Lead-Acid Charger and LED Driver using TPS5402

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ABSTRACT

The TPS5402 device is a non-synchronous buck regulator with a wide operating range from 3.5 to 28 V. The switching frequency of the converters can be set from 50 kHz to 1.1 MHz with an external resistor. Frequency-spread spectrum operation is introduced for EMI reduction. TPS5402 supports pulse-skipping mode to enhance the efficiency at light load, making this device an ideal pick for applications where efficiencies at full load and light loads are a key concern.

This application note focuses on applications beyond the fixed voltage operation of the device, with modification on the standard EVM board available for the part.

Two applications are demonstrated using the TPS5402 device:

1. Lead-acid battery charger
2. LED driver

Design is focused on simple methods to convert a constant voltage supply to constant current supply using the TPS5402.

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1 Lead-Acid Battery Charger

The TPS5402 device is used to charge the lead-acid batteries. Lead-acid batteries follow three stages of charging: constant current, constant voltage (current tappers), and trickle.

With the TPS5402 device, a simple circuit is implemented to charge a lead-acid battery in constant current and constant voltage mode. This circuit is designed to efficiently charge the small lead-acid-battery chargers, which require charge currents up to 1.7 A. Two topologies of battery charging are discussed below:

1. Linear current-tapering charger – lowest cost
2. Constant current – constant voltage charger

Specifications:

A 12-V lead-acid battery is used to test the design. The charger was designed considering the minimum changes required on the standard TPS5402 EVM for the following specifications:

1. Battery charge voltage: 14.6 V
2. Charge current peak: 1.5 A
3. Input voltage: 16 – 28 V_{max}
4. Switching frequency: 270 kHz

Design:

The TPS5402 has an on-board resistance of 100 kΩ at R_{osc} pin, which sets the frequency at 270 kHz. Set the jumper to this option.

Below are the quick calculations for the minimum inductor value. For a detailed discussion on power stage design, refer to the TPS5402 datasheet (SLVSBK4).

$$L_{min} = \frac{V_{OUT} \times (V_{IN(max)} - V_{OUT})}{V_{IN(max)} \times I_{Lripple\%} \times I_{OUT} \times f_{SW}} \quad (1)$$

The $I_{Lripple}$% for this application is 0.3 – 0.4, I_{OUT} = 1.5 A, and the minimum inductor is around 76 µH. The EVM has 82 µH which is sufficient for this design; the 82 µH creates lower ripple current than calculated in the inductor.

Input capacitor and output capacitor selection were done using the equations in datasheet, and resulted in component values close to the values present on the EVM.

