Application Report
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PMP9766 Test Report — Supercapacitor Backup Power Supply With Active Cell Balancing

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ABSTRACT

A backup power supply is an electrical system that provides emergency power to a load when the main power source fails. An appropriate backup power supply provides instantaneous protection from main power interruptions without glitches, by supplying energy which is stored in backup capacitors or batteries. Such backup power supplies are typically used to protect hardware such as telecommunication equipment, solid-state drives (SSDs), storage systems, industrial equipment, or other electrical equipment, where an unexpected power disruption can cause malfunction or data loss.

This application report describes a circuit which addresses instantaneous protection of main power interruptions by using a buck-boost converter and two stacked supercapacitors with active cell balancing. The converter is required between the supercapacitor and the system supply-voltage rail because the supercapacitor's voltage varies. The report also provides the design, schematic, key components, and measurement results showing the performance of the circuit.

1 System Design Overview

In this design, the backup power circuit is based on the TPS63020, a highly-efficient, synchronous, single-inductor, buck-boost converter. Figure 1 shows a simplified block diagram of the circuit.

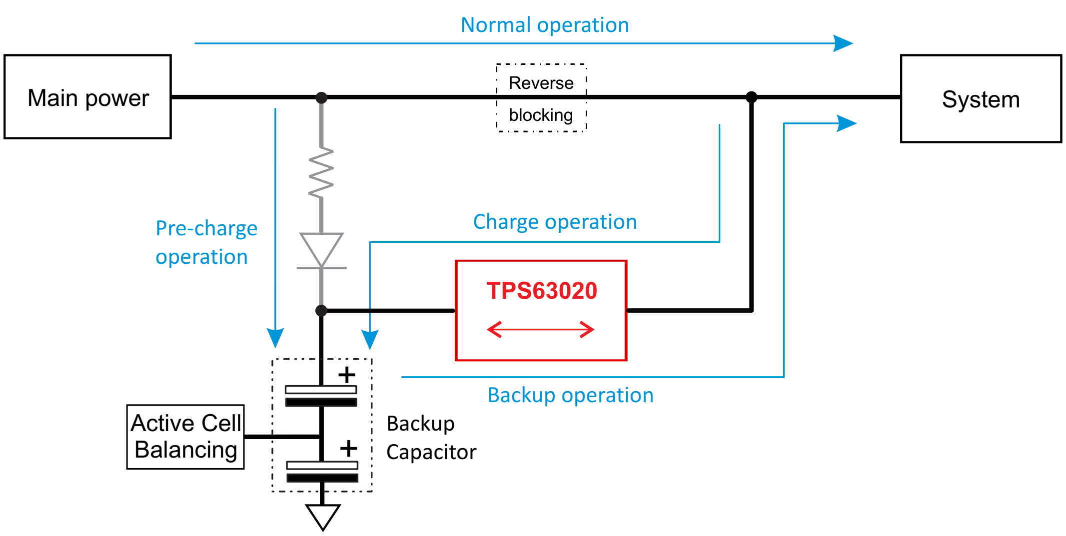

Figure 1. Simplified Block Diagram of the Backup Power System

During normal operation, the main power is directly connected to the system and the backup capacitor is charged using the TPS63020 buck-boost converter. During backup operation, the buck-boost converter supplies the system directly from the backup capacitor. The TPS63020 buck-boost converter supports energy transfer from the input to the output, as well as from the output to the input. With this bidirectional operation, the TPS63020 charges and discharges the backup capacitor in a very efficient and controlled way. Charging the backup capacitor to a voltage level higher than the main power voltage results in a smaller backup capacitor value and smaller solution size to store the same amount of energy. The usable energy stored in the backup capacitor is only limited by the maximum voltage of the buck-boost converter, which is 5.5 V for the TPS63020. Higher voltages are given by the PMP9761 reference design.

The objective of the circuit is to charge the backup capacitor to a programmed voltage level and provide instantaneous backup power in case of a main power interruption for a load up to 15 W. See the TI reference designs library for an example implementation.

2 Schematic

Figure 2 illustrates the circuit of the design example, which consists of a buck-boost converter (TPS63020), an eFuse (TPS25940A), and an IC for active cell balancing (LP2998). The buck-boost converter is used for charging and discharging the backup capacitor consisting of C_1 and C_2. The smart eFuse has integrated back-to-back FETs to prevent reverse current from the system to the main power during main power loss. It also has enhanced built-in protection circuitry like overvoltage protection, soft-start, and current limit. The TPS25940A is not required for this backup power supply design, but is generally used in these applications to provide protection for the system. More details can be found in the TPS25940A data sheet (SLVSCF3). The detailed operation description in the next section is focused on the TPS63020 buck-boost converter.

