AN5230

Application note

75 W digitally controlled constant current HB LED driver

Introduction

The STEVAL–LLL004V1 digitally controlled constant current LED driver features a PFC stage and two DC-DC converters designed to work in transition mode (TM) for optimized efficiency.

The LED driver can deliver 75 W output power and can dim LEDs down to 0.5% maximum brightness level via analog and digital control, and still retain flicker operation.

The STEVAL-LLL004V1 was tested for a wide input voltage rage (85 to 265 V_{AC}) with different LED loads. The overall efficiency, power factor, and Total Harmonic Distortion (THD) of the STEVAL-LLL004V1 were calculated at different loads.

Testing results show high efficiency, a power factor near unity, and low THD% under wide input voltage and load conditions due to the performance of the ST power products as well as the control strategies implemented through the 32-bit STM32F0 series microcontroller.

Figure 1. STEVAL-LLL004V1 test setup

Load: 24 HB white 3.3 V LEDs in series mounted on heatsink

1. Load connected to buck converter

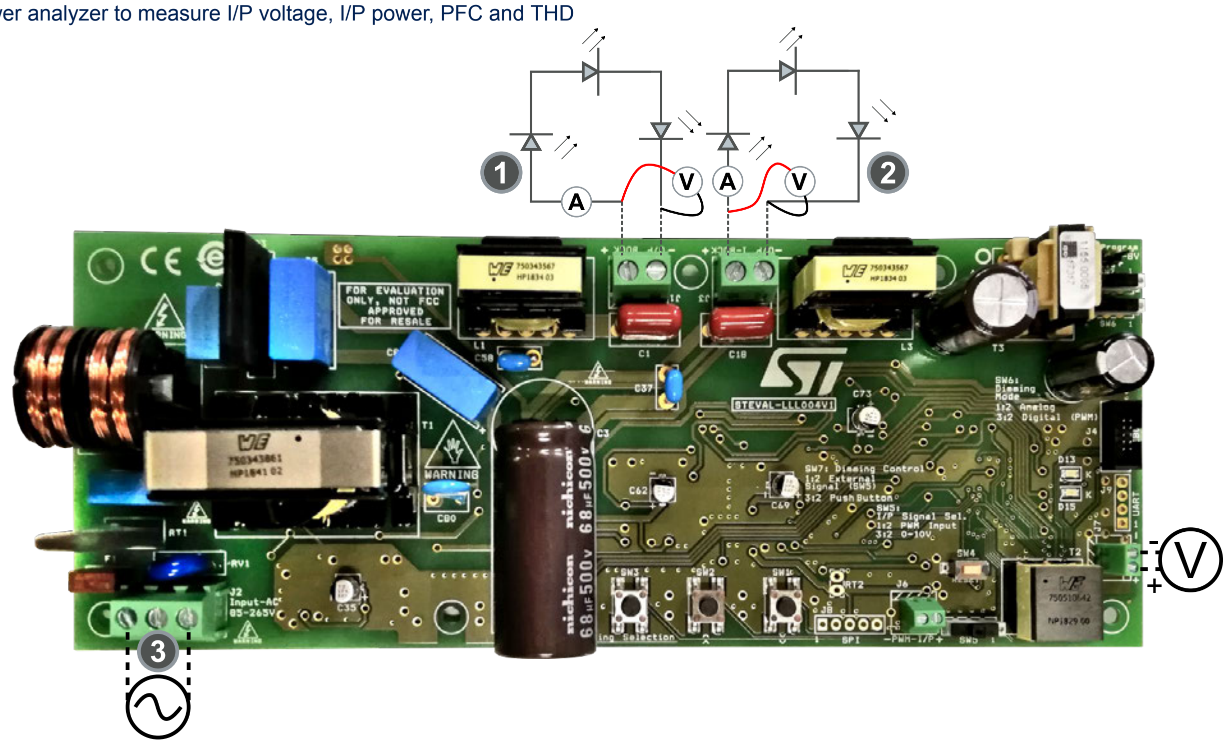
2. Load connection to inverse buck converter

Inputs:

(V) DC power supply with 0-10V control

(~) 85 - 265 V AC mains

3. Power analyzer to measure I/P voltage, I/P power, PFC and THD



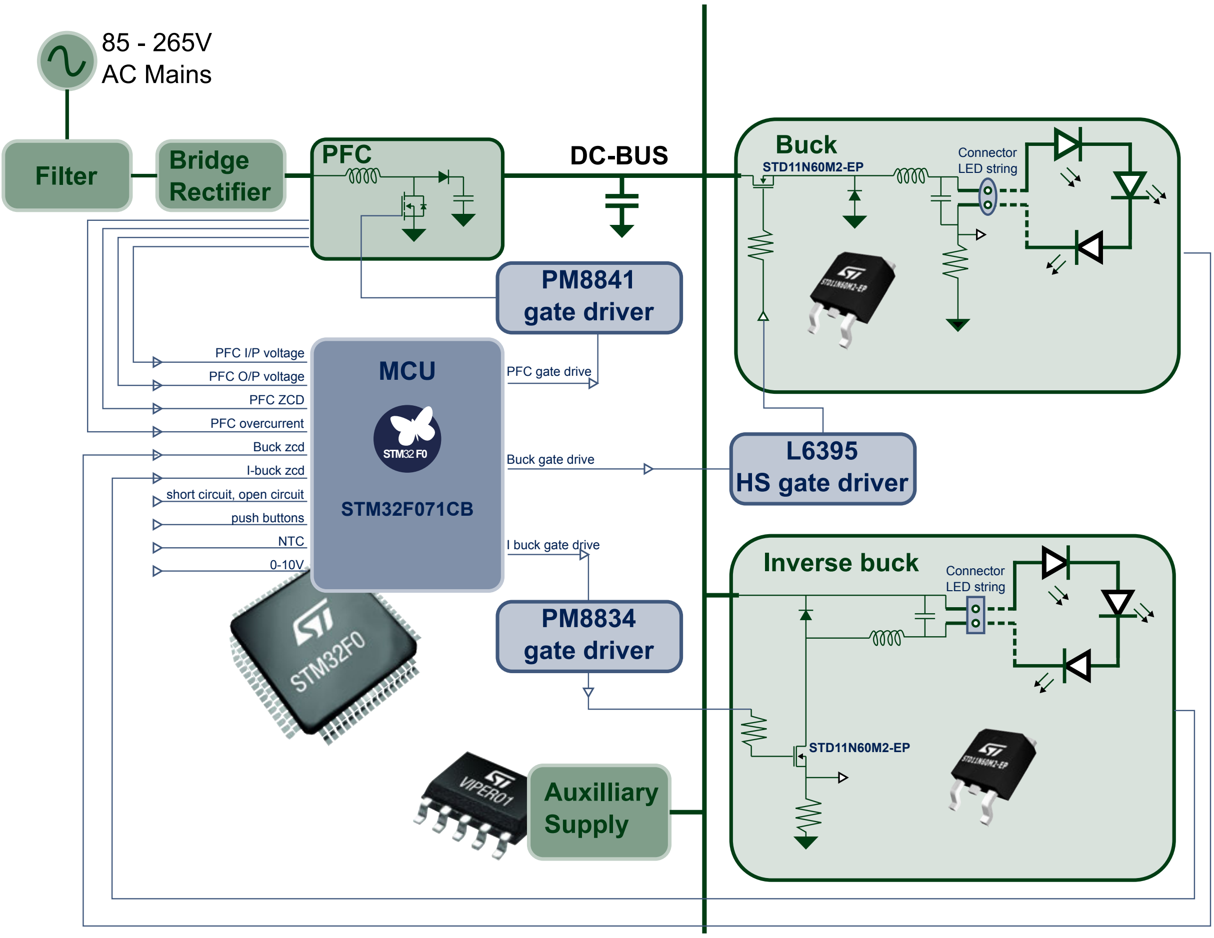
1 STEVAL-LLL004V1 evaluation board overview

The 75 W digitally controlled HB LED driver evaluation board has two power conversion stages:

1. A front end power factor correction (PFC) converter to provide a regulated DC output.
2. A downstream conversion stage with the following converters connected in parallel:
    a. buck converter
    b. inverse buck converter

Both converters in the second stage operate in constant current (CC) mode. In inverse buck topology, the power switch is connected to ground rather than to the high side switch, as in a standard buck topology.

Figure 2. STEVAL-LLL004V1 block diagram



The 32-bit STM32F071CB microcontroller provides digital control for both PFC and buck DC-DC conversion stages, which is highly advantageous in terms of cost and flexibility.

The control algorithm of the LED driver is proven on the 32-bit STM32F071CB MCU from the STM32 family. The MCU controls all three power stages in transition mode, turning ON MOSFET gate just after the inductor current reaches zero. A proportional-integral (PI) control loop has been implemented for the PFC stage, improving control loop stability, line transition and dimming steps behavior, and reducing current and voltage overshoot at start-up. Buck and inverse buck converters work in hysteretic mode. The dimming technique and control can be selected from the toggle switches on the board.

The on-board fast protection circuits provide reliable management of all the essential protection features.

1.1 Features

- Wide input voltage range 85 – 265 V_{AC}
- Transition Mode PFC
- Two constant current outputs working in transition mode based on different topologies:
  – Buck topology
  – Inverse buck topology
- Output current: 500 mA ±2.5%
  – Number of LEDs connected at output: 16 – 24 white LEDs (3.3 V each)
- PFC > 0.97 and THD < 20% at full load with input voltage 85-265 V_{AC}
- Peak Efficiency at maximum load ≅ 90%
- Comprehensive safety protections:
  – Open/no-load circuit protection
  – Short-/overload circuit protection
- Soft start implementation
- LED dimming range: 0.5% to 100%
  – Analog dimming
  – Digital dimming
- Dimming control options:
  – Push button
  – 0-10 V input
- Meet IEC55022 Class B
- WEEE and RoHS compliant

1.2 Electrical specifications

Table 1. STEVAL-LLL004V1 electrical specifications

Parameter	Operation/Mode/Topology	Value/Range
Input voltage range	-	85 - 265 V_{AC}
Power factor at full load	85 -265 V_{AC}	> 0.96
THD at full load	85 -265 V_{AC}	< 20%
PFC output voltage	-	450 V ±2.5%
Min. PFC switching frequency	Transition Mode	35 kHz
Min. PFC switching frequency	Discontinuous Mode	20 kHz
Maximum output power	Buck and inverse buck	75 W
Output voltage (Vout)	Buck	50 - 80 V_{DC}
Buck Converter switching frequency at full load	Transition mode	~100 kHz
Output current (Iout)	Buck (CC)	500 mA ±5%
Output voltage (Vout)	Inverse-buck	50 - 80 V_{DC}
Inverse buck converter switching frequency at full load	Transition Mode	~100 kHz
Output current (Iout)	Inverse buck (CC)	500 mA ±5%
LEDs connected at output	HB white LEDs	16 - 24 (3.3 V each)
Digital dimming frequency	-	500 Hz
Default brightness level	-	100%
Minimum dimming level	-	0.5%

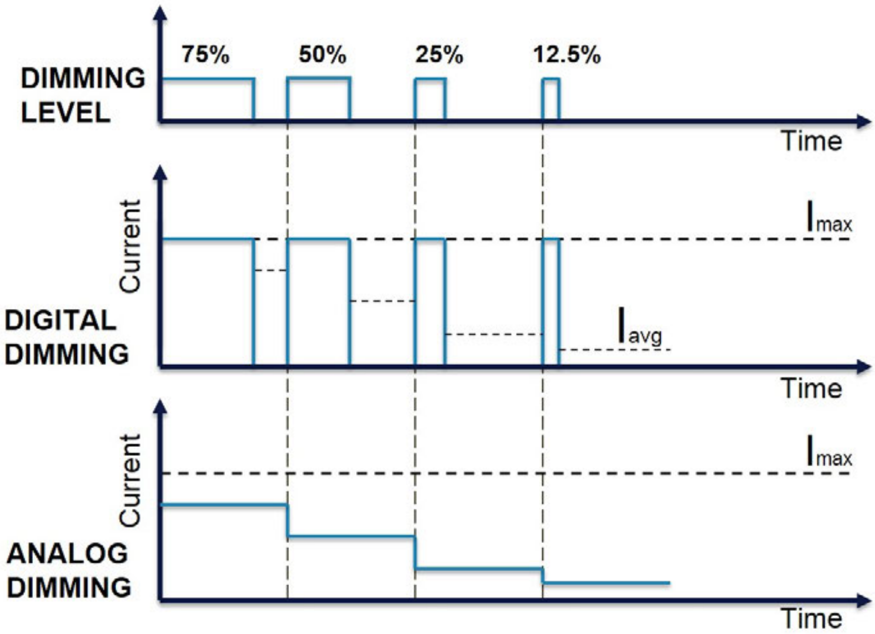
2 Digital and analog dimming with the STEVAL-LLL004V1

The STEVAL-LLL004V1 evaluation board provides for 0-10V input and user buttons to control the brightness of the LEDs, and you can selct between analog or digital.

In digital (pulse width modulation([PWM]) dimming, the average current delivered to the LEDs is the product of the total nominal current and the duty cycle of the dimming function. Therefore, the brightness level is adjusted through the duty cycle.

For analog dimming, LED brightness is managed by changing the magnitude of the current.

Figure 3. Digital vs analog dimming



Both dimming approaches have advantages and disadvantages, which are summarised in the following table.

Table 2. Digital (PWM) dimming vs analog aimming

Digital (PWM) dimming	Analog dimming
No color shift as LED current remains the same	Color shift as LED current changes
Possible current inrush problems	No inrush current
Very linear change in brightness	Less linear change in brightness
Lower optical to electrical efficiency	Higher optical to electrical efficiency
Frequency limitations and concerns	No frequency concern

2.1 How to select dimming options on the board

Use the switches and jumpers described below to set the dimming options on the board. The switches for dimming type (SW6) and dimming control (SW7) must be set before the board is powered.

Step 1. Toggle SPDT switch SW6 to select between digital and analog dimming.

Table 3. SW6 switch for digital or analog dimming

Switch position	Digital (PWM) dimming	Analog dimming
1:2	×	TRUE
3:2	TRUE	×

Step 2. Toggle SPDT switch SW7 to select between external signal and user button for dimming control.

Table 4. SW7 switch for external signal or push button control

Switch position	External signal (0-10 V_{DC} or PWM)	Push button
1:2	TRUE	×
3:2	×	TRUE

Step 3. Toggle SPDT switch SW5 to select between 0-10 V_{DC} and PWM (3.3 V) inputs for external signal dimming control.

The signals are delivered through the following jumpers:

- J6 - PWM (3.3 V)
- J7 - 0-10 V_{DC}

Table 5. SW5 switch for 0-10V or PWM external signal control

Switch position	0-10V input (J7)	PWM input (J6)
1:2	×	TRUE
3:2	TRUE	×

3 Power management and dimming

The STM32 microcontroller (STM32F071CB) on the evaluation board receives zero crossing detection (ZCD) and other input signal inputs to drive the MOSFET gates. Because of this feature, the following power stages on the evaluation board can function in transition mode:

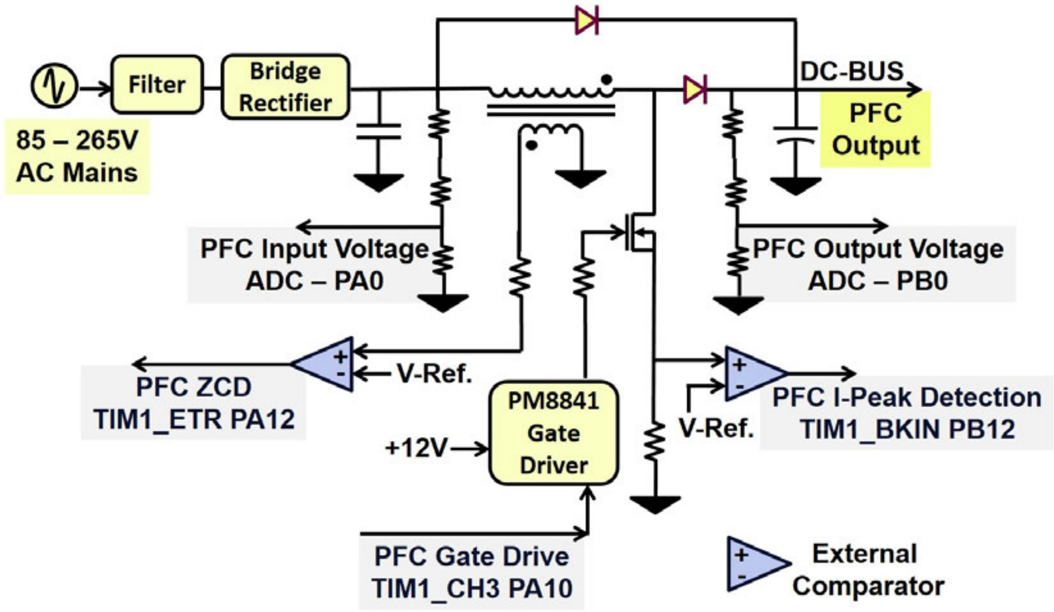
- a PFC boost converter
- a buck converter
- a modified/inverse buck converter

The microcontroller and the gate drive section are supplied through a VIPer012LS 60 kHz high voltage off-line converter, which manages the auxiliary SMPS in flyback topology.

3.1 Power factor correction (PFC) (AC-DC)

The PFC converter receives filtered and rectified AC mains voltage and boosts it to a regulated DC output voltage (DC-BUS). The PFC section ensures the system complies with standard EN61000-3-2 (harmonic current distortion) for lighting equipment at an input active power above 25 W. The wide input voltage range of the PFC converter means the evaluation board with domestic electricity supplies all over the world.

Figure 4. PFC block diagram with TIMER 1 and ADC pin signals



The boost converter consists of:

- a boost inductor
- a controlled power switch
- a catch diode
- an output capacitor
- control circuitry.

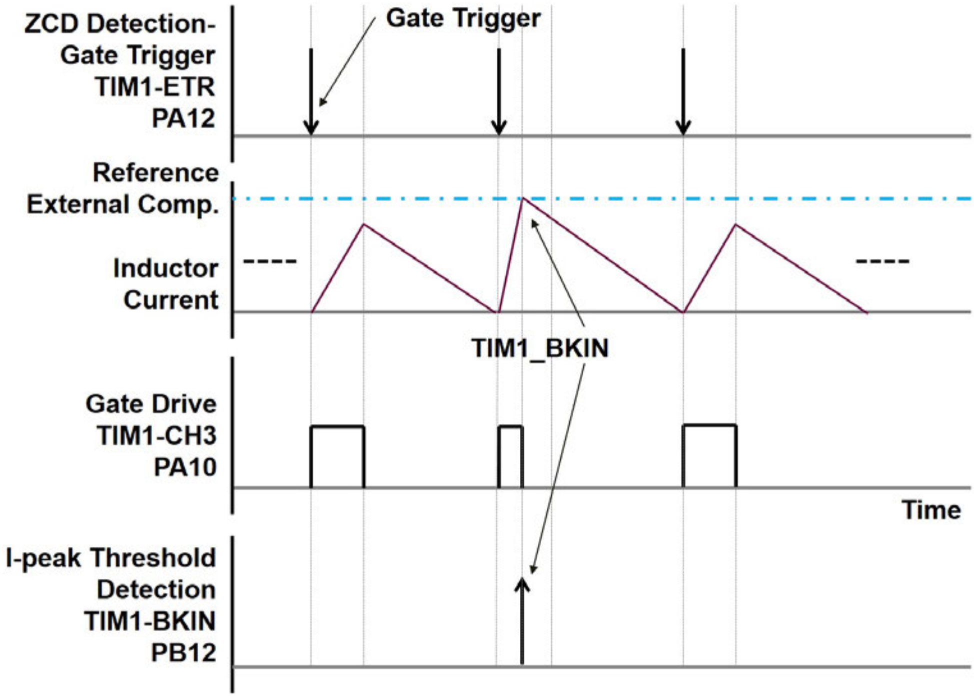
The converter shapes the input current in a sinusoidal fashion, in phase with the input sinusoidal voltage.

The advanced control timer and ADC allow the STM32 microcontroller to drive the converter in Transition Mode.

The PFC output voltage is scaled down through a resistance divider and measured at the ADC of the microcontroller. The microcontroller compares the PFC output voltage with an internal reference voltage to calculate error. The error is fed into the multiplier block and multiplied by a partition of the rectified mains voltage.

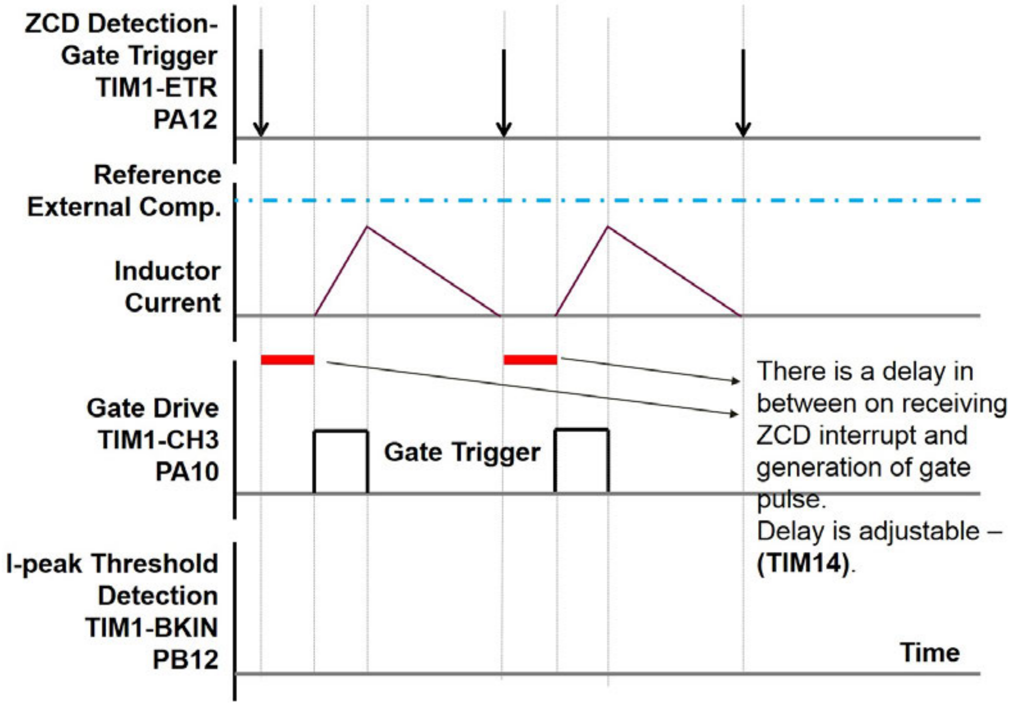
A proportional-integral (PI) control loop is then applied and the MOSFET turn on time after a ZCD interrupt is adjusted.

Figure 5. PFC working in Transition Mode



To handle low load or brightness levels, the PFC converter works in discontinuous mode.

Figure 6. PFC working in Discontinuous Mode



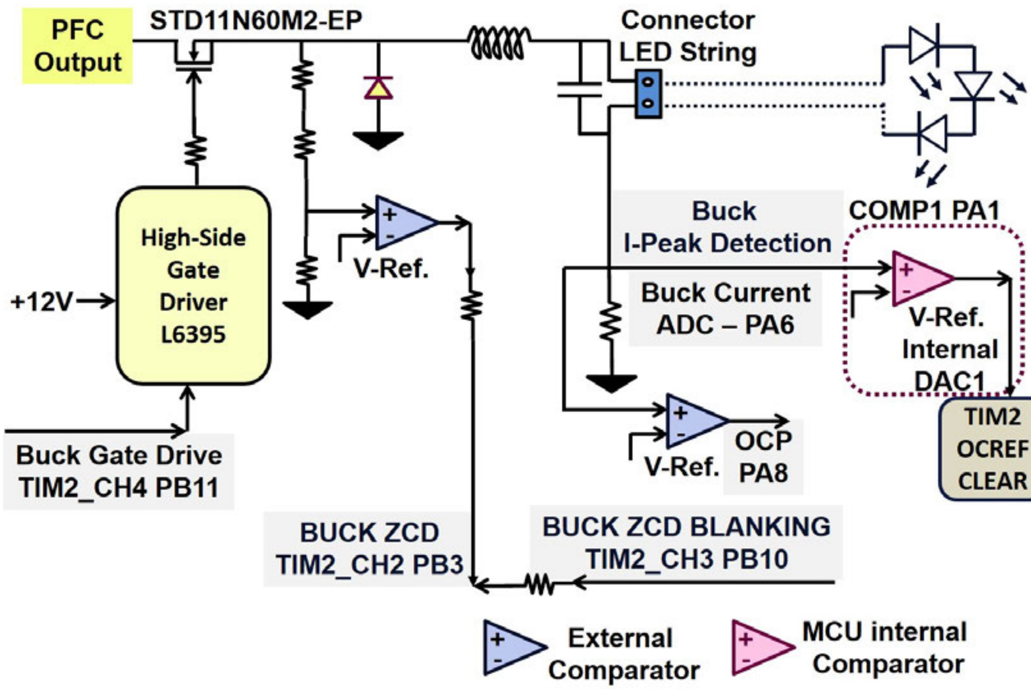
The open circuit protection for the PFC section is managed by the ADC watchdog.

3.2 Buck converter (DC-DC)

The DC-DC buck converter steps down the PFC output voltage according to the number of LEDs connected at the output. The buck converter MOSFET is driven by the L6395 high side gate driver.

The advanced control timer and digital to analog converter (DAC) allow the STM32 microcontroller to drive the buck converter in Transition Mode.

Figure 7. **Buck converter block diagram with TIMER 2 and DAC pin signals**



3.2.1 Buck converter (DC-DC) digital dimming

The buck converter MOSFET is turned on after a ZCD interrupt and turned off again when the inductor current reaches a set threshold.

To avoid false triggering, the blanking time starts after every ZCD interrupt.

The buck converter is turned on and off at 500 Hz (frequency of MCU timer peripheral), and digital dimming is managed by varying the on and off intervals.

