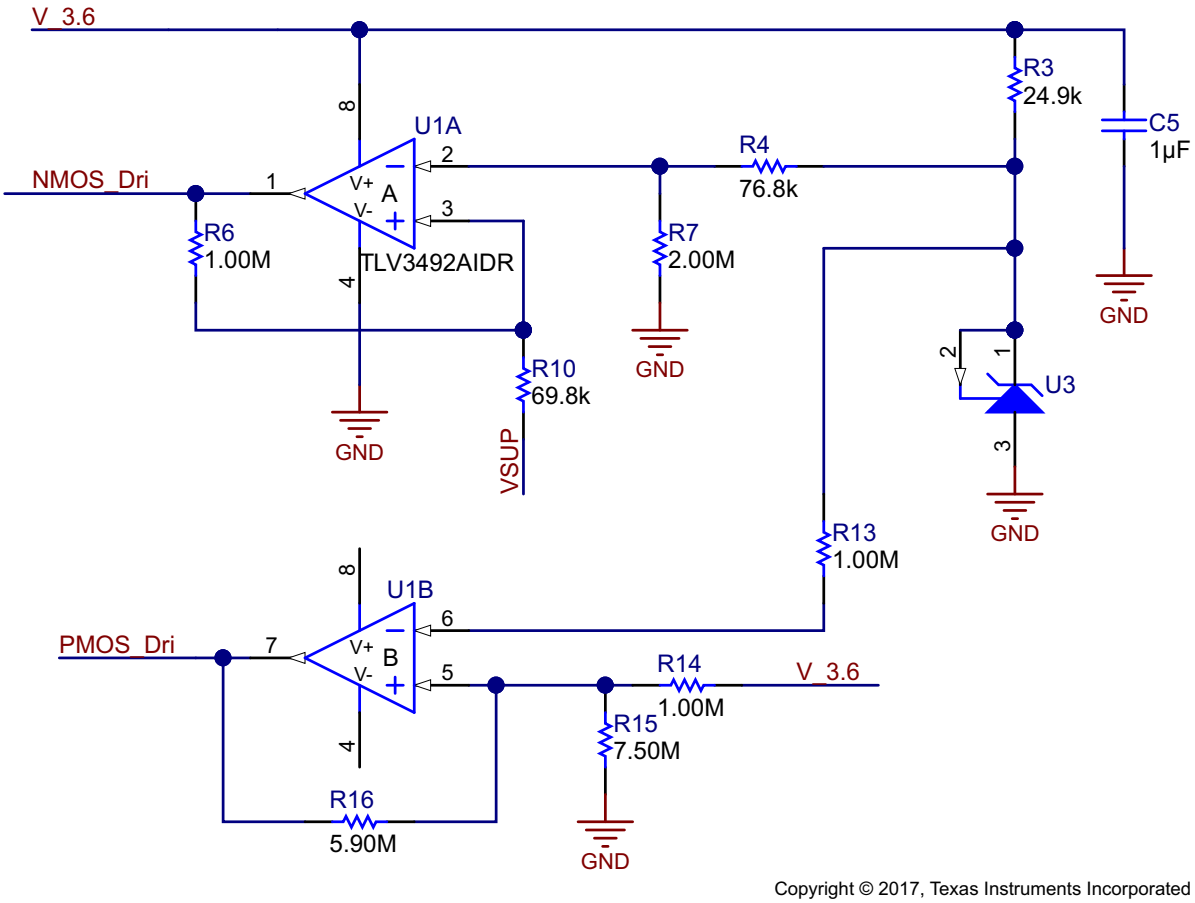

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Figure 5. Schematic of Supercapacitor Protection Circuit

The overcharge protection voltage is set by Equation 2, and the recharging voltage is set by Equation 3:

$$V_{SUP_OV} = 2.5 \times \frac{R_7}{R_4 + R_7} \times \frac{R_6 + R_{10}}{R_6} \quad (2)$$

$$V_{SUP_OV} = \left(2.5 \times \frac{R_7}{R_4 + R_7} - 3.6 \times \frac{R_{10}}{R_6 + R_{10}}\right) \times \frac{R_6 + R_{10}}{R_6} \quad (3)$$

In the U1B circuit of Figure 5, R15 is added to make sure the positive input voltage is lower than the negative input voltage at the beginning of V_3.6 startup. As defined by Equation 4 and Equation 5, U1B outputs high voltage if the V_3.6 voltage is higher than V_3.6_H; U1B outputs low voltage if the V_3.6 voltage is lower than V_3.6_L.

$$V_3.6_H = 2.5 \times \left(\frac{R_{15} \times R_{16}}{R_{15} + R_{16}} + R_{14}\right) \div \frac{R_{15} \times R_{16}}{R_{15} + R_{16}} \quad (4)$$

$$V_3.6_L = 2.5 \times \left(\frac{R_{14} \times R_{16}}{R_{14} + R_{16}} + R_{15}\right) \div R_{15} \quad (5)$$

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3 Getting Started Hardware

The functions of the connectors are described in Table 2.