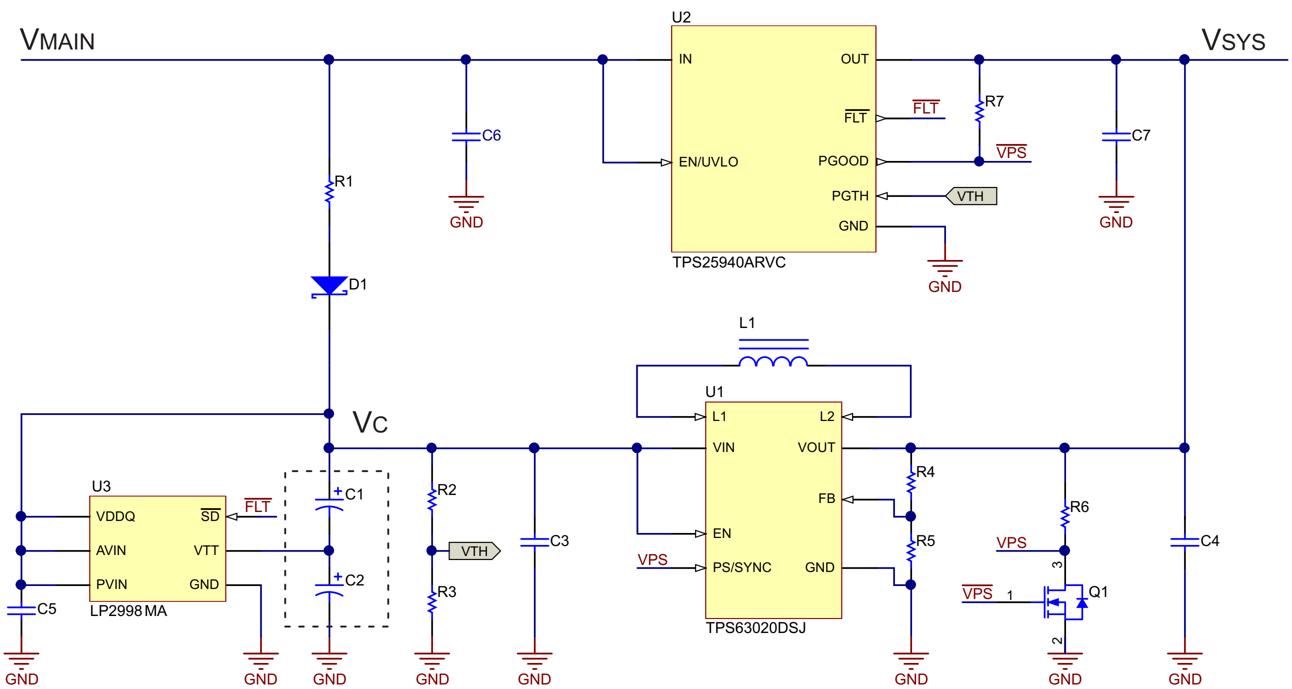

Figure 2. Supercapacitor Backup Power Application Schematic

3 Detailed Operation Description

3.1 Backup Capacitor Pre-Charging Operation

The first time main power is available, there is no voltage on the backup capacitor, and thus no voltage on the input of the TPS63020. Therefore, the backup capacitor must be pre-charged via a diode to the minimum operating input voltage level of the TPS63020 (typical 1.8 V). At this input voltage level, the buck-boost converter starts operating. A series resistor, R_1, is used to program the maximum pre-charge current into the backup capacitor. The pre-charging current linearly decreases with increasing backup capacitor voltage, V_C. Equation 1 defines the pre-charging current.

$$I_{PCH} = \frac{V_{Main} - V_{D1} - V_C}{R_1}$$

where

- V_{Main}: Main power voltage
- V_{D1}: Forward voltage of diode D1
- V_C: Backup capacitor voltage
- R_1: Resistor to set the pre-charging current
- I_{PCH}: Pre-charge current (1)

3.2 Backup Capacitor Charging Operation

The TPS63020 buck-boost converter operates bidirectionally and is able to transfer energy from its input to its output as well as from its output to its input. The latter is used to charge the backup capacitor, connected to the converter's input. Transferring energy from its output to its input in order to charge the backup capacitor, two items have to be fulfilled.