1.1 Modifications to the EVM: Feedback Loop

Linear Current Tapering Charger – Lowest Cost

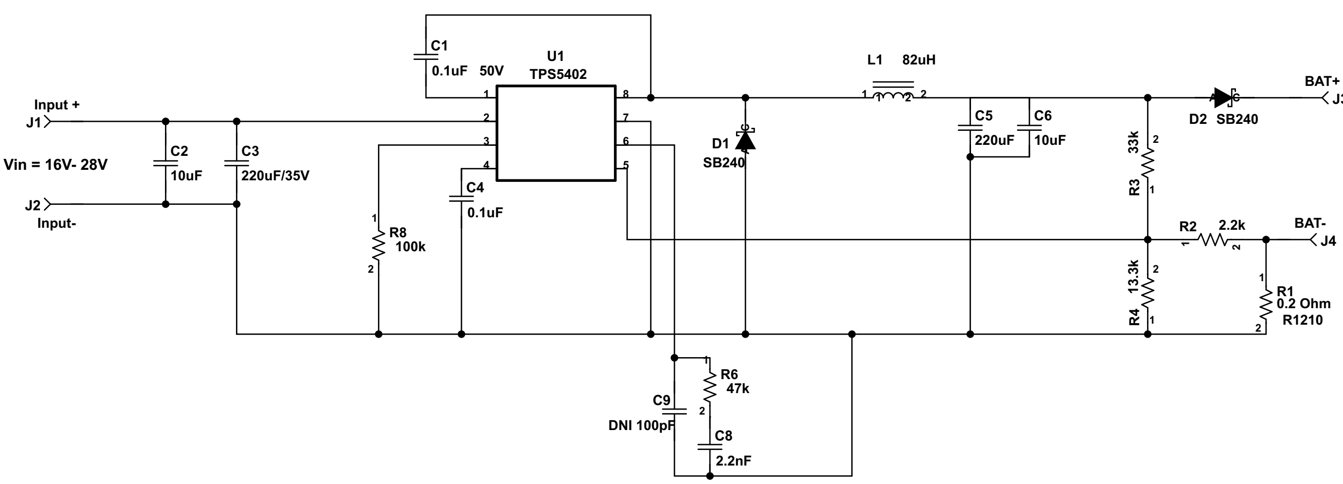

Figure 1. Linear Current Tapering Charger Using TPS5402

The circuit in Figure 1 shows a simple implementation of a battery charger. The charge current tapers off as the battery voltage increases. Diode D2 protects the circuit in case the battery terminals are connected in reverse and it reduces any leakage current from the battery to the circuit.

Resistance R3 and R4||R2 are designed for the maximum output voltage of 14.6 V, eventually charging the battery to 14.3 V.

The V_{fb} voltage due to the battery voltage and the current-sense voltage is plotted in the graph below (see Figure 2).

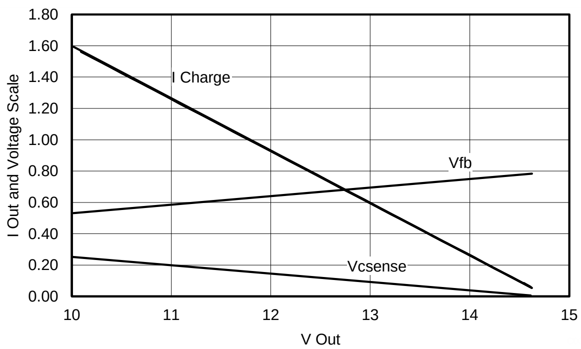

Figure 2. Charger Current, Current Sense Voltage and Feedback Voltage vs. V_{OUT} (Battery Voltage)

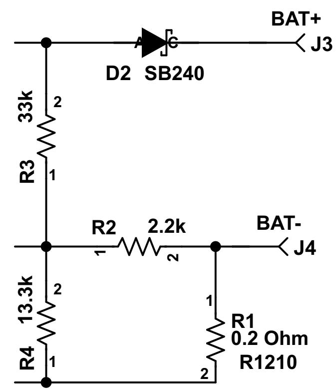

Figure 3. Linear Current Tapering Feedback Section

For an output voltage of 14.6 V and reference voltage of 0.8 V, choose R3 = 33 kΩ and R4||R2 = 1.88 kΩ.

Applying Kirchoff's law, voltage at V_{fb} node, the voltage across the R4 is actually given by Equation 2.

$$V_{R4} = \frac{14.6 \times R4R2}{R3R4 + R2R4 + R2R3} + \frac{V_{R1} \times R3R4}{R3R4 + R2R4 + R2R3} \tag{2}$$

Choosing the voltage divide ratio of about 0.8 for the current sense voltage across R1, solving for the second part of the equation, the results are:

R2 = 1.88k / 0.8 = 2.35 kΩ, choose 2.2 kΩ

R4 = 12.9 kΩ, choose 13 kΩ (3)

Current sense is calculated at a 12-V charging voltage or the user can choose the maximum current from the converter at the worst-case battery voltage. This topology is best suited for applications where the user cuts off the battery from the system well in advance, before the battery enters deep discharge voltages of 9 V or below, or where the user wants to charge the battery at lower currents and at a higher battery voltage, thus allowing a maximum current of about 1.7 A at 9 V. The worst-case battery voltage of 10.3 V, is assumed in this application note so:

$$R1 = \frac{\left[V_{ref} - \left(10\ V \times \frac{R4 \,||\, R2}{R4 \,||\, R2 + R3}\right)\right]}{0.8 \times 1.7}$$

- R1 = 0.19 Ω ~ 0.2 Ω (4)

Where V_{ref} = 0.8 V feedback reference of TPS5402, 10 V is used in calculation, considering the 300-mV drop of diode.

The above implementation ensures that feedback gets the appropriate offset voltage at 10.3-V battery voltage, and does not overload the converter. A more rugged solution is discussed in Section 1.2.

1.2 Constant Current – Constant Voltage Charger

An offset to current-sense feedback is actually derived from a fixed reference voltage. Because the reference voltage is set, the output voltage or battery voltage has no effect on the peak charging current of the battery. The design is implemented with the consideration that the current tapers off or begins to taper off before the battery voltage reaches approximately 13.4 V.

