TI Designs PMP9776

Realizing Output Current Sensing and Limit, Plug-in Detection in Power Bank

Design Overview

A power bank is a portable device that can supply USB power using stored energy in its built-in batteries. This reference design demonstrates a circuit based on the TPS61236 for the USB output port of the power bank. The reference design features a 5V and 2.4A output capability, auto detection of a portable device plug-in, output current sensing and limiting, short circuit protection, temperature protection, and battery voltage indication.

Design Features

- 5V and 2.4A output capability in 95.5% efficiency
- Auto detection when connected to a portable device
- Cable voltage drop compensation.
- Battery voltage indication with four LEDs
- Short circuit protection, temperature limit and protection

Design Resources

PMP9776	All Design files
TPS61236	Datasheet
MSP430G2332	Datasheet
TPS2514	Datasheet

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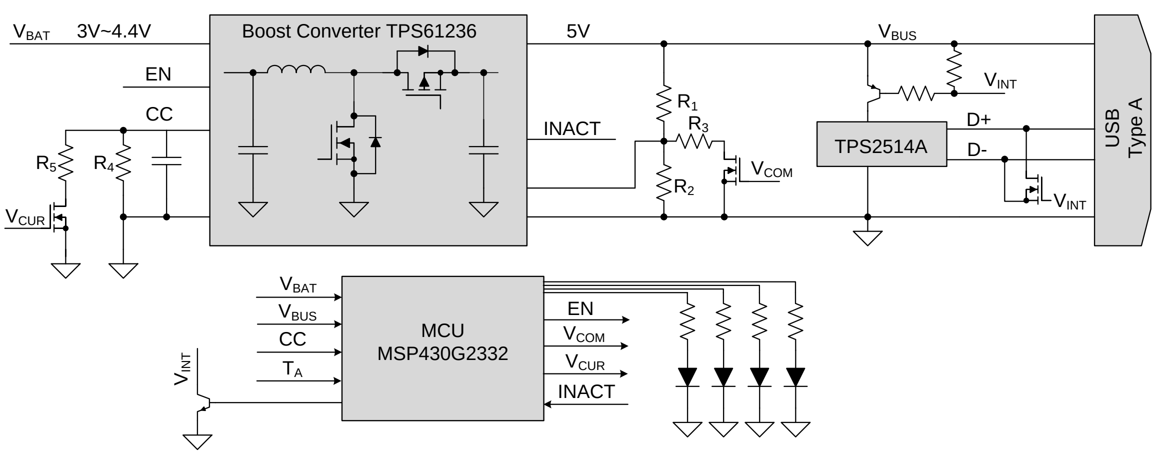

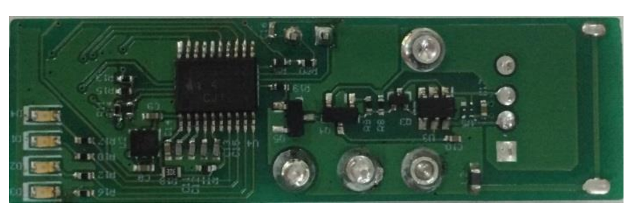

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1 Introduction

The Reference-Design (RD) builds a power circuit for the USB output port used in a power bank, which mostly uses lithium-ion battery or lithium-polymer battery for the energy storage. The input voltage range of the RD is 3 V to 4.4V and the output power can up to 5 V and 2.4 A. The features of the reference design are auto-detection of the portable device plug-in, supporting four of the common dedicated charging schemes, short circuit protection, constant output current operation to limit battery temperature, over temperature protection and the battery voltage indication using the LEDs.

2 Operating Principle

The RD's block diagram is shown in Figure 1. In the system, the boost converter TPS61236 converts the battery voltage to regulated 5V for the V_{BUS}; The USB dedicated charging port controller TPS2514A provides the electrical signatures on the data lines D+ and D- based on the charging scheme; And the MCU MSP430G2332 controls the operation mode of the RD.

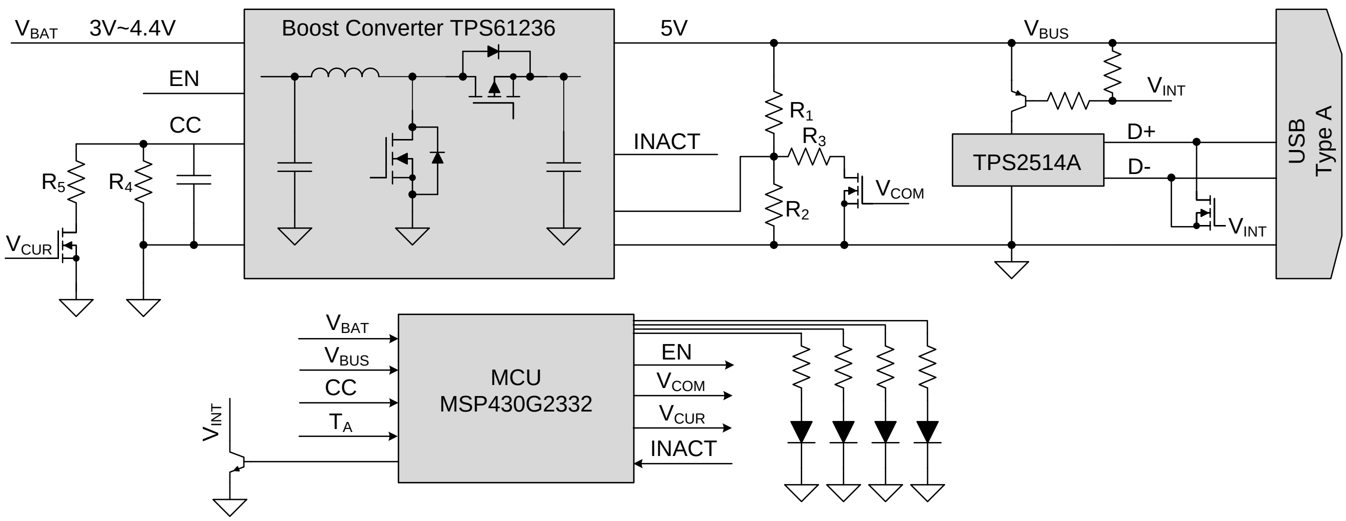


Figure 1: Block Diagram of the Reference-Design

The RD has three operating modes depending on the battery and output current condition: standby mode, active mode and shutdown mode.