First, the converter must be in forced PWM mode. The converter is able to operate in the reverse direction only in this mode. To enable the forced PWM mode, the PS/SYNC pin must be programmed to a logic high level. The TPS63020 data sheet (SLVS916C) shows a detailed description of this mode pin.

Secondly, the output voltage of the TPS63020 must be programmed to a lower value than the system voltage.

As long as these two items are fulfilled, the TPS63020 sinks current from the system voltage V_{SYS}. This way, the converter transfers energy from its output to its input and charges the backup capacitor. The charge current is defined by the negative current limit of the TPS63020 buck-boost converter. Depending on the converters operating mode, either in buck mode or in boost mode, the negative current limit is typically between 0.6 A and 0.8 A.

With the feedback resistor divider consisting of R_4 and R_5, the output voltage of the buck-boost converter must be programmed to a level below the system voltage in normal operation. Ensure that the programmed voltage is below the system voltage including all tolerances of the main power source and the buck-boost converter. Equation 2 defines the programmed output voltage.

$$V_{OUT} = \left(\frac{R_4}{R_5} + 1\right) \times V_{FB}$$

where

- V_{OUT}: Programmed Output voltage of TPS63020
- V_{FB}: Feedback voltage of TPS63020 (500 mV typical)
- R_4, R_5: Resistors of the output voltage divider (2)

When operating in forced PWM mode in a reverse direction, the TPS63020 charges the backup capacitor. As the TPS63020 has no input overvoltage protection, the PS/SYNC pin must be used to stop the charging. Setting the PS/SYNC pin to a logic low level enables power save mode and stops the charging of the backup capacitor. In power save mode, the reverse direction of the TPS63020 is disabled.

Figure 3 shows the basic circuit implementation consisting of a resistor divider and a comparator with an integrated reference voltage source, V_{REF}. When the voltage of the resistor divider reaches the reference voltage, the PS/SYNC pin is set to a logic low level. The TPS3896P a supply voltage supervisor (SVS) device can be used to implement this circuit.

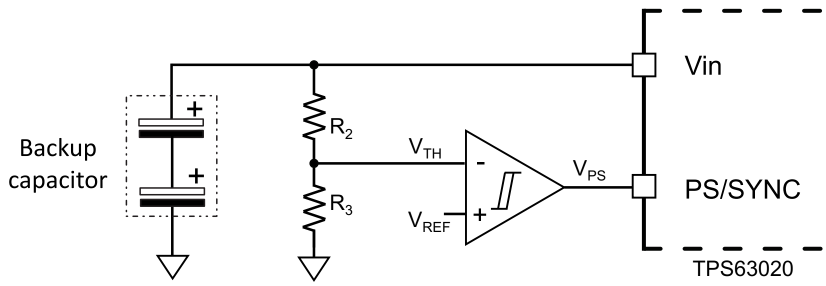

Figure 3. General Implementation to Stop Charging the Backup Capacitor

When the voltage V_{TH} reaches the level of the rising threshold voltage V_{THR} of the comparator, the PS/SYNC signal goes low and the TPS63020 converter stops charging the backup capacitor. Equation 3 defines the backup capacitor voltage when V_{TH} reaches the level of the rising comparator threshold voltage. The maximum voltage at the backup capacitor must be lower than the maximum input voltage rating of the buck-boost converter and within the voltage rating of the backup capacitor.

$$V_{CR} = \left(\frac{R_2}{R_3} + 1 \right) \times V_{THR}$$

where

- V_{CR}: Backup capacitor voltage at comparator rising threshold
- V_{THR}: Comparator rising threshold voltage
- R_2, R_3: Resistors of the voltage divider at the backup capacitor (3)

Due to the leakage current of the backup capacitor, the quiescent current of the TPS63020 and the current through the resistor divider (R_2, R_3), the backup capacitor is slowly discharged. When the voltage V_{TH} reaches the level of the falling threshold voltage V_{THF}, the PS/SYNC pin is pulled to a high level and the TPS63020 converter starts charging the backup capacitor again. In normal steady-state operation, this is an iterative process. The recharge cycle time depends on the leakage currents, the value of the backup capacitor and on the hysteresis of the comparator. Figure 4 shows the voltage at the charged backup capacitor in normal operation.