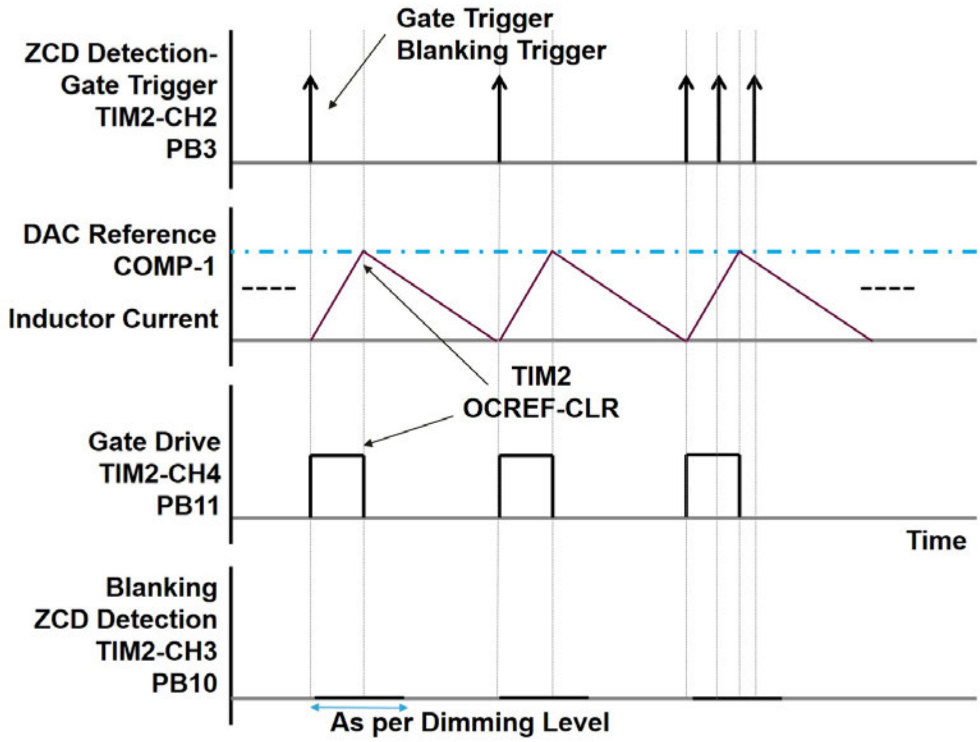
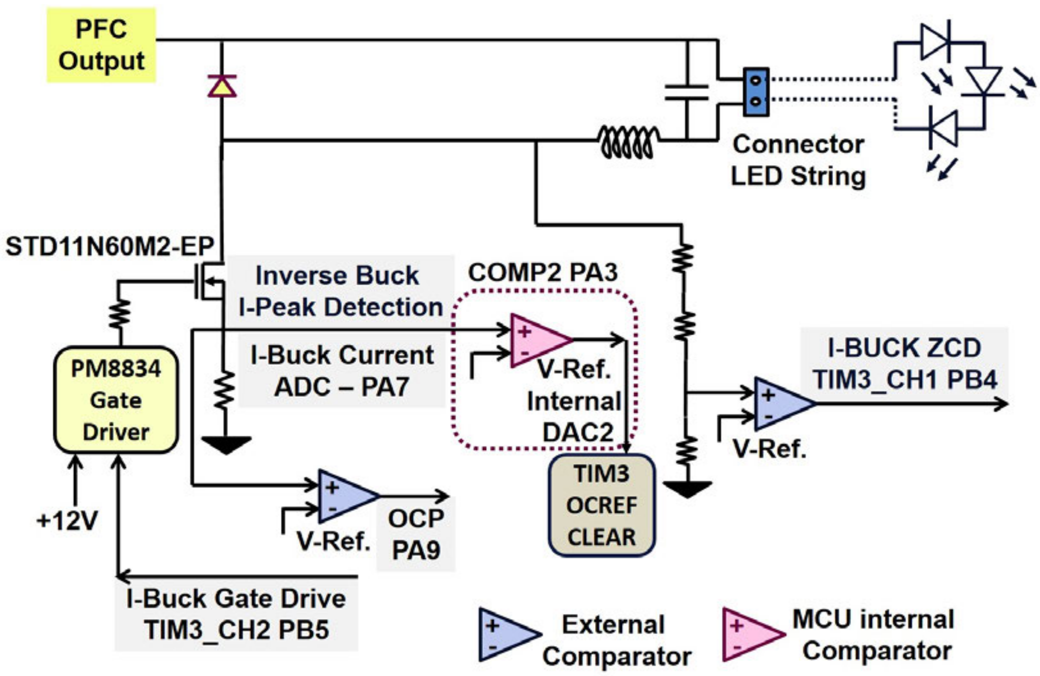


Figure 8. Buck converter working in Transition Mode

3.3 Modified/inverse buck converter (DC-DC)

The DC-DC inverse buck converter steps down the PFC output voltage according to the number of LEDs connected at the output. The advanced control timer and a digital to analog converter (DAC) allow the STM32 microcontroller to drive the inverse-buck converter in Transition Mode.

Figure 9. Inverse buck converter block diagram with TIMER 3, TIMER 15 and DAC pin signals

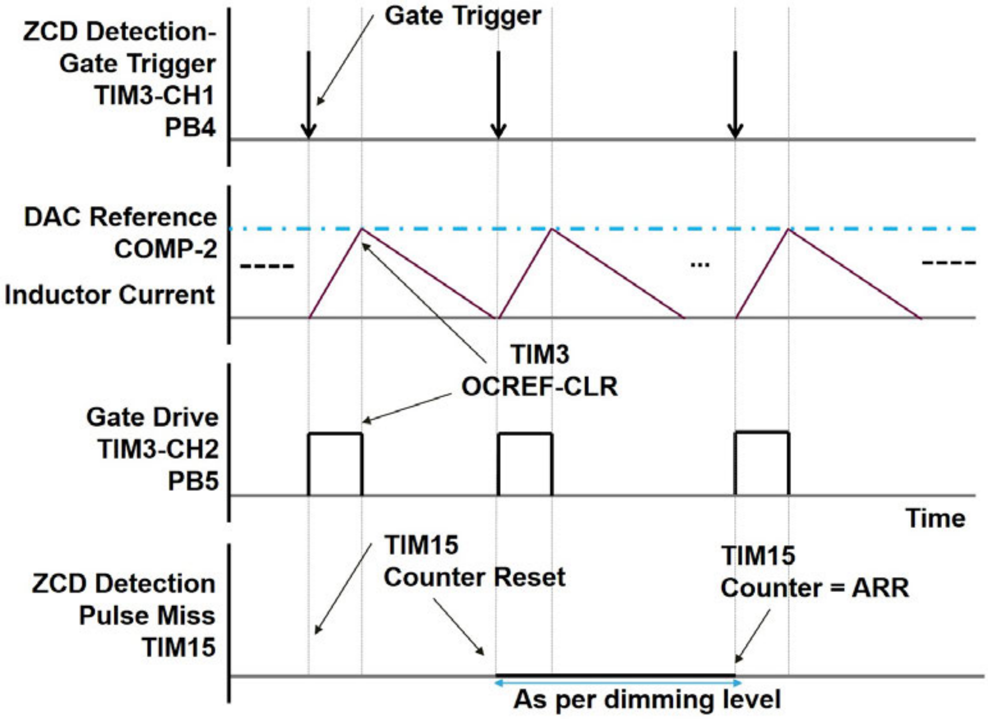


3.3.1 Inverse buck converter digital dimming

The inverse buck converter MOSFET is turned on after a ZCD interrupt and turned off again when the inductor current reaches a set threshold.

The inverse buck converter is turned on and off at 500 Hz (frequency of MCU timer peripheral), and digital dimming is managed by varying the on and off intervals.

Figure 10. **Inverse buck converter operating in Transition Mode**

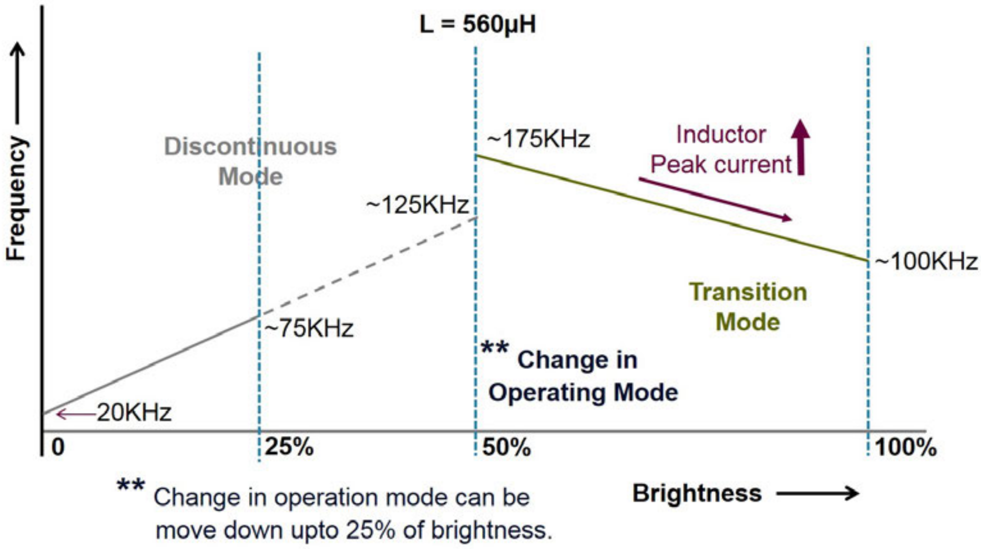


3.4 Buck converter and inverse buck converter analog dimming

Analog dimming is implemented using an internal MCU comparator and a digital to analog converter (DAC) peripheral. According to the dimming level, the current threshold (inductor peak current) at the non-inverting end of the internal comparator is adjusted with the help of the DAC.

Dimming is limited when using inductor peak current control in Transition Mode. To function at lower brightness levels, the converter must switch to Discontinuous Mode.

Figure 11. Analog dimming for buck converter and inverse buck converter



4 STEVAL-LLL004V1 transformers and inductors

4.1 Power factor correction (PFC) transformer

Table 6. PFC transformer details

PARAMETER	VALUE	TEST CONDITIONS
Manufacturer	WURTH	-
Part Number	750343861, Rev02	-
Inductance (pins 3-4)	760 µH ±10%	Meas. at 100 kHz, 10 0mV
Turn ratio	(10.42):(1.00), ±2%	(3 - 7):(9 - 11)

Figure 12. PFC Transformer electrical and pin pattern diagram

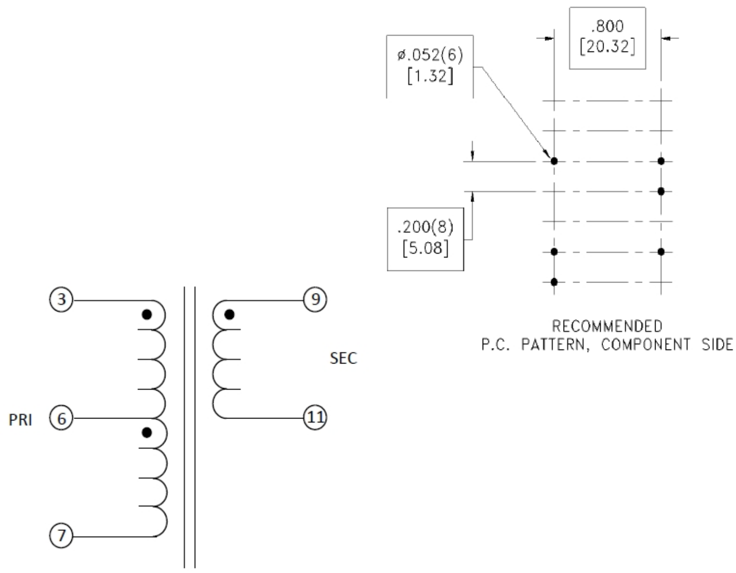
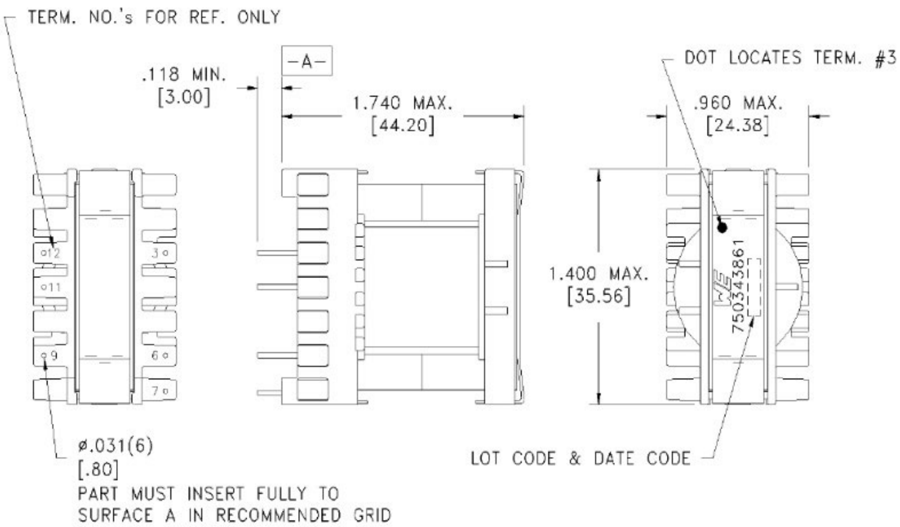


Figure 13. PFC transformer size and dot location



4.2 Buck and inverse buck inductor

Table 7. Buck and inverse buck inductor locations

PARAMETER	VALUE	TEST CONDITIONS
Manufacturer	WURTH	
Part Number	750343567, Rev03	
Inductance (pins 3-8)	560 µH ±10%	Meas. at 100 kHz, 100 mV

Figure 14. Buck and inverse buck inductor electrical and pin pattern diagram

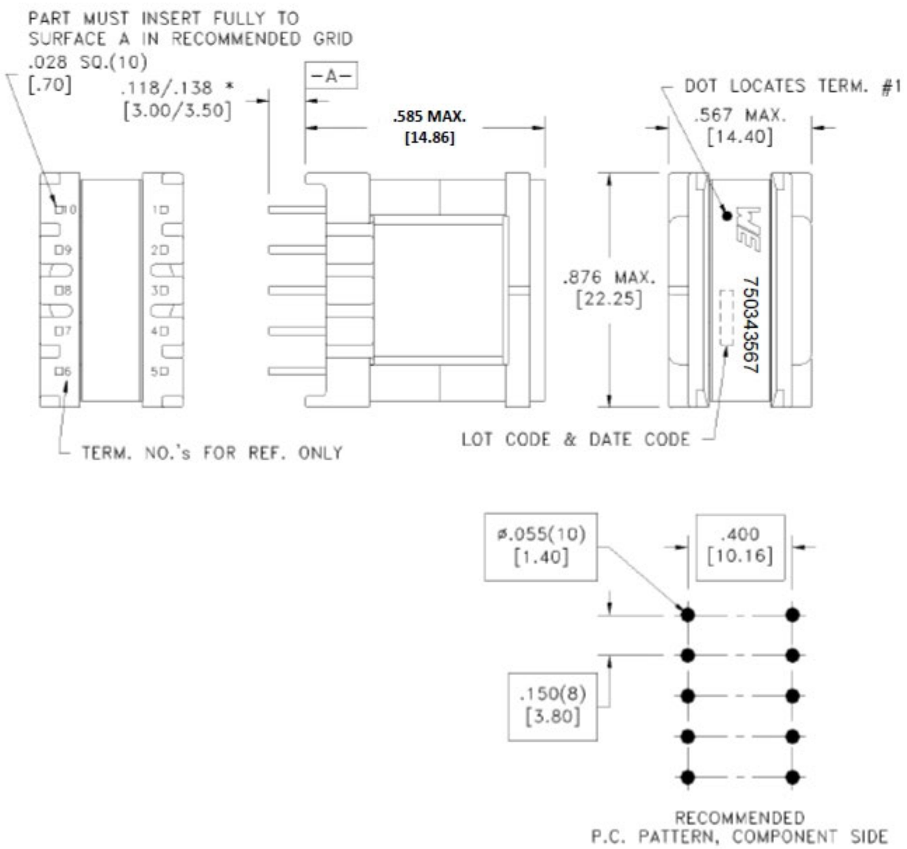
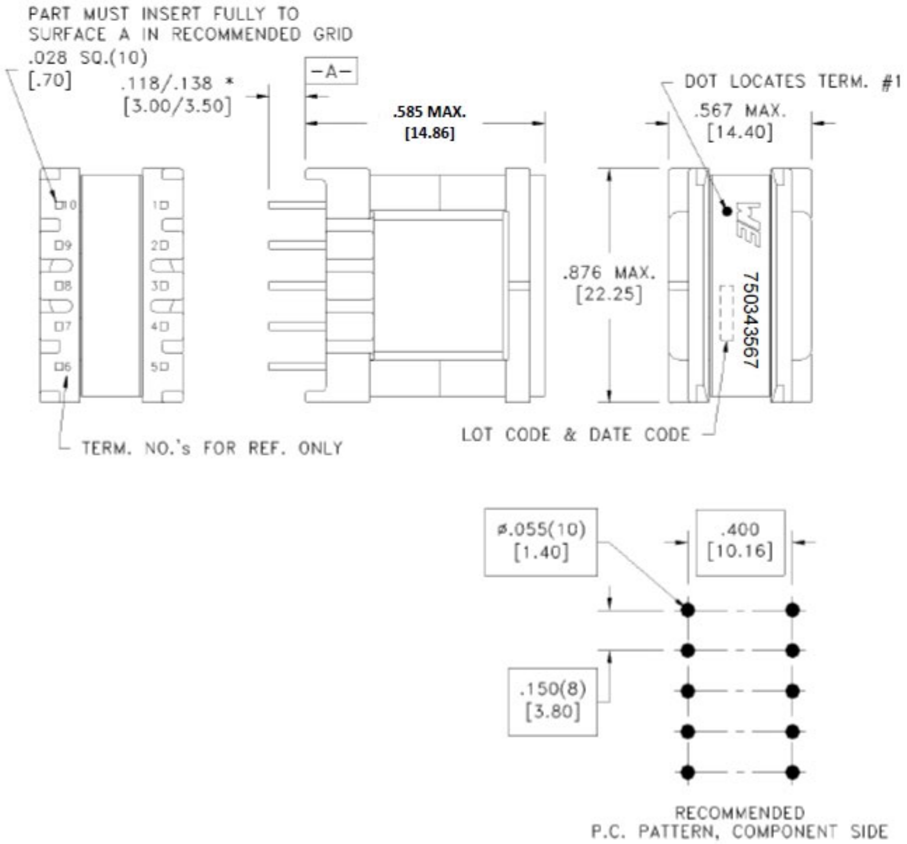


Figure 15. Buck and inverse buck inductor size and dot location



4.3 Flyback transformer

Table 8. Flyback transformer details

PARAMETER	VALUE	TEST CONDITIONS
Manufacturer	AQ Magnetica	
Part Number	1155.0005, Rev00	
Inductance (pins 4-1)	2.54 mH ±15%	Meas. at 1 kHz
Leakage Inductance	20 µH max.	Meas. at 10 kHz
Turn ratio	(6.00):(1.00), ±2%	(4 - 1):(8 - 5)
Turn ratio	(12.00):(1.00), ±2%	(4 - 1):(6 - 5)

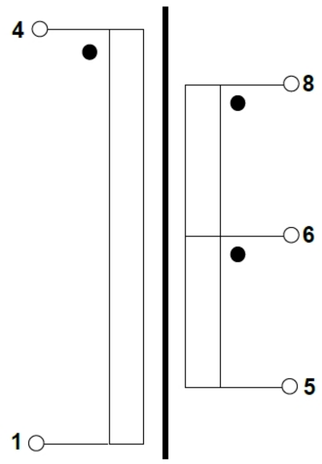


Figure 16. Flyback transformer electrical and pin pattern diagram

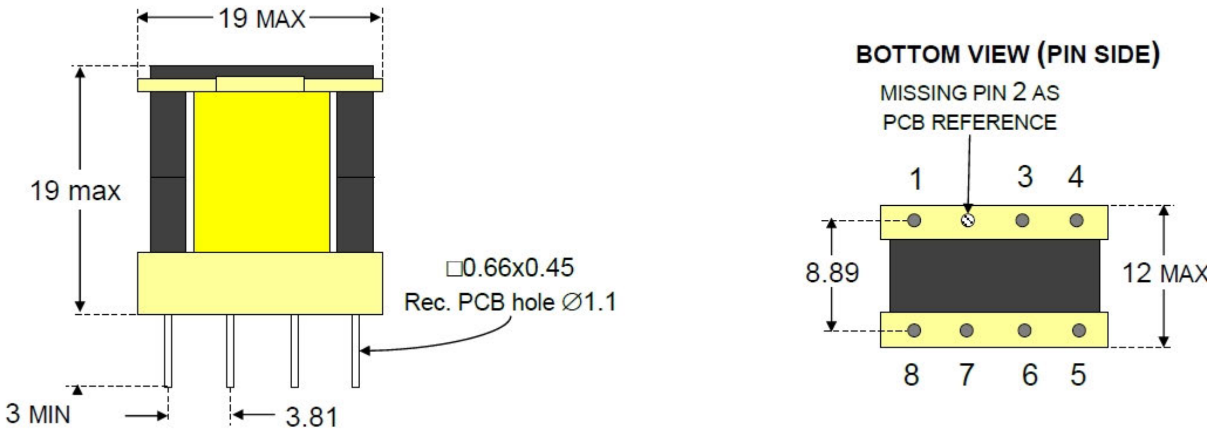


Figure 17. Flyback transformer size and dot location

4.4 Isolation transformer 0–10V

Table 9. Isolation transformer details

PARAMETER	VALUE	TEST CONDITIONS
Manufacturer	WURTH	
Part Number	750510642, Rev00	
Inductance (pins 6-10)	1.35 H ±10%	Meas. at 10 kHz, 100 mV
Leakage Inductance	12 µH max.	Meas. at 100 kHz, 10 0mV
Turn ratio	(1.00):(1.00), ±1%	(10 - 6):(3 - 1)
Turn ratio	(1.00):(1.00), ±1%	(10 - 6):(5 - 3)

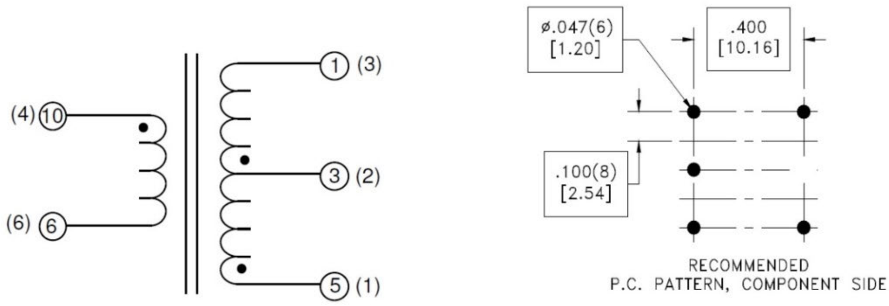


Figure 18. 0-10V transformer electrical and pin pattern diagram

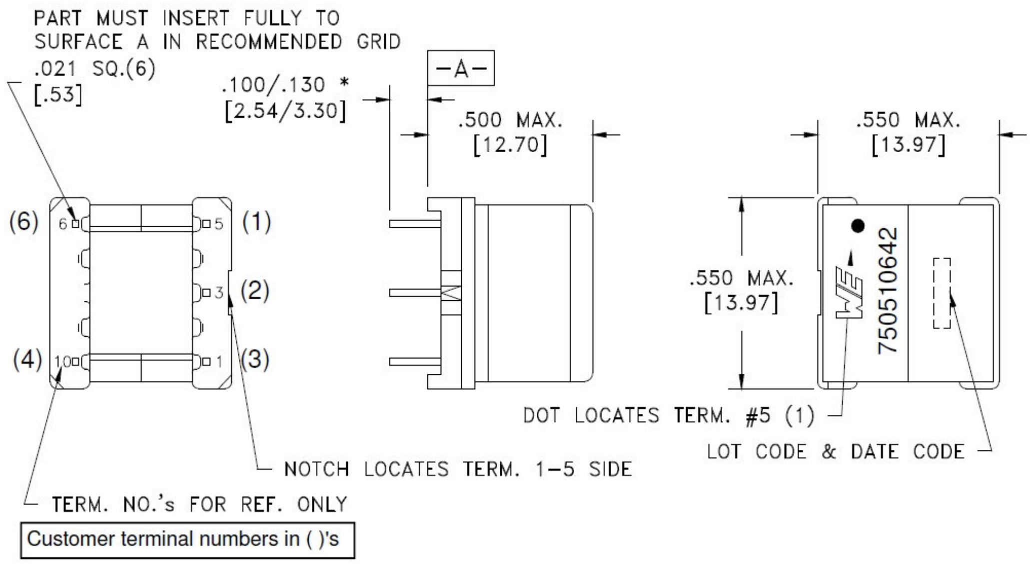


Figure 19. 0-10V transformer size and dot location

5 Firmware implementation

The PFC converter, two DC-DC converters, dimming provision and safety mechanisms are all controlled by the STM32 microcontroller.

The following flowcharts summarize the firmware logic.

