Application note

Digitally controlled DC-DC converter with L5964 for automotive applications

Introduction

To meet the latest connectivity and fast charging requirements of portable devices, the very popular USB plug has evolved from a simple PC interface with limited power supply capabilities to the USB type-C standard capable of supporting multimedia devices, rapid battery recharging and supplying power to many types of portable devices with same standard connector.

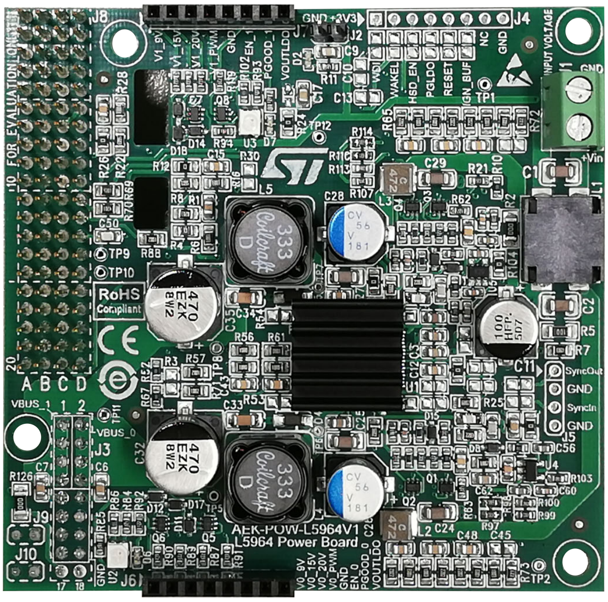
The AEK-POW-L5964V1 power board is designed to operate as a power supply in USB Type-C systems for automotive and transportation applications or to supply multimedia infotainment devices in car body applications.

The board has two independent converters that can deliver a selectable fixed output voltage or a set of variable ones, and power level selection is performed via MCU control for an output current of up to 3 A on both channels. The converters are accompanied by all the necessary protections against failures like overcurrent and overtemperature.

The board also includes monitoring circuits for input and output voltages and status LEDs. Appropriate filtering is implemented to minimize EMI.

The board is designed according to the AutoDevKit initiative, with a dedicated driver and basic demo software available in SPC5-Studio.

Figure 1. AEK-POW-L5964V1 digitally controlled DC-DC converter with L5964



1 Main characteristics and board description

The AEK-POW-L5964V1 evaluation board is designed for USB-PD 3.0 compliant, infotainment, in car dc-dc applications. Its high efficiency and small size render the board suitable for applications involving limited available space.

AEK-POW-L5964V1 board features:

- Dual channel, independent, step-down regulators with integrated synchronous MOSFETs
- Output current up to 3 A each channel
- Channels can be paralleled to obtain a higher current supply
- Input voltage range from 6 to 14 V
- Digitally selectable fixed output voltages: 3.3 - 5 - 9 V
- PWM programmable output voltages with 20 mV steps over a range of 3.3 - 11 V
- Outputs protected against short-circuit and overcurrent
- Input and output voltage monitors (UV or OV) and power good signals
- Thermal protection thanks to the integrated thermal sensor
- Additional 3.3 V output by internal linear regulator
- Watchdog, reset, in/out synchronisation for available converters
- Board size: 84.7 mm x 81.3 mm
- Maximum component height: 10 mm
- Automotive grade qualified ST components
- Included in the AutoDevKit initiative
- CE certified
- RoHS and China RoHS compliant
- WEEE compliant

The main DC-DC converter in the power board is the L5964 monolithic dual 3.5 A step-down switching regulator with LDO. It integrates control, power switches and monitoring circuits for both channels and additional features like Watch Dog, Wake up, Reset, etc.

The power board is designed to work with an MCU board like the AEK-MCU-C4MLIT1. However, to build a complete 2-port USB-PD system, you need to add an AEKD-USBTYPEC1 evaluation kit, which includes an MCU board and a dual-port USB Type-C function board (AEK-USB-2TYPEC1). The kit also allows you to test the USB power delivery protocol stack.

2 Connectors and interfaces

The power board AEK-POW-L5964V1 has the following interface connectors:

- Input connector J1: is connected to the 12 Vdc power source and can accept an input voltage from 6 Vdc up to 26 Vdc.
- Output connector J3: both converter outputs are connected to J3, including GND signal; it is a standard 2x9-pins female mounted on bottom side of the board, and is plugged to the AEK-USB-2TYPEC1 USB Type-C expansion board.
- Signal connectors J9, J10: are mounted on bottom side of the board, for connection to the USB Type-C expansion board; their purpose is to short certain signals once the power board is plugged onto the USB Type-C expansion board to allow the delivery of the right voltage levels from the power board to the USB ports.
- Signal connector J8: this 4x20-pin connector carries all signals necessary to control and monitor the power board from the MCU. This male/female connector can be used to stack additional boards on top. The 4x20 pins on the female side are used to connect the power board to an SPC58 discovery board 4x37 male connector from lines 18 to 37.

Table 1. AEK-POW-L5964V1 signals to and from the MCU

Type	Signal name	MCU port	J8 pin #	Signal type / IN/OUT	To/From	Description
1	V0_3V3	PF11	A5	Flag - 3.3 V (GPIO) / IN	From MCU	O/p voltage setting - fixed
1	V1_3V3	PA0	B4	Flag - 3.3 V (GPIO) / IN	From MCU	O/p voltage setting - fixed
2	I_SENSE_0	PI6	B10	Analog / IN	From Exp. board	Buck2 o/p current sensing
2	I_SENSE_1	PG10	B15	Analog / IN	From Exp. board	Buck1 o/p current sensing
3	V1_PWM	PE6	C1	3.3 V – var. duty / IN	From MCU	O/p voltage setting - fixed
3	V0_PWM	PE5	D1	3.3 V – var. duty / IN	From MCU	O/p voltage setting - fixed
5	CC_REF_0	PE2	D17	3.3 V – var. duty / IN	To CC E/A Buck2	Buck2 CC E/A reference
5	CC_REF_1	PF14	C6	3.3 V – var. duty / IN	To CC E/A Buck1	Buck2 CC E/A reference
1	V0_20V	PF2	D3	Flag - 3.3 V dc (GPIO) / IN	From MCU	O/p voltage setting - fixed
1	V0_15V	PB11	D4	Flag - 3.3 V dc (GPIO) / IN	From MCU	O/p voltage setting - fixed
1	V0_9V	PC2	D5	Flag - 3.3 V (GPIO) / IN	From MCU	O/p voltage setting - fixed
1	V1_20V	PH1	D9	Flag - 3.3 V (GPIO) / IN	From MCU	O/p voltage setting - fixed
1	V1_15V	PK1	C9	Flag - 3.3 V (GPIO) / IN	From MCU	O/p voltage setting - fixed
1	V1_9V	PD4	D18	Flag - 3.3 V (GPIO) / IN	From MCU	O/p voltage setting - fixed
5	EN_0	PD12	D8	Flag - 3.3 V (GPIO) / IN	From MCU	Enable buck2
5	EN_1	PM2	D19	Flag - 3.3 V (GPIO) / IN	From MCU	Enable buck1
4	TJ_TEST_F	PB7	D13	Analog (1÷2 V) / OUT	To MCU ADC	Chip temperature sensing
6	PGOOD_0	PI4	D11	Open Collector / OUT	To MCU ADC	VBUS_0 out of tolerance è LOW
6	PGOOD_1	PI7	C10	Open Collector / OUT	To MCU ADC	VBUS_0 out of tolerance è LOW
4	VBUS_0_ADC	PG9	D12	Analog - 0.5÷1.7 V / OUT	To MCU ADC	VBUS_0 o/p voltage sensing
4	VBUS_1_ADC	PG6	C12	Analog - 0.5÷1.7 V / OUT	To MCU ADC	VBUS_1 o/p voltage sensing
4	VIN_ADC	PB6	C13	Analog - 0.9÷2.7 V / OUT	To MCU ADC	I/p voltage sensing

Type	Signal name	MCU port	J8 pin #	Signal type / IN/OUT	To/From	Description
7	5V	-	B20	dc power supply	To J3-17 (VCONN)	5 V from SPC58 discovery board
7	VEXT	-	D20	dc power supply	To J3-18	12 V SPC58 discovery board I/P voltage - unused
7	VEXT_P	-	A20	dc power supply	From MCU board	12 V I/P voltage – jumper - unused
7	VEXT_P	-	B20	dc power supply	From MCU board	12 V I/P voltage - jumper - unused
7	3V3_CH	-	C20	dc power supply	From MCU board	3.3 V from SPC58 discovery board - unused
5	GND	-	C19		From MCU board	GND

Table 2. Pin type legend

Pin type	Purpose
1	Signals setting for fixed o/p voltage
2	Signals for programmable cc loop
3	Signals for programmable o/p voltage
4	Analog signals for MCU ADCs
5	Signals mandatory for board operation
6	Digital flag signals
7	dc supply/GND on 4x 19-pin connector

- Test connectors J6, J7: two connectors, one for each buck converter, are provided for test purposes. The signals available are LDO o/p voltage, EN, PGOOD, o/p voltage selection flags. By shorting certain pins like LDO and EN, it is possible to obtain converter operation without the MCU connected. In the same way, it is also possible to easily select the o/p voltage.
- Synchronization connector J5: L5964 has two pins to synchronize the buck converters in case of operation with other converters working as slaves. Additionally, it delivers a synchronization signal that can be used to synchronize other converters working as masters. Because these features are not used on the power board, this connector is not mounted.
- Signal IN/OUT connector J4: Other functions embedded in the L5964 to control the MCU are unused, but available on connector J4. This connector is not mounted on the board.

3 Functional blocks and circuit descriptions

The block descriptions and concepts associated with converter Buck2 supplying VBUS_0 are exactly applicable to the mirrored circuits for Buck1 supplying VBUS_1, only the component references change.