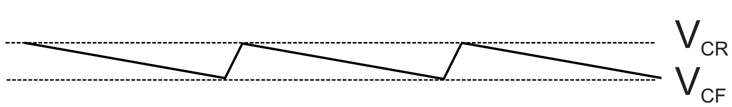

Figure 4. Backup Capacitor Voltage in Steady State

Equation 4 defines the backup capacitor voltage when the resistor divider reaches the level of the falling comparator threshold voltage.

$$V_{CF} = \left(\frac{R_2}{R_3} + 1 \right) \times V_{THF}$$

where

- V_{CF}: Backup capacitor voltage at comparator falling threshold
- V_{THF}: Comparator falling threshold voltage
- R_2, R_3: Resistors of the voltage divider at the backup capacitor (4)

The design in this document, shown in Figure 2, uses a comparator which is integrated in the TPS25940A device. Because the comparator output of the TPS25940A is inverted, an additional inversion of the signal is necessary, which is achieved by R_6 and Q_1. See the TPS25940A data sheet (SLVSCF3A) for a more detailed description.

3.3 Backup Operation

In the backup case, when the main power is shorted, a reverse current flows from the system to the main power. This adds additional load to the backup power system. To prevent reverse current in case of a main power loss event, the TPS25940A device is used in the example to disconnect the main power from the system. This device is a smart eFuse with integrated back-to-back FETs and enhanced built-in protection circuitry and provides true reverse current blocking when a main power fail condition is detected. If these features are not required, a diode or a MOSFET can prevent reverse current.

In case of a main power loss when the system voltage drops below the programmed output voltage level of the TPS63020, the buck-boost converter immediately starts regulating the system voltage. Depending on the required backup time and backup power, Equation 5 calculates the minimum required value of the backup capacitor. V_{CL} is the lowest level the backup capacitor can be discharged to, which is the minimum operating input voltage of the TPS63020 buck-boost converter. As shown before, V_{CF} is the voltage level of the backup capacitor where it reaches the falling comparator threshold voltage. This voltage is the worst-case value for the charged backup capacitor voltage in normal operation.

$$C_{min} = \frac{2 \times T \times P}{\eta \times (V_{CF}^2 - V_{CL}^2)} \tag{5}$$

where

- C_{min}: Minimum value of the required backup capacitor
- V_{CF}: Backup capacitor voltage at comparator falling threshold
- V_{CL}: Minimum discharge voltage of the backup capacitor, defined by the minimum input voltage of the TPS63020
- η: Efficiency of the TPS63020
- T: Backup time
- P: Backup power

3.4 Cell Balancing Operation

Since supercapacitor cells have a low maximum cell voltage due to technology limits, they are usually stacked in series to reach the required voltage level. However, the tolerance of a supercapacitor cell leads to imbalanced voltage during the charge/discharge cycle and can exceed the absolute maximum ratings. This has an impact on the supercapacitor's lifetime. Therefore an active cell balancing circuit is used in this design. In this example it is implemented using the LP2998 device. The output of the LP2998 is capable of sinking and sourcing up to 1.5 A continuous current while regulating the output voltage equal to V_C / 2. This prevents capacitor overvoltage conditions while charging the stacked supercapacitors.

4 Example

In this example, the main power voltage is 3.3 V and the TPS63020 provides instantaneous backup power for the system in case of a main power interruption. Ensure that the programmed output voltage of the TPS63020 is below the system voltage including all tolerances of the main power source and the buck-boost converter. With an estimated 6% total tolerance, the converter output voltage is programmed to 3.1 V. A constant system power of 1.55 W is provided for a backup time of 6.5 s which corresponds to an energy of 10 Ws.

Calculations:

The resistor R_1 sets the pre-charge current flowing through the diode. With a resistance of 10 Ω and a diode voltage drop of 0.3 V, the maximum pre-charge current is calculated:

- I_{PCH} = 300 mA (Equation 1)

The output resistor divider is used to program the output voltage of the TPS63020 converter. With given values of R_4 = 390 kΩ and R_5 = 75 kΩ, the output voltage is calculated:

- V_{OUT} = 3.1 V (Equation 2)

The resistor divider at the converter's input is used to program the maximum voltage level of the backup capacitor. With values of R_2 = 1 MΩ, R_3 = 243 kΩ, V_{THR} = 0.99 V, and V_{THF} = 0.92 V (see TPS25940A data sheet (SLVSCF3A), V_{CR} and V_{CF} are calculated:

- V_{CR} = 5.06 V (Equation 3)
- V_{CF} = 4.7 V (Equation 4)

The voltage V_{CR} is within the maximum input voltage level of the TPS63020 converter as well as within the maximum voltage of the stacked supercapacitor cells.