2.1 Standby mode

The RD has two types of standby modes: Standby mode 1, in which the battery's open circuit voltage is lower than 3.5 V or ambient temperature is higher than 60^{o}C; Standby mode 2, in which the battery's open circuit voltage is higher than 3.5 V but TPS61236's output current is lower than 50 mA (typical).

- **Standby mode 1**: Depending on the material of the battery, this RD decides that there is little energy in the battery when its open circuit voltage is lower than 3.5 V and it stays at standby mode 1. In this mode, the TPS61236, TPS2514A and LED are disabled. The MCU starts ADC (Analog-to-Digital Converter) to detect the battery voltage in every four seconds. The current consumption during the ADC period is approximate 200µA, while the current consumption is approximate 3 µA in the rest period. The ADC period lasts 100ms, so the average input current is approximate 8µA at this condition. The RD also stays at this mode when ambient temperature is higher than 60^{o}C.
- **Standby mode 2**: When the open circuit voltage of the battery is higher than 3.5 V, the boost converter TPS61236 is enabled and output typical 5 V for V_{BUS}. The RD will stay at this mode if the load of V_{BUS} is lower than typical 50mA. The LEDs and TPS2514A are disabled and the MCU enter very low power sleep mode. The V_{INT} in Figure 1 is equal to V_{BUS}, so the USB data lines D+ and D- is short by the NMOSFET. the current consumption in this mode is approximate 22µA

2.2 Active Mode

The RD exits the standby mode 2 and enters active mode when the load of V_{BUS} is higher than 50 mA (typical). At active mode, the MCU keeps detecting the battery voltage, V_{BUS}, CC pin voltage (refer to the TPS61236 datasheet for the pin function description) and the ambient temperature through the ADC functions; The V_{INT} is pulled down to ground by the MCU, so the TPS5214A is powered on and the N-MOSFET between D+ and D- lines is open.

There are three states of active mode depending on the load and the battery condition.

- **Active mode 1:** the RD enters this mode when the battery voltage is higher than 3.5 V and load current of V_{BUS} is lower than 1.6 A. The V_{COM} in Figure 1 is in low voltage, and the VBUS voltage is determined by R_1, R_2; the V_{CUR} is in high voltage to turn on the MOSFET, so the output current limit is determined by R_4, R_5.
- **Active mode 2:** the RD enters this mode when the output current is higher than 1.6 A. The V_{COM} becomes logic high level, which turn on the N-MOSFET and parallels the R_3 with R_2. The V_{BUS} will increase typical 100 mV to compensate the voltage drop over the USB cable.
- **Active mode 3:** this mode is triggered when ambient temperature (or battery temperature in real application) is higher than 45°C. The V_{CUR} becomes logic low level and disconnects R_5 from CC pin of TPS61236. The output current limit of the boost converter decreases to a value determined only by R_4, which is set to 1 A in the RD. Once entering this mode, The RD does not exit this mode until the portable device is disconnected for more than 4 seconds or the RD is reset by shutdown mode.

2.3 Shutdown mode

The RD shuts down if one of the three conditions occurs: the PCB temperature higher than 60°C (or battery temperature in the real application), V_{BUS} short circuit or battery voltage lower than 3V during active mode. After entering the shutdown mode, the MCU will reset the RD once every 4 seconds. The RD is back to normal operation if all the three faults are removed.

2.4 Mode Transition

The transition conditions between the modes are showed in Figure 2, where:
V_{BAT} is voltage of the battery detected by the MCU;
H, L means logic high and logic low respectively;

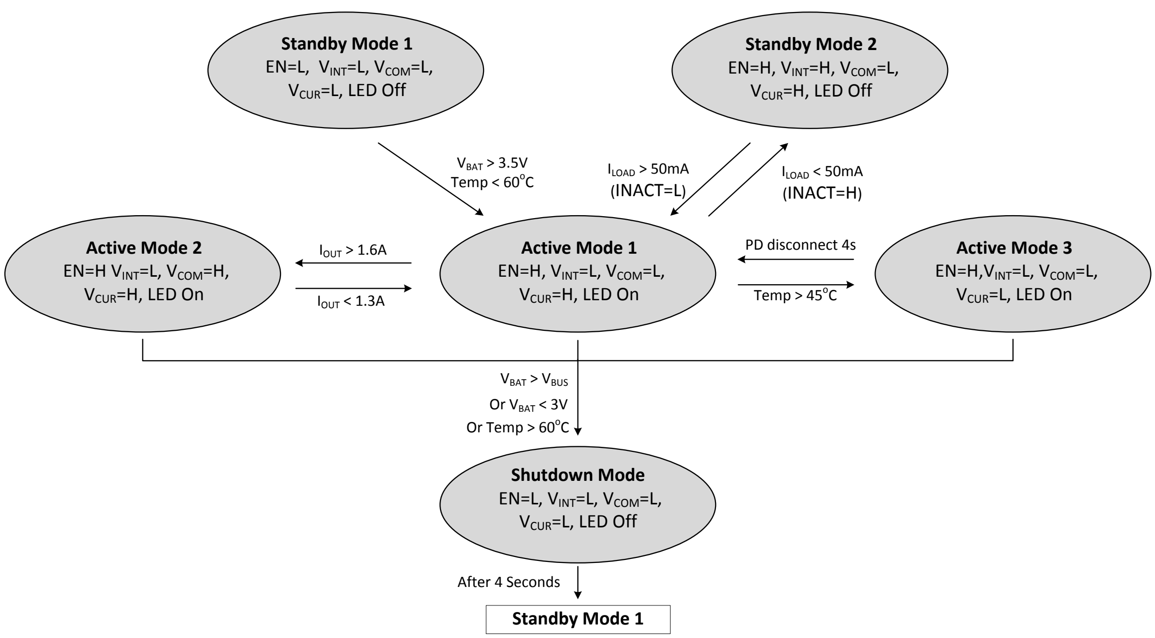


Figure 2: Modes Transition Conditions

The most important mode transition is between standby mode 2 and active mode 1. When there is no portable device connected with the USB port, the RD operates at standby mode 2. To minimize the power consumption at this mode, the TPS2514A (consume 155µA at 5V power supply) is powered down and the MCU stops operating. An N-MOSFET shorts data lines D+, D- in this mode. Once a portable device is plugged into USB port of the RD, three steps will happen sequentially for the handshaking between the portable device and the RD as shown in Figure 3 (refer to the TPS2514A datasheet for the detail information):

S1. V_{INT} is logic high, so the TPS2514A powers off, D+ and D- is short together. The portable device identifies the USB port as the dedicated charging port and starts to sinks current.