Table 2. Function of Connectors

CONNECTORS	DESCRIPTION
J1	Input voltage of the boost converter and the supercapacitor charging circuit
J2	Supercapacitor voltage
J3, J4	CT input
J5, J8	Ground of the supercapacitor
J6	Primary battery
J7	Reference design output

To demonstrate the energy harvest and the supercapacitor charging circuit function, the primary battery is not attached during the following bench test. Connect J3 and J4 to the secondary side of the CT or simulation current source. Connect the J7 and J8 to the system load. The circuit starts to operate if there is current flowing into J3 and J4.

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4 Testing and Results

4.1 Startup With Supercapacitor Out of Charge

Using a DC current source to simulate the CT and the rectifier, the startup waveform is shown in Figure 6 when the average input current is 3 mA. The supercapacitor voltage is zero, so the reference design is powered by the energy from the CT. The TPS61021 starts operating when the VIN+ reaches 0.9 V. The output voltage of the TPS61021A V_3.6 ramps up to 3.6 V within one second. The Q3 closes as V_3.6 reaches 3.3 V, so the VOUT ramps up to 3.3 V quickly and then follows the V_3.6. At the beginning, VOUT rushes to 1 V for a short period because Q3 conducts when the power for the comparator is not ready. After VOUT is stable at 3.6 V, VIN+ also becomes stable at approximately 1.6 V. This voltage is the minimum amount to charge the supercapacitor.

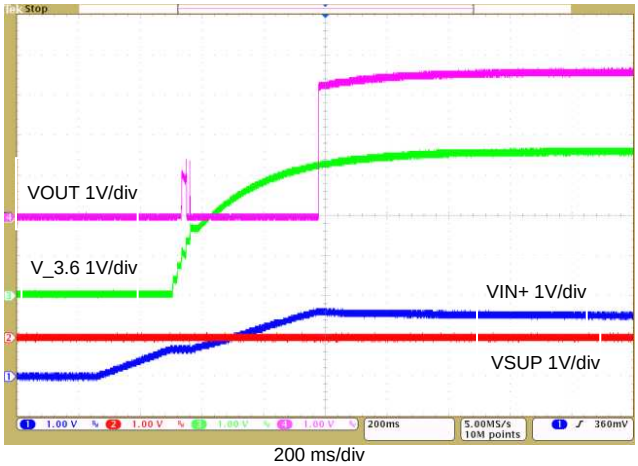

Figure 6. Startup With 3-mA Input Current and 4-kΩ Load

4.2 Supercapacitor Overvoltage Protection

The supercapacitor overcharge voltage and the recover voltage can be simply measured by removing the supercapacitor or applying a large charging and discharging current to the reference design. When the supercapacitor is removed and the input current is 3 mA, the stable waveform is shown in Figure 7. The supercapacitor stops charging when the VSUP reaches 2.6 V. The VSUP starts charging again when the voltage falls below 2.4 V. The VOUT keeps stable during this period.

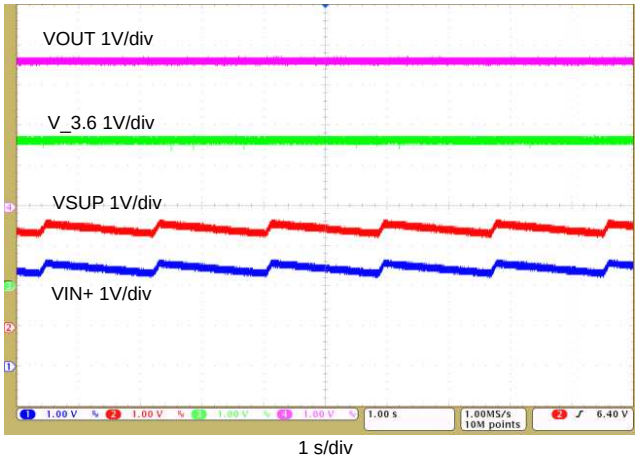

Figure 7. Overcharge Protection Measurement With 3-mA Input Current

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At a 2-A input current condition, the operating waveform is shown in Figure 8. The VSUP slowly drop down to 2.4 V by the 50-mA load, then the 10-F supercapacitor starts charging. The VSUP ramps up quickly because of the large input current. When VSUP reaches 2.6 V, the supercapacitor stops charging. As a result, VSUP decreases toward 2.4 V again. VOUT keeps stable during this period.