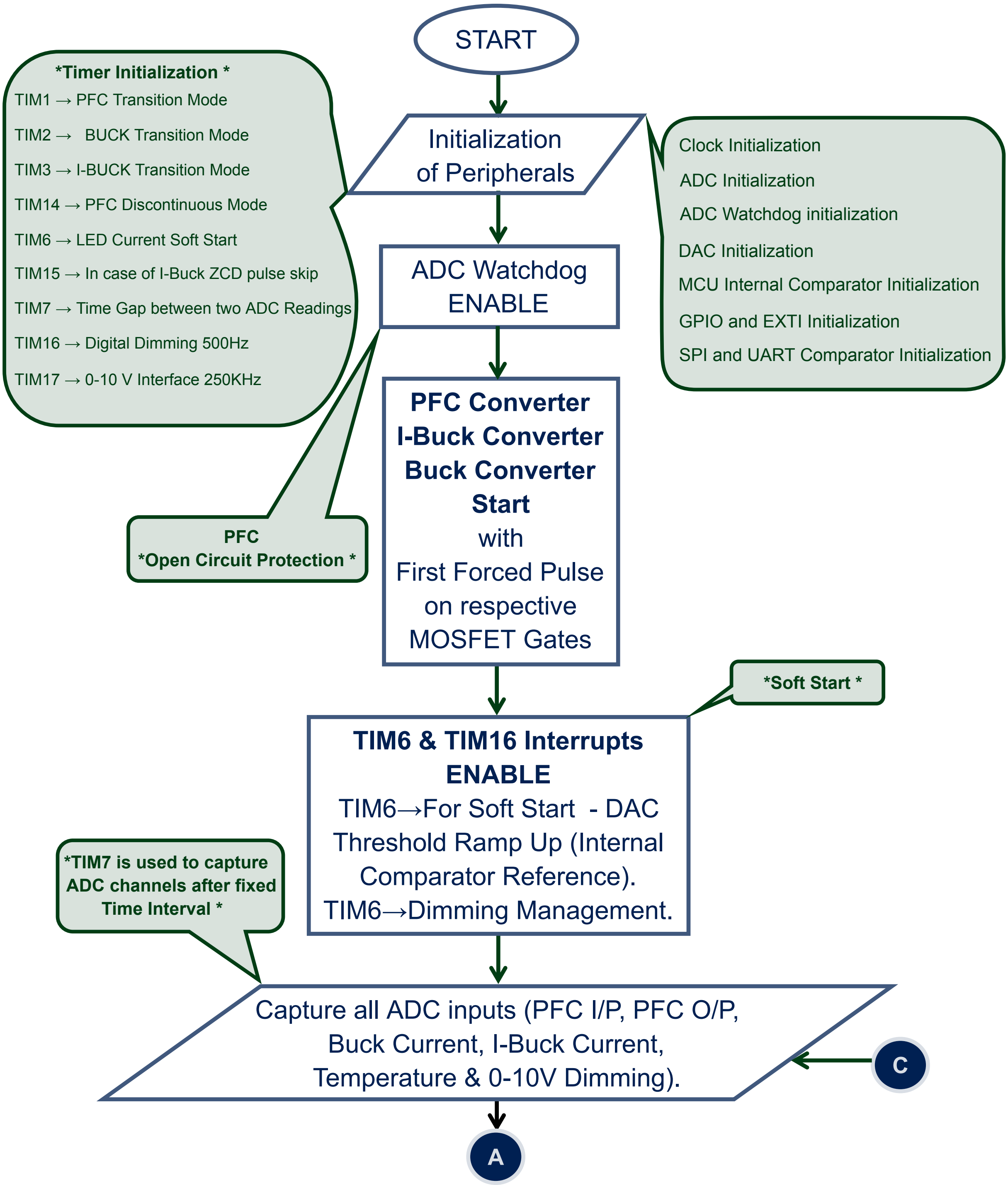
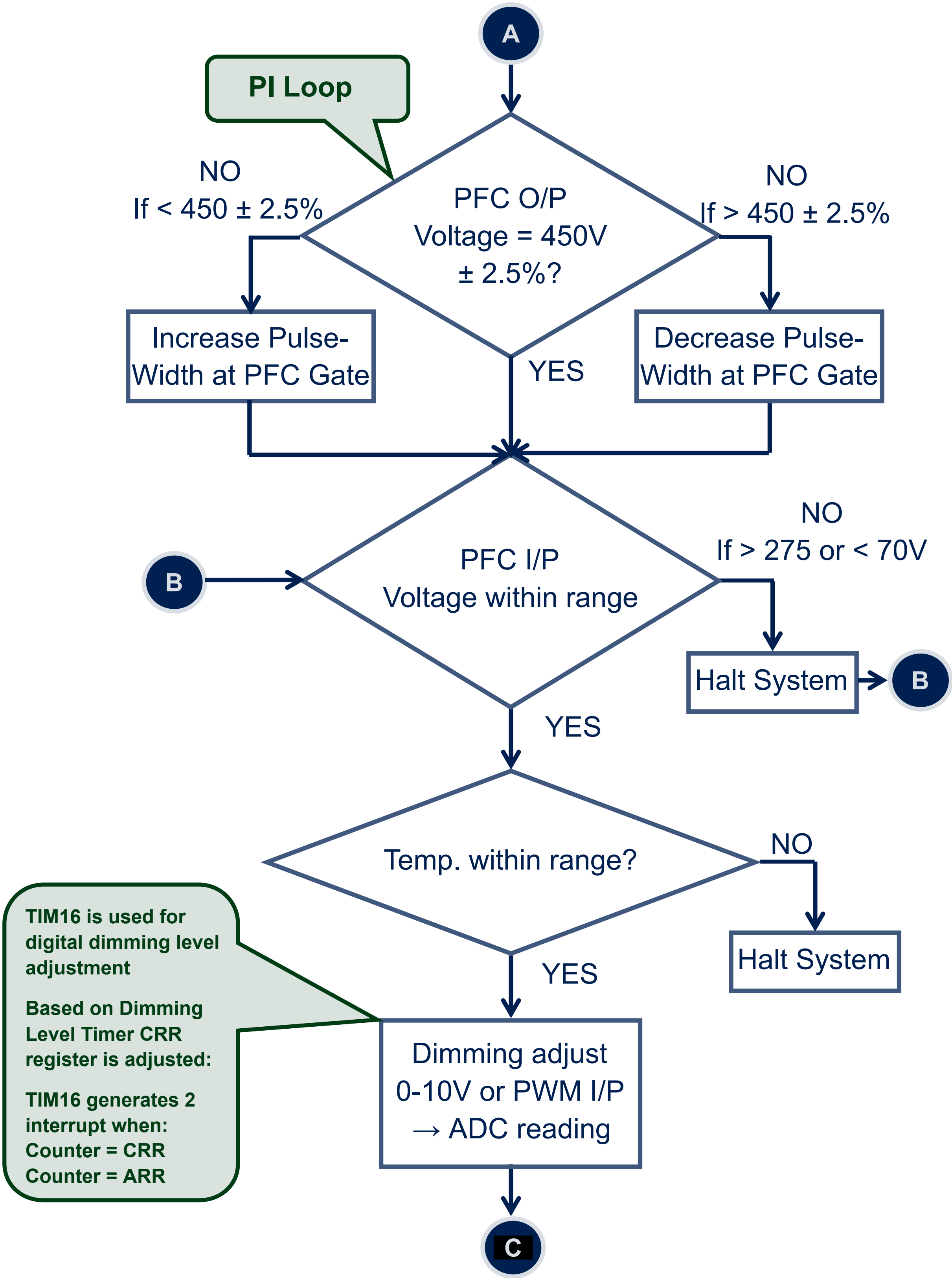


Figure 20. STEVAL-LLL004V1 firmware flowchart - I

Figure 21. STEVAL-LLL004V1 firmware flowchart - II



6 STEVAL-LLL004V1 test results

6.1 Efficiency, power factor, and THD

The following figures show the LED driver performance in terms of efficiency, power factor, and THD.

Figure 22. Input mains voltage vs efficiency at 100% brightness

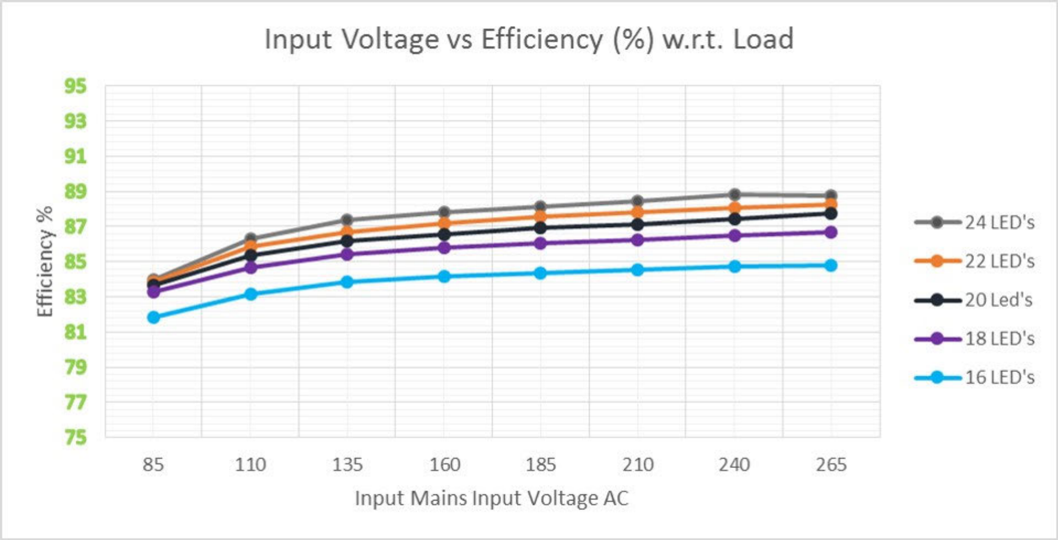


Figure 23. Input mains voltage vs power factor at 100% brightness

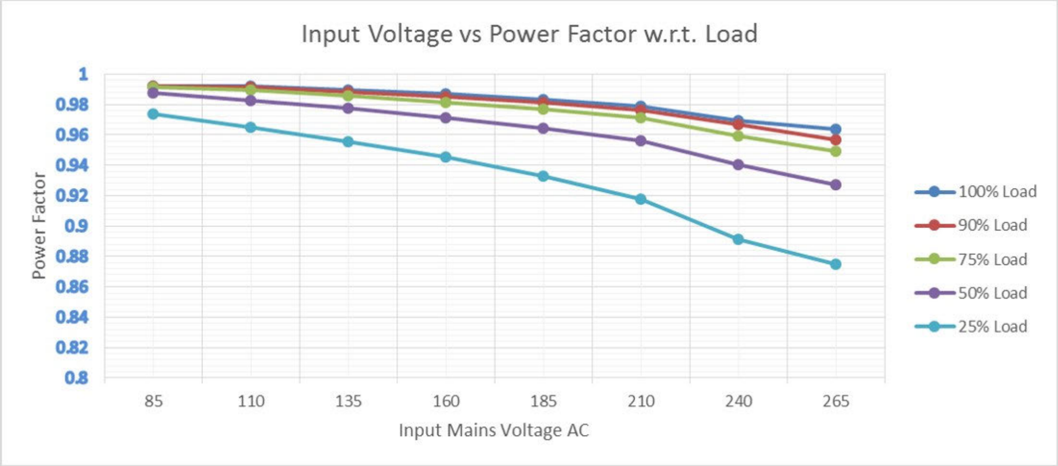
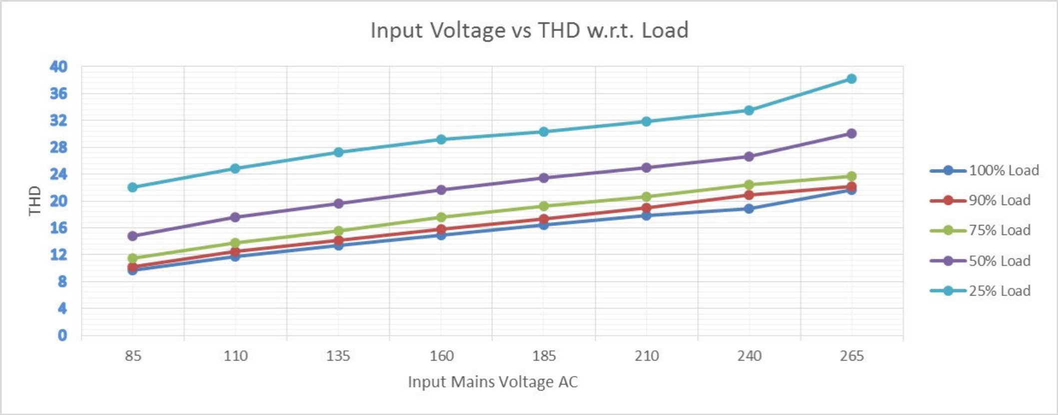


Figure 24. **Input mains voltage vs THD at 100% brightness**



6.2 DC-DC performance

Both DC-DC converters based on buck topology and inverse-buck topology work in constant current mode. The figures below show the DC-DC performance in terms of current regulation at different loads.

Figure 25. **Buck converter - input mains voltage vs output current at 100% brightness**

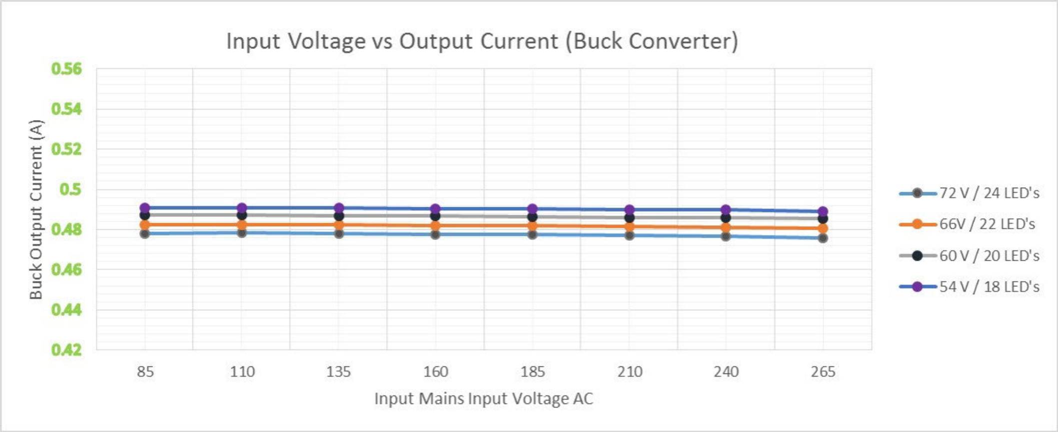
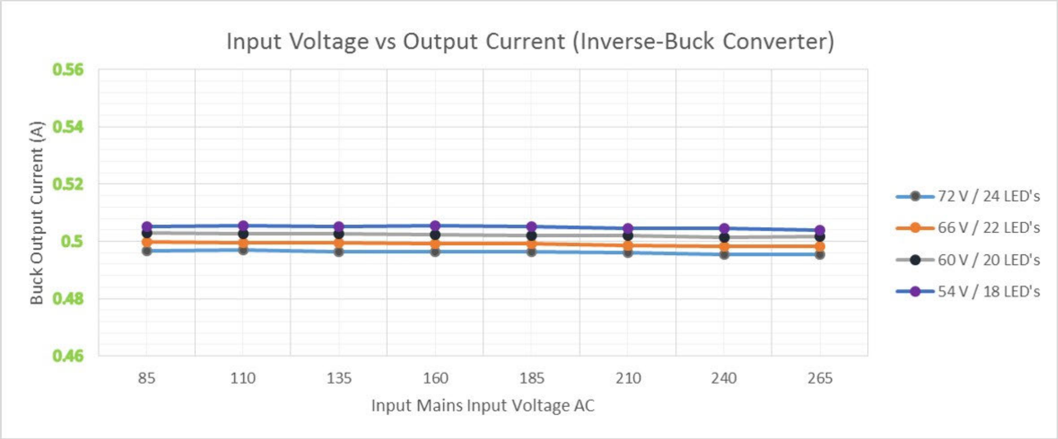


Figure 26. **Inverse buck converter - input mains voltage vs output current at 100% brightness**



7 Typical Waveforms

7.1 Power factor correction (PFC)

Figure 27. PFC - V_{CE} vs $I_{Inductor}$ vs V_{GE} at 110 V_{AC}

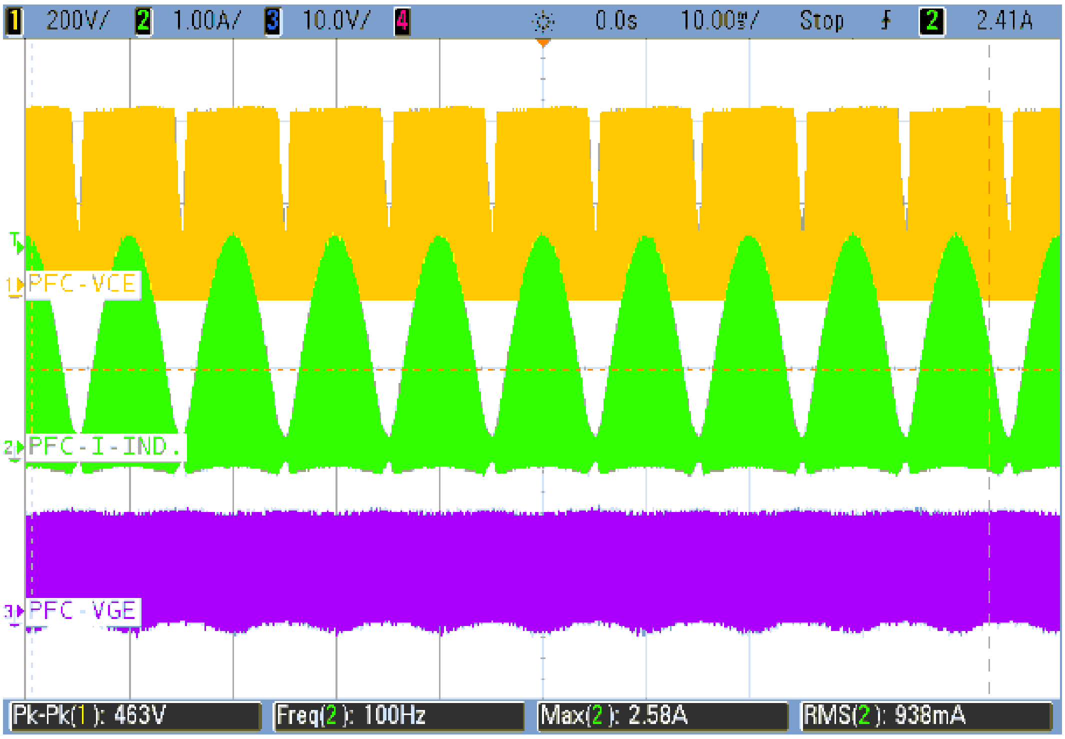


Figure 28. PFC - V_{CE} vs $I_{Inductor}$ vs V_{GE} at 230 V_{AC}

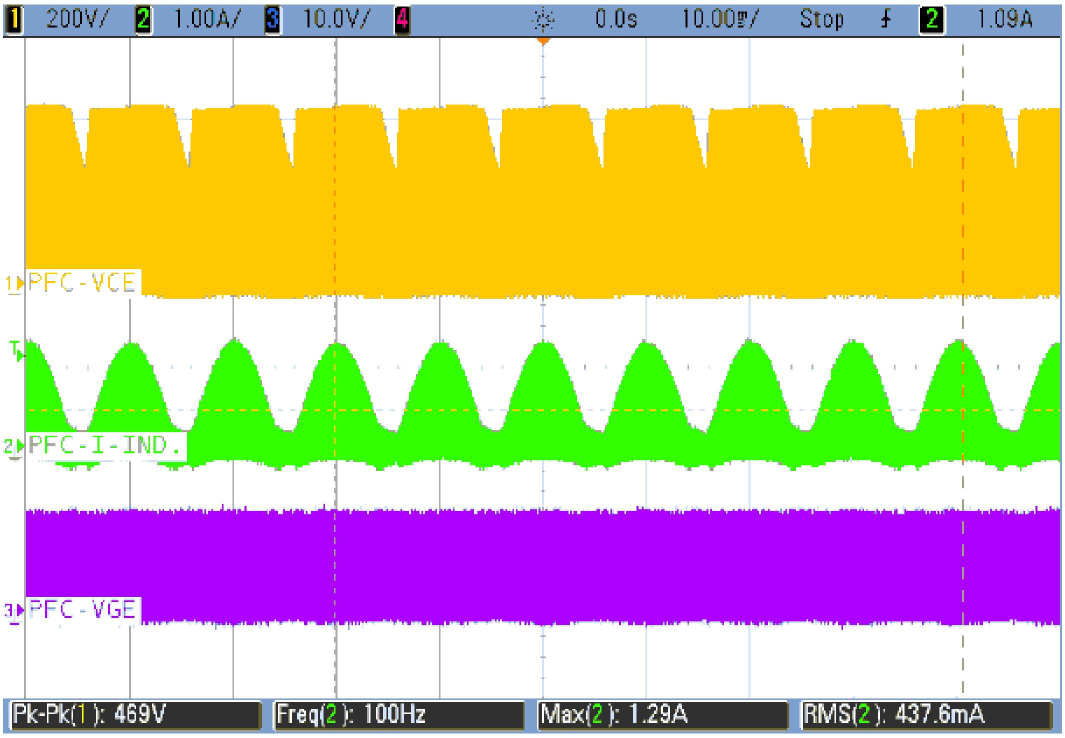


Figure 29. PFC - V_{CE} vs ZCD vs $I_{Inductor}$ vs V_{GE} at 110 V_{AC} - Zoom

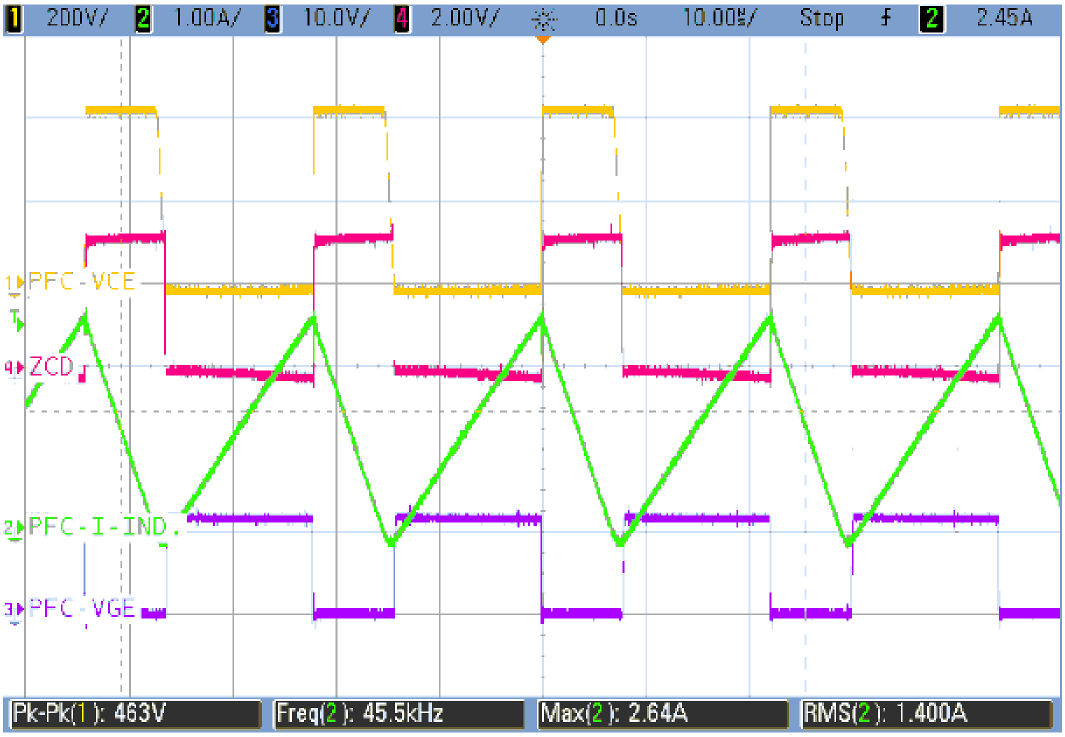


Figure 30. PFC - V_{CE} vs ZCD vs $I_{Inductor}$ vs V_{GE} at 230 V_{AC} – Zoom

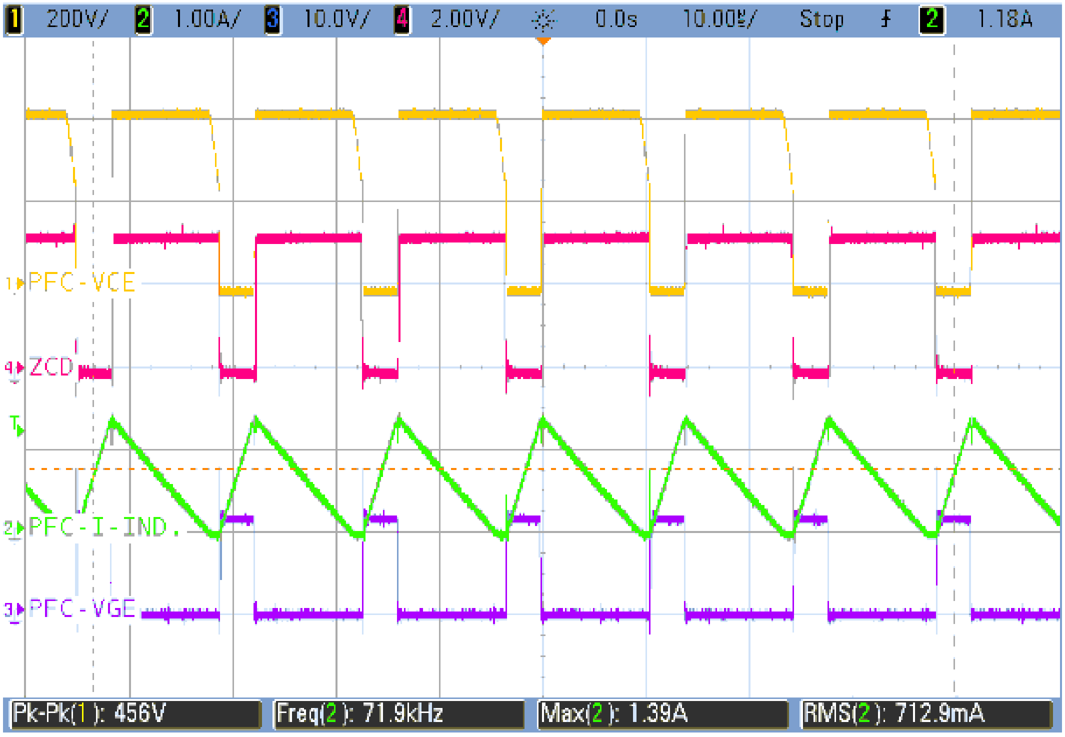
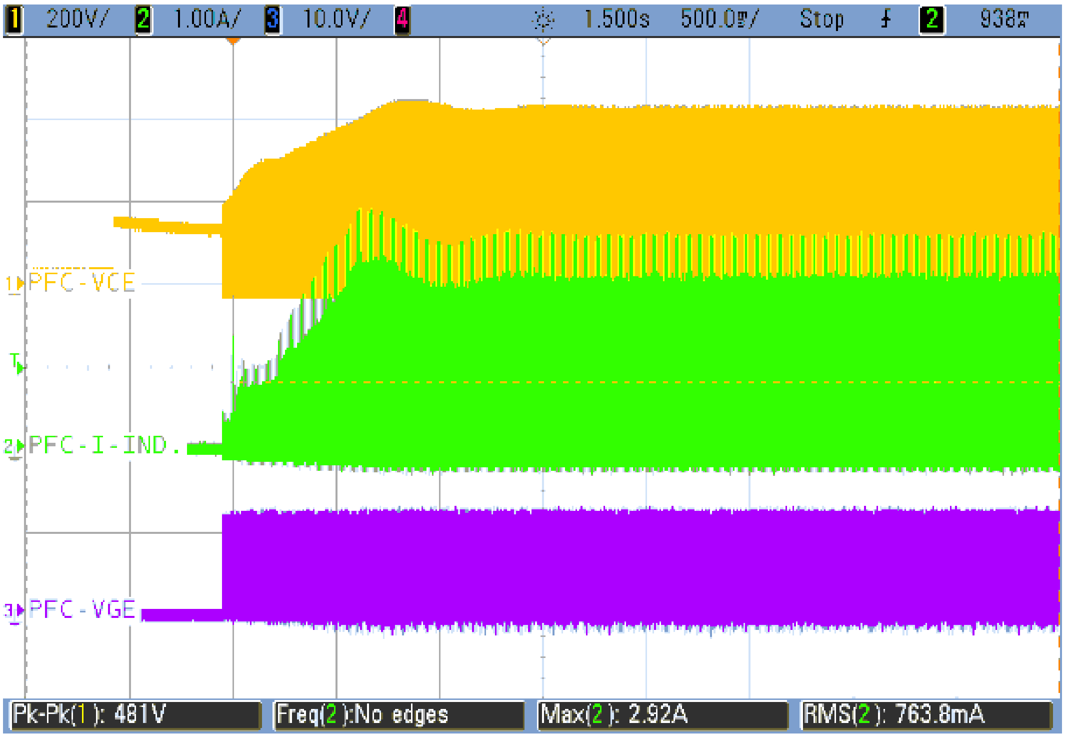