3.1 Power stages and buck converters

The two converters delivering the output voltages are based on a typical buck topology with synchronous rectification to increase the efficiency. Both switches are N-channel MOSFETs, integrated in the L5964. The switching frequency selected is 250 kHz for both converters in order to obtain a good compromise between component sizes and switching losses. The L5964 manages operation of both converters 180° out-of-phase to minimize the input ripple. The operating frequency of both converters can be selected by resistors R34 and R35.

Both stages have an individual Pi-filter input to minimize the differential mode noise (C24, L2, C25, C26). The output power stage only needs an inductor and an electrolytic capacitor (L4 and C32) for energy storage at any switching cycle. An additional small ceramic capacitor is added in parallel with the electrolytic capacitor to decrease noise spikes. To protect from negative spikes due to the parasitic inductances, a small Schottky diode is added in parallel (D4) on each phase pin.

As the conducted noise generated by converters can affect other external circuits, an additional Pi-filter is placed (C1, L1, C2) close to the input connector to filter both differential and common mode noise.

3.2 Output voltage regulation loops

The L5964 embeds two regulation circuits to independently control the output voltage of both converters in a typical current mode with slope compensation. All the blocks needed for the control portion are integrated; only the compensation network (R53, C21, C23) and the feedback network have to be connected externally. The voltage loop error amplifier is a trans-conductance type and the compensation network is a typical type-2 network connected to ground.

The feedback network is more complex than a usual simple voltage divider because the functions required by the USB-PD specification are implemented through this block. As soon as input voltage is provided, the power board supplies a fixed default voltage (5 V); a different fixed output voltage is selectable via the MCU. The power board also supplies a variable voltage from 3.3 V to 11 V to support the Programmable Power Supply (PPS) Voltage mode according to the USB Power Delivery standard version 3.0. The fixed voltage and PPS operating modes can be independently applied on each of the two L5964 converters, so a converter can regulate a fixed voltage on one channel while the other channel is regulated according to the PPS at any voltage in the available range.

Figure 2. Fixed output voltage feedback loop schematic-1

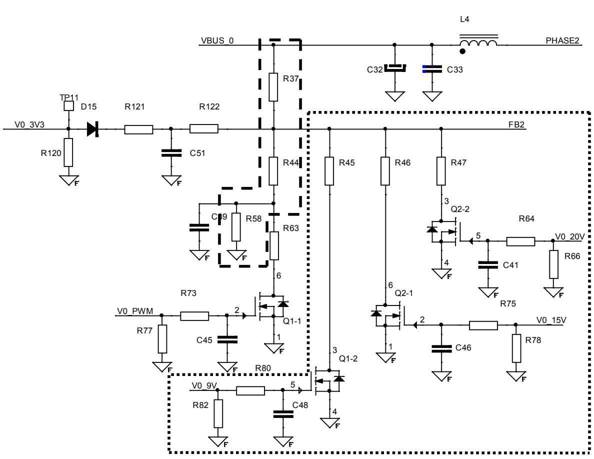
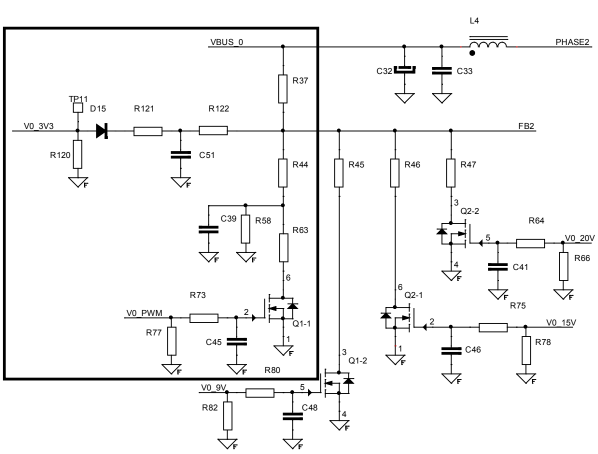


Figure 3. Variable output voltage feedback loop for PPS-Voltage mode schematic-2



The feedback circuit schematic above can be split into the functional blocks described below.

Default output voltage

If no voltage selector signal is applied to the power board, the default output voltage is 5 V according to the USB-PD specification. The components used to set the default voltage are included in the area inside the dashed line: R37, R44, R58 implement a typical fixed voltage divider. The inverting input of the error amplifier is connected to the common point of the FB2 feedback voltage divider.

Fixed output voltages

Apart from the default 5 V, the USB-PD specification recommends the additional 9 V, 15 V, 20 V fixed output voltages. As the converter topology is buck, the power board can only deliver output voltages below the input; that is, 5 V and 9 V. However, the circuitry required to support operation at 15 V and 20 V is in place, and these higher voltages may be supported by future versions of the L5964. If the higher voltages are not needed, this section can be removed from your design.

The power board provides different output voltages when one or more resistors are placed in parallel to change the voltage set point. The MCU provides a TTL signal activating one or more of the three small signal MOSFETs that tie R45, R46, R47 to GND. These resistors are visible inside the dotted line in Figure 2. Resistor R37 is the top resistor of the feedback divider and is shared if other bottom resistors are tied to GND to obtain higher voltages.

An additional 3.3V is available for USB-PD PPS operation and can also be used as a supply voltage when the board is used as generic power supply. Both converters can deliver all mentioned voltages up to maximum current of 3 A each.

For both channels, the fixed output voltage can be set independently by providing signals according to the table below. If no output voltage overrides are set by the MCU, the board delivers the default 5 V voltage. Each converter has to be enabled by pin EN_x = H and signal CC_VREF_x has to be set at 3.3 Vdc, even if the current limiting function by the output current regulation loop is unused.

Table 3. Fixed output voltage selection table

VBUS_x	Vx_3V3	Vx_9V	Vx_15V	Vx_20V	Vx_PWM	EN_x	CC_VREF_x
5 V	L	L	L	L	OFF	H	H
9 V	L	H	L	L	OFF	H	H
15 V	L	H	H	L	OFF	H	H
20 V	L	H	H	H	OFF	H	H

Variable output voltage for PPS-Voltage mode

The AEK-POW-L5964V1 power board also allows programming the output voltage in a range from 3.3 V to 11 V, as required by the USB Power Delivery 3.0 specification for the Programmable Power Supply (PPS) operation.

In the PPS implementation by ST, the MCU delivers two dedicated signals to each converter: one is a dc TTL fixed signal (Vx_3V3, e.g. an MCU GPIO), and the other is a PWM TTL signal where its duty cycle is proportional to the required output voltage (Vx_PWM). These signals are provided the on 4x20 pin connector J8.

The dc TTL fixed signal Vx_3V3 is required to decrease the 5 V default output voltage to 3.3 V; this functionality is implemented through a circuit injecting current into the FB1 node (see solid line rectangle section in Figure 3).

When any other higher output voltage is needed, the PWM signal Vx_PWM with a suitable duty is applied. This signal provides an on-off operation on the small signal MOSFET Q1 which, by means of R63, will partially discharge C39. As C39 and R63 have a larger time constant compared to the PWM signal, the result is an integration of the PWM signal coming from the MCU. R44 then removes some current from the feedback node, thus causing an increase in the output voltage proportional to the duty of the PWM signal coming from the MCU.

As this is an analog circuit, the minimum variation for a single step depends on the granularity of the PWM signal driving the small signal MOSFET Q1. Once the converter is in PPS-Voltage mode, the signals setting fixed output voltages have to be set Low.

The relationship between the PWM signal from the MCU and the output voltage for VBUS_0 is:

$$VBUS\_0 = R37 \times \left(\frac{V_{FB0}}{R44 + \frac{R58 \times R63}{\delta \times R58 + R63}} - \frac{VGPIO - V_{FB0} - V_F}{R121 + R122} \right) + V_{FB0} \quad (1)$$

Where:

- VBUS_0 = output voltage
- V_{FB0} = L5964 feedback voltage of voltage loop
- VGPIO = peak voltage of the PWM signal, V0_PWM (typ. 3,3 V, from MCU)
- VF = Schottky diode D15 forward voltage drop
- δ = duty cycle of V0_PWM signal (from MCU)
- R37, R44, R58, R63 = PWM circuit resistors (on power board)
- R121, R122 = setting resistors of the output voltage at 3.3 V (on power board)

As shown by the formula, the output voltage changes only due to the duty cycle of the control signal coming from MCU, while the other elements can be considered constant. Given that the signal frequency is not involved in the calculation, the same frequency can be selected in a wide range of possible values.

Alternatively, the MCU can work by delivering a fixed on-time signal and changing the frequency to obtain the duty cycle needed to supply the load with the output voltage required.

In Figure 4, the above equation is represented as a diagram showing the output voltage VBUS_x versus the duty of signal from MCU, Vx_PWM. Figure 5 instead shows the duty necessary to obtain a desired output voltage.