S2. The output current of the TPS61236 changes the INACT from logic high to logic low. The falling edge wakes up the MCU which changes the VINT and EN to logic low to disable the boost converter. The V_{BUS} drop to 1.8V after 400ms delay set by the MCU.

S3. After the 400ms timer expires, the TPS61236 is enabled and V_{BUS} recover to 5V again. The portable device triggers the handshaking process with the RD through D+, D- again. As the TPS2514A is powered on in this time, the device will adapt its D+, D- signal to the voltage compatible with the USB charging protocol of the portable device. The charge current is approximate 2 A after the system is stable.

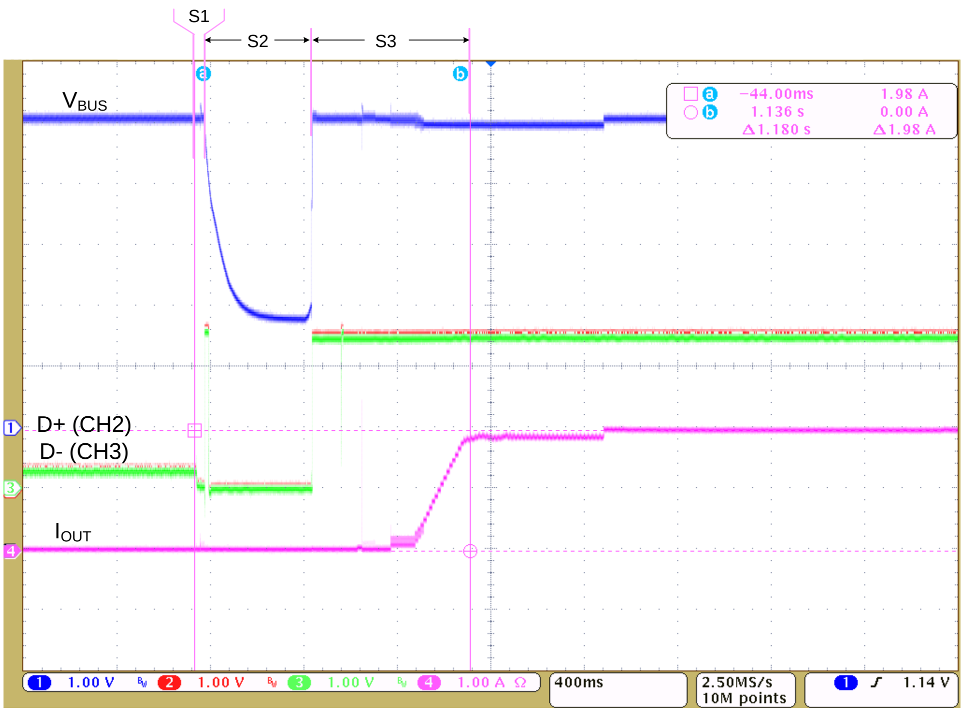


Figure 3: Waveform after Connecting an IPAD AIR with the Reference Design

2.5 LED Indication

There are four LEDs in the RD to indicate the battery voltage during the active mode. The battery voltage divides into four ranges: 3 V ~ 3.5 V, 3.5 V ~ 3.7 V, 3.7 V ~ 3.9 V and higher than 3.9 V. The MCU detects the battery voltage and turns on one, two, three or four LEDs based the voltage ranges.

3 Circuit implementation

3.1 Boost Converter TPS61236

The schematic of the TPS61236 is shown in Figure 4.

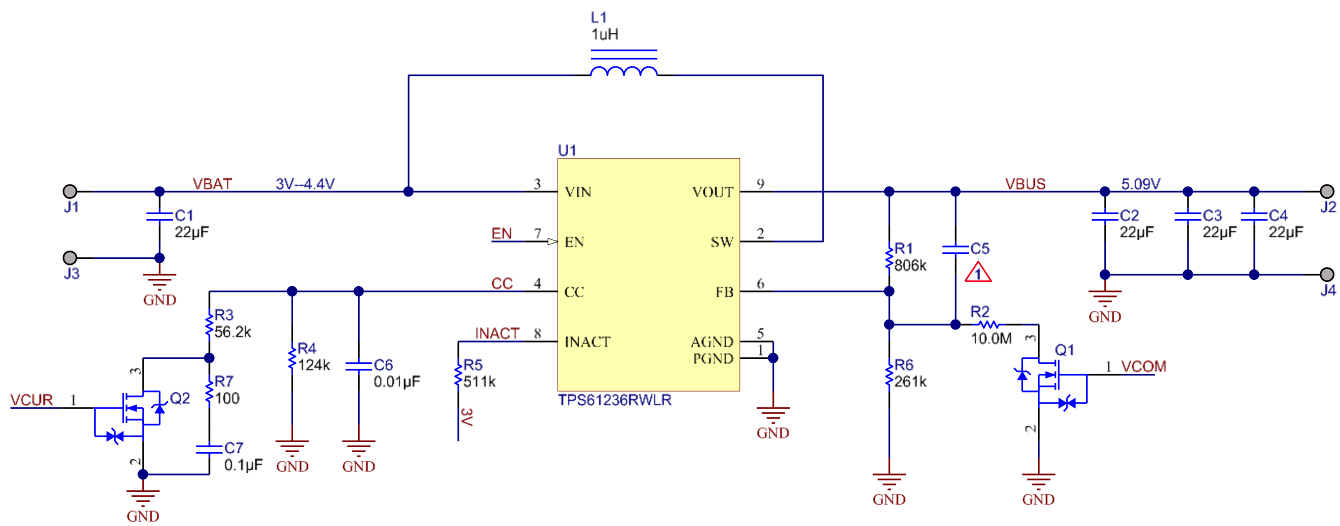


Figure 4: Schematic of the TPS61236

When V_{COM} is logic low level and Q1 is off, the V_{BUS} voltage is defined by formula (1), where V_{REF} is the reference voltage for the feedback error amplifier.

$$V_{BUS} = V_{REF} \cdot \frac{R_1 + R_6}{R_6} = 5.09V \tag{1}$$

When V_{COM} is logic high level, the V_{BUS} voltage will change to formula (2), of which the voltage is 100mV higher.

$$V_{BUS} = V_{REF} \cdot \frac{R_1 + (R_6 // R_2)}{(R_6 // R_2)} = 5.19V \tag{2}$$

The TPS61236 has a CC pin to control the average output current at the value according formula (3), where the R_{CC} is the resistor between this pin and GND.

$$I_{OUT\_CC} = \frac{1.244}{R_{CC}} \cdot 100000 \tag{3}$$

When V_{CUR} is logic low, the output current limit is 1A; when V_{CUR} is logic high, the output current limit is 3.2A. During normally operation, the voltage of the CC is approximately linear with the output current of TPS61236, defined by formula (4). Using this feature, the MCU can detect the output current of the RD.

$$V_{CC} = \frac{I_{OUT} \cdot R_{CC}}{100000} \tag{4}$$

The output current limit tolerant could be ±20% because of the IC process and temperature. So the maximum output current requirement should be not higher than 2.56 A if the current limit is set to 3.2 A.