Figure 31. PFC Startup V_{CE} vs $I_{Inductor}$ vs V_{GE} at 110 V_{AC}



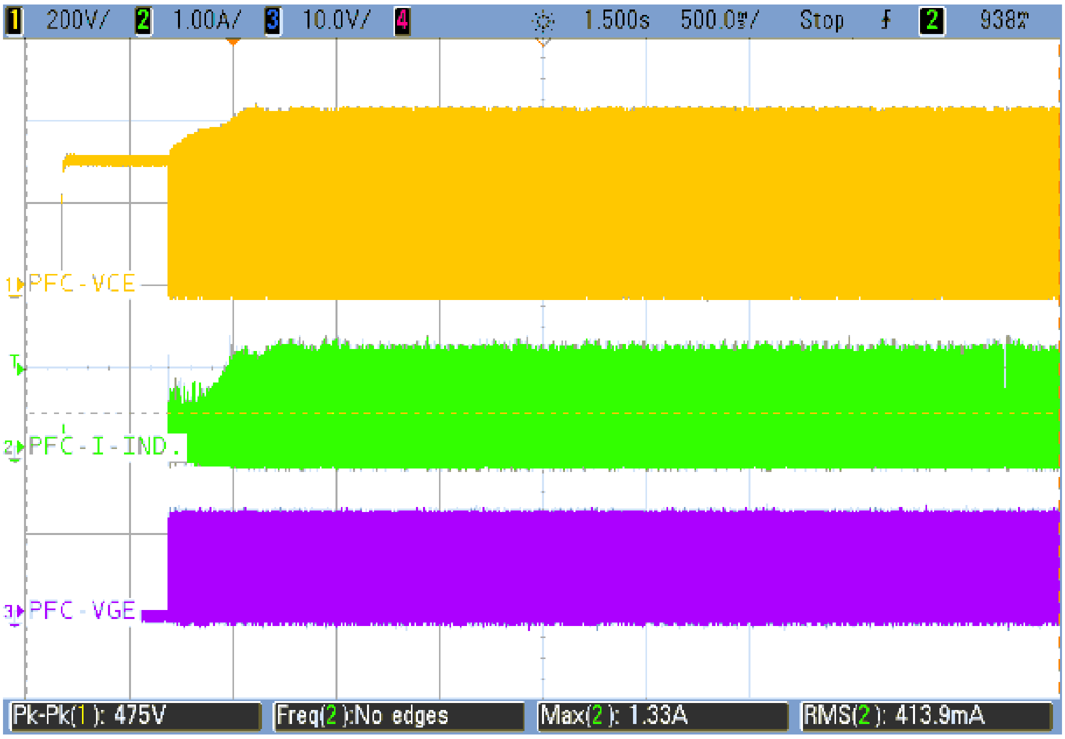


Figure 32. PFC Startup V_{CE} vs $I_{Inductor}$ vs V_{GE} at 230 V_{AC}

Figure 33. PFC working in Discontinuous Mode V_{CE} vs ZCD vs $I_{Inductor}$ vs V_{GE} at 110 V_{AC}

Figure 34. PFC working in Discontinuous Mode V_{CE} vs ZCD vs $I_{Inductor}$ vs V_{GE} at 230 V_{AC}

7.2 Buck Converter

Figure 35. Buck Converter - V_{CE} vs ZCD vs $I_{Inductor}$ vs V_{GE} at 110 V_{AC}

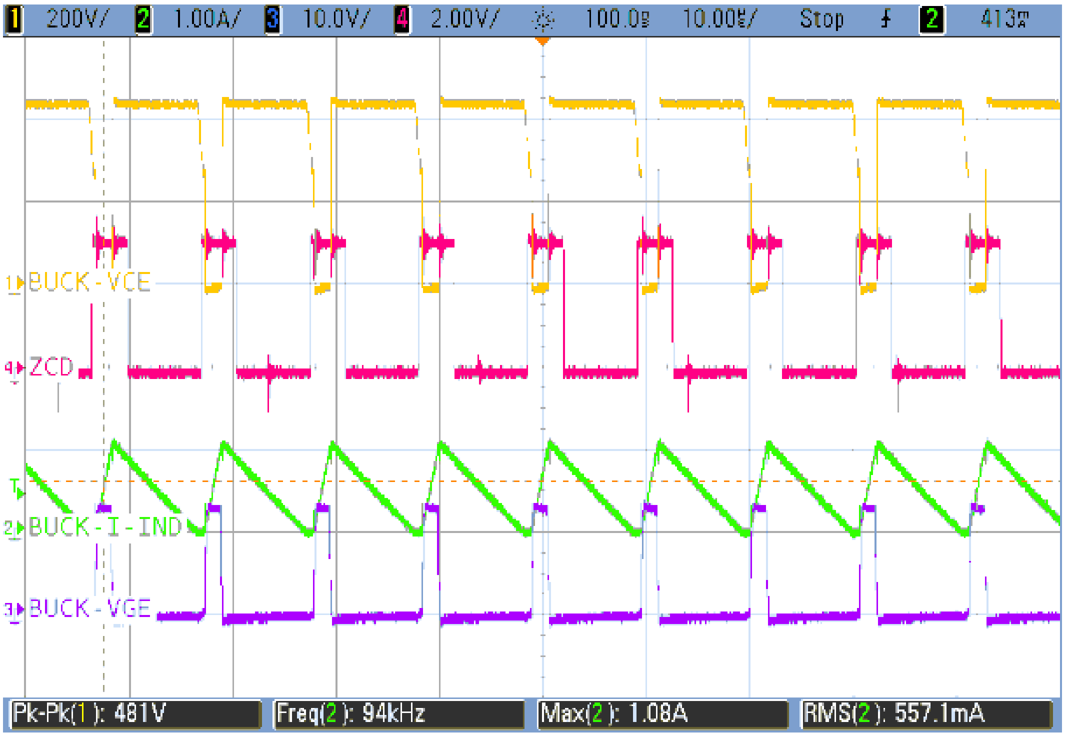
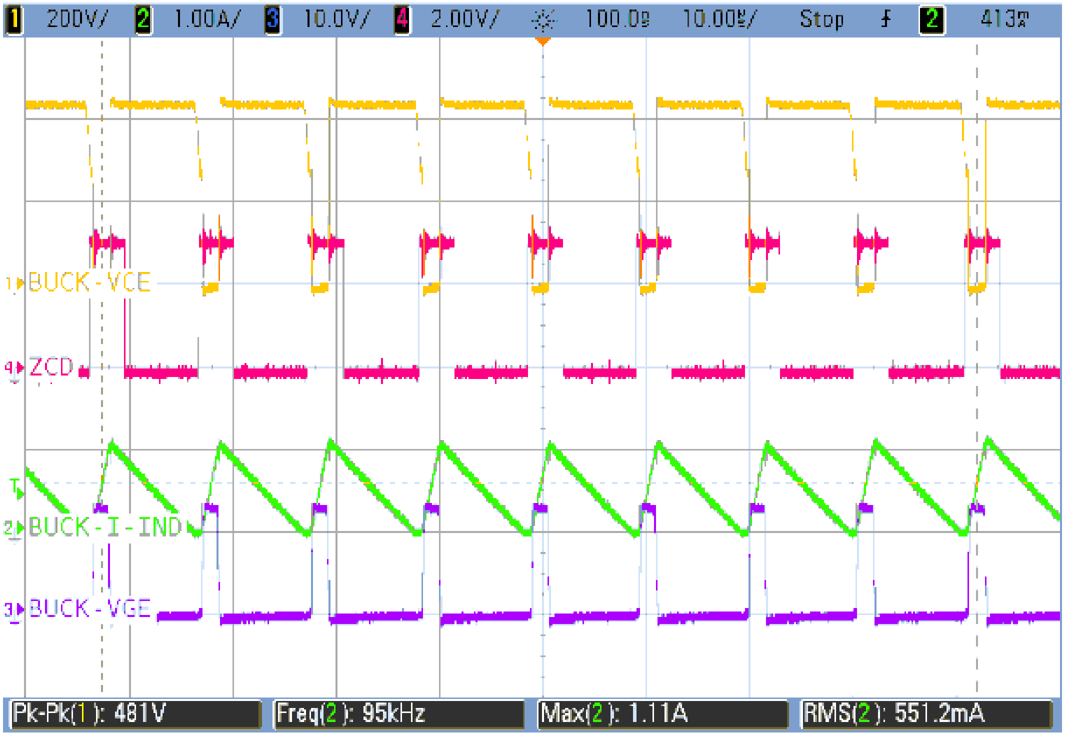
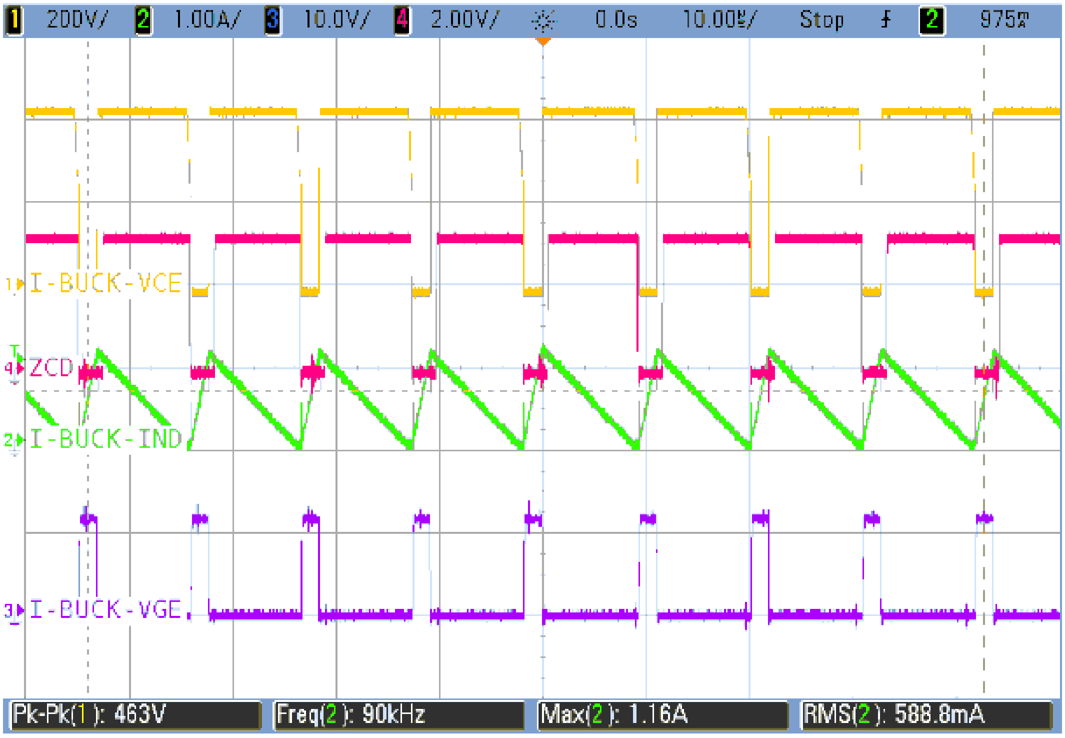


Figure 36. Buck Converter - V_{CE} vs ZCD vs $I_{Inductor}$ vs V_{GE} at 230 V_{AC}



7.3 Modified/inverse cuck converter

Figure 37. Inverse-Buck Converter - V_{CE} vs ZCD vs $I_{Inductor}$ vs V_{GE} at 110 V_{AC}



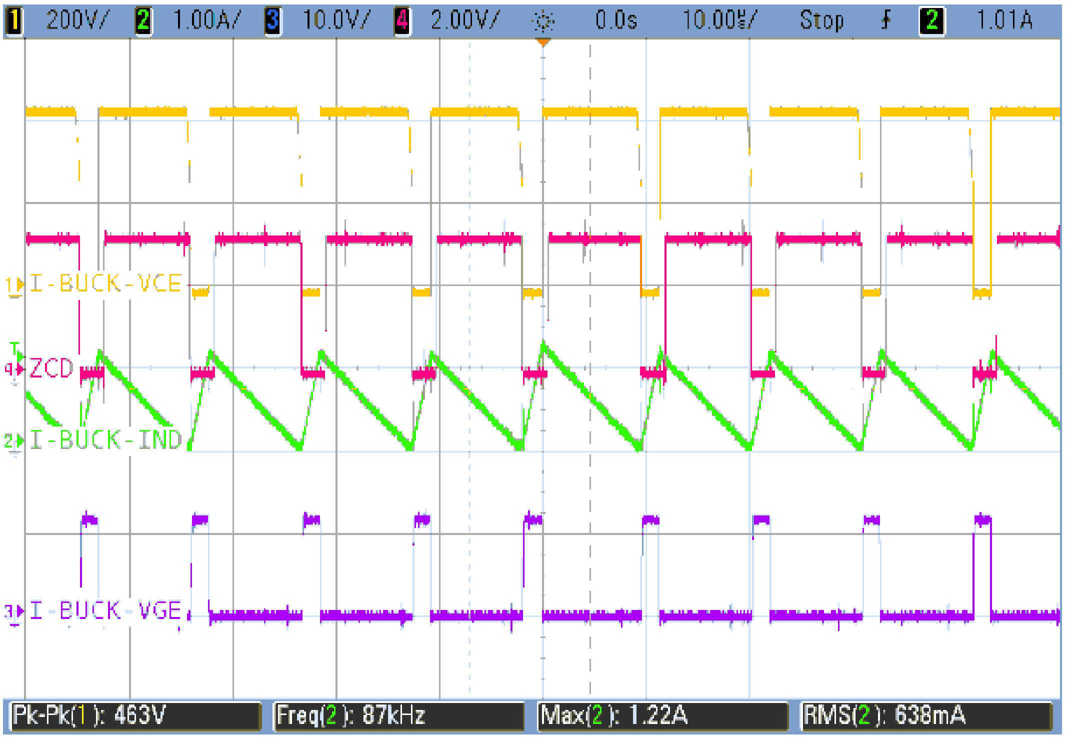


Figure 38. Inverse-Buck Converter - VCE vs ZCD vs IInductor vs VGE at 230 V_{AC}

8 Dimming

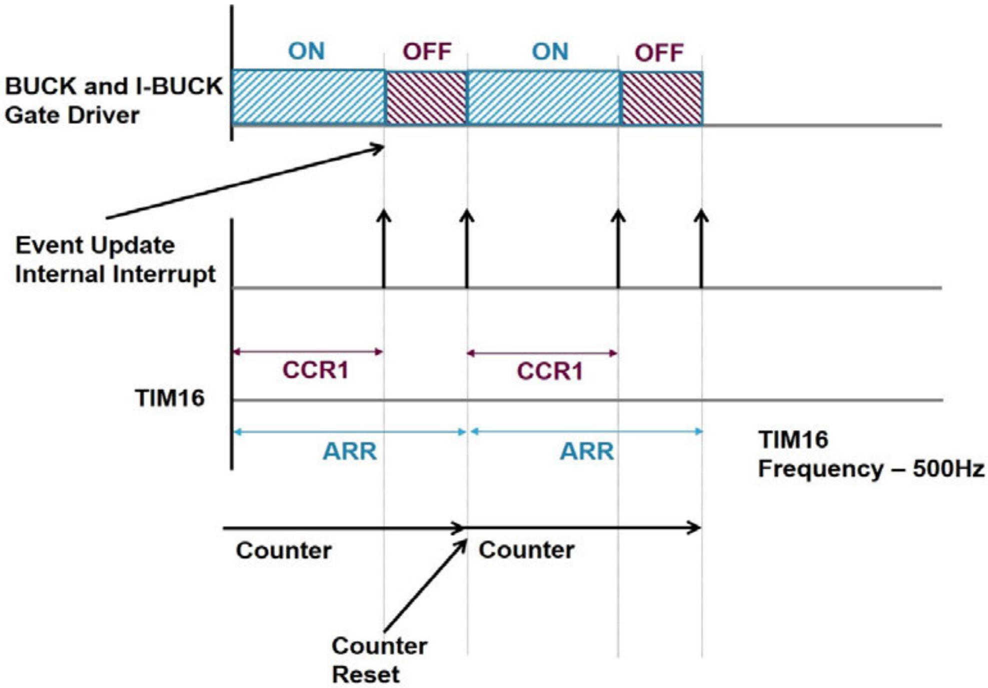
The LEDs connected at the output of the DC-DC converters can be dimmed by analog and digital means.

8.1 Digital dimming

For digital dimming, TIMER 16 on the STM32F07xx is used. The LED current is turned ON and OFF at a fixed 500 Hz frequency.

As the LEDs always turn ON at a nominal current level, and the average current to the LEDs is the product of the total nominal current and the duty cycle of the dimming function, the brightness level can be adjusted by adjusting the duty cycle (CCR1).

Figure 39. **Digital dimming - TIMER 16 management**



8.1.1 Buck Converter

Figure 40. Buck converter - Digital dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 100%

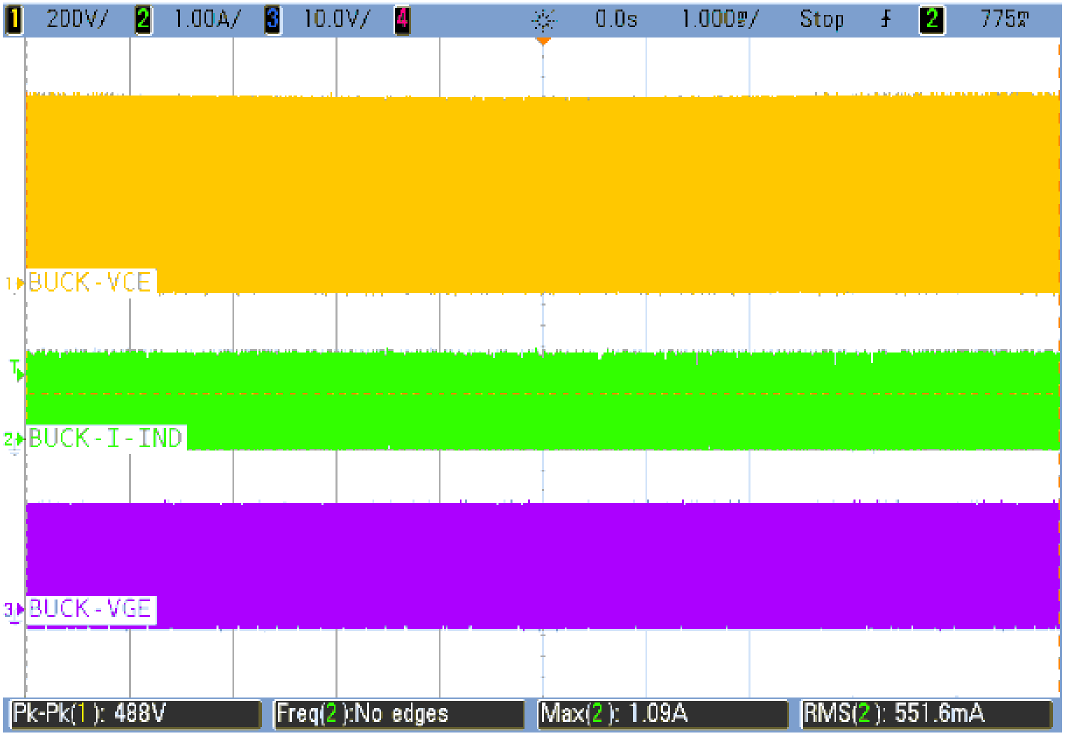


Figure 41. Buck converter - Digital dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 50%

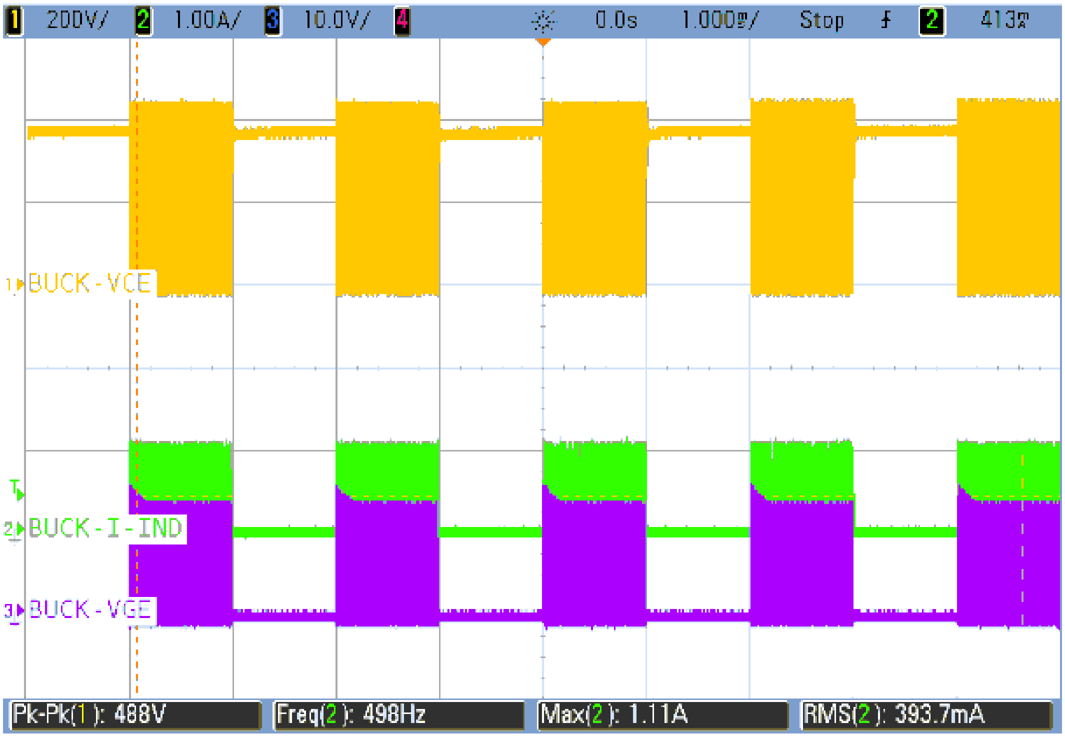


Figure 42. Buck converter - Digital dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 10%

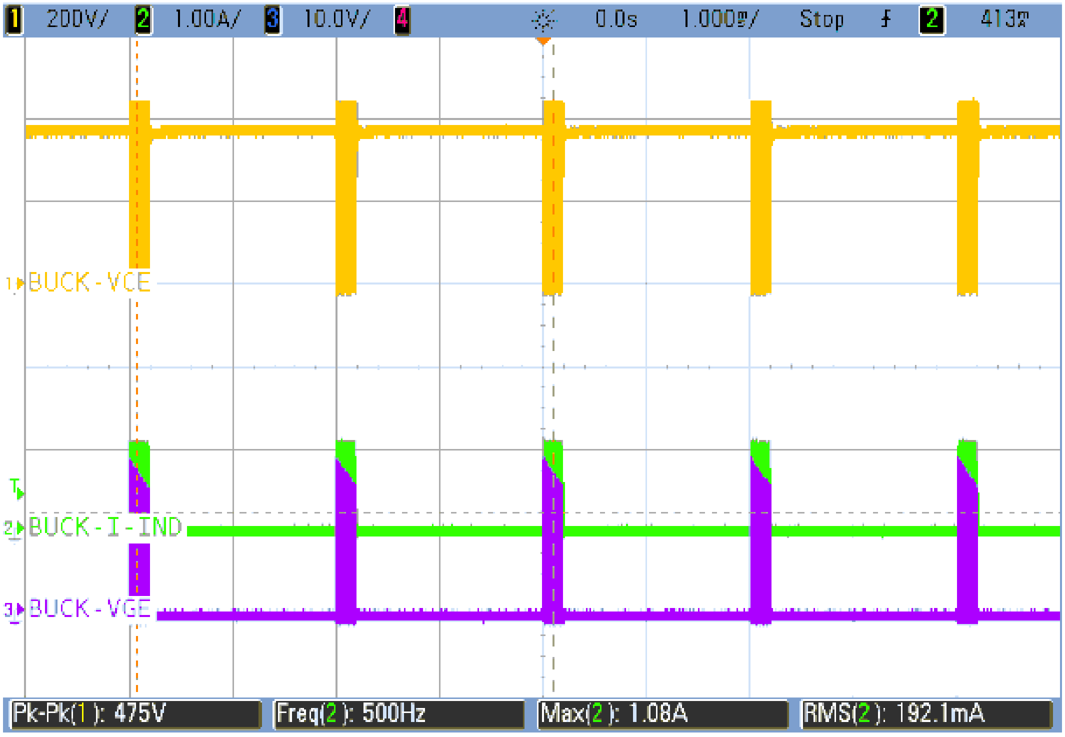


Figure 43. Buck converter - Digital dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 0.5%

Figure 44. Buck Converter - Digital dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} vs ZCD at 0.5% - Zoom