Figure 4. Vout vs. Vx_PWM duty

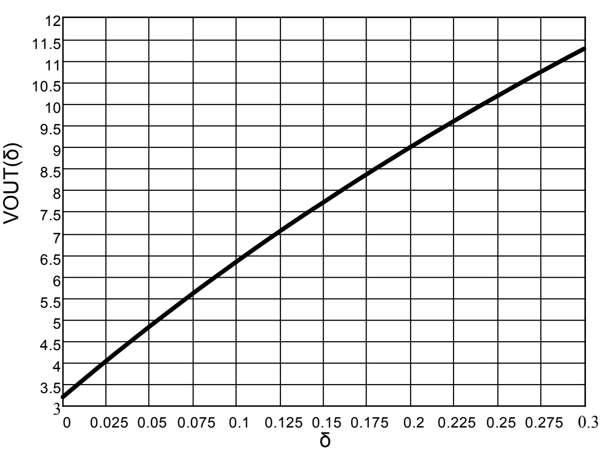
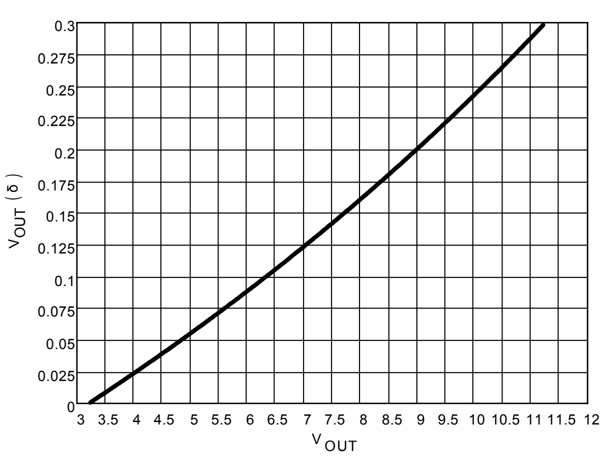


Figure 5. Vx_PWM duty vs. Vout



The signals required for variable output voltage operation are given in Table 4. If the Vx_PWM signal from MCU is not applied, or it has duty = 0, the board delivers the default 3.3 V. The desired output voltage can be set applying the Vx_3V3 signal to each channel and the relevant Vx_PWM signal with suitable $T_{on\text{-}time}$ and frequency. As for fixed output voltage operation, each converter has to be enabled by EN_x = H and signal CC_VREF_x has to be set at 3.3 Vdc.

Table 4. Variable output voltage selection table

VBUS_x	Vx_3V3	Vx_9V	Vx_15V	Vx_20V	Vx_PWM	EN_x	CC_VREF_x
5 V	H	L	L	L	ON	H	H
9 V	H	L	L	L	ON	H	H
15 V	H	L	L	L	ON	H	H
20 V	H	L	L	L	ON	H	H

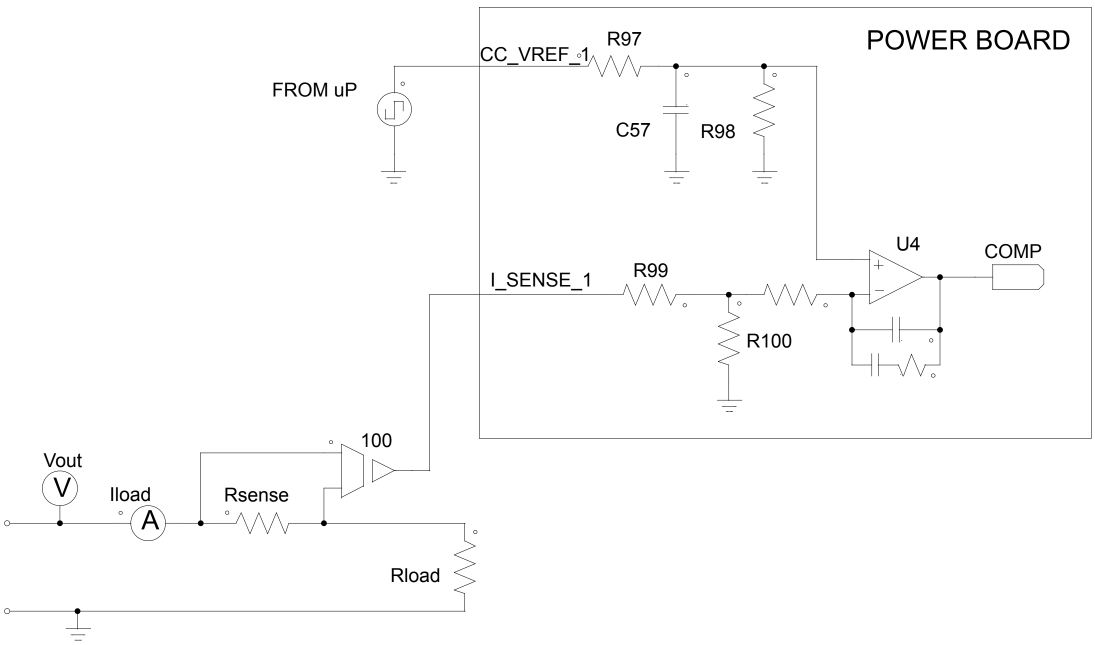
3.3 Output current regulation loops

The AEK-POW-L5964V1 embeds the circuitry on both converters to support constant current operation. In this operating mode, the converter changes from maintaining constant output voltage like a voltage generator to limiting the output current like a current source. This functionality is not only required to limit the output power in case of failures, but also for battery charging or when connecting a load that behaves as a voltage source, as in the USB-PD 3.0 load direct charging operation.

The simplified schematic of the constant output current feedback loop for Buck2 is shown in Figure 6. The circuit is based on an additional error amplifier in which the output pin is OR-ed with the voltage loop error amplifier output pin COMP. The voltage and current loops always complement each other, regulating the output voltage or current according the load resistance value.

The error amplifier inverting input is connected to the current sensing circuit. The current sensing circuitry is not present on the AEK-POW-L5694V1 power board as it is implemented on the AEK-USB-2TYPEC1 dual-port USB Type-C expansion board, and the signals can be routed to the power board via the 4x20 pin connector J8 (I_SENSE_x).

Figure 6. Simplified schematic for constant output current feedback loop (Buck2, VBUS_0)



Output current is set by the MCU via a CC_VREF_x signal for each converter, which are TTL PWM signals with variable duty proportional to the output current set point. Both are connected on the 4x20 pin connector J8. This circuitry meets the PPS current requirement of the USB-PD specification 3.0, which requires control over the maximum output current from 0 A to 3 A with 50 mA steps and allows the direct “cold” charging control of the batteries.

The constant current circuit implements a feedback network sensing the output load current. An equivalent sensing resistor producing a voltage on the inverting pin of U4 can be calculated as:

$$\mathrm{Re}\,q_{sense} = Rs \times Ksns \times \frac{R100}{R100 + R99} = 0.909\Omega \quad (2)$$

Where:

- Rs = output current sensing resistor (on USB-PD expansion board)
- Ksns = gain of sense amplifier (on USB-PD expansion board)
- R100 = divider resistor (on power board)

- R99 = divider resistor (on power board)

Presuming the perfect integration of the waveform by capacitor C57, the reference voltage *Vref_x* applied at non-inverting pin of U4 is:

$$Vref\_x = CC\_VREF\_x \times \delta \times \frac{R97}{R97 + R98} \quad (3)$$

Where:

- CC_VREF_x = Peak voltage of the PWM signal (typ. 3,3 V, from MCU)
- δ = Duty cycle of the PWM signal (from MCU)
- R97 = divider resistor (on power board)
- R98 = divider resistor (on power board)

Combining Eq. (2) and Eq. (3), and considering the constant quantities in both, we can simplify these into the following equation:

$$Iout_x = \frac{\partial}{0.286} \quad (4)$$

The above equations are linear and thus perfect linear proportionality is achieved among the duty cycle variations of the signal CC_VREF_x coming from the MCU and the output current of the same buck converter channel.

3.4 Overcurrent protection

The L5964 integrates protection functions such as embedded pulse-by-pulse overcurrent protection to limit the current peak converters in an overcurrent or short-circuit event. The trigger threshold can be set at 50% or 100% through the OCPSETx pins.

3.5 Power good signals

Converters are provided with undervoltage (UV) and overvoltage (OV) protections, fully integrated into the L5964. The IC internal circuitry monitors the FBx pin of both converters and pulls down the relevant pin if the voltage deviates from nominal value. On the power board, the power good signals are combined and connected to the MCU via the 4x20 pin connector J8 (PGOOD_x); PGOODx signals are active low.

Note: The PGOOD signal goes low during constant current control because the load resistance causes the output voltage to drop below the nominal value, and the voltage loop is not regulated.

To simplify the interface with MCU, the PGOOD_x signals can be delayed by a capacitor connected to pins #64 and #2 if necessary.

3.6 Voltage monitoring

To control the converters via the MCU, both the input voltage and output voltages are supplied via their respective voltage divider, scaling to a level compatible with microcontroller ADCs. A small capacitor for noise filtering is provided too. These signals (VIN_ADC and VBUS_x_ADC) are connected to the 4x20 pin connector J8.

3.7 Temperature monitor and overtemperature protection

The L5964 has a dedicated pin with a voltage proportional to the chip temperature (pin TJTEST). The signal from this pin is filtered and sent to the MCU via the 4x20 pin connector J8. Additionally, if the L5964 temperature increases excessively, an internal protection stops the converter duty until the temperature has returned to acceptable levels.

3.8 LEDs

The board has LEDs to highlight certain signal activation.