With a buck-boost converter efficiency of 80% and a minimum backup capacitor voltage of 1.8 V, the value of the required backup capacitor is calculated:

- C_{min} = 1.2 F (Equation 5)

In this design example, two stacked 3-F capacitors (2.7-V rated) are selected to achieve the required backup power. This results in 1.5-F total backup capacitance.

5 Test Results

The following tests were performed with the same conditions and values as shown in the example in Figure 2, unless otherwise noted. The main power voltage is 3.3 V and the load is represented by an electronic load, which draws 0.5 A constantly. The following plots show the main power voltage, the system voltage, the voltage at the PS/SYNC pin of the buck-boost converter and the voltage at the backup capacitor.

5.1 Backup Capacitor Pre-Charging and Charging Operation

Figure 5 shows the pre-charging and charging of the backup capacitor. As soon as the main power is present, the capacitor starts being pre-charged. After the backup capacitor voltage reaches the minimum operating input voltage level of the TPS63020 (typical 1.8 V), the converter starts operating and charges up the backup capacitor. At the programmed voltage level of 5 V, the PS/SYNC signal goes low and the buck-boost converter stops charging the backup capacitor.

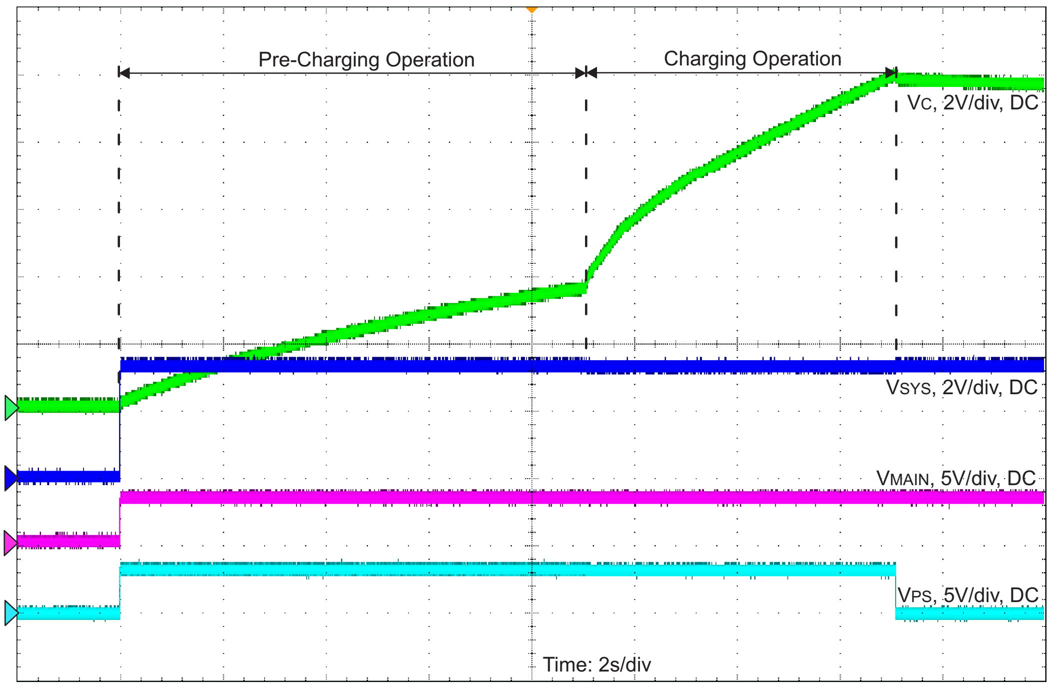

Figure 5. Pre-Charging and Charging of the Backup Capacitor

5.2 Backup Operation

Figure 6 shows the backup operation. If the main power fails, the TPS63020 converter immediately starts regulating the system voltage to its programmed output voltage. The backup capacitor is discharged and its voltage decreases slowly. When the backup capacitor voltage reaches the minimum voltage of the TPS63020, the converter stops operating and the system voltage decreases. In this scope plot, the backup time is about 6.5 s. Larger backup capacitor values result in a longer backup time, referring to Equation 5.