8.1.2 Inverse buck converter

Figure 45. Inverse buck converter - Digital dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 100%

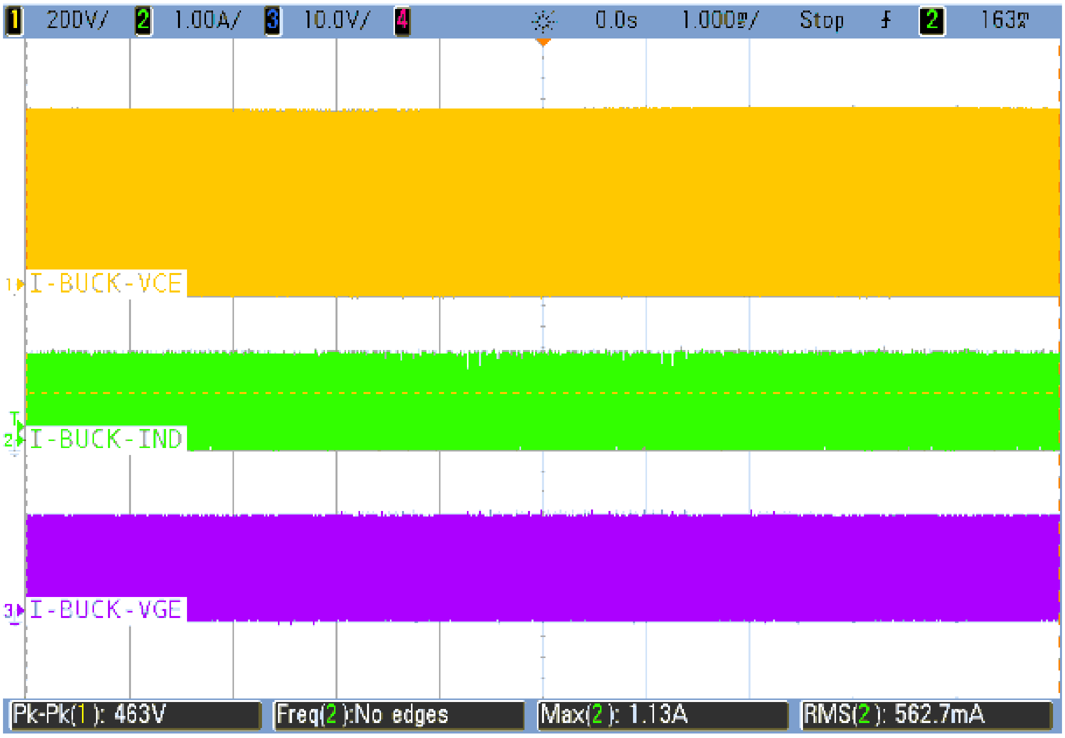


Figure 46. Inverse buck converter - Digital dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 50%

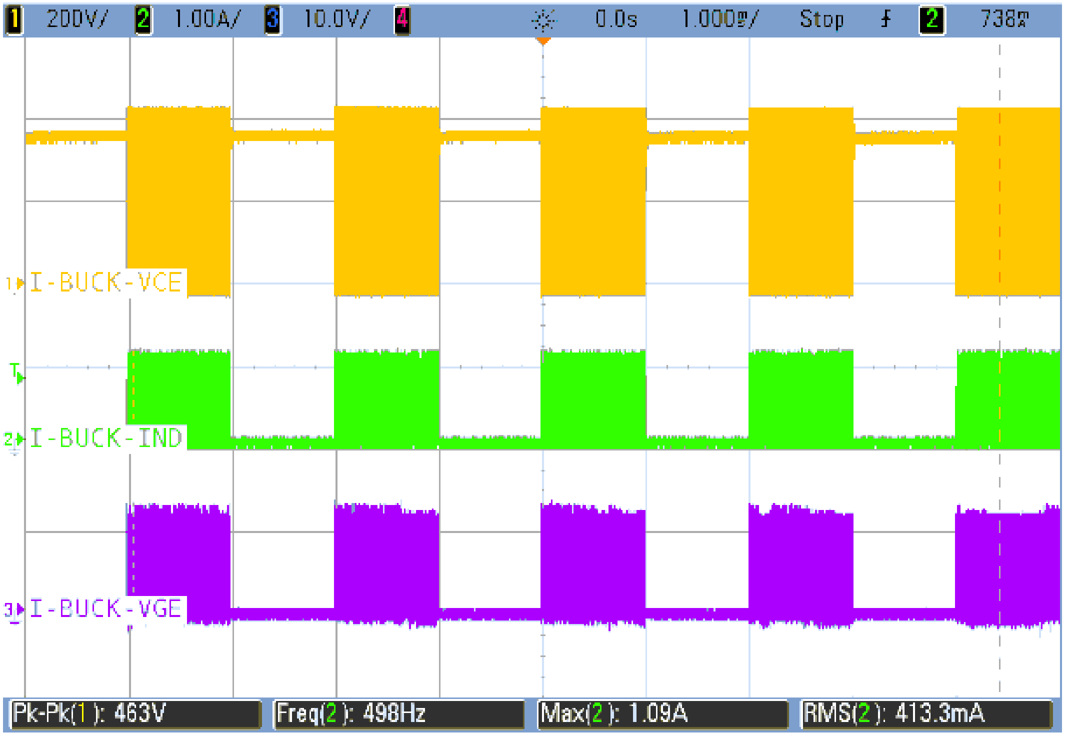


Figure 47. Inverse buck converter - Digital dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 10%

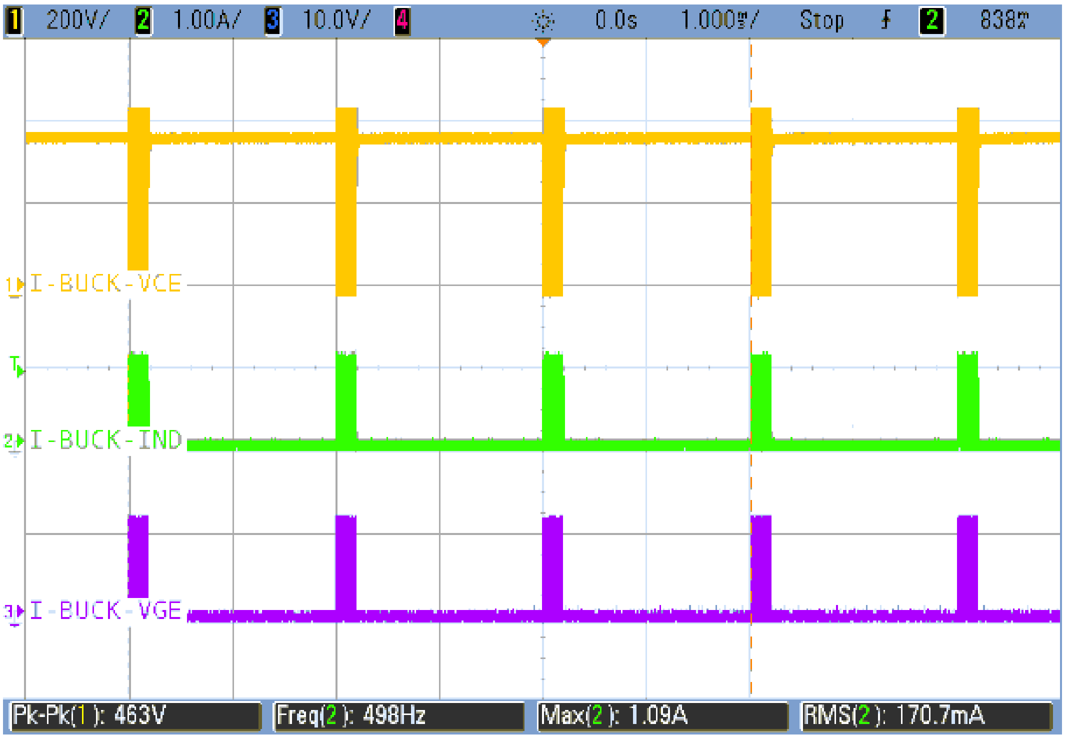


Figure 48. Inverse buck converter - Digital dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 0.5%

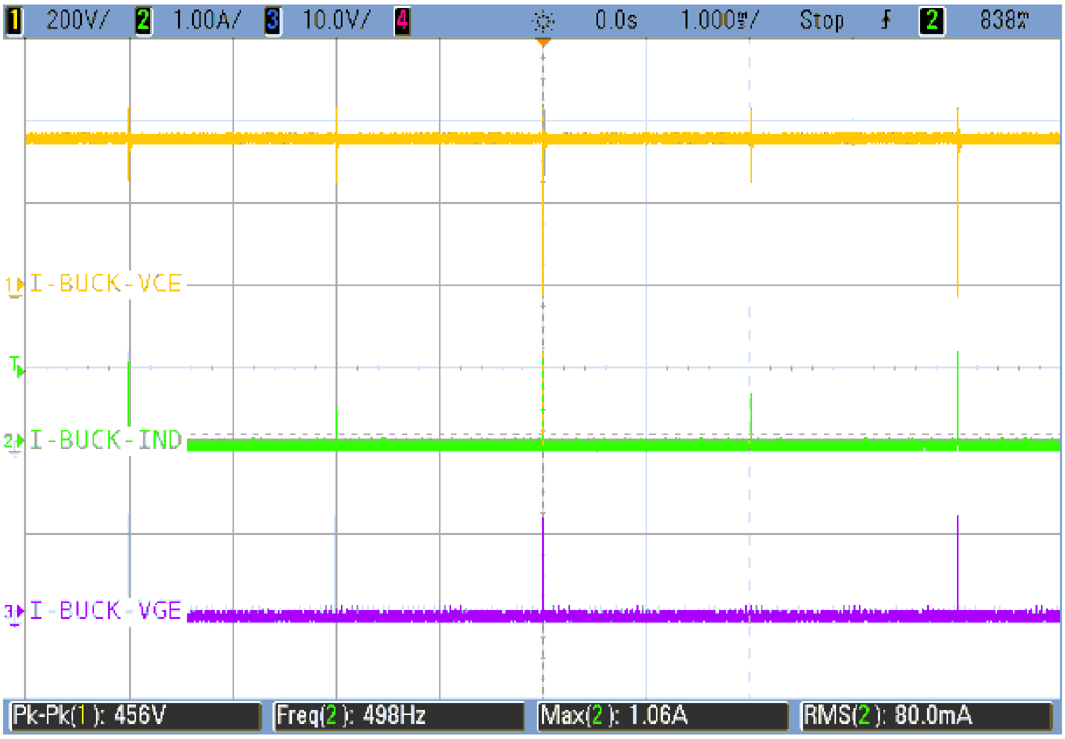
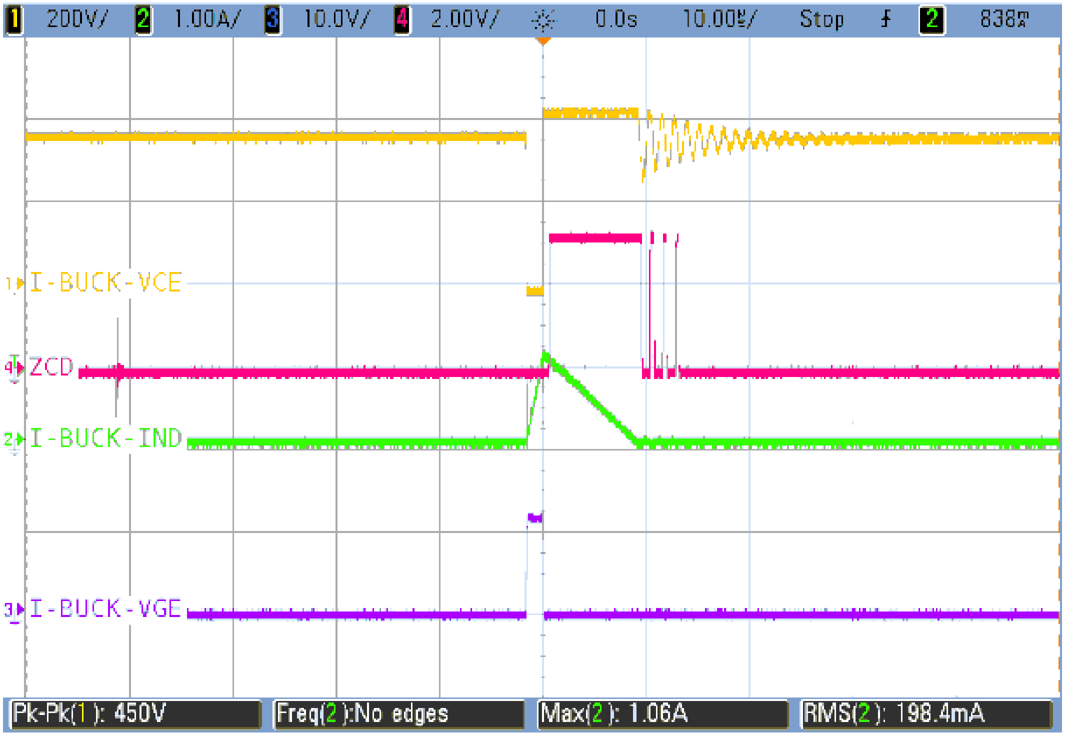


Figure 49. Inverse buck converter - Digital dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} vs ZCD at 0.5% - Zoom



8.2 Analog dimming

For analog dimming, the LED current remains continuous, but the amount of current is changed. Analog dimming is implemented with an MCU internal comparator and a digital to analog converter (DAC) peripheral. The current threshold (inductor peak current) at the non-inverting end of internal comparator is adjusted by help of the DAC.

The LEDs can only be dimmed to a certain extent in Transition Mode, so the DC-DC buck converter is switched to Discontinuous Mode when lower dimness levels are required.

8.2.1 Buck converter

Figure 50. Buck converter - Analog dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 100%

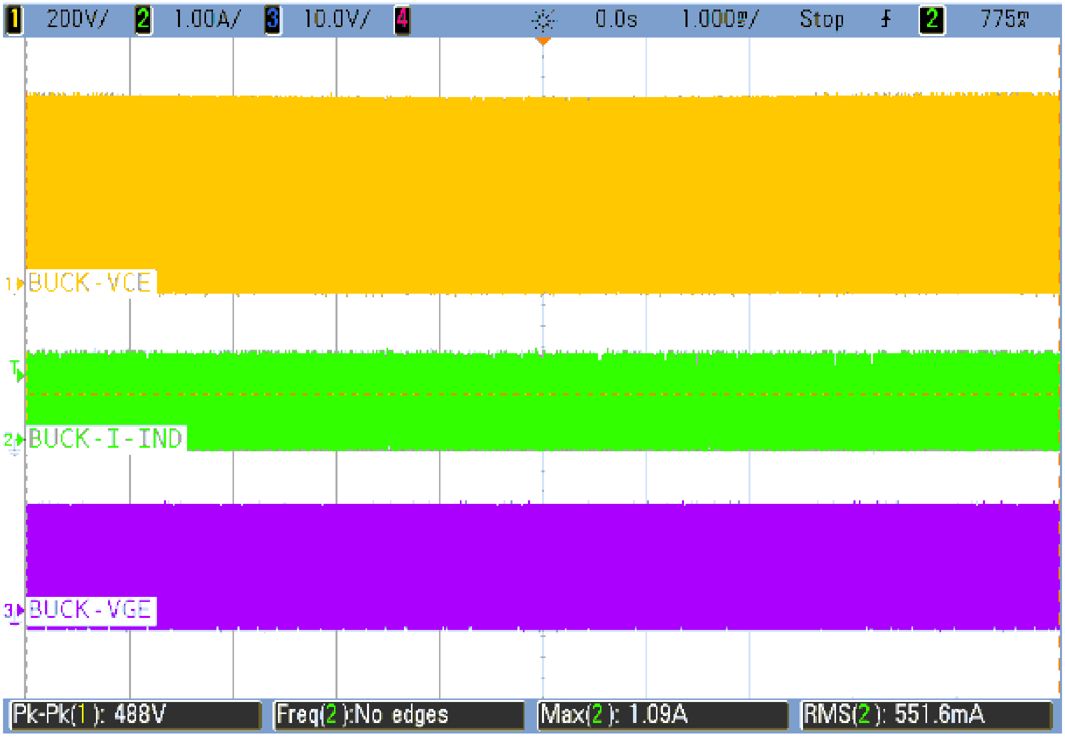


Figure 51. Buck converter - Analog dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 50%

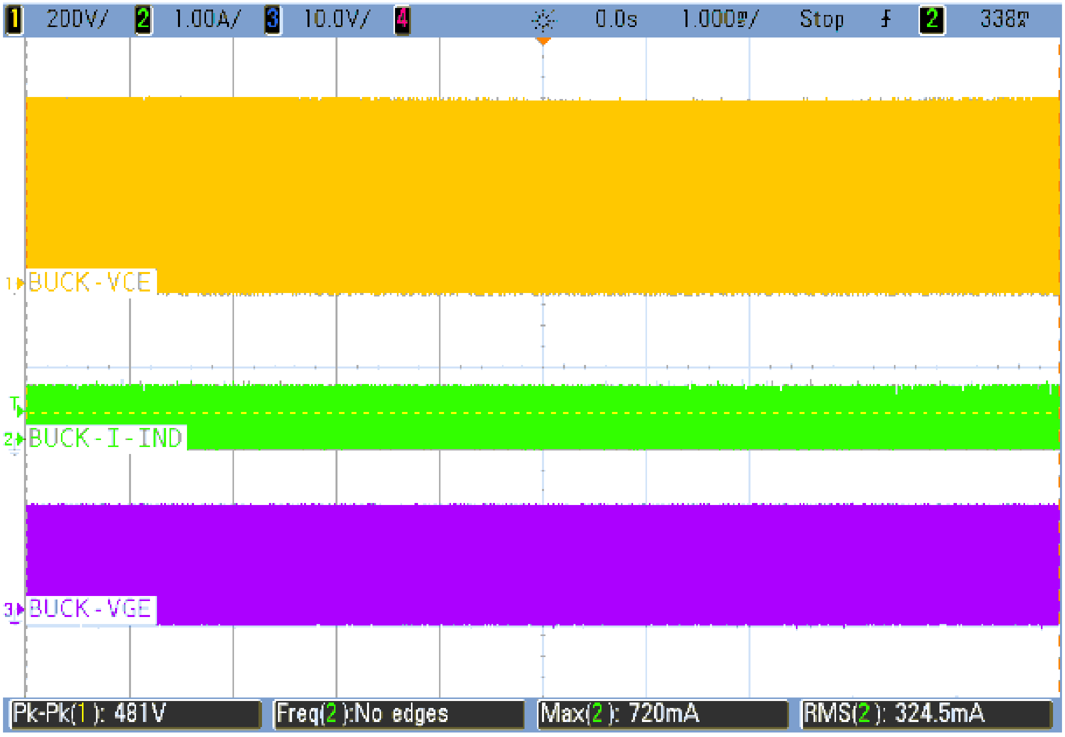


Figure 52. Buck converter - Analog dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 10%

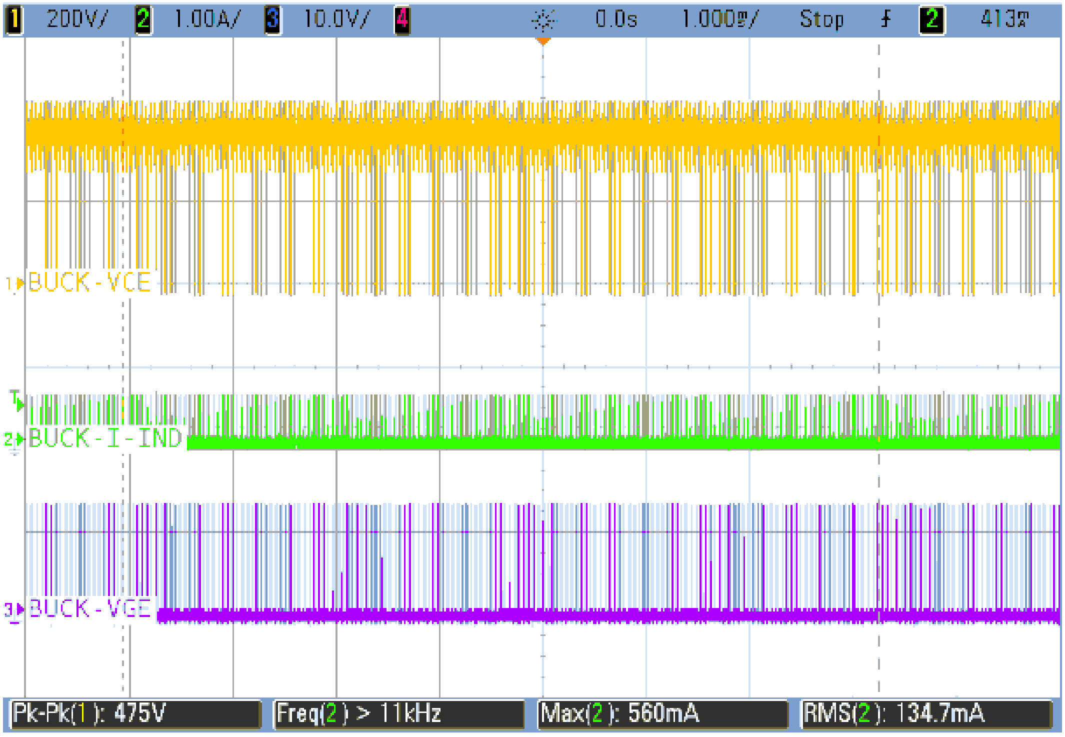
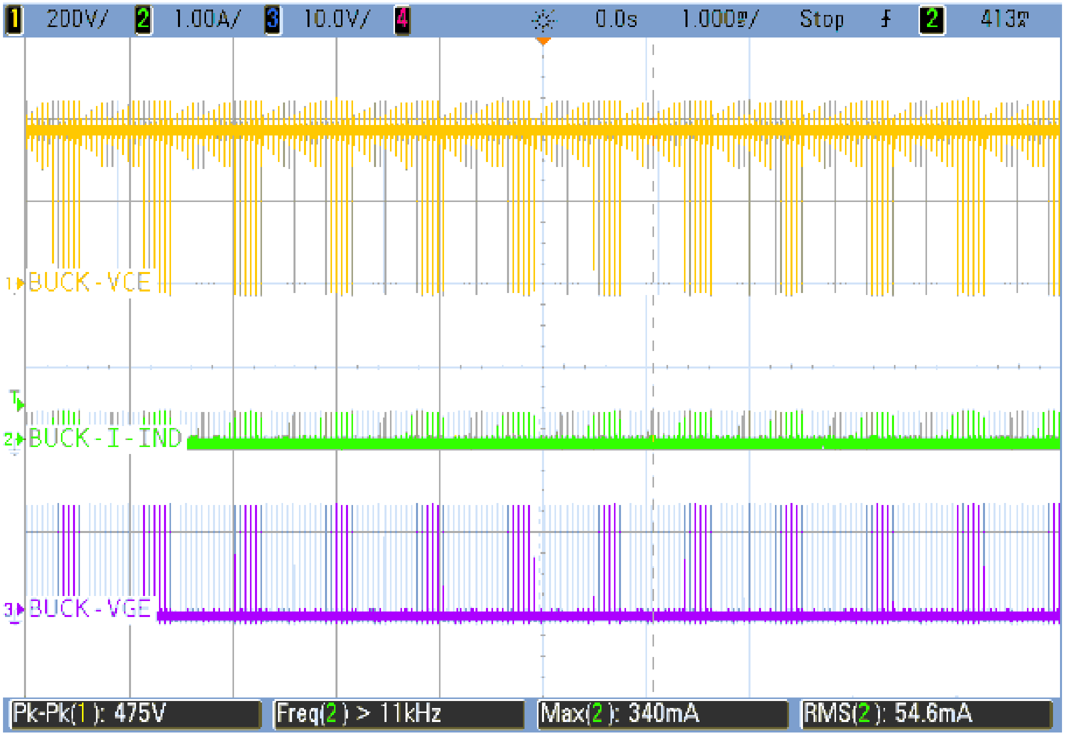
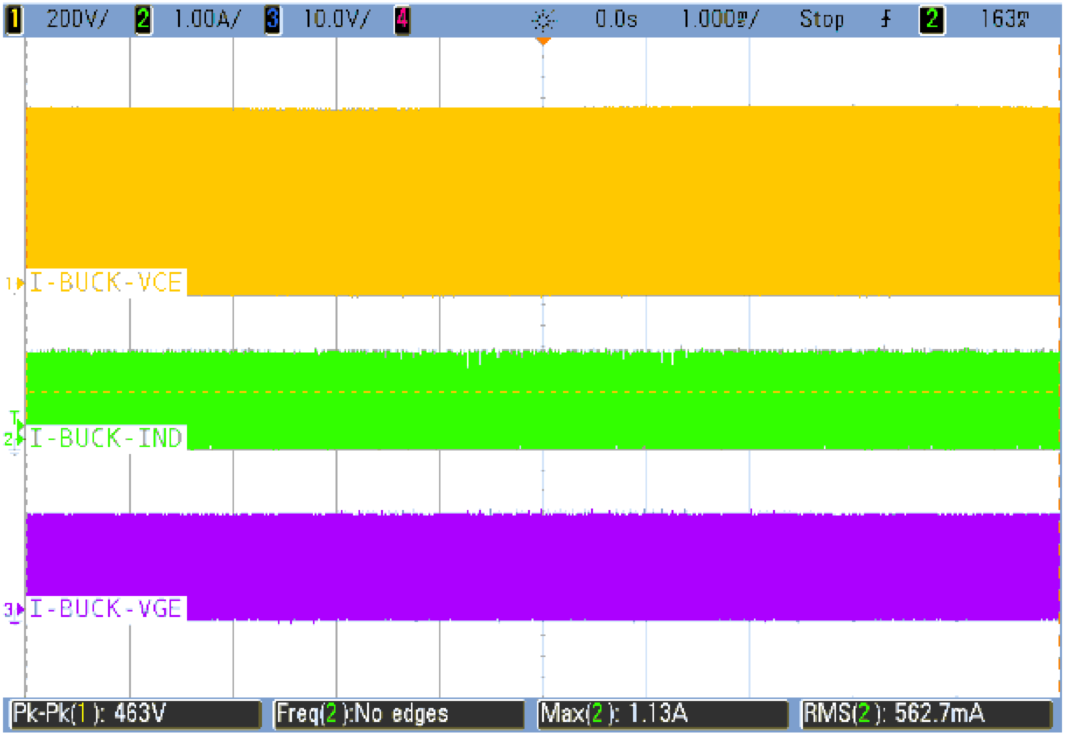