Table 5. Signal LEDs

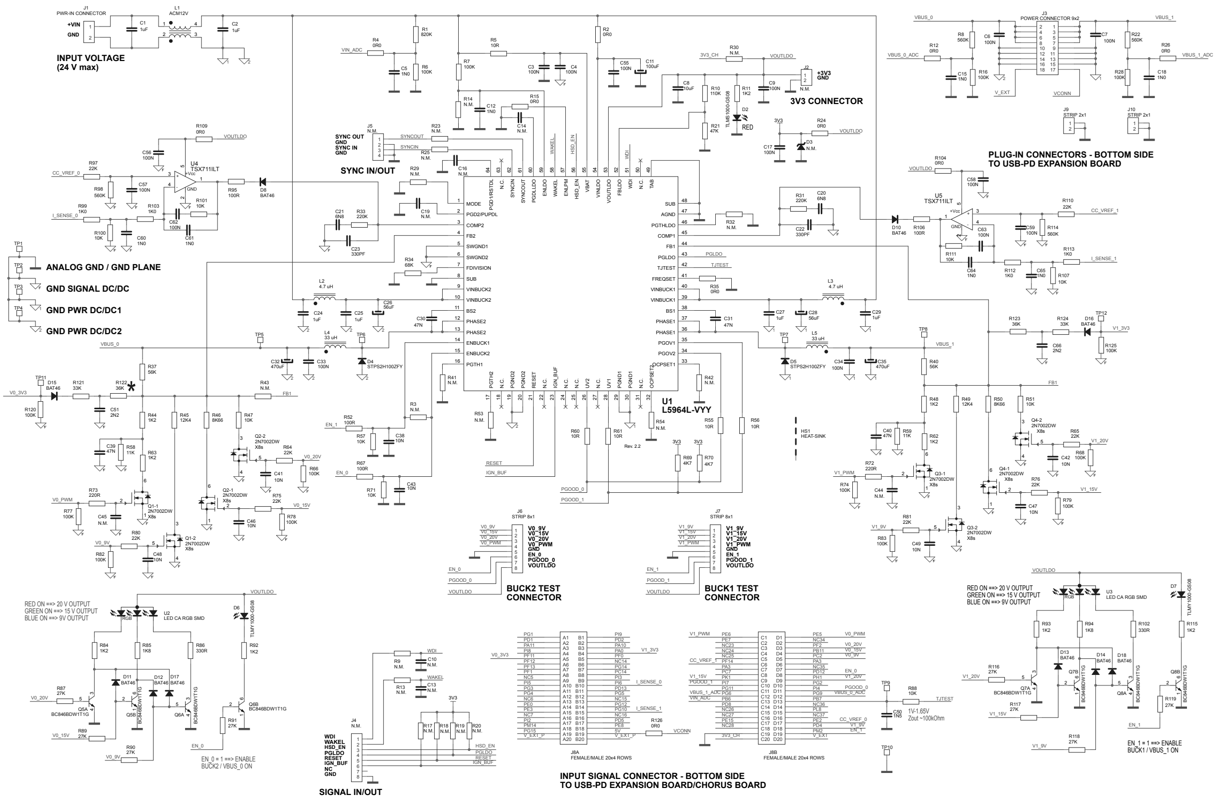
Signal	LED	Color	Status
VOUTLDO	D2	Red	ON
EN_0; EN_1	D6; D7	Yellow	ON
Vx_9V	U2; U3	Blue	ON
Vx_15V	U2; U3	Green	ON
Vx_20V	U2; U3	Red	ON

3.9 LDO and additional functions

The L5964 integrates an LDO used to supply 3.3 V to some auxiliary circuits like the constant current error amplifiers or the LEDs, and is also connected to one of the test connector pins for evaluation purposes. The LDO output voltage can be programmed by a divider connected to a dedicated pin, the maximum limiting current is 380 mA in normal mode, and it may also be used to supply the system MCU. LDO power dissipation should be considered when calculating the total losses of the L5964 to provide enough margin for long term operation. A power good pin is provided and is available on J4.

Additional functional blocks integrated in the L5964 are Watch Dog input, WakeL, High-Side Driver Enable, Reset and Ignition buffer. These functions are currently unused on the power board, but are available on connector J4 for additional custom functionality.

Figure 7. AEK-POW-L5964V1 schematic diagram



4 Connecting the power board

The AEK-POW-L5964V1 power board can be connected to an MCU board.

When connecting the boards, ensure that the pins in row #20 of the power board connector J8 coincide with pins in row #37 of the X9 (4x37-pins) connector of the MCU. The additional connections and signals required by the power board and MCU are listed in Table 6.

Figure 8. Power board plugged on MCU board

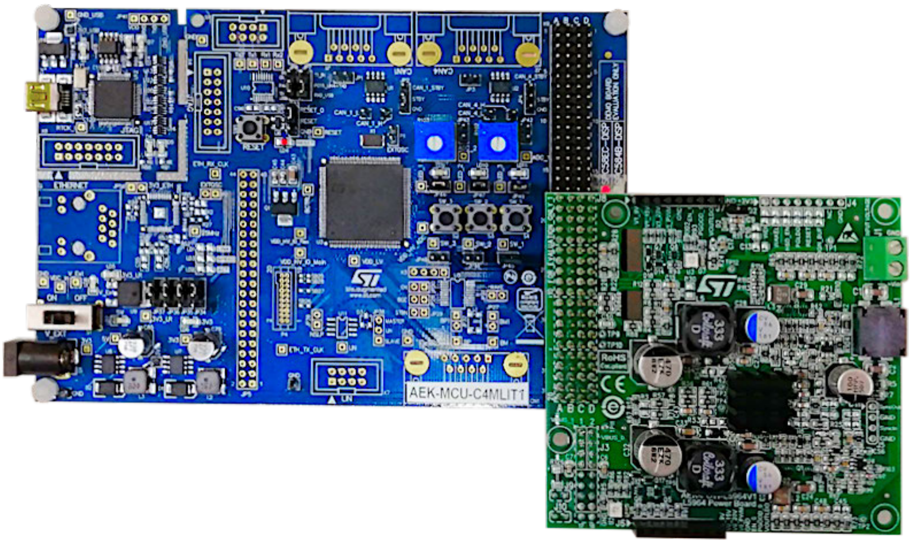


Table 6. Connections for operation with MCU

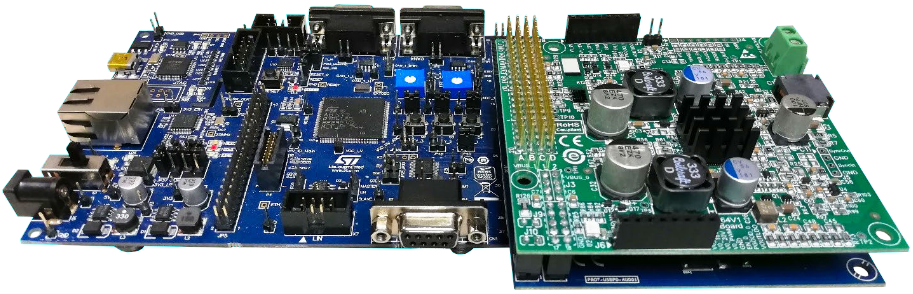
Connector	Board/position	Type	Voltage	Remarks
J1	Power board / top layer	Screw connector	12 V typ @6 A	Input power connector
J8	Power board / bottom layer	4 x 20-pins 2.54mm pitch		Signal connector, plugged to X9 of the MCU. J8 row 20 has to match X9 row 37 of the MCU
J3	Power board / bottom layer	2 x 9-pins 2.54mm pitch		Output voltage connector
X5	AEK-MCU-C4MLIT1 / top layer	Jack	12 V typ @1 A	MCU power connector
P3	AEK-MCU-C4MLIT1 / top layer	USB-Mini		USB cable for communication with MCU

4.1 Operation with USB Type-C function board (AEK-USB-2TYPEC1)

The AEK-POW-L5964V1 power board is designed to provide the required voltages to a complete 2-port USB-PD 2.0 unit, which can be implemented with the AEKD-USBTYPEC11 kit with an MCU and dual-port USB Type-C function board (AEK-USB-2TYPEC1).

In Figure 9, the power board is oriented above the USB Type-C function board to facilitate air flow for cooling of the power circuits. Check that all connector pins match correctly with bottom ones when plugging the boards. The USB type-C functional board is plugged onto the MCU board by aligning pins #39 and #40 of connectors J101 and J102 with pins #37 row A to D of the X9 (4x37 pins) connector of the MCU. The MCU provides the signals required to operate the entire system, and the software provided allows evaluation of board functionality and the USB-PD 2.0 protocol.

Figure 9. **Power board with MCU board and 2-port USB-PD interface board**



For power board with MCU testing, the following connections and signals are required:

Table 7. **Connections for operation with complete USB PD kit**

Connector	Board/position	Type	Voltage	Remarks
J1	Power board / top layer	Screw connector	12V typ. @ 6A	Input power connector
J3	Power board / bottom layer	2 x 9-pins 2.54mm pitch	-	Output voltage connector
X5	AEK-MCU-C4MLIT1 / top layer	Jack	12V typ @ 1A	MCU power connector
P3	AEK-MCU-C4MLIT1 / top layer	USB-mini	-	USB cable for communication with MCU

4.2 Standalone operation

The AEK-POW-L5964V1 board can also operate with limited functionality in standalone mode without MCU control. While some of the MCU signals must be compensated with external signals, standalone operation allows the overall design to be simplified as the circuitry associated with MCU control can be omitted. This solution is suitable for supplying power to infotainment, multimedia, and other car body applications, and for testing the board in general.

The signals to be applied can be found in Table 1 or in Table 3. The basic signals for converter operation excluding the input supply voltage are:

- EN_x set high
- voltage selector signals set high according to the required output voltage
- CC_VREF_x set to 3.3 Vdc (the 3.3 V from the LDO can be used to provide the required voltage to the CC_VREF_x pin)

5 Fixed output voltage and efficiency at 12 Vdc input voltage

This section provides some test results for the board in standalone mode. The main parameters were checked and the efficiency was calculated at different loads. The input voltage was a nominal 12 Vdc, and the loads were similar on both channels through an active load working in constant current mode. Input and output voltages were measured at the board connectors. All measurements were recorded after after 30 minutes warm-up time.