The schematic in Figure 4 shows the implementation of the constant current and constant voltage charger.

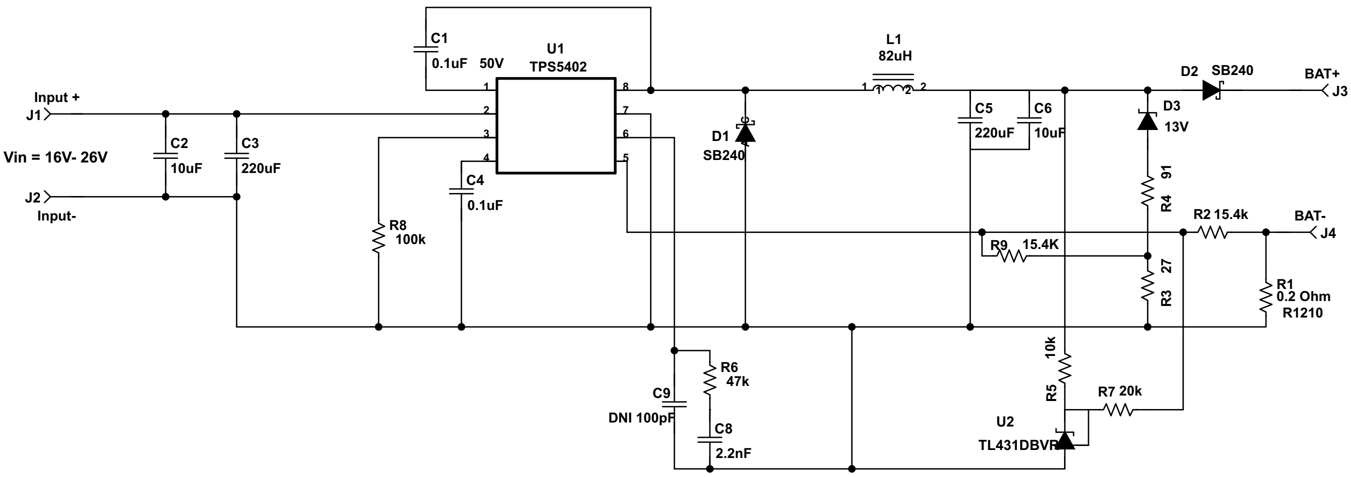

Figure 4. Constant Current and Constant Voltage Charger Implementation using TPS5402

Power stage components remain the same as in the previously discussed design. Note only the feedback section is changed to keep the charge current independent of the battery voltage. The main purpose of this change is to incorporate an external reference to keep the current sense resistance low and improve the efficiency of the circuit.

The feedback consists of two components: a feedback-pin offset circuit consisting of the TL431 device for current sense, and an overvoltage circuit consisting of Zener D3, R4 and R3. Equation 5 calculates the feedback voltage, as seen on pin 5, which is compared to the internal 0.8 V used to regulate the power stage.

$$V_{fb} = \frac{2.5 \times R9R2}{R9R2 + R9R7 + R7R2} + \frac{V_{R1} \times R9R7}{R9R2 + R9R7 + R7R2} + \frac{V_{R3} \times R2R7}{R9R2 + R9R7 + R7R2} \text{ Volts} \tag{5}$$

Note that the TL431 device reference voltage is 2.5 V, the voltage across the current sense resistor is V_R1 and is the voltage used for the overvoltage or constant voltage feedback is V_R3. Equation 5 is written assuming R9 >> R3 and R2 >> R1, which in this case always holds true.

The first part of the equation is set so that 0.7 V is added through the TL431 device as shown in Equation 6.

$$\frac{2.5 \times R9R2}{R9R2 + R9R7 + R7R2} = 0.7\text{ V} \tag{6}$$

To design a sensing part, the user must watch for a momentary short of the Bat+ terminal at the current sense resistors. This short creates a momentary surge at the sense pin. To keep the surge within limits choose R2 = R9, creating approximately less than 0.4 ratio and simplifying Equation 3.

Choosing R7 = 20 kΩ, R2 = R9 = 15.55 kΩ, and choosing a standard value of 15.4 kΩ, results in a correct value of Equation 4 at approximately 0.694 (see Equation 7).

$$\frac{V_{R3} \times R2R7}{R9R2 + R9R7 + R7R2} = V_{R1} \times 0.361 = V_{ref} - 0.694$$

(from Equation 6) (7)

Note that V_{R3} is not considered at this stage because it adds voltage only after the Zener starts conducting.