Figure 53. Buck converter - Analog dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 0.5%



8.2.2 Inverse buck converter

Figure 54. Inverse buck converter - Analog dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 100%



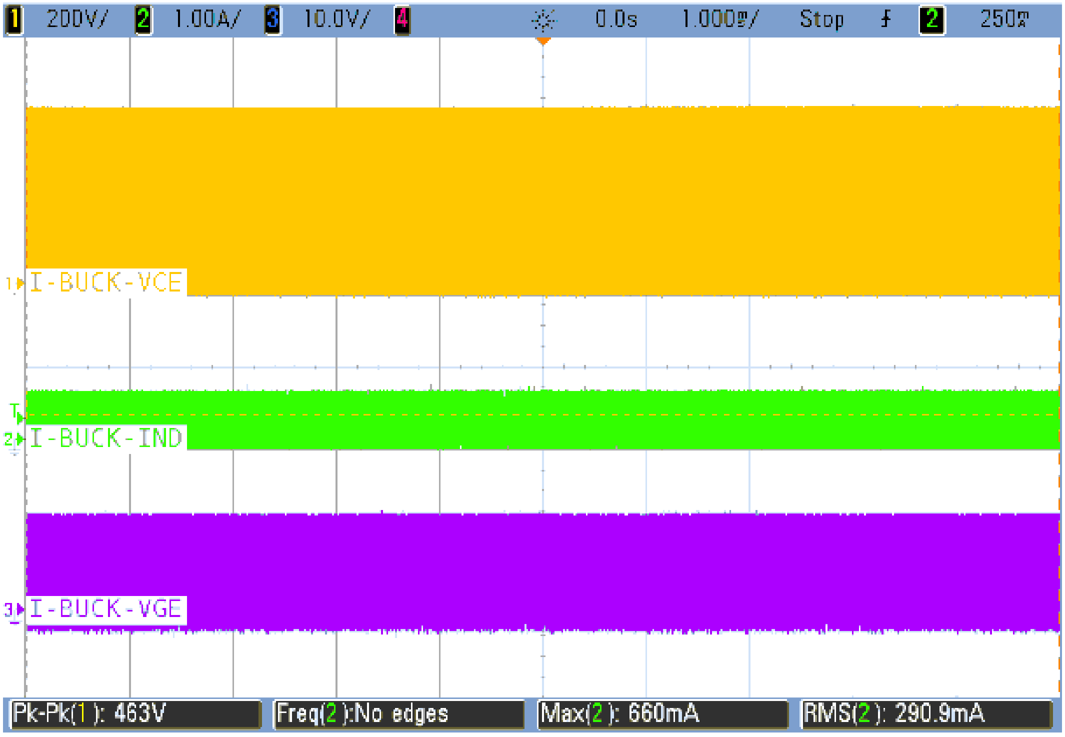


Figure 55. Inverse buck converter - Analog dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 50%

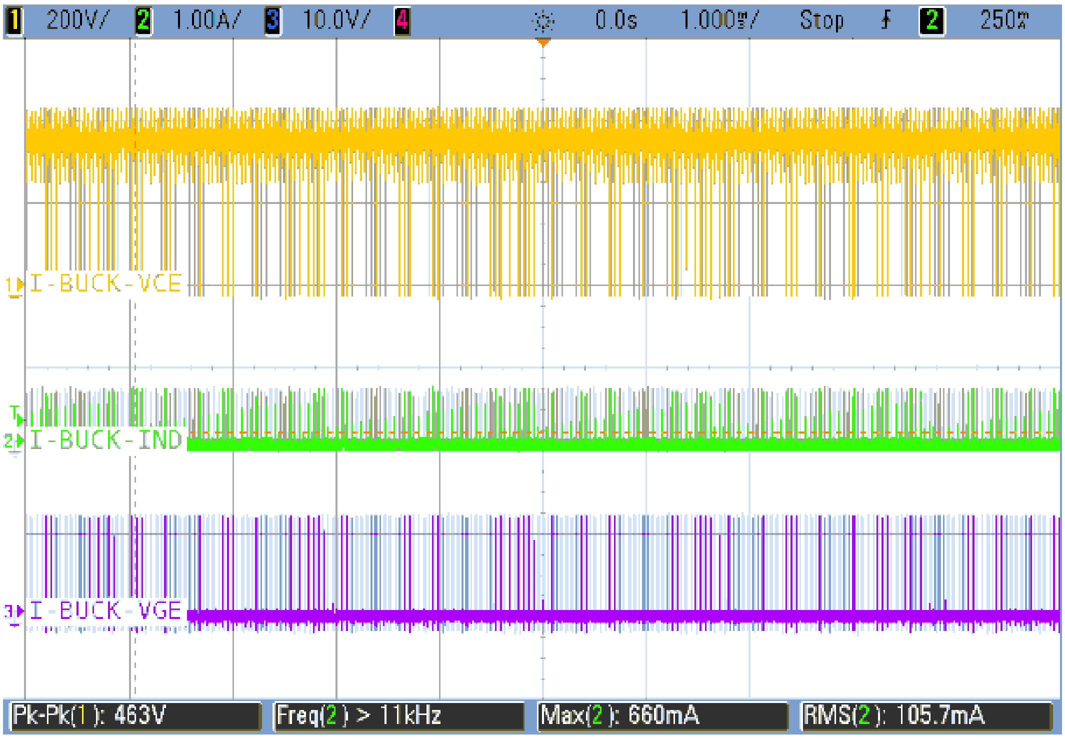
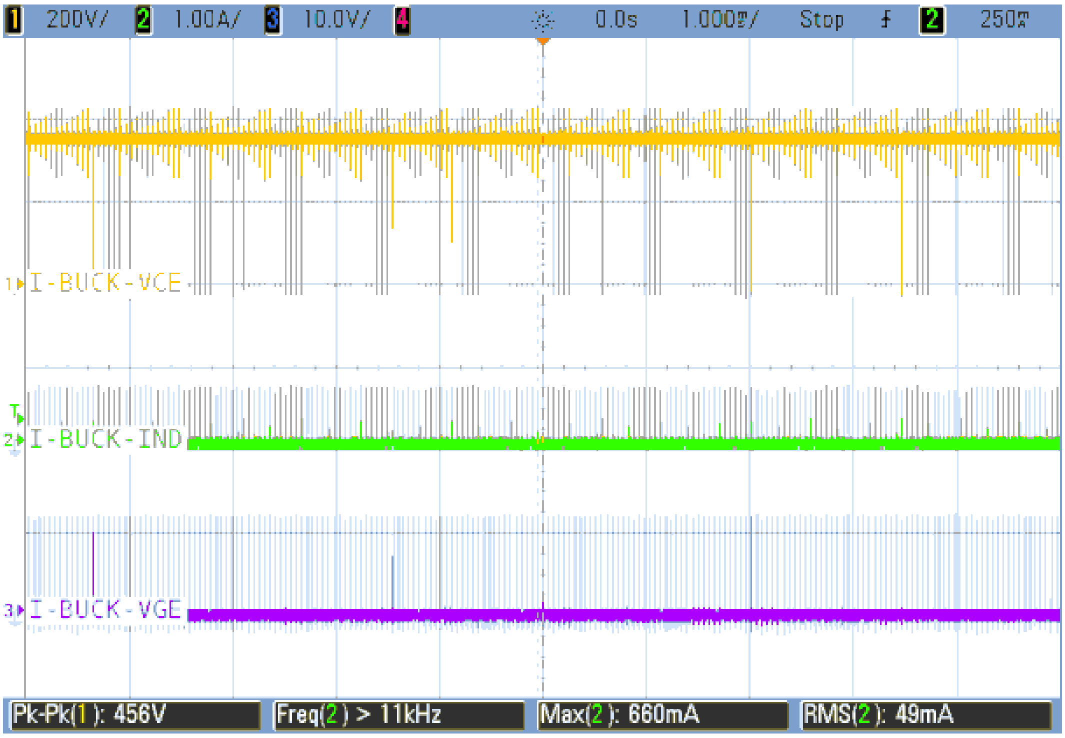


Figure 56. Inverse buck converter - Analog dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 10%

Figure 57. Inverse buck converter - Analog dimming - V_{CE} vs $I_{INDUCTOR}$ vs V_{GE} at 0.5%



9 Board protections

The STEVAL–LLL004V1 is a digitally controlled constant current LED driver. The LED driver draws power from universal AC mains (85-265V) over the entire brightness range (0.5-100%).

The board is equipped with comprehensive safety features like short-circuit, open circuit, input undervoltage, and input overvoltage.

9.1 PFC Response

The following figures show the PFC section response with respect to the transition in input mains voltage from 110V to 230 V_{AC} and 230V to 110 V_{AC}.

Figure 58. **PFC output voltage vs input mains voltage (110V to 230 V_{AC})**

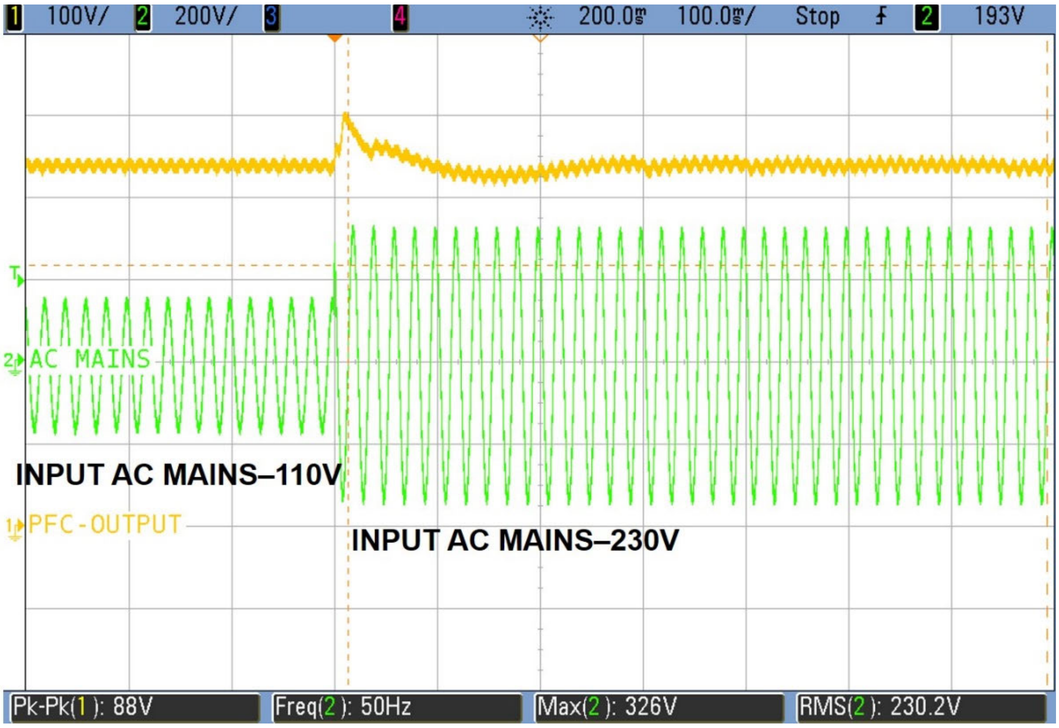
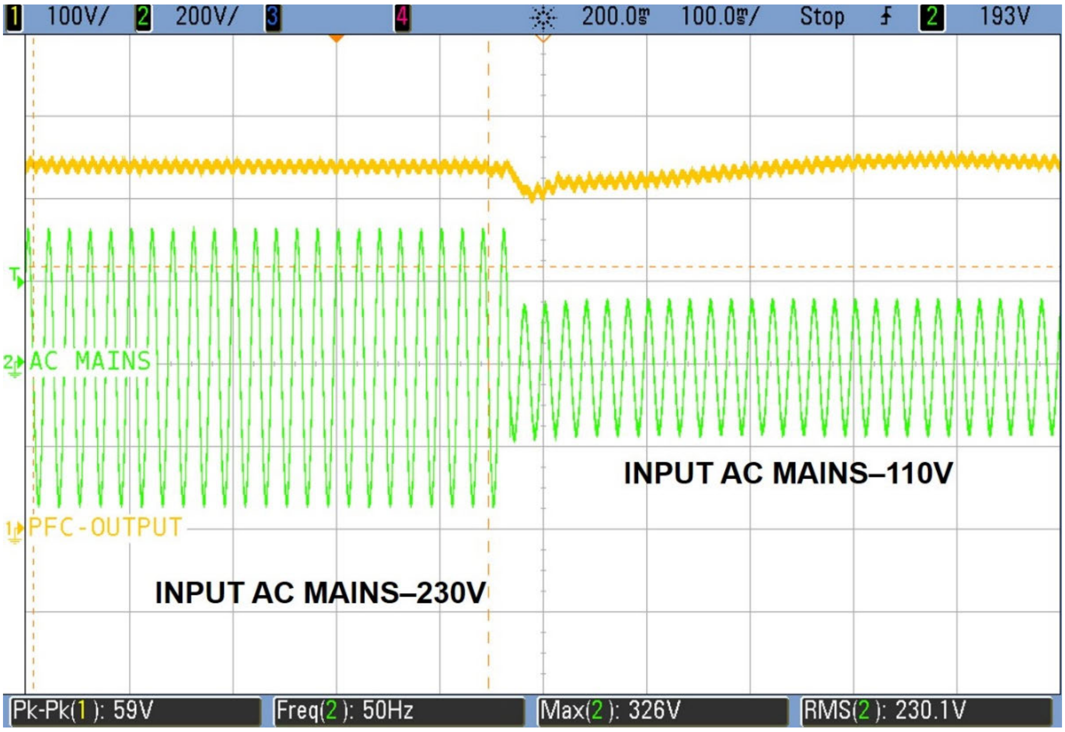


Figure 59. PFC output voltage vs input mains voltage (230V to 110 V_{AC})



9.2 Short-circuit protection

9.2.1 Buck converter

Figure 60. Buck short-circuit protection V_{CE} vs $I_{Inductor}$ vs I_{LED}

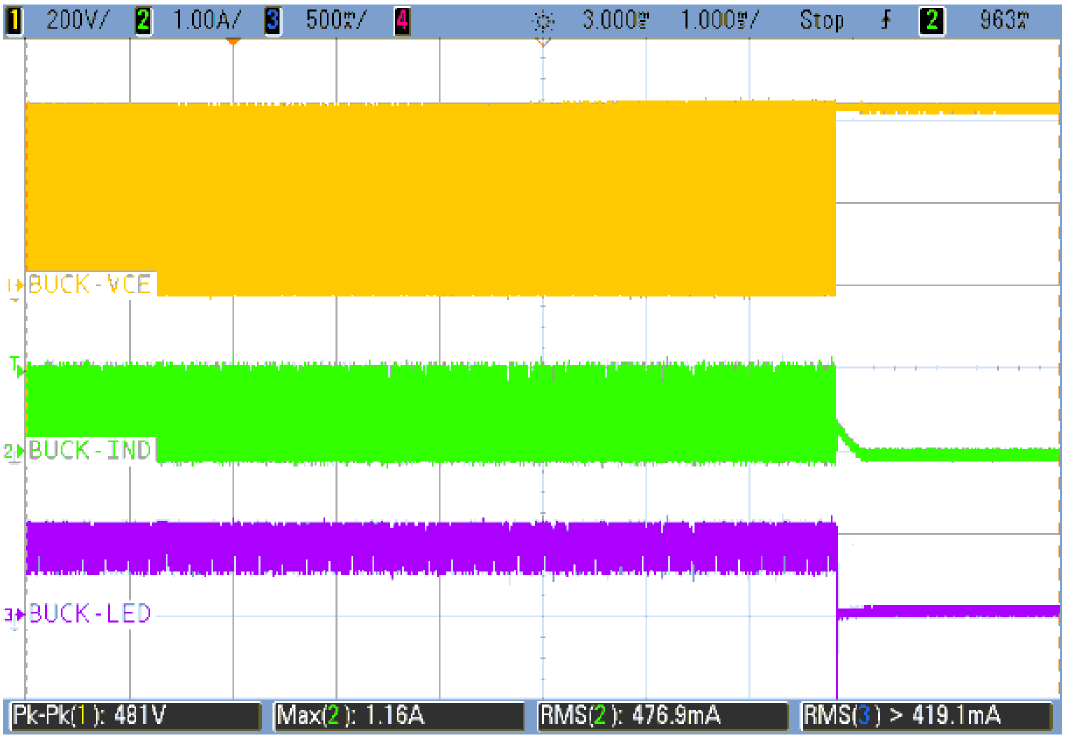
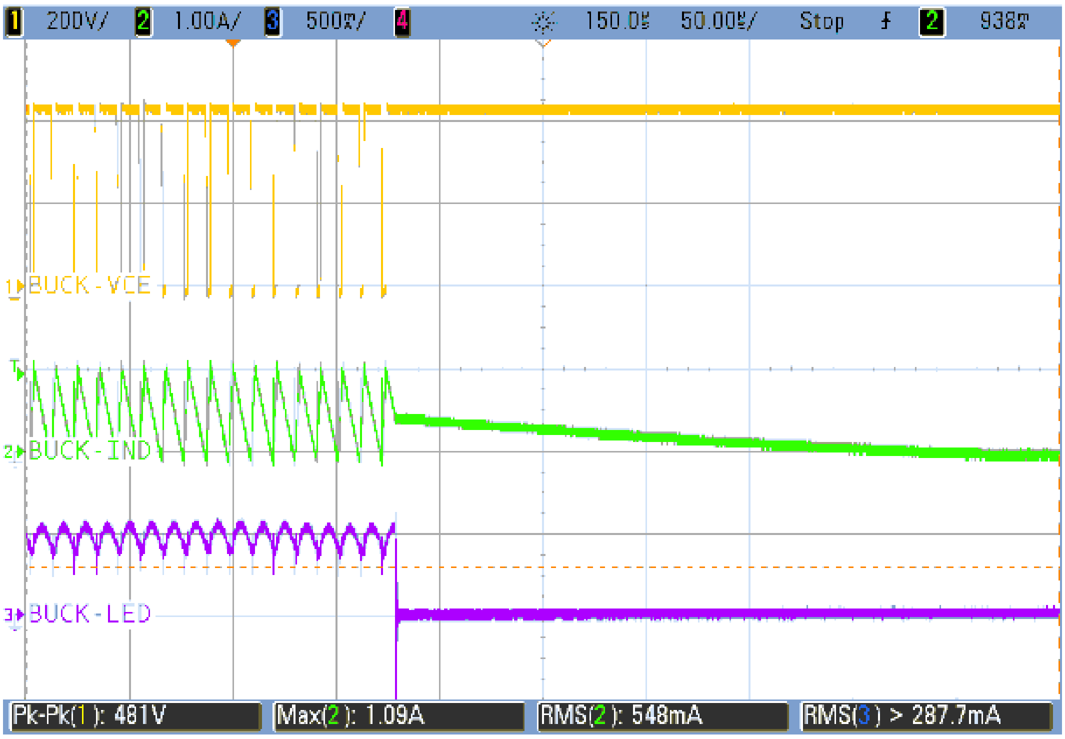


Figure 61. Buck short-circuit protection V_{CE} vs $I_{Inductor}$ vs I_{LED} - Zoom



9.2.2 Inverse buck converter

Figure 62. Inverse buck short-circuit protection V_{CE} vs $I_{Inductor}$ vs I_{LED}

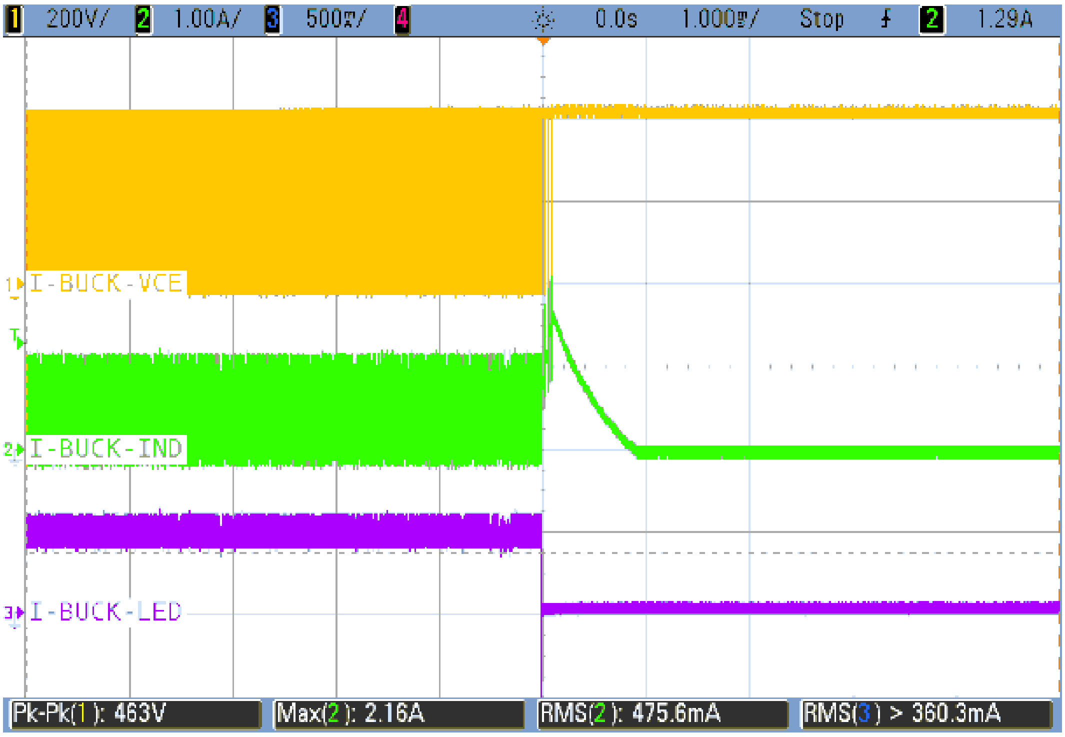
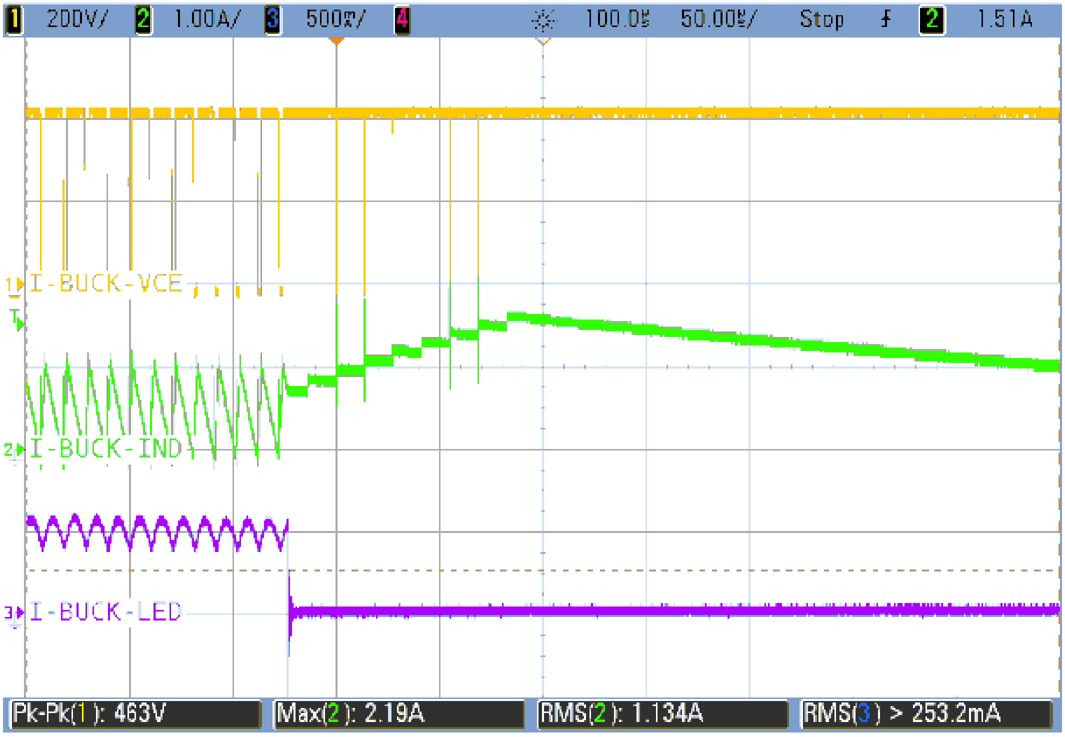


Figure 63. Inverse buck short-circuit protection V_{CE} vs $I_{Inductor}$ vs I_{LED} - Zoom



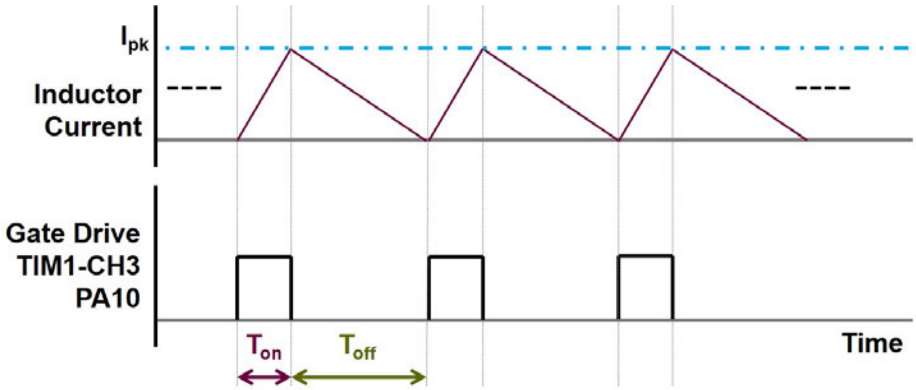
10 Inductor calculations

10.1 PFC inductor

Table 10. **PFC design parameters**

Parameter	Value/Range
Input Voltage Range	85 – 265 V_{AC}
Power Factor (PF) at Full Load (85V–265V)	> 0.96
Efficiency Target of STEVAL-LLL004V1	> 90%
PFC Output Voltage	450 ±2.5%
Min. PFC switching frequency (Transition Mode) Fsw	35 kHz
Maximum output power (Buck + Inverse-Buck)	75 W
ETD29 Core Area	71 mm²
△B	0.3

Figure 64. **PFC Switching in Transition Mode**



PFC – Maximum Input Power (P_{in}): $Pin = \frac{\text{Pout}}{\eta} = \frac{75\text{W}}{0.9} = 83.33\text{W}$ (1)

For subsequent calculations, the maximum input power is considered to be 90W.