The TPS61236 can indicate the load status by the INACT pin. The INACT pin is open drain output pin. It outputs high impedance when the load current is smaller than 50mA (typical), and short to GND when the load current is high. The RD utilizes this function to detect if a portable device is plugged in and wake up the MCU from the low power sleep mode.

The selection principle of the components for other pins can be found in the datasheet of TPS61236 (SLVSCK4).

3.2 Microcontroller MSP430G2332

The schematic of the MSP430G2332 is shown in Figure 5. The TPS78230 is a 500nA ultra-low quiescent current, 3V output LDO for the power of the MCU. Pin 2, 3,4,5 of the MCU are used as ADC port to sense the battery voltage, bus voltage of the USB (TPS61236 output voltage), the voltage of the CC pin and the voltage determined by the NTC resistor respectively.

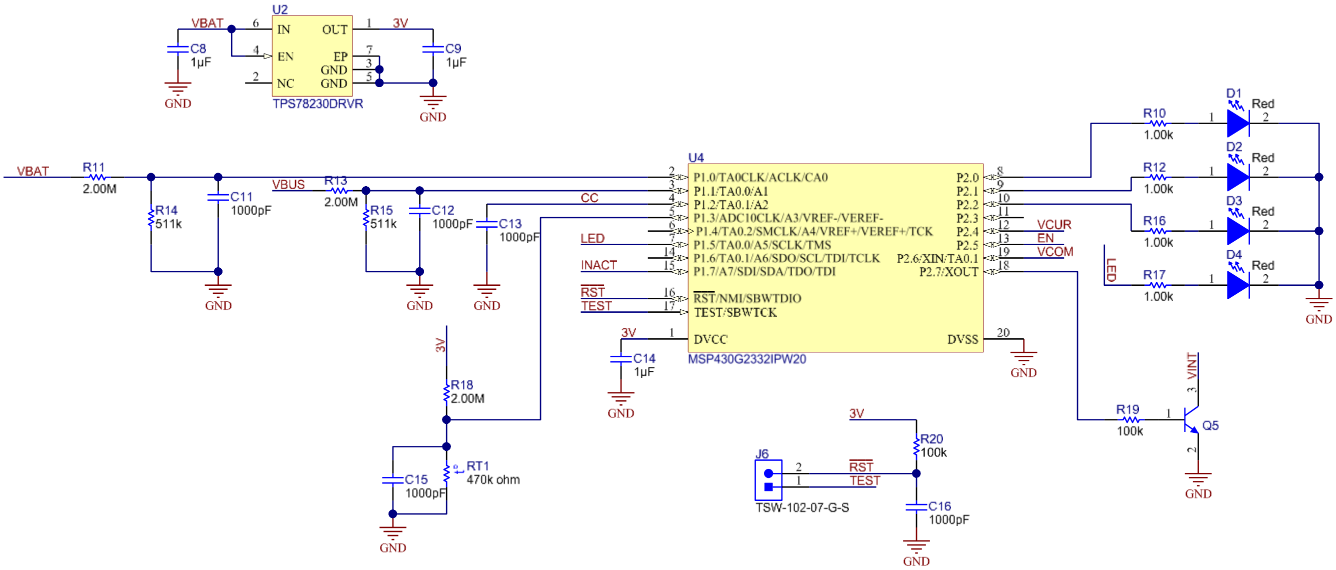


Figure 5: Schematic of the MSP430G2332

Pin 15 of the MCU (P1.7) is used as logic input, and also an interrupt to wake up the MCU from low power mode (Standby Mode 2).

Other pins are used as logic output. Refer to the datasheet of MSP430G2332 for detail description of each pin function.

3.3 USB Charging Port Controller TPS2514A

The schematic for TPS2514A and USB type-A port is shown in Figure 6. Depending on the operating mode, the V_{INT} is pulled up to V_{BUS} or down to ground by the MCU:

- When V_{INT} is pulled up to V_{BUS}, the Q4 is turned off and the TPS2514A is powered off; the Q3 is turned on and D+ and D- are short. The portable device still recognizes the dedicated charging port but the charging current would be not higher than 1.5A.
- When V_{INT} is pulled down to ground, the Q4 is turned on and TPS2514A is powered on; the Q3 turns off and isolates D+ and D-. The TPS2514A integrate an auto-detect feature to adjust its D+ and D- voltage for difference portable devices. (refer to the datasheet for more detail)

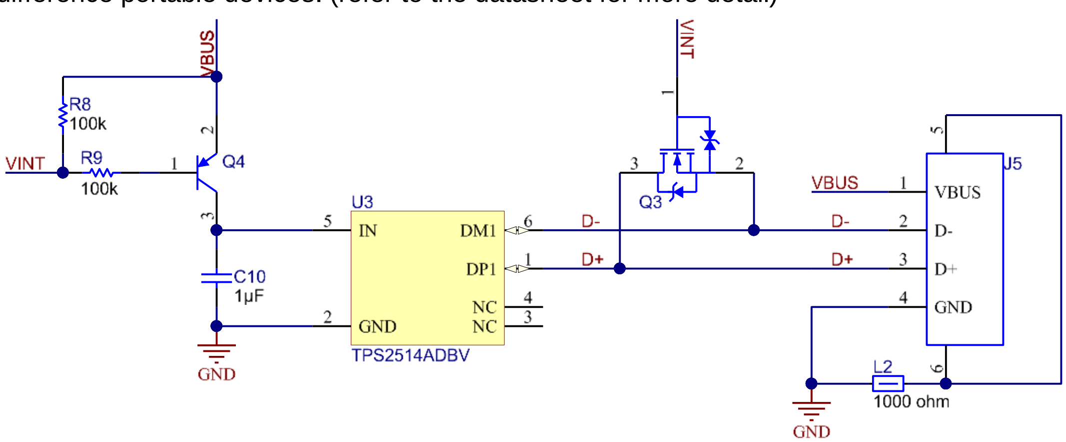


Figure 6: Schematic of TPS2514A and USB type-A port

The L2 between GND and the case of type-A port helps to reduce the EMI

4 Test Result

4.1 Efficiency

The efficiency of the reference design is shown in Figure 7. With 3.6V battery voltage, the efficiency of the RD reaches 97% at 1.1A output current, and 95% at 2.4A output current. High efficiency of the RD will help to extend the battery life time and improve the thermal performance of a real product.