V_{R1} = 0.293 V

Now designing for I_{OUT} of 1.5 A, R_1 = 0.195 Ω. Choose a standard value resistance of 0.2 Ω. The graph in Figure 6 shows the variation of the feedback voltage with the current through the sense resistor.

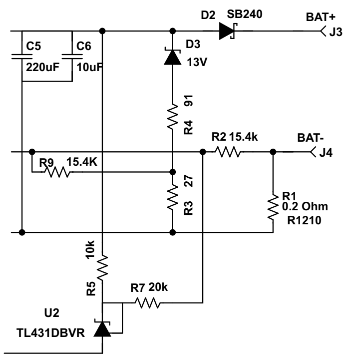

Figure 5. Constant Current and Constant Voltage Charger Feedback Section

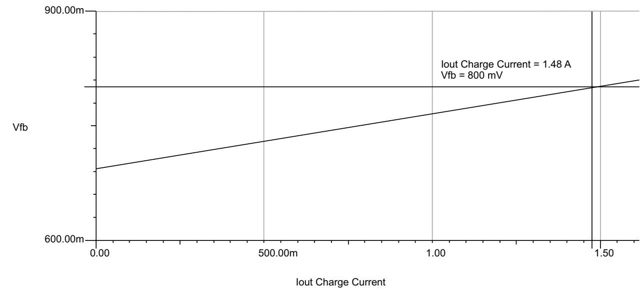

Figure 6. Feedback Pin Voltage Change vs. Charge Current, Showing 800 mV at 1.48 A

For the output constant voltage section, use the Zener diode D3 of 13 V. The purpose is to measure 14.3 V across the battery and add the remaining 0.1 V to the feedback voltage, just like in the current sense section (see Equation 8).

$$\frac{V_{R3} \times R2R7}{R9R2 + R9R7 + R7R2} = V_{R1} \times 0.361 = V_{ref} - 0.694$$

(from Equation 6)

- V_{R3}= 0.293 V at 14.3 V (8)

The Zener diode 13-V current for this calculation is around 11 mA as implied in Equation 9.

$$\frac{V_{bat} - V_{zener}}{R4 + R3} = 11\,\text{mA} \Rightarrow R4 + R3 = 118\ \Omega$$

where

- R3 = 0.293 / 0.01 = 26.6 Ω, choosing 27 Ω, R4 = 91 Ω (9)

The following relationship between V_{fb} and battery voltage is shown in Figure 7.

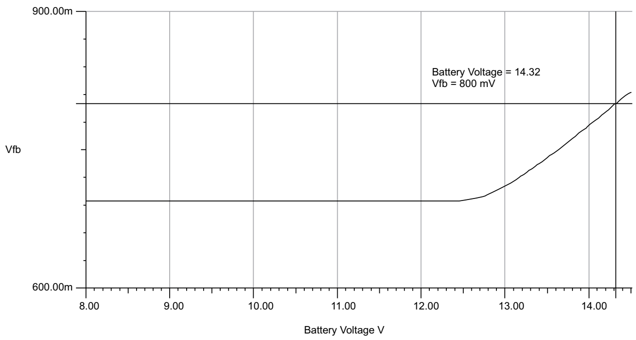

Figure 7. Feedback Voltage vs. Battery Voltage

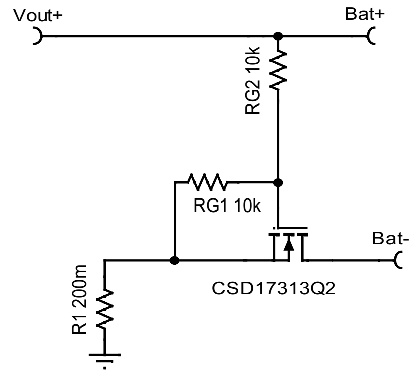

Figure 8. Low Loss Implementation of Reverse Battery Connection Circuit using MOSFET

The user is able to also remove the D2 and use a MOSFET in the configuration shown in Figure 8 to improve efficiency. A lower R_{dson} MOSFET ensures better efficiencies at higher charge currents.