Table 8. Voltage measurements and efficiency calculation

- VLDO = 3.308 V

Vin (V)	Iin (mA)	Pin (W)	Vbus0 (V)	Ibus0 (A)	Vbus1 (V)	Ibus1 (A)	Pout0 (W)	Pout1 (W)	Efficiency
12.470	0.459	5.72	5.055	0.508	5.079	0.500	2.568	2.541	89.26%
12.390	0.798	9.89	9.123	0.508	9.177	0.500	4.634	4.590	93.30%
12.370	0.894	11.06	5.048	1.007	5.072	1.000	5.081	5.072	91.81%
12.230	1.584	19.37	9.119	1.007	9.173	1.000	9.183	9.173	94.75%
12.140	1.833	22.25	5.043	2.008	5.067	2.000	10.126	10.133	91.04%
11.810	3.299	38.96	9.114	2.009	9.169	2.000	18.310	18.337	94.06%
12.200	2.839	34.64	5.044	3.012	5.068	3.002	15.193	15.214	87.79%
12.000	4.979	59.75	9.167	3.002	9.109	3.012	27.523	27.436	91.99%

Table 8 and Figure 10 show a very high effeciency above 91 % when the converters are both working at 9 V output voltage for any output current value.

Figure 10. Overall efficiency vs. output current

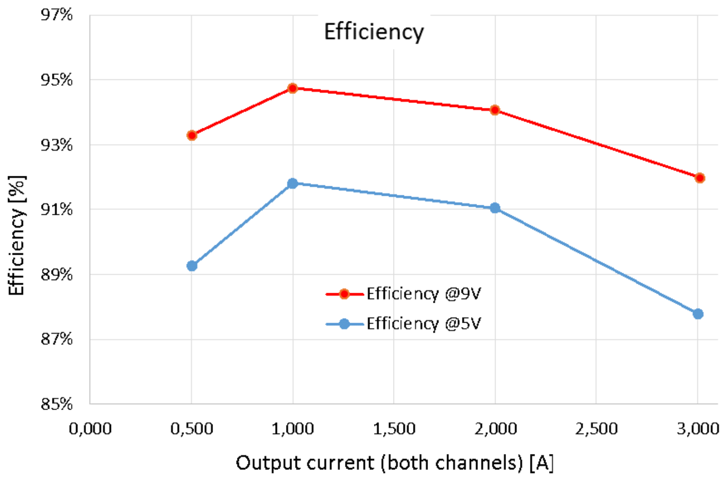


Figure 11 shows the output voltage and phase waveforms of the two buck converters. Both converters are synchronized and working at 283.6 kHz. The top waveforms relate to the Buck1 converter delivering 9 V on VBUS_1, while the bottom one is supplying 5 V. The Measurements on the right side show the difference in duty cycle together with output voltages.

Figure 11. Buck waveforms – Vin = 12.5V, Vbus_1 = 9 V @ 3 A, Vbus_0 = 5 V @ 3 A

- Legend: CH1:VBUS_1; CH3: PHASE1 (TP7); CH2: VBUS_0; CH4: PHASE2 (TP6)

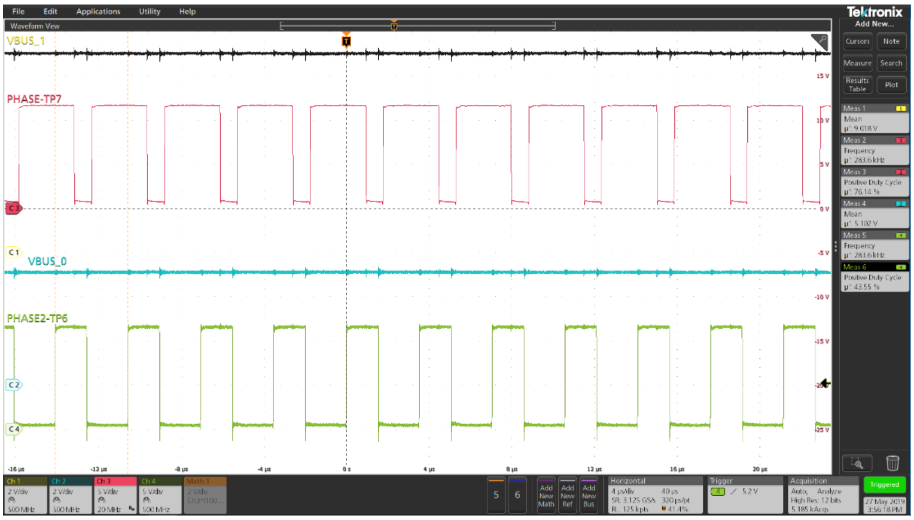
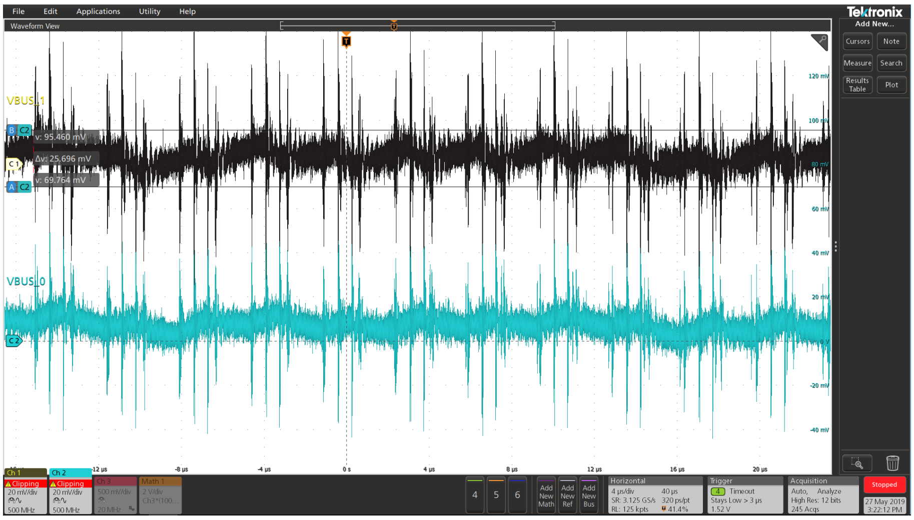


Figure 12 shows a maximum ripple of 25 mV by the channel working at maximum output power. Spikes and high frequency noise visible in the picture are not significant because it is radiated noise picked-up by the probe ground wire.

Figure 12. Output voltage ripple - Vin = 12.5V, Vbus_1 = 9 V @ 3 A, Vbus_0 = 5 V @ 3 A

- Legend: CH1: VBUS_1; CH2: VBUS_0



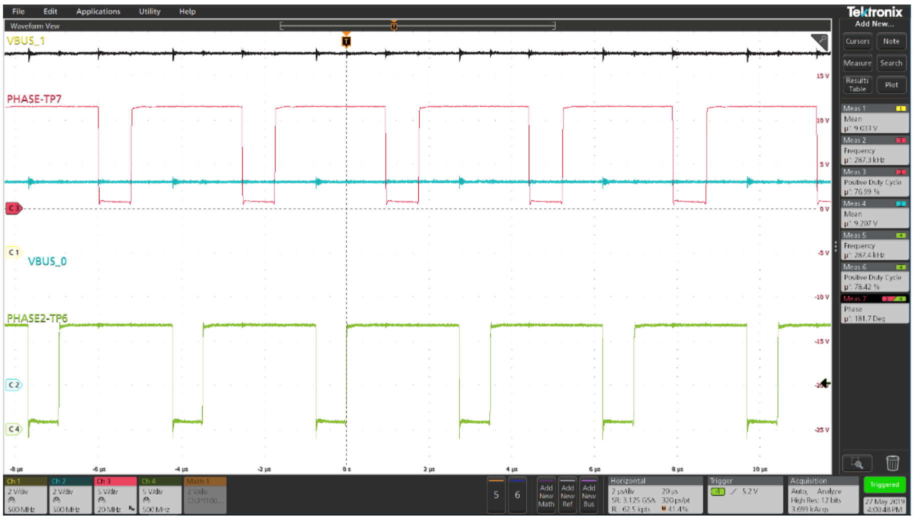
A significant contribution to differential mode noise reduction is given by the L5964 interleaving operation. The two converters are 180° out of phase, which minimizes input current ripple. This helps reduce the differential mode noise and optimize the buck input capacitor sizes.

Additionally, lower ripple current means significantly lower stress for input capacitors, which increases their lifetime.

The interleaving operation can easily be observed when both converters are working at the same duty cycle. Figure 13 demonstrates the out-of-phase operation mentioned above, the phase shift is measured on right side of the image.

Figure 13. **Buck waveforms – Vin = 12.5V, Vbus_1 = 9 V @ 3 A, Vbus_0 = 9 V @ 3 A**

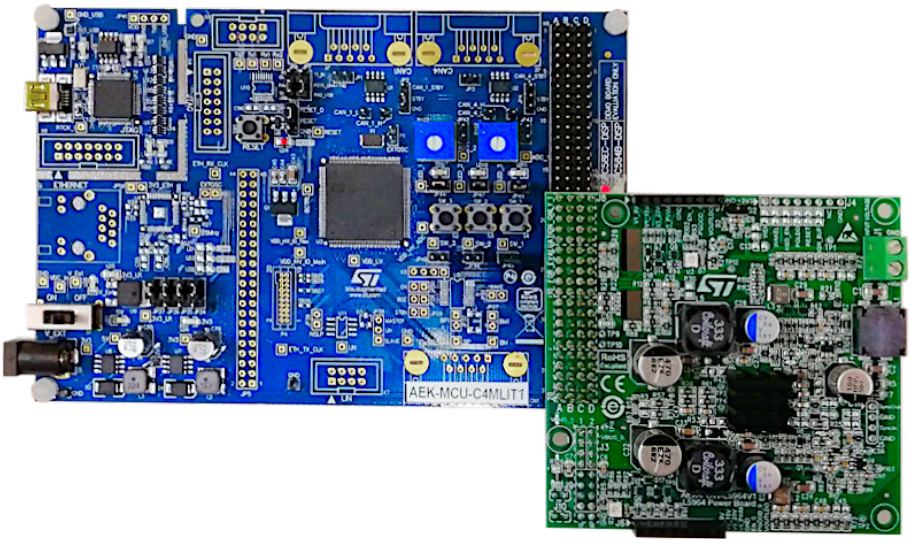
- Legend: CH1: VBUS_1; CH3: PHASE1 (TP7); CH2: VBUS_0; CH4: PHASE2 (TP6)