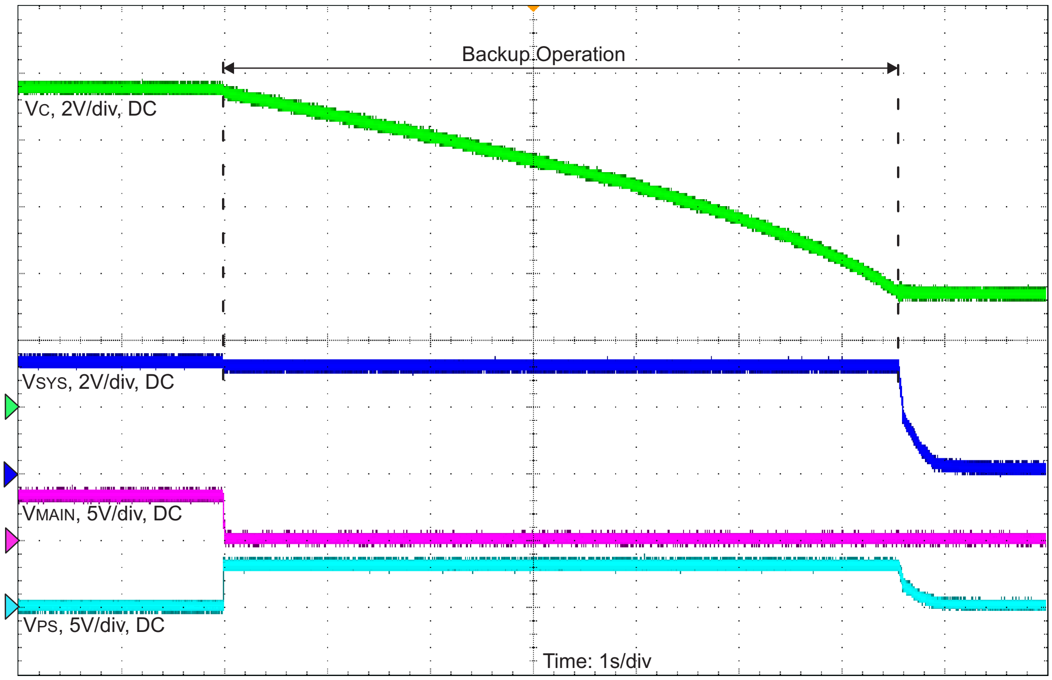

Figure 6. Backup Operation

5.3 *Normal Operation*

Figure 7 shows the backup power supply in normal, steady-state operation. The main power is directly connected to the system and both have the same voltage level. The capacitor slowly discharges through leakage currents. After the backup capacitor voltage level reaches the comparator threshold voltage V_{CF}, the PS/SYNC signal goes high and the backup capacitor is charged again. In this design example, the recharge period is 330 s.