1.3 Results

The circuit was tested in the lab with a slight modification to charge the battery to 14.8 V. A lower Zener voltage of 13.3 V causes the current to taper early at approximately 12 V (see Figure 7). This taper voltage changes by using a Zener voltage close to the cut-off voltage and choosing the R4 and R3 resistance according to Equation 9.

Figure 9 shows the constant-current behavior of the design, and that the current reaches zero when the battery charges to 14.8 V.

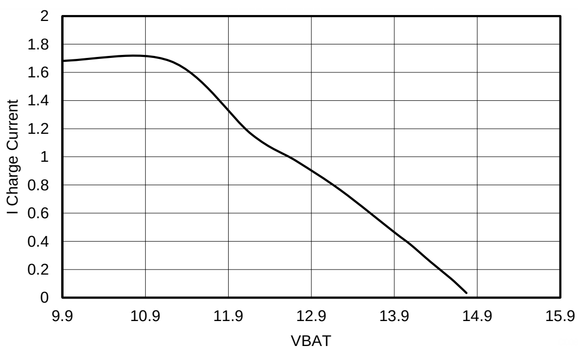

Figure 9. Bench Result of Charge Current vs. Battery Voltage using EVM Modification of TPS5402

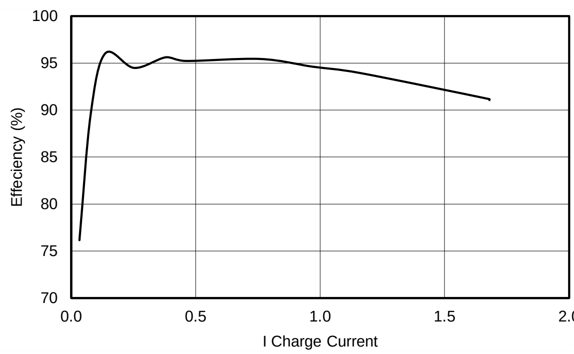

Figure 10. Efficiency Plot vs. Charge Current using EVM Modification of TPS5402

Efficiency measurements were performed at 16-V input voltage and at the battery terminals before the D2 diode, so diode power loss was not considered (see Figure 10). The efficiency stayed above 91% throughout the operation, mostly at 95%, until the battery entered a sub 100-mA charge current range, where the efficiency was measured at 86% with a 70-mA charge current.

2 LED Driver Design

The TPS5402 device, as discussed in the above battery charge configuration, is used in the below configuration to drive LEDs.

A simple LED-driver design is designed with the specifications below:

1. LED voltage 3.3-V LEDs and three in series: 9.9 V
2. LED current : 0.5 A
3. Input voltage: 10 – 28 V_{max}
4. Switching frequency: 270 kHz

Again, with minimum changes to the EVM and using Equation 1: L = 150 µH. The inductor is unchanged at 82 µH, which results in higher ripple current in the inductor. Note that for improved performance, change the inductor for the reference design on the board.

Keeping the power section the same without changing the input, output capacitors, and compensation values, the schematic is shown in Figure 11.