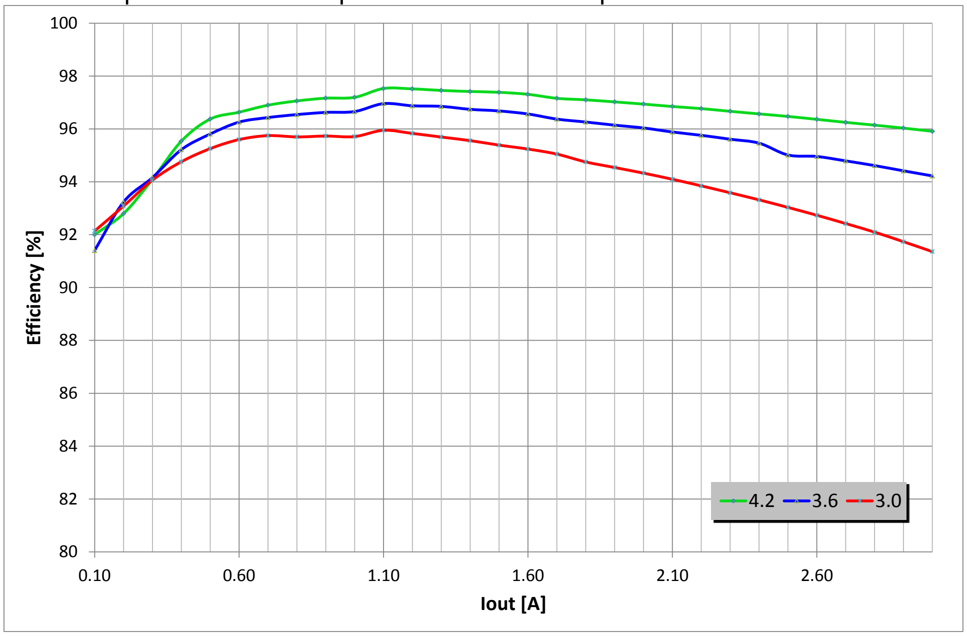
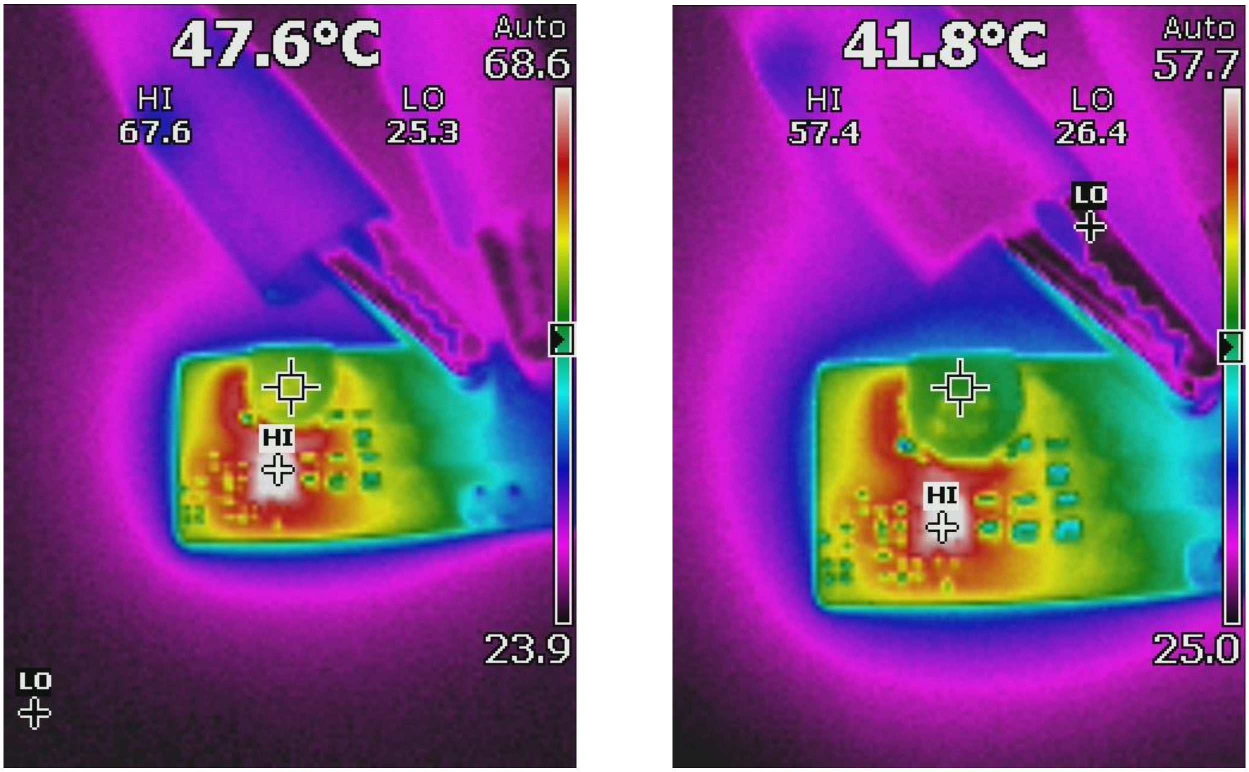


Figure 7: Efficiency of the Reference Design

4.2 Thermal Performance

The thermal performance of the RD is shown in Figure 8. The measurement condition of the left image in V_{IN}=3V, ambient temperature 25ºC, free wind and 2.4A output current, which is the maximum input current of the IPAD. The hottest point is 67.6ºC at the boost converter TPS61236. The right image is measured at V_{IN}=3.6, in which the hottest point is approximate 10ºC lower than 3V input voltage condition because of higher efficiency.