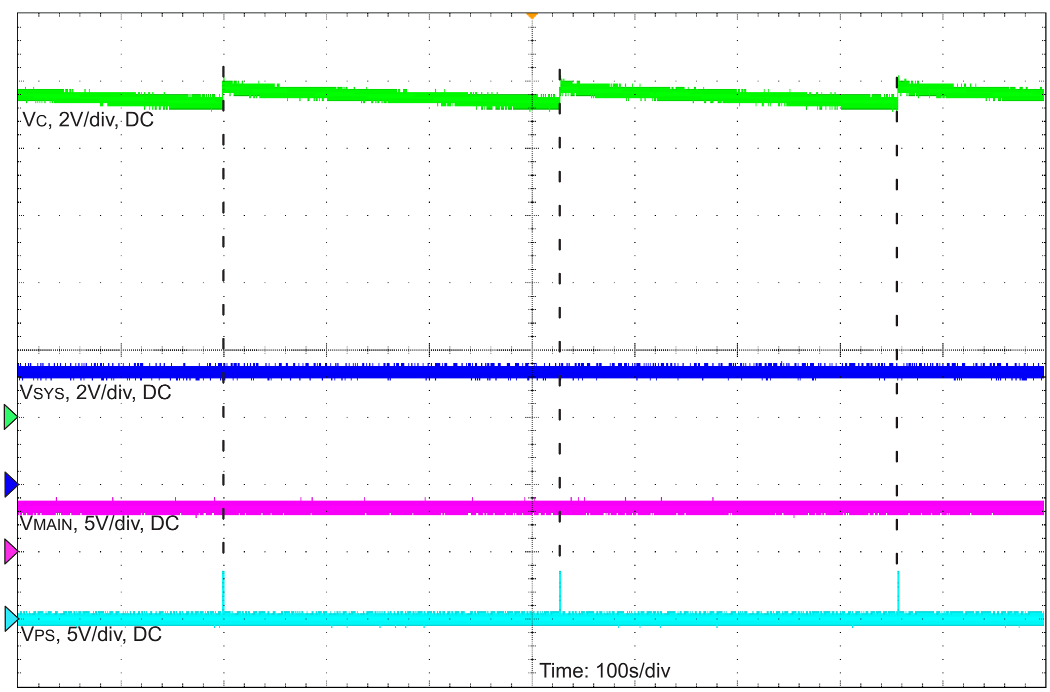

Figure 7. Normal Steady-State Operation

5.4 Supercapacitor Cell Balancing Operation

To show the functionality of the active cell balancing circuit, a 1:2 supercapacitor mismatch was used in this chapter. C1 has a value of 3 F and C2 a value of 6 F. In the following plots, the backup capacitor voltage V_C, the voltage in the middle of the two supercapacitors V_{CMID} and the balancing current I_{BAL} are displayed. Figure 8 shows the active cell balancing operation during pre-charging and charging operation. As soon as V_C reaches the minimum operating voltage of the LP2998, it starts regulating the V_{CMID} equal to V_C / 2. This prevents capacitor overvoltage conditions while charging the unbalanced stacked supercapacitors.

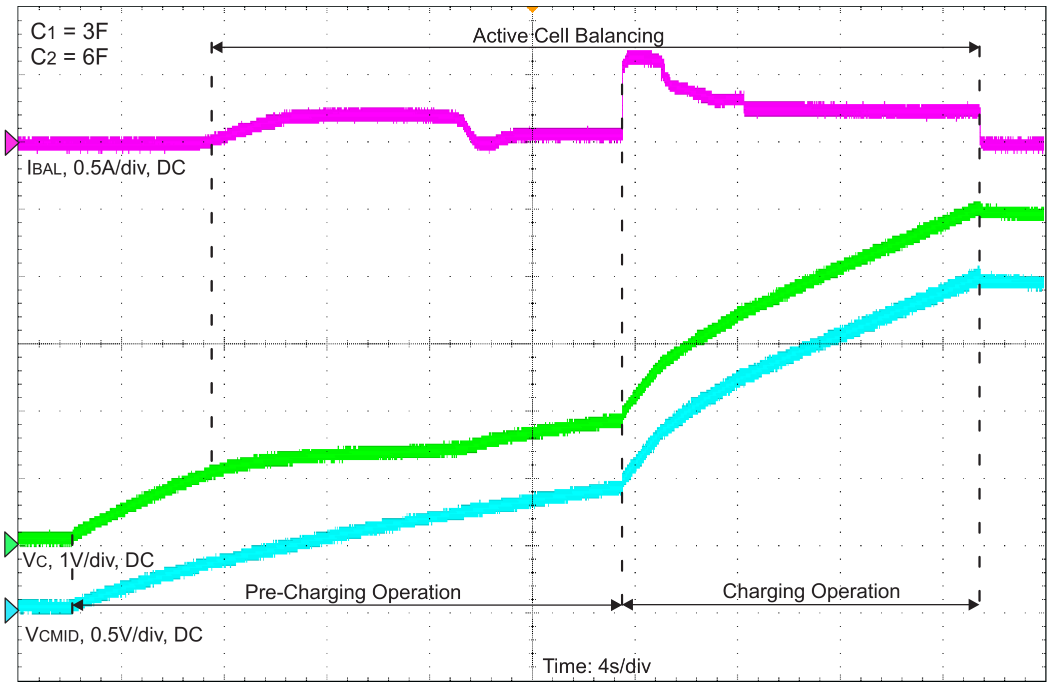

Figure 8. Cell Balancing Operation During Charge Operation

Figure 9 and Figure 10 show the backup operation with enabled and disabled active cell balancing. Disabling the cell balancing circuit during the backup operation results in longer backup time since no energy is needed for the balancing operation. In this comparison, the backup time increases from 7 seconds to 10 seconds. During backup operation with disabled balancing circuit, the cell voltage only decreases and thus no overvoltage condition can occur while discharging the stacked supercapacitors. In the design example in Figure 2, the shutdown pin of the LP2998 is connected to the fault pin of the TPS25940A and the active cell balancing is disabled during the backup operation.