6 Operation with MCU

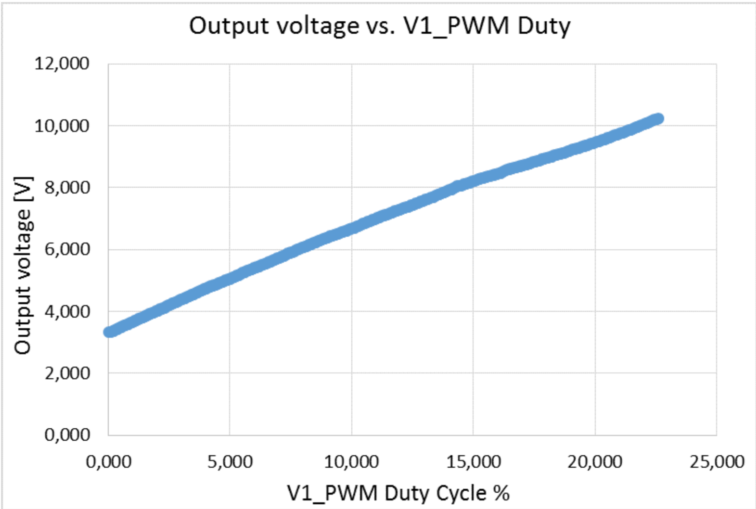
The AEK-POW-L5964V1 power board is designed to operate with an MCU control board. When connecting the boards, ensure that the pins in row #20 of the power board connector J8 coincide with pins in row #37 of the X9 (4x37-pins) connector of the MCU.

Figure 14. **Power board plugged on MCU board**



6.1 Variable output voltage (PPS-V mode)

Figure 15. **VBUS_1 output voltage vs. V1_PWM duty cycle**



The above figure shows the characteristics of the power board controlled by the MCU and the simulation of the voltage steps of the USB-PD PPS-V function from 3.3 V to 10.2 V with incremental steps of 20 mV.

The test results relate to an open loop operation, where the board output voltage is set by the PWM signal and only measured by employing an MCU ADC without any sort of regulation or adjustment of the output voltage by the MCU. This gives an idea of the precision of the power and control circuits of the power board, which shows very high linearity and monotonic behavior of the output voltage versus the duty cycle.

Thanks to functionality like the PPS-V mode operation, the board can be used to supply very precise voltages to critical loads or devices requiring very fine supply voltage adjustment, or to implement precise digital cable drop compensation.

Figure 16 shows some waveforms for PPS-V operation. We can observe that the Buck1 converter is delivering 5.85 V to the output load and the V1_PWM signal frequency is 142.1 kHz with duty cycle 7.806 %. The other signals on the oscilloscope image both have logic levels high: EN_1 enables Buck1 converter operation, while PGOOD_1 high signals that the output voltage regulation loop is working properly and the voltage level is appropriate.

Figure 17 shows an increased measured voltage of 10.68 V because the V1_PWM signal now has a frequency of 294.1 kHz with duty cycle 25.72 %. The channel 2 signal is the voltage on cathode converter measured at about 3.3 V because the signal CC_VREF_1 is higher than the current feedback signal I_SENSE_1. Therefore, the current loop error amplifier U5 is not regulating the output current while the output voltage is being regulated by the voltage loop through the L5964 error amplifier.

The signal on channel 3 is the PHASE_1 voltage measured in TP1. It represents a typical waveform for a buck converter on switching elements before the output filter.

Figure 16. Waveform details during PPS-V operation – Vin = 12 V, Iout = 1 A

- Legend: CH1: VBUS_1; CH2: EN_1; CH3: PGOOD_1; CH4: V1_PWM

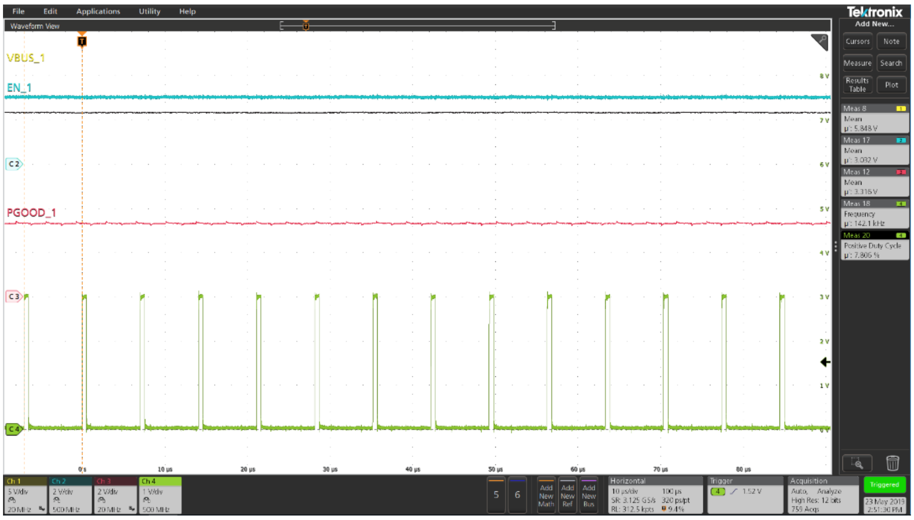
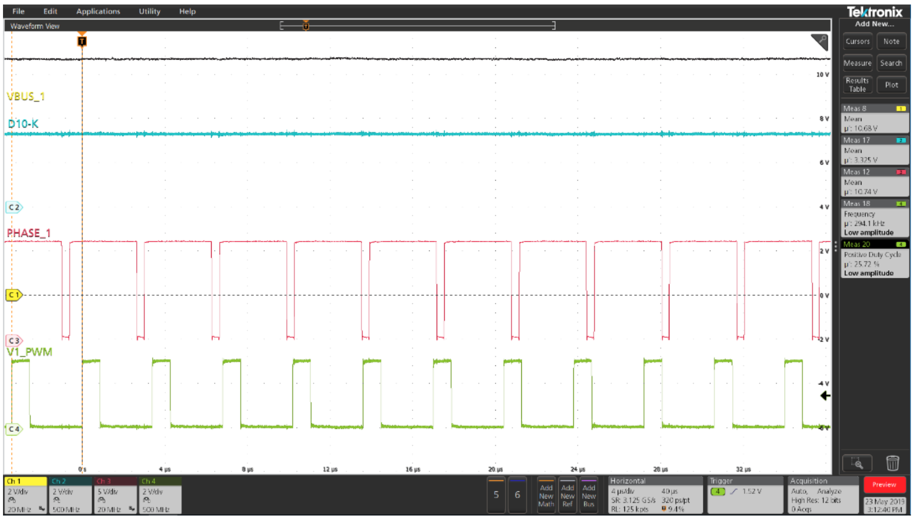


Figure 17. Waveform details during PPS-V operation-2 – Vin = 12 V, Iout = 1 A

- Legend: CH1: VBUS_1; CH2: D10-K VOLTAGE; CH3: VPHASE_1; CH4: V1_PWM



6.2 Programmable output current control

The PPS feature of USB-PD 3.0 for load direct charging requires tight output current control. The power board is designed to support this feature with output current controlled by the MCU in a range from 0 to 100% with 50 mA steps, as recommended by the USB Power Delivery specification.

Figure 18. VBUS_1 Output current vs. CC_VREF_1 Duty Cycle

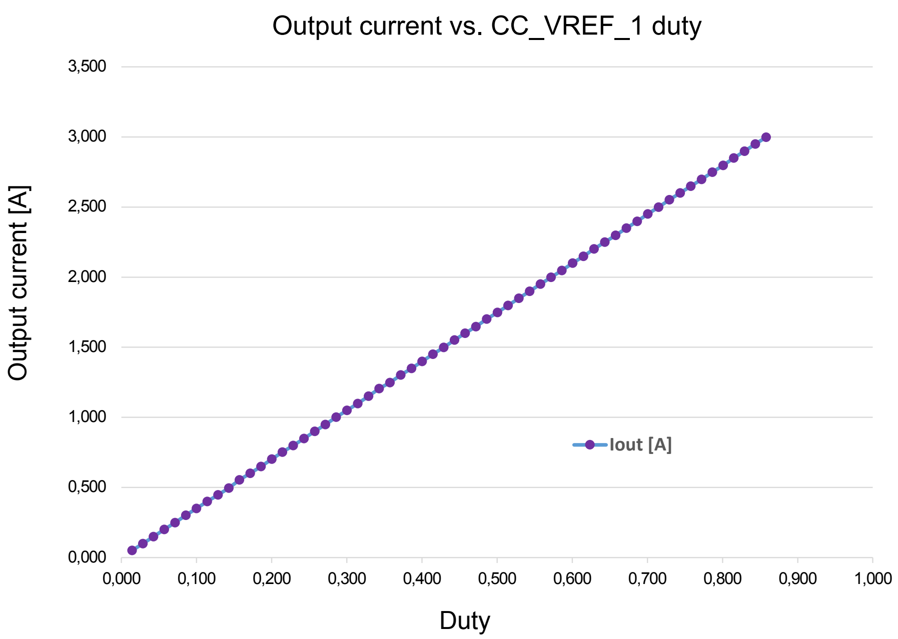


Figure 18 shows the setup with the power board limiting the output current and simulating the current steps of the USB-PD PPS-I function from 50 mA up to 3 A, with incremental steps of 50 mA. Even in this case, the test results relate to open loop operation, where the board output current is set by the PWM signal CC_VREF_x only. In this case, the MCU does not have its own additional feedback loop on the output current as it would in a comprehensive USB-PD application. This method provides a good indication of the precision of the power and control circuits of the power board, and the diagram shows excellent linearity and monotonic behaviour of the output current versus the duty cycle.