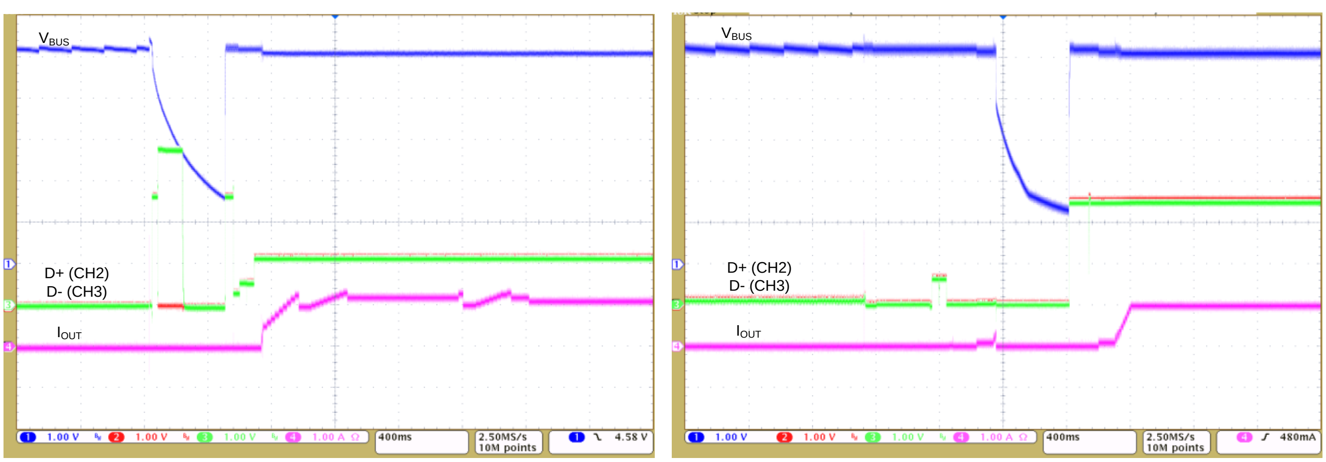


(a) V_{IN}=3V **(b) V_{IN}=3.6V**

Figure 8: Thermal Performance at 2.4 A I_{OUT}

4.3 Detection and Charge of the Portable Device

Figure 9 shows the waveforms of the V_{BUS} voltage and output current, data lines voltage when a portable device is connected to the RD. the left image is with the Galaxy S4 from Samsung and the right images is with the IPhone 5S from Apple. As explaining in Figure 3, the RD disables the boost converter TPS61236 and enables the USB controller TPS2514A after the MCU detects a portable device is attached. Then it enables the boost converter again after 400ms seconds delay. Finally the TPS2514A automatically provides the correct electrical signatures on the data lines and the mobile phones are charged.



(a) With Samsung Galaxy S4 (b) With Iphone 5S

Figure 9: Connection with Portable Device

4.4 Short Circuit Protection

Figure 10 shows the short circuit waveform of the RD. The V_{BUS} drops down to zero when the short circuit happens. The MCU disables the TPS61236 when detecting this short circuit and tries to restart the TPS61236 in every four seconds. The V_{BUS} voltage will recover to 5V if the short circuit is removed.

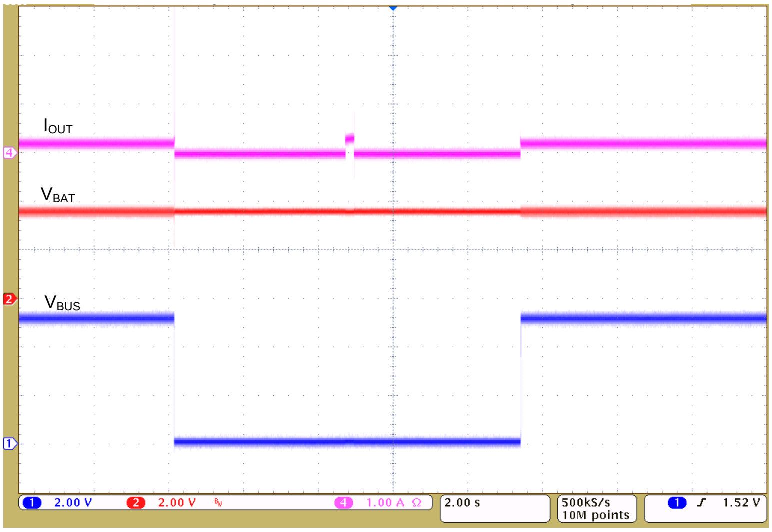


Figure 10: Short Circuit Waveform

4.5 Constant Output Current Operation

The Figure 11 shows the CC pin function of the TPS61236. The MCU continues to detect the temperature of the RD (or the battery in real application) during discharging. It sets the V_{CUR} from logic high to logic low when the temperature is higher than 45ºC, so the TPS61236 limit its output current at 1A which is lower than the discharge current at V_{BUS}=5V condition. As the portable device has a function that decreases its charge current with the V_{BUS} dropping down, the whole system will get into a stable state, at which the V_{BUS} is lower than 5 V and I_{OUT} is equal to the value set by the CC, 1 A.

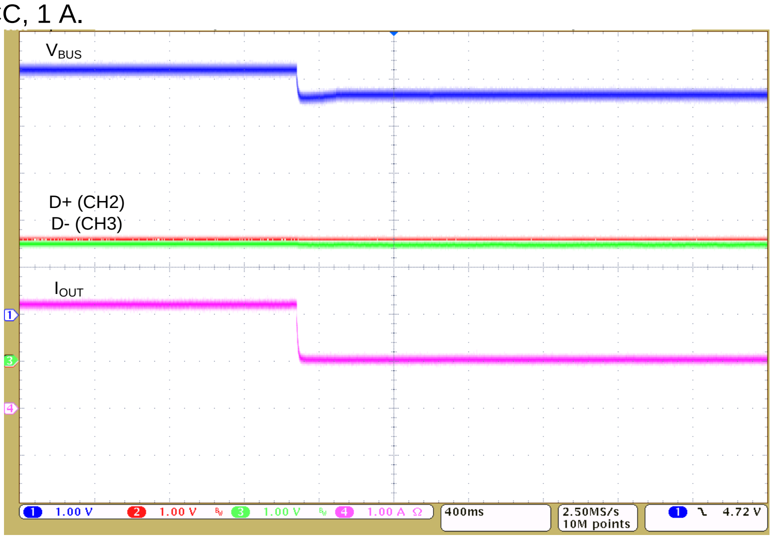


Figure 11: CC Function Operating with IPAD-AIR

4.6 Cable Voltage Drop Compensation

The RD increase the V_{BUS} voltage by 100 mV when the output current is higher than 1.6 A to compensate the voltage drop caused by the resistance of the cable. The V_{BUS} voltage recovers to normal value when the I_{OUT} is lower than 1.3 A, as shown in Figure 12.