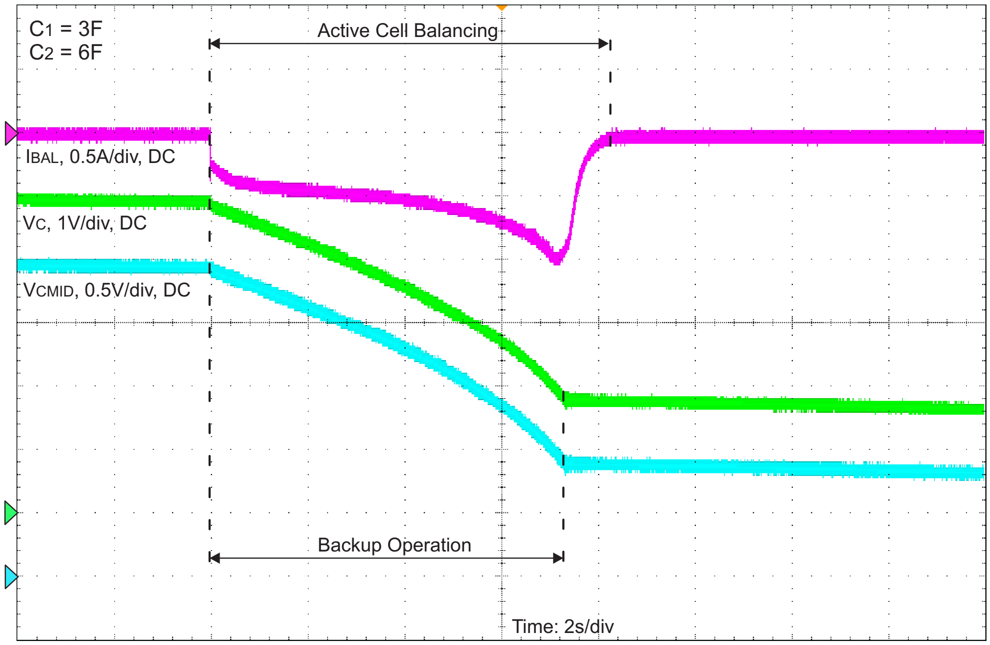

Figure 9. Backup Operation With Enabled Cell Balancing

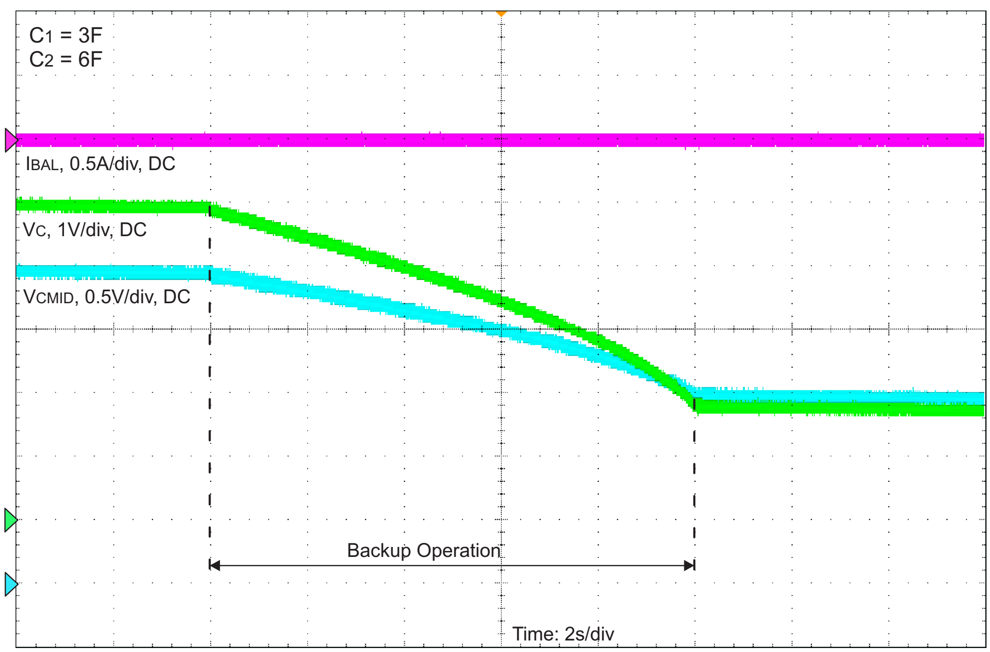

Figure 10. Backup Operation With Disabled Cell Balancing

6 Conclusion

Using the TPS63020 buck-boost converter for a supercapacitor backup power system brings some major advantages:

- Wide usable backup-capacitor voltage range (1.8 to 5.5 V)
- Active Backup Capacitor Cell Balancing
- Automatic switchover from main power to backup power
- Up to 15-W output power
- Small and high efficiency single converter solution
- No glitches at the transition from main power to backup power operation
- Backup-capacitor type and size are selectable to meet backup power needs
- Support of pulsed loads connected to a weak supply

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