PFC – Input RMS Current (I_{in}): $Iin = \frac{\text{Pin}}{\text{Vac(min)xPF}} = \frac{90}{85\text{x}0.96} = 1.103\text{A}$ (2)

PFC – Peak Inductor Current (I_{pk}): $Ipk = 2\text{x}\sqrt{2}\text{x}Iin = 2\text{x}\sqrt{2}\text{x}1.103 = 3.119A$ (3)

$$Ipk = 2\text{x}\sqrt{2}\text{x}1.103 = 3.119A$$

PFC – On Time (T_{on}): $Vin = \text{L}\int\frac{dI}{dt}$ (4)

$$Vin\text{x}Ton = \text{Lx}Ipk$$

Substituting

$$Vin = \sqrt{2}\text{x}Vac$$

$$Ton = \frac{L\text{x}Ipk}{\sqrt{2}\text{x}Vac}$$

PFC – Off Time (T_{off}): $(Vin - Vout) = \text{L}\int\frac{dI}{dt}$ (5)

$$(Vin - Vout)\text{x}Toff = \text{Lx}\int_{Ipk}^{0}dI$$

$$(Vin - Vout)\text{x}Toff = -\text{Lx}Ipk$$

Substituting

$$V_{in} = \sqrt{2}\text{x}Vac$$

$$Toff = \frac{LxIpk}{(Vout - \sqrt{2}xVac)}$$

$$\text{PFC – Inductance (L): } fsw = \frac{1}{Ton + Toff} = \frac{\sqrt{2}xVacx(Vout - \sqrt{2}xVac)}{LxIpkxVout} \quad (6)$$

$$fsw = \frac{\sqrt{2}xVacx(Vout - \sqrt{2}xVac)}{Lx2x\sqrt{2}xIinxVout}$$

Substituting from equation 2 and 3:

$$fsw = \frac{Vac^2xPFx\left(Vout - \sqrt{2}xVac\right)}{Lx2xPinxVout}$$

Rearranging:

$$L = \frac{Vac^2xPFx\left(Vout - \sqrt{2}xVac\right)}{2xfswxPinxVout}$$

Substituting the design parameters from Table 10:

$$L = \frac{85x85x0.96x(450 - \sqrt{2}x85)}{2x35000x90x450} = 806.85\mu H$$

The inductance used for the PFC converter is 760µH.

$$\text{PFC – Number of turns (N): } N > \frac{LxIpk}{\Delta BxAe} > \frac{760x10^{-6}x3.119}{0.3x71x10^{-6}} = 111turns \quad (7)$$

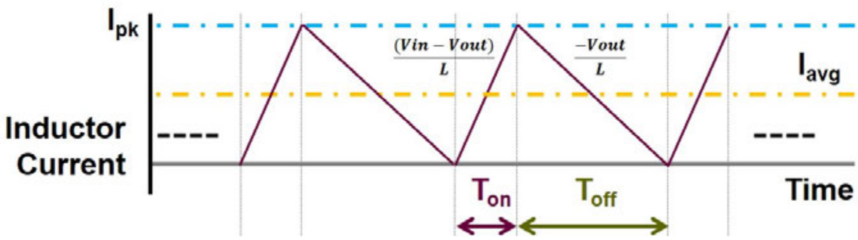
$$N > \frac{760x10^{-6}x3.119}{0.3x71x10^{-6}} = 111turns$$

10.2 Buck and inverse buck inductor

Table 11. Buck and inverse buck design parameters

Parameter	Value/Range
Input Voltage Range	450 ±2.5%
Output Voltage at Full load	75 V
Switching Frequency	~100 kHz
Maximum Output Current	500 mA
E20 Core Area	31.9 mm^2
ΔB	0.3

Figure 65. Buck and inverse buck switching in Transition Mode



The peak current of the buck and inverse-buck inductor can be calculated from the slope of the inductor current, knowing the switching period and duty cycle D of our converter:

$$\text{Buck and Inverse-Buck – Inductance (L): } \frac{(Vin - Vout)xTon}{L} = Ipk \quad (8)$$

Substituting:

$$Ton = D\mathrm{x}T$$

$$\frac{(Vin - Vout)\mathrm{xDxT}}{\mathrm{L}} = \mathrm{I}pk$$

$$\frac{(Vin - Vout)\mathrm{xD}}{\mathrm{Lx}f} = \mathrm{I}pk$$

Substituting:

$$\mathrm{D} = \frac{\mathrm{V}in}{\mathrm{V}out}$$

$$\frac{(Vin - Vout)\mathrm{xV}in}{\mathrm{LxV}out\mathrm{x}f} = \mathrm{I}pk$$

Rearranging the terms:

$$\frac{(Vin - Vout)\mathrm{xV}in}{\mathrm{I}pk\mathrm{xV}out\mathrm{x}f} = \mathrm{L}$$

In transition or critical conduction mode

$$\mathrm{I}pk = 2\mathrm{xI}out$$

$$\frac{(Vin - Vout)\mathrm{xV}in}{2\mathrm{xI}out\mathrm{xV}out\mathrm{x}f} = \mathrm{L}$$

Substituting the values:

$$\mathrm{L} = \frac{(450 - 75)\mathrm{x}75}{2\mathrm{x}0.5\mathrm{x}100000\mathrm{x}450} = 625\mu H$$

The inductance used for the buck and inverse buck converter used on the STEVAL-LLL004V1 is 560 μH.

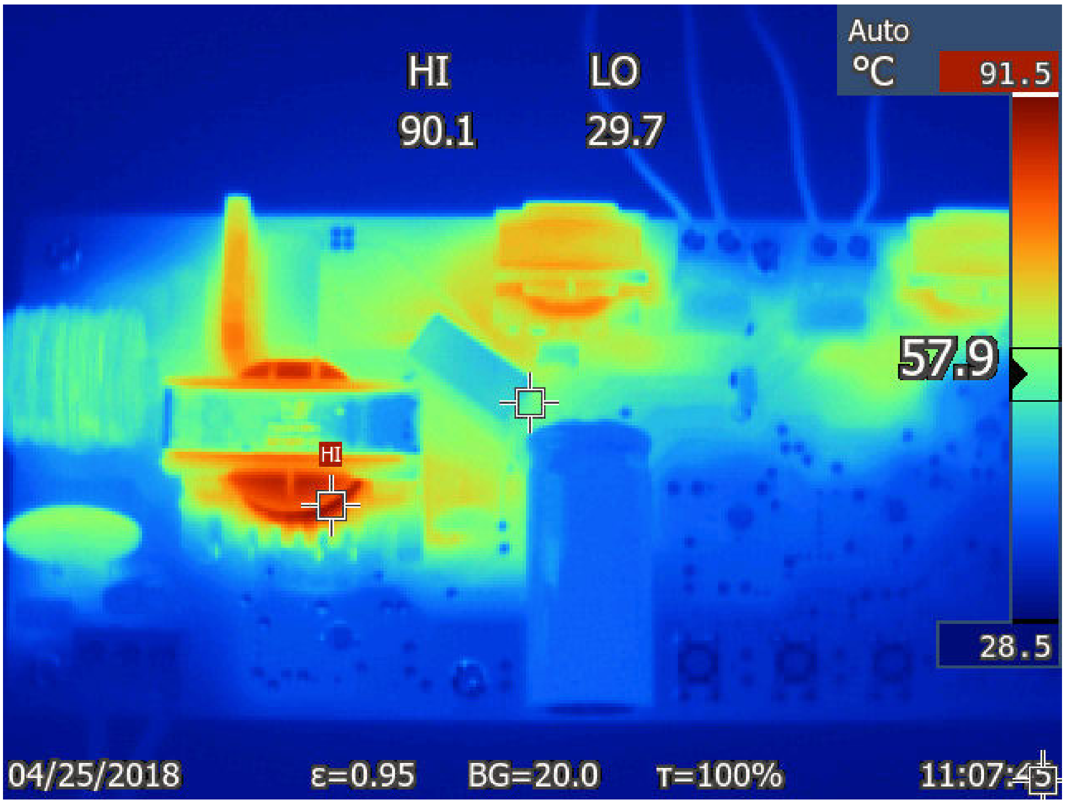
PFC – Number of turns (N): $\mathrm{N} > \frac{\mathrm{LxI}pk}{\Delta\ B\mathrm{xA}e}$ (9)

$$\mathrm{N} > \frac{560\mathrm{x}10^{-6}\mathrm{x}1}{0.3\mathrm{x}31.9\mathrm{x}10^{-6}} = 59\mathrm{turns}$$

11 Thermal measurements

Thermal analysis of the board was performed using an IR camera at 110 V_{AC} and 230 V_{AC} mains input, under full load conditions at 30 °C ambient temperature.

Figure 66. STEVAL-LLL004V1 top side thermal measurement at 110 V_{AC}



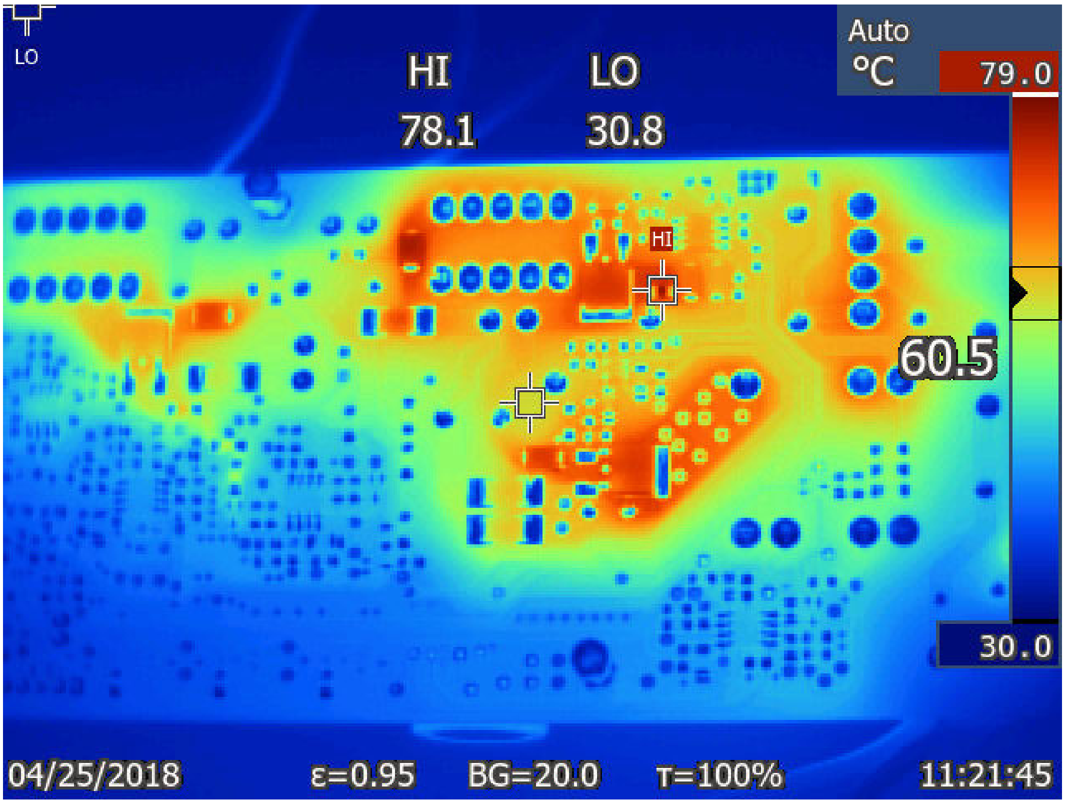


Figure 67. STEVAL-LLL004V1 bottom side thermal measurement at 110 V_{AC}

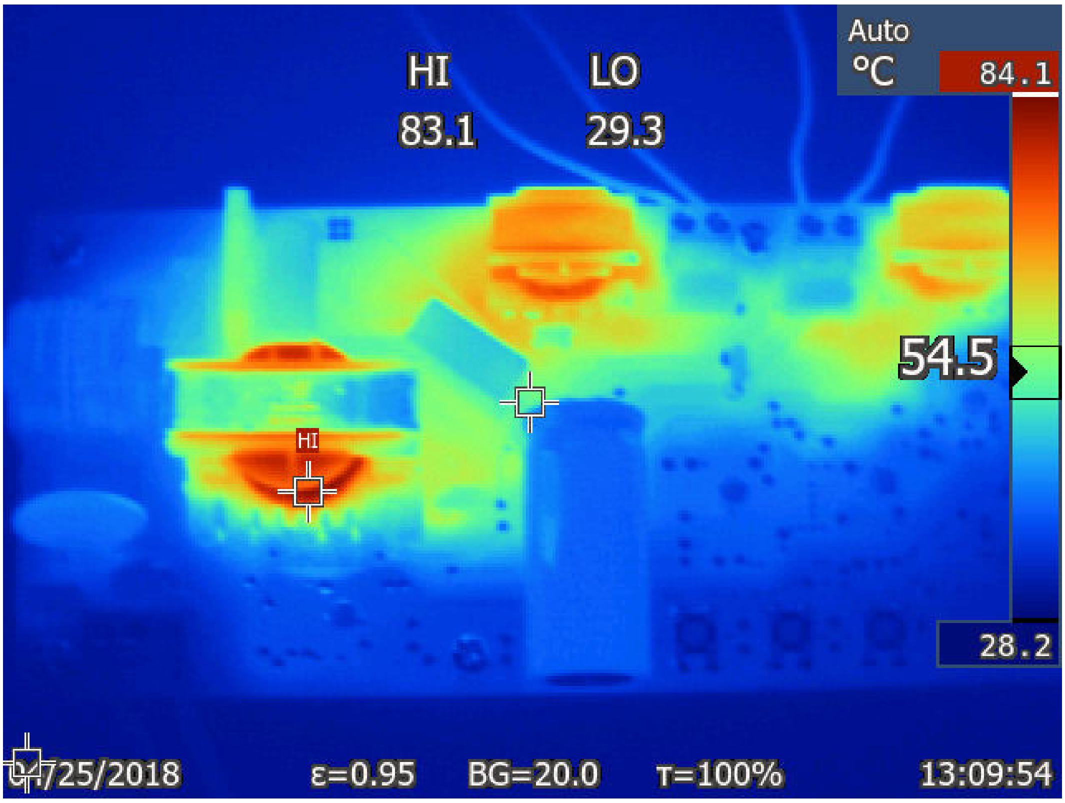
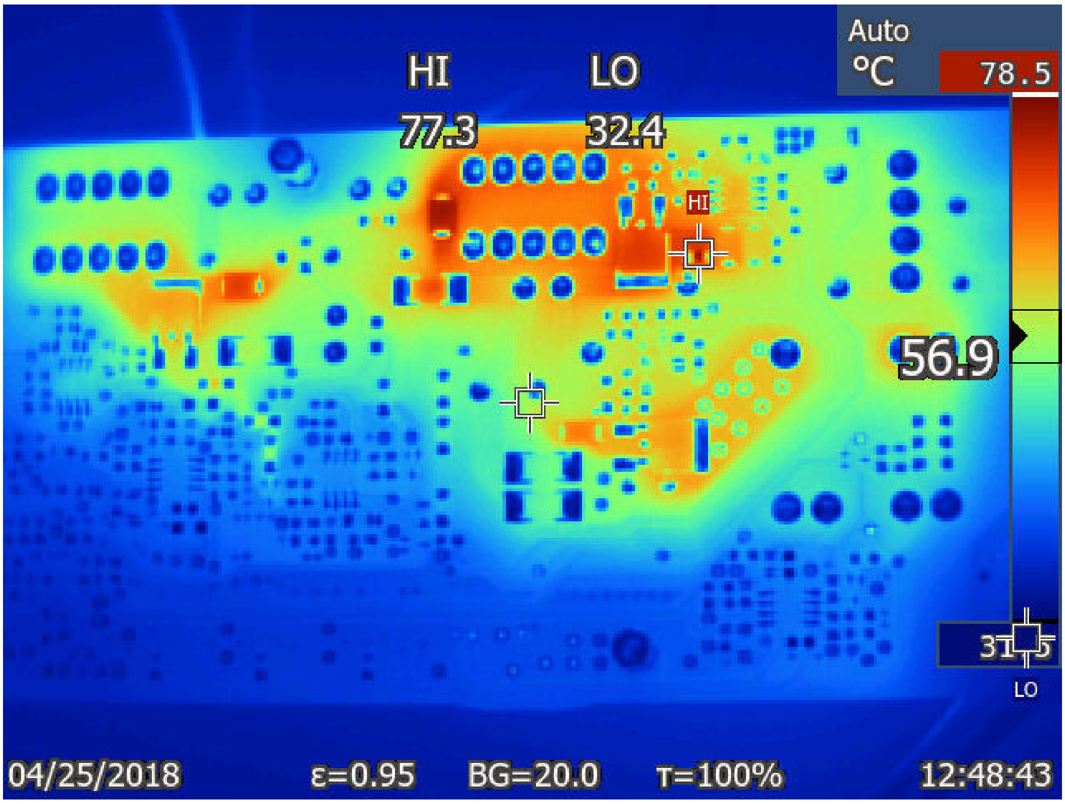


Figure 68. STEVAL-LLL004V1 top side thermal measurement at 230 V_{AC}

Figure 69. STEVAL-LLL004V1 bottom side thermal measurement at 230 V_{AC}



12 EMI Measurements

A pre-compliance test against the EN55022 (Class B) European normative with average detector was performed using an EMC analyzer and a LISN. Average measurements at full load, T.AMB = 25 °C".

Figure 70. **Average measurements at 115 V_{AC}, full load, T_{AMB} = 25°C**

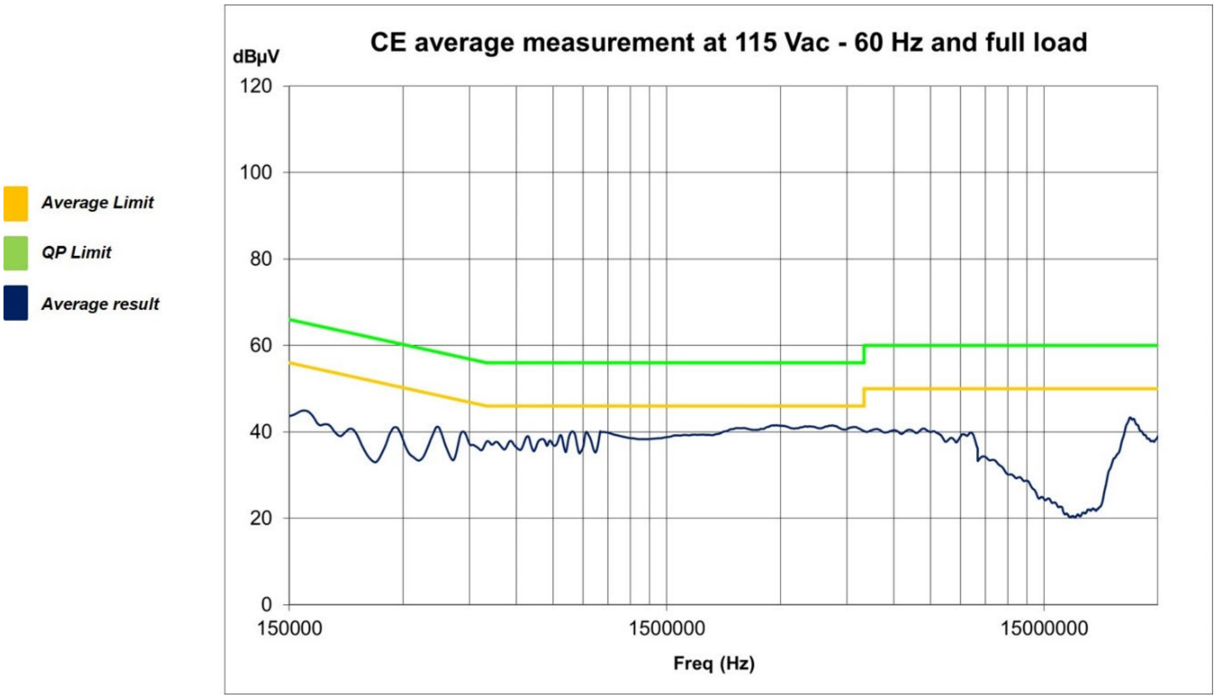
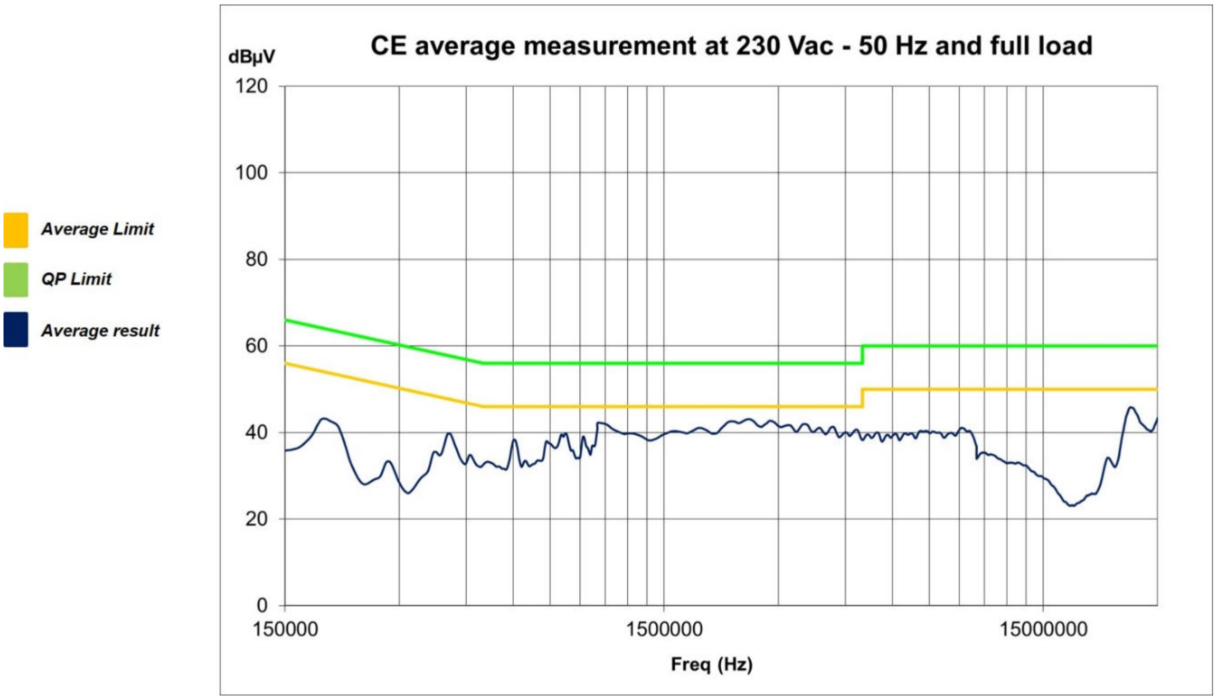