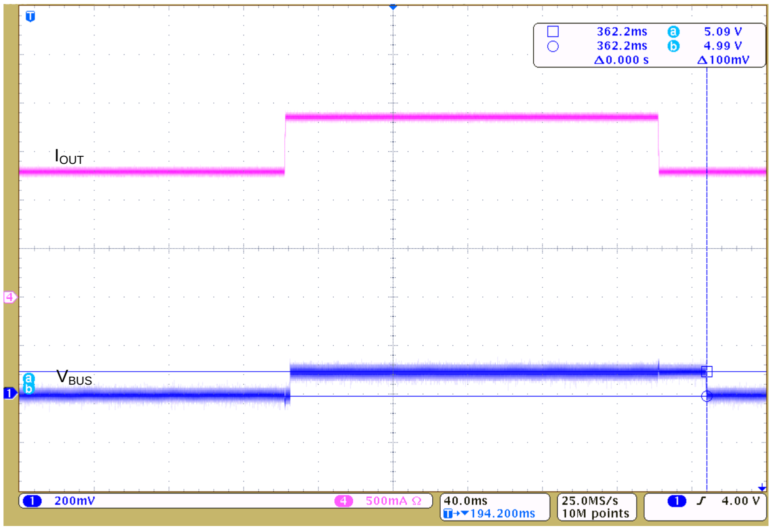


Figure 12: Cable Voltage Drop Compensation

5 Schematic, Bill of Materials and PCB Layout

5.1 Schematic

Figure 13 shows the whole schematic of the RD.

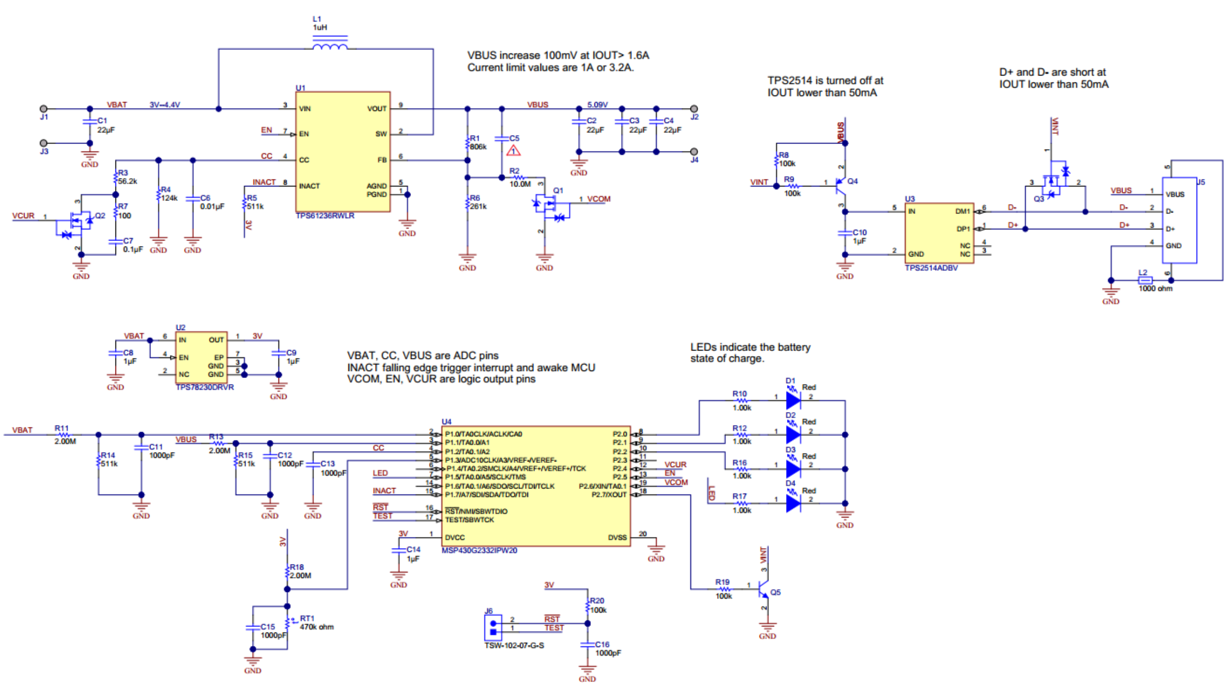


Figure 13 PMP9776 Schematic

5.2 Bill of Materials

The bill of materials in the reference design is shown in Table 1.