Figure 19 shows the waveform for PPS-I operation, where converter Buck1 is regulating the output current at 1.5 A on a resistive load, while the output voltage is 5.55 V due to the effect of the load resistance. The reference PWM signal CC_VREF_1 has frequency 26 kHz with duty cycle 44.3 %.

The other signal on the oscilloscope image is the I_SENSE_1 current feedback signal coming from the sensing circuit, which is required by the error amplifier U5 to close the regulation loop. The D10-K (cathode) is now at a level where the output current has the proper programmed value. In this case, the L5964 voltage loop is not working and its error amplifier is not working, it is just delivering the maximum output current because the voltage loop is open.

Figure 19. **Waveforms detail during PPS-I operation – Vin = 12 V, Iout = 1.5 A**

- Legend: CH1: VBUS_1; CH2: I_SENSE_1; CH3: D10-K VOLTAGE; CH4: CC_VREF_1

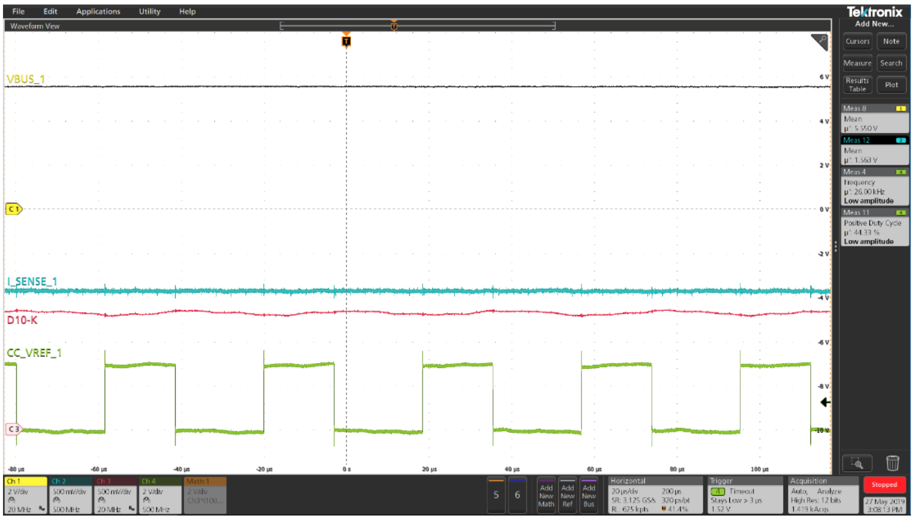
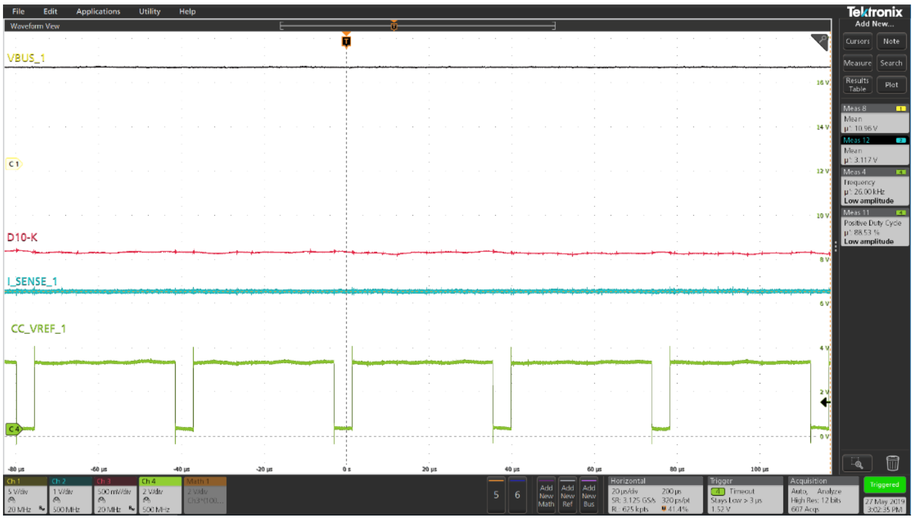


Figure 20. **Waveforms detail during PPS-I operation-2 – Vin = 12V, Iout = 3 A**

- Legend: CH1: VBUS_1; CH2: D10-K VOLTAGE; CH3: VPHASE_1; CH4: V1_PWM



Similar traces were captured in Figure 20 for an output current of 3 A. It is possible to note the longer duty cycle of the CC_VREF_1 signal and the increased level of the current feedback signal I_SENSE_1. The D10-K signal is also higher because of the higher programmed current.

During constant output current operation, the converter output voltage has to be programmed at a value higher than the expected maximum output voltage range; otherwise, the output voltage loop will limit the output voltage. Once operating in constant current mode, the converter behaves as a current source. Therefore, programming a proper value of the output voltage by the PPS-V function or by fixed output voltage flags implements overvoltage protection that can prevent the converter from supplying the load with excessive voltage.

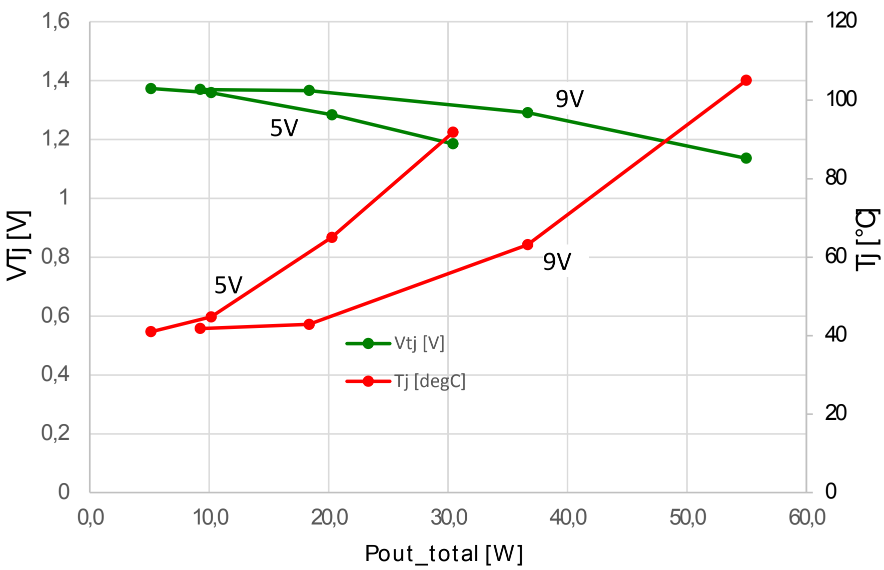
7 Operating temperature measurements

The operating temperature was measured using the internal temperature sensor, which provides a voltage that is inversely proportional to the junction temperature. Figure 21 shows how the junction temperature always remains in a safe operating range, which helps guarantee long term operation.

The temperature measurements were performed during efficiency testing of the converters working with the same voltage and current on both channels. The ambient temperature was 27 °C.

It is clear that the junction temperature depends on the cooling capability of the device. With proper cooling, the heat sink can be eliminated, or the cheaper L5964Q-V0Y version using the VQFPN-48 package can be used to replace the tested L5964L-VYY version using the LQFP64 package with exposed pad up.

Figure 21. Vtj and Tj vs. Pout



8 Bill of materials

Table 9. **Bill of materials**

Item	Q.ty	Ref.	Part / Value	Description	Manufacturer	Order code
1	2	C1, C2	1μF, 50V, ±10%	Ceramic Capacitor MLCC - X7R, 1206 [PCB 1210]	AVX	12065C105KAT2A
2	4	C24, C25, C27, C29	1μF, 50V, ±10%	Ceramic Capacitor MLCC - X7S, 1206	AVX	1206YZ105KAT2A
3	8	C3, C4, C6, C7, C9, C17, C55, C62	100nF (0.1μF), 50V, ±10%	Ceramic Capacitor MLCC - X7R, 0805	KEMET	C0805T104K5RACTU
4	2	C33, C34	100nF (0.1μF), 50V, ±10%	Ceramic Capacitor MLCC - X7R, 1206	KEMET	C1206S104K5RACTU
5	5	C56, C57, C58, C59, C63	100nF (0.1μF), 50V, ±10%	Ceramic Capacitor MLCC - X7R, 0603	MURATA	GCJ188R71H104KA12D
6	5	C5, C12, C15, C18. C61	1nF (1000pF), 50V, ±10%	Ceramic Capacitor MLCC - X7R, 0805	MURATA	GCM216R71H102KA37J
7	3	C60, C64, C65	1nF (1000pF), 50V, ±10%	Ceramic Capacitor MLCC - X7R, 0603	MURATA	GRM033R71H102KA12D
8	1	C8	10μF, 10V, ±10%	Ceramic Capacitor MLCC - X7R, 0805	MURATA	GRM21BR71A106KA73L
9	1	C11	100μF, 50V, ±20%	Ell. Capacitor - EEEFP1H101AP, dia. 8 x 10 mm	PANASONIC	EEEFP1H101AP
10	2	C20, C21	6.8nF (6800pF), 50V, ±10%	Ceramic Capacitor MLCC - NPO, 0805	MURATA	GCM216R71H682KA37J
11	2	C22, C23	330pF, 50V, ±10%	Ceramic Capacitor MLCC - NPO, 0805	MURATA	GCJ216R71H331KA01J
12	2	C26, C28	56μF, 35V, ±20%	ELCAP - PCV1V560MCL1GS, dia. 8 x 10 mm	NICHICON	PCV1V560MCL1GS
13	2	C30, C31	47nF (0.047μF), 50V, ±10%	Ceramic Capacitor MLCC - X7R, 0805	MURATA	GCE21BR71H473KA01L
14	2	C39, C40	47nF (0.047μF), 50V, ±10%	Ceramic Capacitor MLCC - GRM serries - COG, 0805	MURATA	GRM21B3U1H473JA01
15	2	C32, C35	470μF, 25V, ±20%	ELCAP - EEHZK1E471P, dia. 10 x 10 mm	PANASONIC	EEHZK1E471P
16	7	C38, C42, C43, C46, C47, C48, C49	10nF (0.010μF), 50V, ±10%	Ceramic Capacitor MLCC - X7R, 0805	MURATA	GCM219R71H103KA37J
17	1	C41	10nF (0.010μF), 50V, ±10%	Ceramic Capacitor MLCC - COG, 0805	MURATA	GRM31M3U1H104JA01
18	1	C50	1.5nF (1500pF), 50V, ±10%	Ceramic Capacitor MLCC - COG, 0805	MURATA	GCD216R71H152KA01D
19	2	C51, C66	2.2nF (2200pF), 50V, ±10%	Ceramic Capacitor MLCC - NP0, 0603	MURATA	GCD188R71H222KA01D