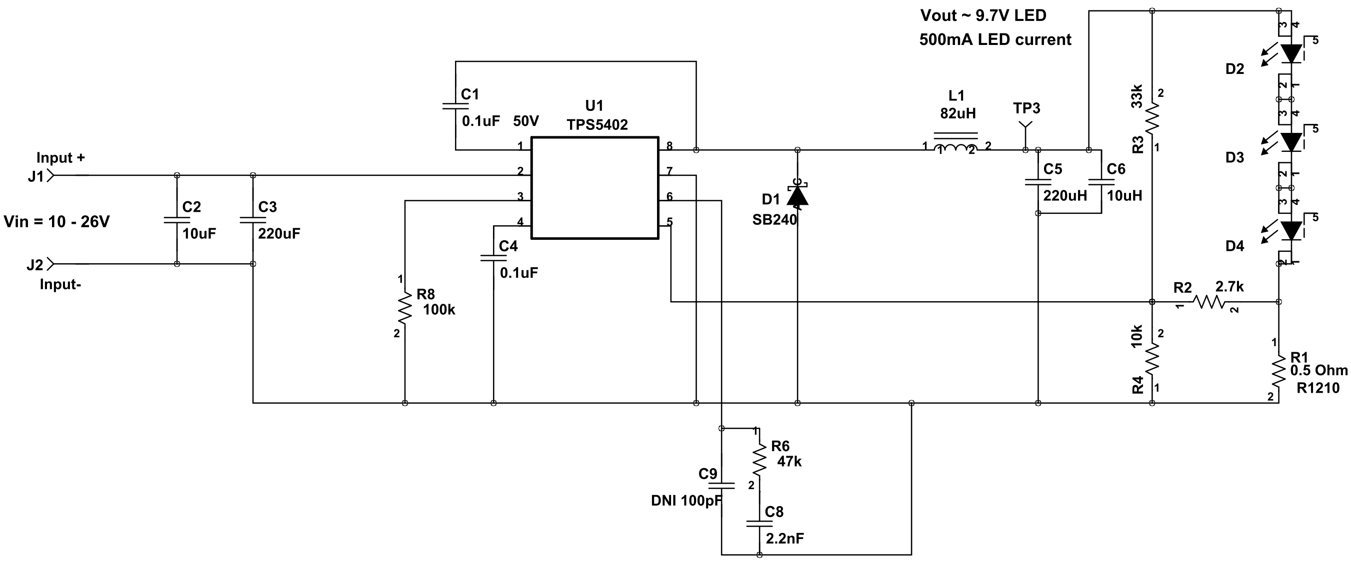

Figure 11. Simple LED Driver Implementation using TPS5402

2.1 Feedback Section

For feedback design, use Equation 2, and change the values of output voltage to 9 V:

$$V_{R4} = \frac{9.9 \times R4R2}{R3R4 + R2R4 + R2R3} + \frac{V_{R1} \times R3R4}{R3R4 + R2R4 + R2R3} \tag{10}$$

Choose a reference offset from output around 0.6 V:

$$\frac{9.9 \times R4R2}{R3R4 + R2R4 + R2R3} = 0.6 \tag{11}$$

Using R3 = 33 kΩ, and using R4 || R2 as a standard value of 2.13 kΩ.

Keeping the ratio R2 / (R2 + R4) = 0.8 (approximately) in calculations, to create a smaller sense resistance and to lower the conduction loss, use R4 = 10 kΩ, and R2 = 2.7 kΩ as standard values. The actual ratio value is given by Equation 9, resulting in Equation 12.

$$V_{R1} = \frac{(0.8 - 0.6) \times (R3R4 + R2R4 + R2R3)}{R3R4} = 0.263\ V = I_{led} \times R1 \tag{12}$$

Solving for a 0.5-A current, R1 = 0.526 Ω, choose R1 = 0.5 Ω.

Because the switch current for the internal MOSFET of the TPS5402 device is 2.2 A, the user can design LED drivers up to 1.7-A of continuous current for specific input and output voltages.

2.2 Results

The efficiency versus input voltage for the schematic in Figure 11 is shown in Figure 12.

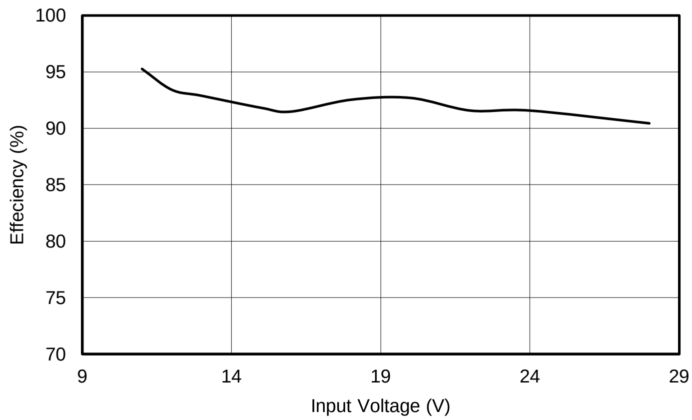

Figure 12. Efficiency vs. Input Voltage for LED Driver using TPS5402

The efficiency for the design is above 90% at a higher voltage of 28 V, and at a lower voltage of 10 V, the efficiency is approximately 93%.

3 Conclusion

The TPS5402 device works in constant current for lead-acid-charging and LED-driver applications. The methods to achieve high efficiencies by altering the feedback sections are discussed in this application note. As observed in this application note, the TPS5402 device shows high efficiency characteristics.

4 References

1. TPS5402 Data Sheet (SLVSBK4)
2. TPS5402 EVM User's Guide (SLVU775)
3. *Understanding Buck Power Stages in Switch Mode Power Supplier* (SLVA057)