Table 1 PMP9776 Bill of Material

Designator	Description	Manufacturer	PartNumber	Quantity
C1, C2, C3, C4	CAP, CERM, 22uF, 10V, +/-20%, X5R, 0805	MuRata	GRM21BR61A226ME44	4
C5	CAP, CERM, 10 pF, 50 V, +/- 5%, C0G/NP0, 0402	MuRata	GRM1555C1H100JA01D	1
C6	CAP, CERM, 0.01 µF, 50 V, +/- 10%, X7R, 0402	MuRata	GRM155R71H103KA88D	1
C7	CAP, CERM, 0.1 µF, 25 V, +/- 10%, X7R, 0402	MuRata	GRM155R71E104KE14D	1
C8, C9, C10, C14	CAP, CERM, 1 µF, 10 V, +/- 10%, X5R, 0402	MuRata	GRM155R61A105KE15D	4
C11, C12, C13, C15, C16	CAP, CERM, 1000 pF, 50 V, +/- 10%, X7R, 0402	MuRata	GRM155R71H102KA01D	5
D1, D2, D3, D4	LED, Red, SMD	Avago	HSMC-C190	4
J1, J2, J3, J4	Terminal, Turret, TH, Double	Keystone	1502-2	4
J5	Connector, Receptacle, USB Type A, R/A, Bottom Mount TH	Wurth Elektronik	614 104 150 121	1
J6	Header, 100mil, 2x1, Gold, TH	Samtec	TSW-102-07-G-S	1
L1	Inductor, Shielded, Metal Composite, 1 µH, 9.4 A, 0.009 ohm, SMD	Toko	FDSD0630-H-1R0M	1
L2	Ferrite Bead, 1000 ohm @ 100 MHz, 0.2 A, 0603	Wurth Elektronik	74279266A	1
Q1, Q2, Q3	MOSFET, N/P-CH, 20 V, 0.63 A, SOT-416	Vishay-Siliconix	SI1012CR-T1-GE3-ND	3
Q4	Transistor, PNP, 40 V, 0.2 A, SOT-23	Fairchild Semiconductor	MMBT3906	1
Q5	Transistor, NPN, 40 V, 0.2 A, SOT-23	Fairchild Semiconductor	MMBT3904	1
R1	RES, 806 k, 1%, 0.063 W, 0402	Vishay-Dale	CRCW0402806KFKED	1
R2	RES, 10.0 M, 1%, 0.063 W, 0402	Vishay-Dale	CRCW040210M0FKED	1
R3	RES, 56.2 k, 1%, 0.063 W, 0402	Vishay-Dale	CRCW040256K2FKED	1
R4	RES, 124 k, 1%, 0.063 W, 0402	Vishay-Dale	CRCW0402124KFKED	1
R5, R14, R15	RES, 511 k, 1%, 0.063 W, 0402	Vishay-Dale	CRCW0402511KFKED	3
R6	RES, 261 k, 1%, 0.063 W, 0402	Vishay-Dale	CRCW0402261KFKED	1
R7	RES, 100, 1%, 0.063 W, 0402	Vishay-Dale	CRCW0402100RFKED	1
R8, R9, R19, R20	RES, 100 k, 1%, 0.063 W, 0402	Vishay-Dale	CRCW0402100KFKED	4
R10, R12, R16, R17	RES, 1.00 k, 1%, 0.063 W, 0402	Vishay-Dale	CRCW04021K00FKED	4
R11, R13, R18	RES, 2.00 M, 1%, 0.063 W, 0402	Vishay-Dale	CRCW04022M00FKED	3
RT1	Thermistor NTC, 470k ohm, 5%, 0402	MuRata	NCP15WM474J03RC	1
U1	7-A Synchronous Boost Converter with Programmable Output Current Limit, RWL0009A	Texas Instruments	TPS61236RWLR	1
U2	Single Output LDO, 150 mA, Fixed 3 V Output, 2.2 to 5.5 V Input, with 0.5 uA Quiescent Current, 6-pin SON (DRV), -40 to 125 degC, Green (RoHS & no Sb/Br)	Texas Instruments	TPS78230DRVR	1
U3	USB Dedicated Charging Port Controller, DBV0006A	Texas Instruments	TPS2514ADBV	1
U4	16 MHz Mixed Signal Microcontroller with 4 KB Flash, 256 B SRAM and 16 GPIOs, 20-pin SOP (PW), Green (RoHS & no Sb/Br)	Texas Instruments	MSP430G2332IPW20	1

5.3 PCB Layout

Figure 14 and Figure 15 show the layout of the reference design. The output capacitor of the boost converter must be placed closed to the IC. And the copper thick is 2oz to help to improve the efficiency and thermal performance.

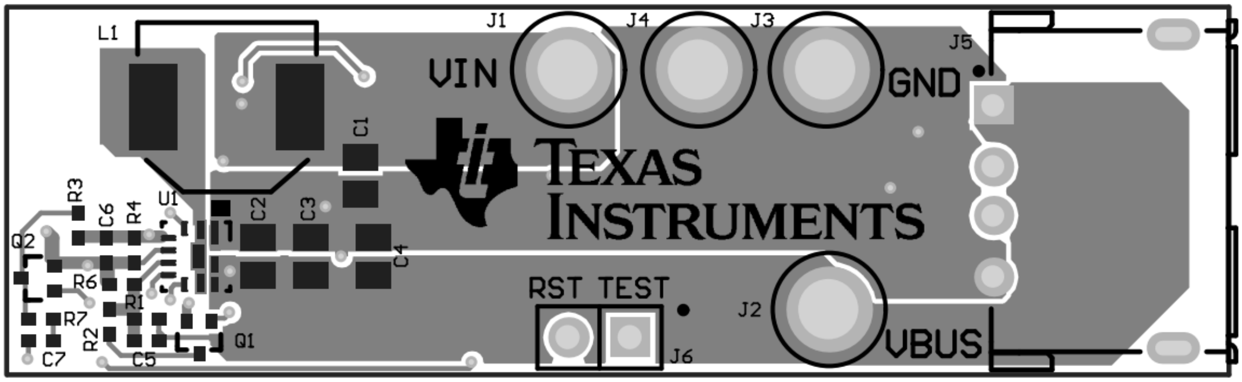


Figure 14 PMP9776 Top Overlay, Top Layer and Top Paste

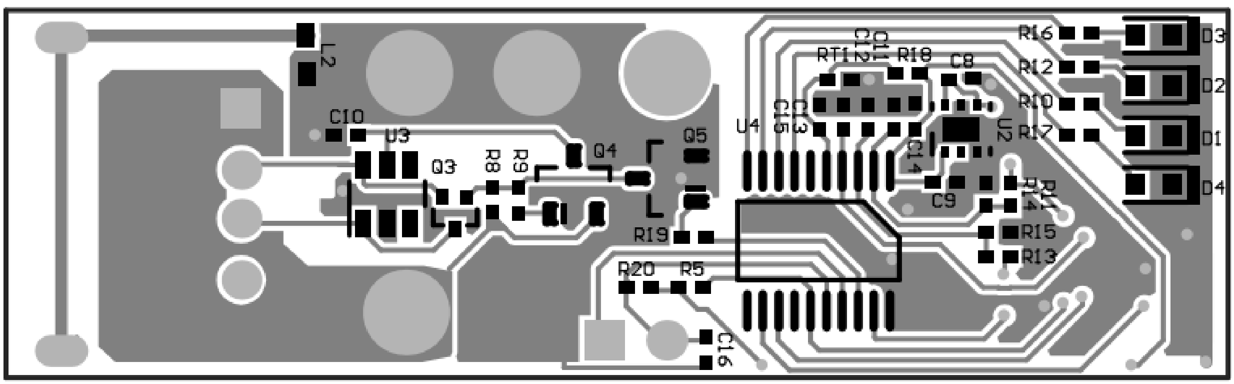


Figure 15 PMP9776 Bottom Overlay and Bottom Layer