Item	Q.ty	Ref.	Part / Value	Description	Manufacturer	Order code
20	7	C10, C13, C14, C16, C19, C44, C45 NOT MOUNTED	-	Ceramic Capacitor MLCC , 0805	-	-
21	1	D2	Red	LED, low current, 0603	VISHAY	TLMS1000-GS08
22	1	D3 NOT MOUNTED	-	SOD-323	-	-
23	2	D4, D5	100V, 2A	Automotive Power Schottky Rectifier, SOD-123Flat	ST	STPS2H100ZFY
24	2	D6, D7	Yellow	LED, low current, 0603	VISHAY	TLMY1000-GS08
25	10	D8, D10. D11, D12, D13, D14, D15, D16, D17, D18	100 V, 150mA	General Purpose Signal Schottky Diode, SOD-323	ST	BAT46JFILM
26	1	HS1	-	Heat sink, 15x15x8 (H) mm	FISCHER ELECTRONIK	ICK SMD E15
27	1	J1	PITCH 5.0 mm - 2-WAY	Power-in connector	PHOENIX CONTACT	MKDSN 1,5/ 2
28	3	J2, J4, J5 NOT MOUNTED	-	-	-	-
29	1	J3	2.54 mm	STRIP FEMALE 9 x 2 Power connector BOTTOM SIDE	SAMTEC	-
30	2	J6, J7	2.54 mm	STRIP FEMALE 8 x 1 - TOP SIDE	SAMTEC	-
31	2	J8A, J8B	2.54 mm	FEMALE/MALE 20 x 4- BOTTOM SIDE	SAMTEC	-
32	2	J9, J10	2.54 mm	STRIP FEMALE 2 x 1 pin - BOTTOM SIDE	SAMTEC	-
33	1	L1	ACM12V	CM Filter, 12 x 11 mm H = 6 mm	TDK	ACM12V-701-2PL-TL00
34	2	L2, L3	4.7 µH	Shielded power inductor, 4 x 4 mm H = 3 mm	COILCRAFT	XAL4030-472ME
35	2	L4, L5	33 µH	Shielded power inductor, 12x12 mm - H = 8 mm	COILCRAFT	MSS1278T-333
36	8	Q1-2, Q1-1. Q2-1, Q2-2, Q3-2, Q3-1, Q4-2, Q4-1	2N7002DW	Small signal mosfet, SOT-363	INFINEON	2N7002DW
37	8	Q5A, Q5B, Q6A, Q6B, Q7B, Q7A, Q8B, Q8A	BC846BDW1T1G	Dual NPN BJT, SOT-363	ONSEMI	BC846BDW1T1G

Item	Q.ty	Ref.	Part / Value	Description	Manufacturer	Order code
38	18	R3, R9, R13, R14, R17, R18 R19, R20. R23, R25, R29 R30, R32, R41, R42, R43 R53, R54 NOT MOUNTED	-	0805	-	-
39	8	R4, R12, R15, R24, R26 R35, R104, R109	0R0, 1/8W, ±5%	SMD STD FILM RES - 250ppm/°C, 0805	VISHAY	-
40	2	R2, R126	0R0, 1/4W, ±5%	SMD STD FILM RES - 250ppm/°C, 1206	VISHAY	-
41	1	R1	820K, 1/8W, ±5%	SMD STD FILM RES - 100ppm/°C, 0805	VISHAY	-
42	1	R5	10R, 1/4W, ±5%	SMD STD FILM RES - 250ppm/°C, 1206	VISHAY	-
43	4	R55, R56, R60, R61	10R, 1/8W, ±5%	SMD STD FILM RES - 250ppm/°C, 0805	VISHAY	-
44	12	R6, R7, R16, R28, R66, R68, R74 R77, R78, R79, R82, R83	100K, 1/8W, ±1%	SMD STD FILM RES - 100ppm/°C, 0805	VISHAY	-
45	2	R120, R125	100K, 1/10W, ±5%	SMD STD FILM RES - 250ppm/°C, 0603	VISHAY	-
46	4	R52, R67, R95, R106	100R, 1/10W, ±5%	SMD STD FILM RES - 250ppm/°C, 0603	VISHAY	-
47	1	R10	110K, 1/10W, ±1%	SMD STD FILM RES - 100ppm/°C, 0603	VISHAY	-
48	2	R31, R33	220K, 1/8W, ±5%	SMD STD FILM RES - 250ppm/°C, 0805	VISHAY	-
49	2	R72, R73	220R, 1/8W, ±5%	SMD STD FILM RES - 250ppm/°C, 0805	VISHAY	-
50	2	R86, R102	330R, 1/10W, ±5%	SMD STD FILM RES - 250ppm/°C, 0603	VISHAY	-
51	2	R8, R22,	560K, 1/8W, ±1%	SMD STD FILM RES - 100ppm/°C, 0805	VISHAY	-
52	2	R98, R114	560K, 1/10W, ±1%	SMD STD FILM RES - 100ppm/°C, 0603	VISHAY	-
53	2	R57, R71	10K, 1/8W, ±5%	SMD STD FILM RES - 200ppm/°C, 0805	VISHAY	-

Item	Q.ty	Ref.	Part / Value	Description	Manufacturer	Order code
54	2	R88, R101	10K, 1/8W, ±1%	SMD STD FILM RES - 100ppm/°C, 0805	VISHAY	-
55	4	R47, R51, R100, R107	10K, 1/10W, ±1%	SMD STD FILM RES - 100ppm/°C, 0603	VISHAY	-
56	1	R111	10K, 1/10W, ±5%	SMD STD FILM RES - 250ppm/°C, 0603	VISHAY	-
57	2	R58, R59	11K, 1/10W, ±1%	SMD STD FILM RES - 100ppm/°C, 0603	VISHAY	-
58	2	R45, R49	12K4, 1/10W, ±1%	SMD STD FILM RES - 100ppm/°C, 0603	VISHAY	-
59	2	R99, R113	1K0, 1/10W, ±1%	SMD STD FILM RES - 100ppm/°C, 0603	VISHAY	-
60	2	R103. R112	1K0, 1/10W, ±5%	SMD STD FILM RES - 250ppm/°C, 0603	VISHAY	-
61	4	R44, R48, R62, R63	1K2, 1/10W, ±1%	SMD STD FILM RES - 100ppm/°C, 0603	VISHAY	-
62	5	R11, R84, R92, R93, R115	1K2, 1/10W, ±5%	SMD STD FILM RES - 250ppm/°C, 0603	VISHAY	-
63	2	R85, R94	1K8, 1/10W, ±5%	SMD STD FILM RES - 250ppm/°C, 0603	VISHAY	-
64	6	R64, R65, R75, R76, R80, R81	22K, 1/8W, ±5%	SMD STD FILM RES - 250ppm/°C, 0805	VISHAY	-
65	2	R97, R110	22K, 1/10W, ±1%	SMD STD FILM RES - 100ppm/°C, 0603	VISHAY	-
66	8	R87, R89, R90, R91, R116, R117, R118, R119	27K, 1/10W, ±5%	SMD STD FILM RES - 250ppm/°C, 0603	VISHAY	-
67	2	R121, R124	33K, 1/10W, ±1%	SMD STD FILM RES - 100ppm/°C, 0603	VISHAY	-
68	2	R122, R123	36K, 1/10W, ±1%	SMD STD FILM RES - 100ppm/°C, 0603	VISHAY	-
69	1	R21	47K, 1/10W, ±1%	SMD STD FILM RES - 100ppm/°C, 0603	VISHAY	-
70	2	R37, R40	56K, 1/8W, ±1%	SMD STD FILM RES - 100ppm/°C, 0805	VISHAY	-

Item	Q.ty	Ref.	Part / Value	Description	Manufacturer	Order code
71	2	R69, R70	4K7, 1/8W, ±5%	SMD STD FILM RES - 250ppm/°C, 0805	VISHAY	-
72	1	R34	68K, 1/8W, ±5%	SMD STD FILM RES - 250ppm/°C, 0805	VISHAY	-
73	2	R46, R50	8K66, 1/10W, ±1%	SMD STD FILM RES - 100ppm/°C, 0603	VISHAY	-
74	2	U2, U3	RGB	LED CA SMD	KINGBRIGHT	AAA3528LSEEZGKQBKS
75	12	TP1, TP2, TP3, TP4, TP5, TP6 TP7, TP8, TP9, TP10, TP11, TP12	-	TEST POINT - PCB METALLIZED HOLE	-	-
76	1	U1	3.5A	Monolithic dual step-down switching regulator with LDO, LQFP-64	ST	L5964L-VYY
77	2	U4, U5	GBP 2.7MHz, 16V	Precision (200uV), rail-to-rail CMOS Op-Amp, single, SOT23-5L	ST	TSX711ILT

Revision history

Table 10. **Document revision history**

Date	Version	Changes
01-Jul-2019	1	Initial release.

Contents

List of tables

List of figures