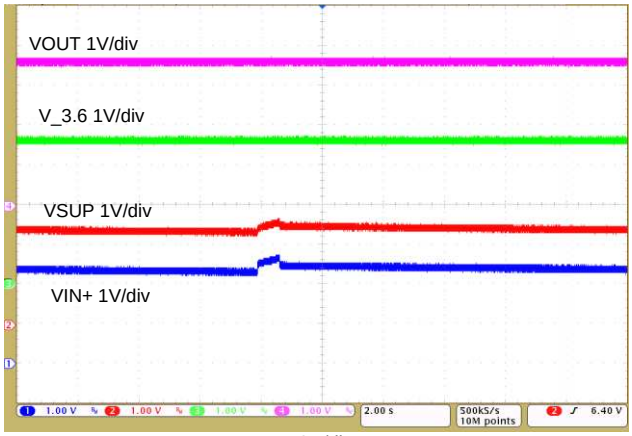

Figure 8. Overcharge Protection Measurement With 2-A Input Current

4.3 Supercapacitor Charging and Discharging

Figure 9 shows the waveform that supercapacitor voltage ramps from 0 to 2.6 V with a 500-mA input current. The supercapacitor voltage stops charging if the voltage reaches 2.6 V. The output voltage keeps stable during the charging period.

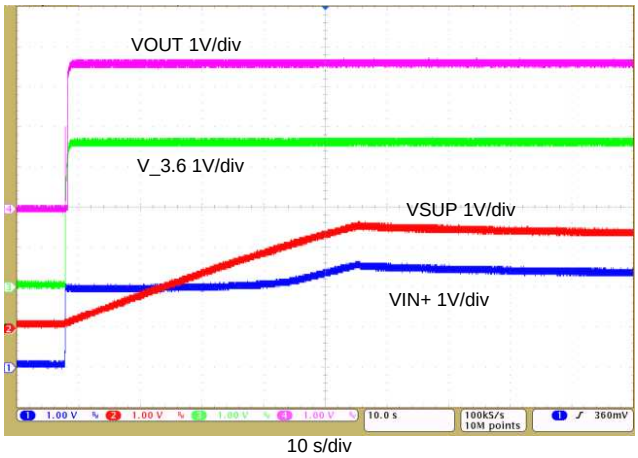

Figure 9. Supercapacitor Charging With 500-mA Input Current

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Figure 10 shows the discharge waveform of the supercapacitor by a 50-mA load at the VOUT after the CT input is removed. The minimum supercapacitor voltage is 0.8 V, at which condition VOUT becomes out of regulation.

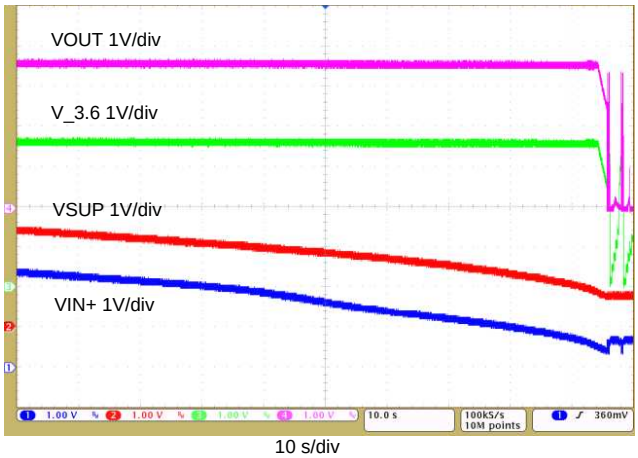

Figure 10. Supercapacitor Discharge Waveform With 50-mA Load

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5 Design Files

5.1 Schematics

To download the schematics, see the design files at TIDA-01385.

5.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01385.

5.3 Layout Prints

To download the layer plots, see the design files at TIDA-01385.

5.4 Altium Project

To download the Altium project files, see the design files at TIDA-01385.

5.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01385.

5.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01385.

6 Related Documentation

This design guide did not use any related documentation.

6.1 Trademarks

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7 About the Author

JASPER LI is a power application engineer for the Texas Instruments Boost Converter Solution Group. In this role, he supports worldwide customers, writes application notes, and develops reference designs. Since 2013 his focus has been on ultra-low-power applications. Jasper received his master's degree in power electronics in 2013 at Zhejiang University in China.

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