Figure 71. **Average measurements at 230 V_{AC}, full load, T_{AMB} = 25°C**



13 STEVAL-LLL004V1 layout

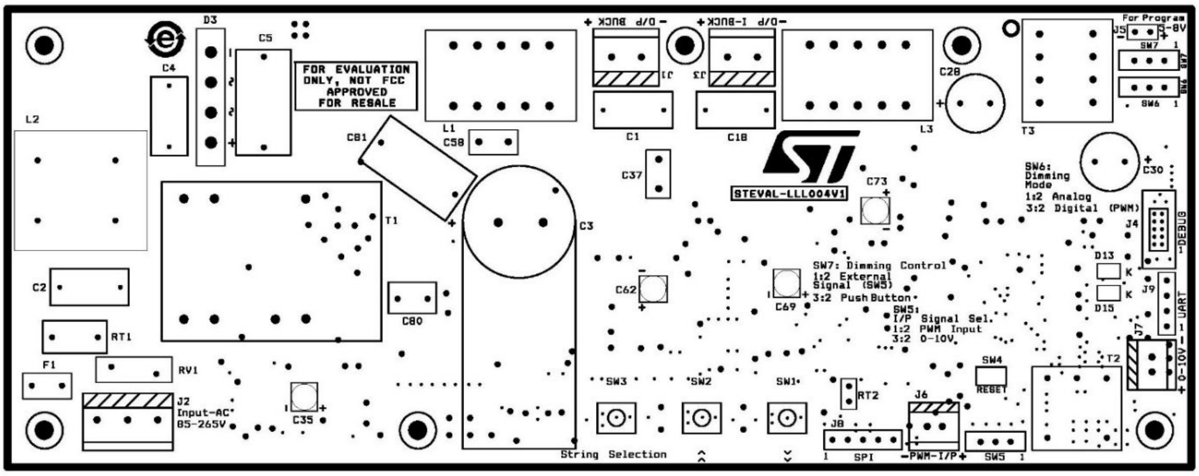


Figure 72. STEVAL-LLL004V1 layout top layer silk screen and drill

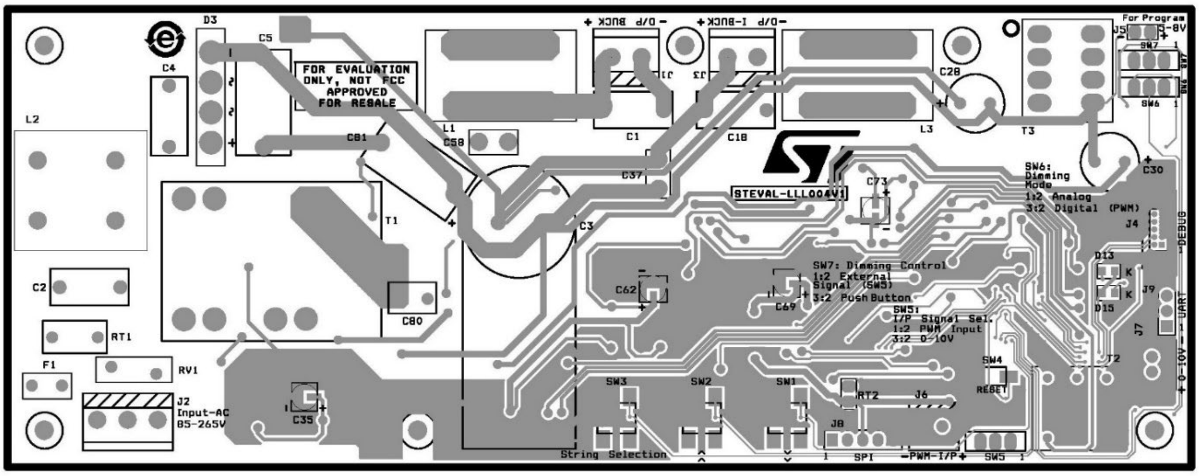


Figure 73. STEVAL-LLL004V1 layout top layer

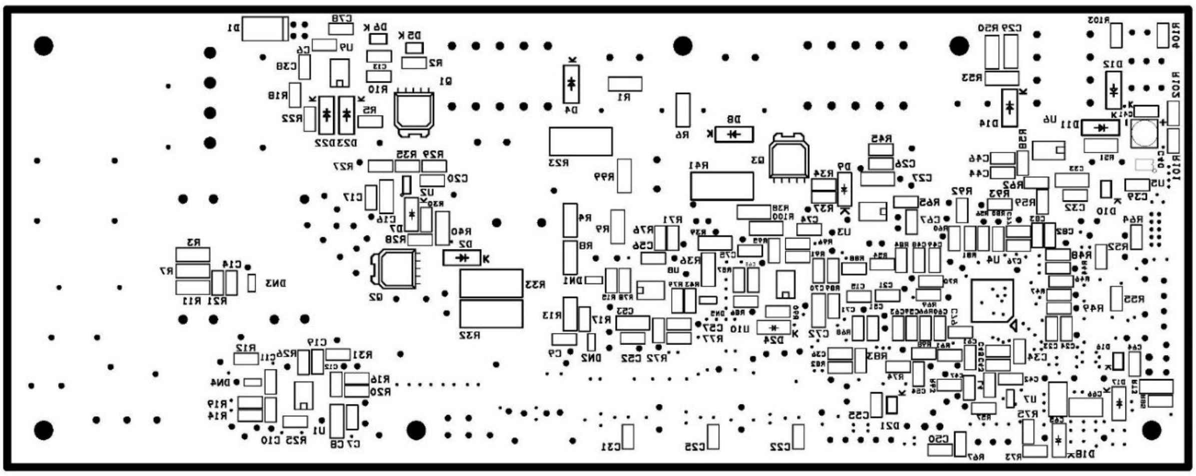
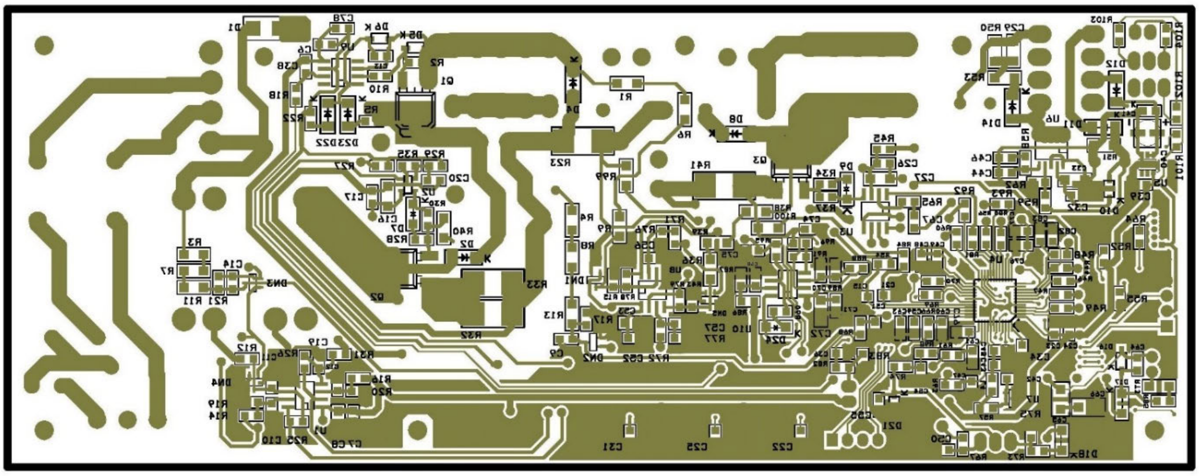


Figure 74. STEVAL-LLL004V1 layout bottom layer silk screen and drill

Figure 75. STEVAL-LLL004V1 layout bottom layer



14 STEVAL-LLL004V1 schematic diagrams

Figure 76. STEVAL-LLL004V1 schematic - PFC converter

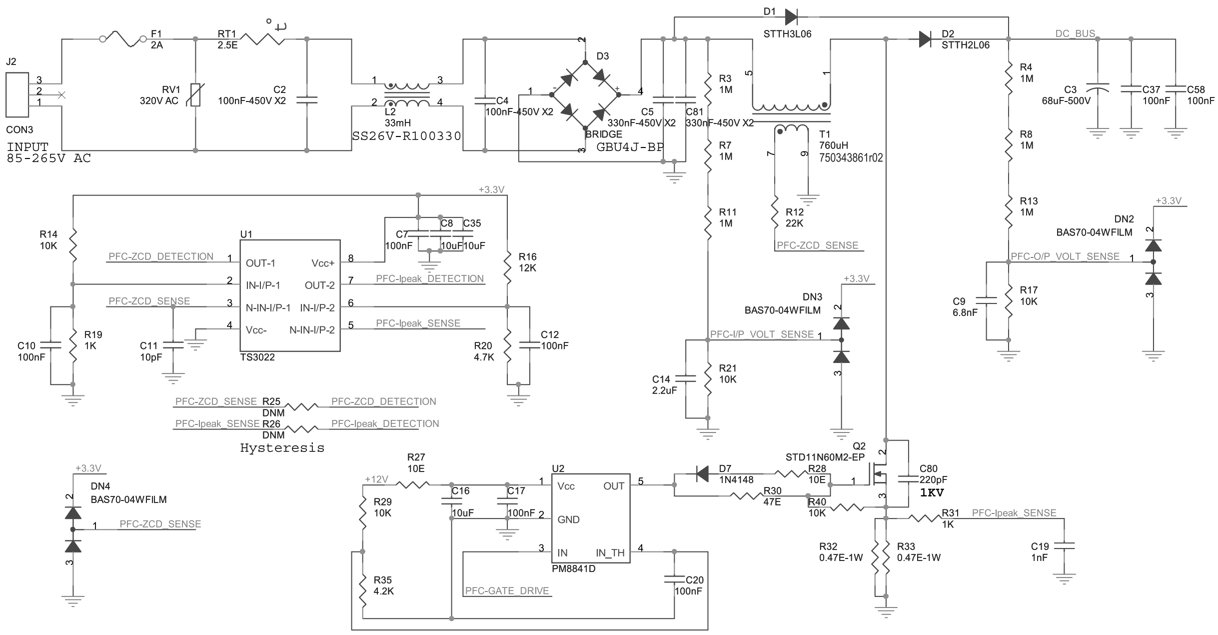


Figure 77. STEVAL-LLL004V1 schematic - inverse buck converter

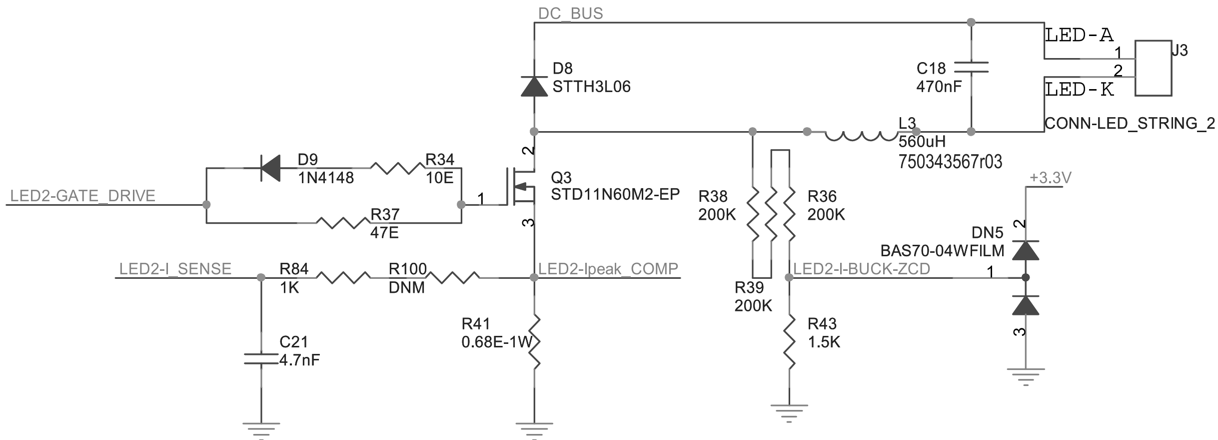


Figure 78. **STEVAL-LLL004V1 schematic - buck converter**

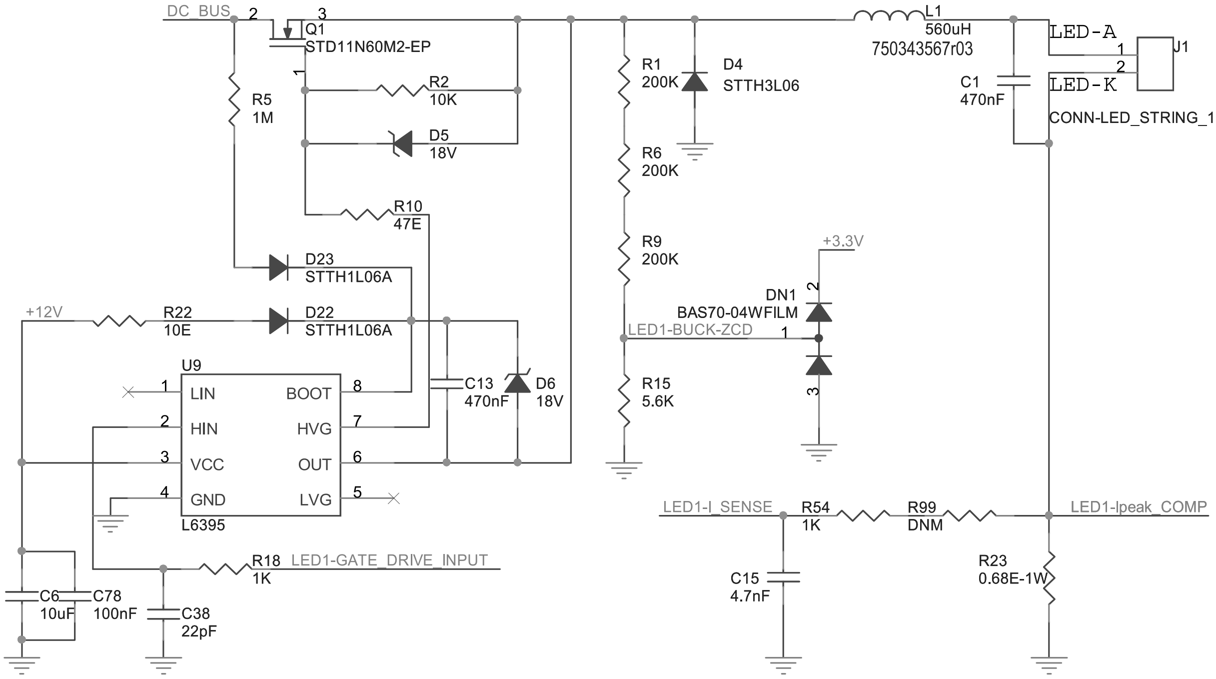


Figure 79. **STEVAL-LLL004V1 schematic - auxiliary power supply**

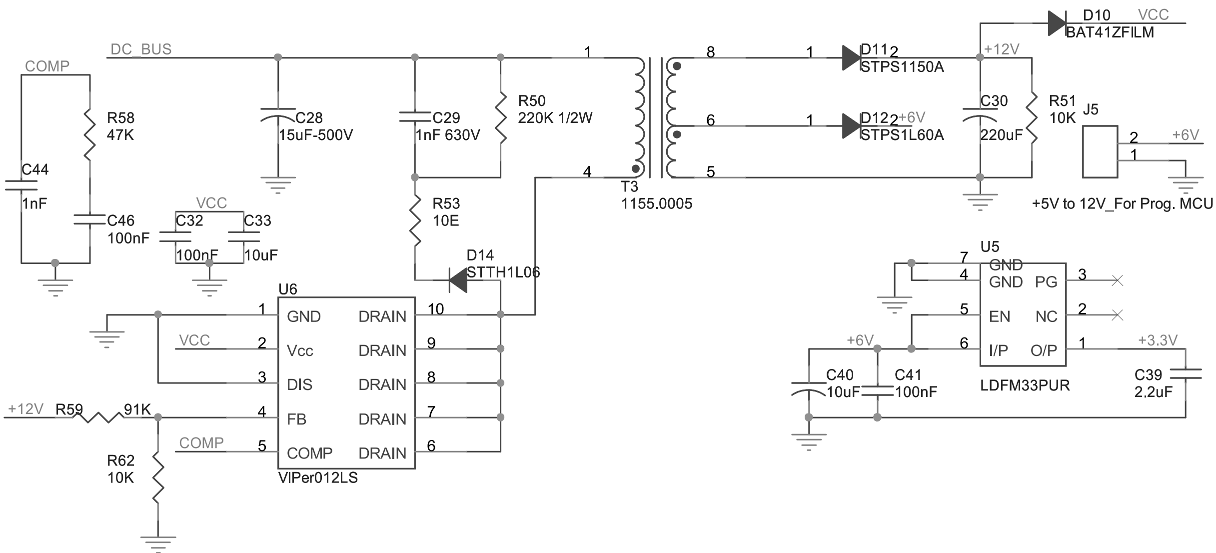


Figure 80. STEVAL-LLL004V1 schematic - STM32 microcontroller

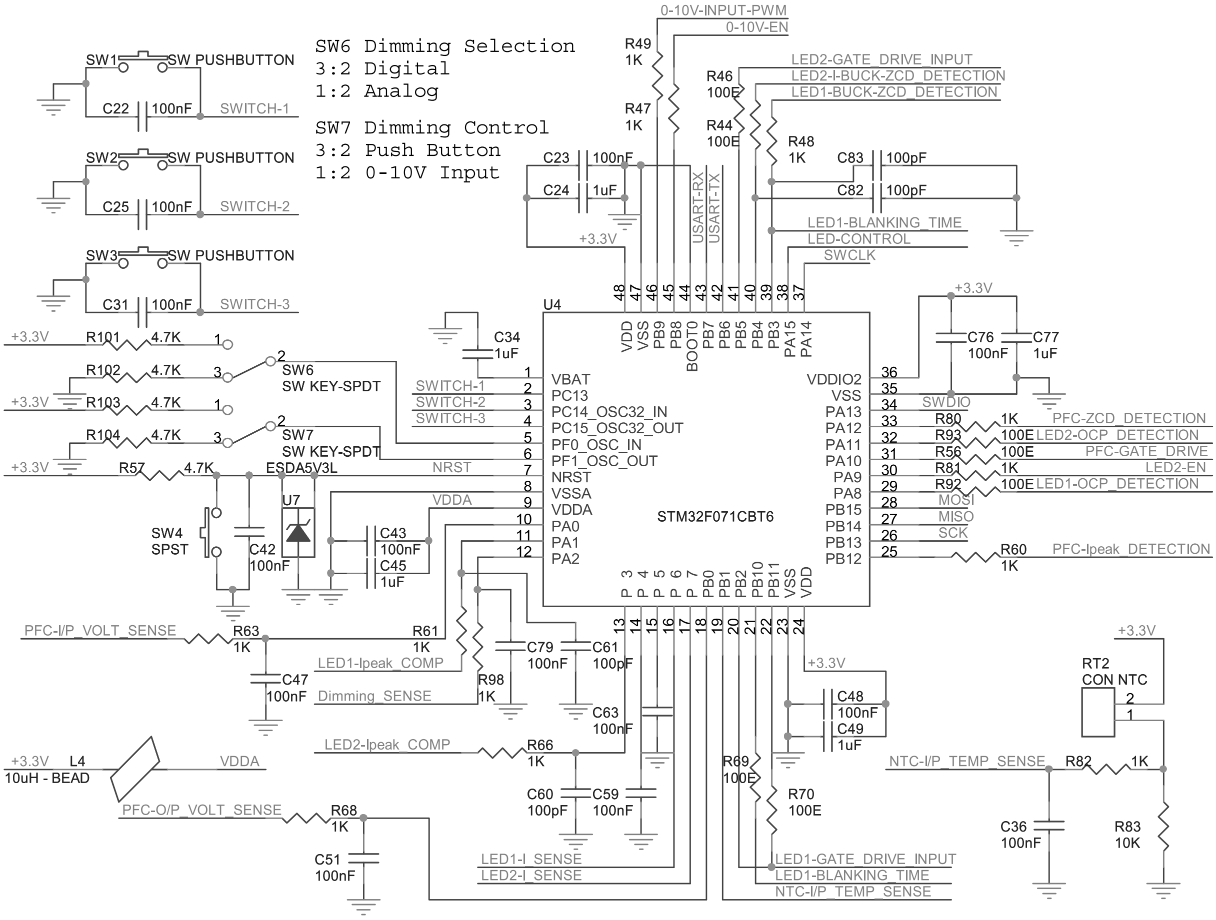
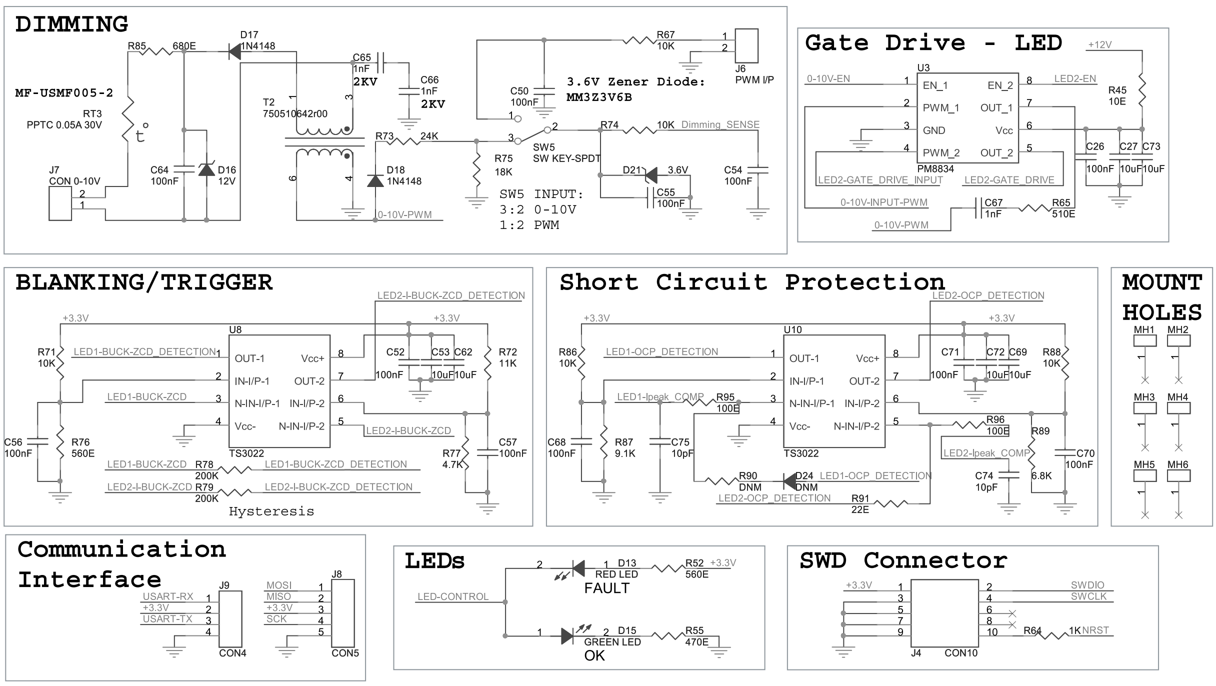


Figure 81. STEVAL-LLL004V1 schematic - miscellaneous



15 Bill of materials

Table 12. **STEVAL-LLL004V1 bill of materials**

Item	Q.ty	Ref.	Part / Value	Description	Manufacturer	Order code
1	3	U1, U8, U10		Rail-To-Rail 1.8 V High-Speed Dual Comparator	ST	TS3022IDT
2	1	U2	1A	1 A Low-Side Gate Driver	ST	PM8841D
3	1	U3	4A	4 A Dual Low-Side MOSFET Driver	ST	PM8834TR
4	1	U4		ARM®-based 32-bit MCU	ST	STM32F071CBT6
5	1	U5	3.3V	500 mA very Low Drop Voltage Regulator	ST	LDFM33PUR
6	1	U6	240mA	Energy Saving Off-Line High Voltage Converter	ST	VIPer012LS(TR)
7	1	U7		Dual Transil™ Array For ESD Protection	ST	ESDA5V3L
8	1	U9		High Voltage High And Low-Side Driver	ST	L6395D
9	3	Q1, Q2, Q3	600V	N-channel Power MOSFET In A DPAK Package	ST	STD11N60M2-EP
10	3	D14, D22, D23		Turbo 2 Ultrafast High Voltage Rectifier	ST	STTH1L06A
11	1	D10		Low Capacitance Small Signal Schottky Diodes	ST	BAT41ZFILM
12	1	D11	150V	Power Schottky Rectifier	ST	STPS1150A
13	1	D12	60V	Power Schottky Rectifier	ST	STPS1L60A
14	5	DN1, DN2, DN3, DN4, DN5		Low Capacitance, Low Series Inductance And Resistance Schottky Diodes	ST	BAS70-04FILM
15	3	D1, D4, D8		Turbo 2 Ultrafast High Voltage Rectifier	ST	STTH3L06U
16	1	D2		High Efficiency Ultrafast Diode	ST	STTH2L06A
17	2	C1, C18	470nF, 450VDC, ±10%	Film Capacitors	PANASONIC ELECTRONIC COMPONENTS	ECW-FD2W474Q1
18	2	C2, C4	100nF, 305 VAC, ±20%	Film Capacitors 10mm L/S Class X2	EPCOS / TDK	B32921C3104M

Item	Q.ty	Ref.	Part / Value	Description	Manufacturer	Order code
19	1	C3	68µF, 500V, ±20%	Aluminum Electrolytic Capacitors	NICHICON	UCY2H680MHD
20	2	C5, C81	330nF, 305VAC, ±20%	Film Capacitors	EPCOS (TDK)	B32922C3334M000
21	6	C8, C16, C27, C33, C53, C72	10µF, 50V, ±20%	Multilayer Ceramic Capacitors	ANY	ANY
22	1	C6	10µF, 35V, ±20%	Ceramic Capacitors	ANY	ANY
23	5	C35, C40, C62, C69, C73	10µF, 35V, ±20%	Aluminum Electrolytic Capacitors	PANASONIC	EEE-FK1V100UR
24	34	C7, C10, C12, C17, C20, C22, C23, C25, C26, C31, C32, C36, C41, C42, C43, C46, C47, C48, C50, C51, C52, C54, C55, C56, C57, C59, C63, C64, C68, C70, C71, C76, C78, C79	100nF, 50V, ±10%	Ceramic Capacitors	ANY	ANY
25	2	C37, C58	100nF, 630V, ±10%	Multilayer Ceramic Capacitors MLCC - Leaded	MURATA ELECTRONICS	RDER72J104K4K1H03B
26	1	C9	6.8nF, 25V, ±10%	Ceramic Capacitors	ANY	ANY
27	3	C11, C74, C75	10pF, 25V, ±10%	Ceramic Capacitors	ANY	ANY
28	1	C13	470nF, 50V, ±10%	Ceramic Capacitors	ANY	ANY
29	2	C14, C39	2.2µF, 25V, ±10%	Ceramic Capacitors	ANY	ANY
30	2	C15 ,C21	4.7nF, 16V, ±10%	Ceramic Capacitors	ANY	ANY
31	3	C19, C44, C67	1nF, 25V, ±10%	Ceramic Capacitors	ANY	ANY
32	2	C65, C66	1nF, 2KV, ±5%	Ceramic Capacitors	AVX Corporation	1210GC102KAT1A
33	5	C24, C34, C45, C49, C77	1µF, 16V, ±10%	Ceramic Capacitors	ANY	ANY
34	1	C28	15µF, 500V, ±20%	Aluminum Electrolytic Capacitors	NICHICON	UCY2H150MHD
35	1	C29	1nF, 630V, ±5%	Ceramic Capacitors	TDK CORPORATION	C3216C0G2J102J085AA
36	1	C30	220µF, 63V, ±20%	Aluminum Electrolytic Capacitors	Nichicon	UPW1J221MPD
37	1	C38	22pF, 16V, ±10%	Ceramic Capacitors	ANY	ANY
38	4	C60, C61, C82, C83	100pF, 16V, ±10%	Ceramic Capacitors	ANY	ANY

Item	Q.ty	Ref.	Part / Value	Description	Manufacturer	Order code
39	1	C80	220pF, 2KV, ±5%	Film Capacitors	MURATA ELECTRONICS	DEA1X3D221JA2B
40	1	D3	4A/600V	Bridge Rectifiers	MICRO COMMERCIAL COMPONENTS (MCC)	GBU4J-BP
41	2	D5, D6	18V, 500mW, ±5%	Diodes - Zener - Single	ON SEMICONDUCTOR	MMSZ5248BT1G
42	4	D7, D9, D17, D18	1N4148, 75V	Switching Diode	Nexperia USA Inc.	PMLL4148L,115
43	1	D13	1.8V/20mA	LED Red Diffused	OSRAM OPTO SEMICONDUCTORS INC.	LH R974-LP-1
44	1	D15	2.2V/20mA	LED Green Diffused	OSRAM OPTO SEMICONDUCTORS INC.	LG R971-KN-1
45	1	D16	12V, 1/2 W, ±5%	Zener Diodes	VISHAY SEMICONDUCTORS	MMSZ4699-E3-18
46	1	D21	3.6V, 500 mW, ±5%	Zener Diode	ON SEMICONDUCTOR	MMSZ4685T1G
47	1	D24	Do not mount			
48	1	F1	2A, 2A/300V	Fuses with Leads	LITTLEFUSE	36912000000
49	2	J1, J3	10A/300V	Connector - LED Output: Fixed Terminal Blocks 2P 5.08mm	PHOENIX CONTACT	651-1888687
50	1	J2	20A/300V	Connector - AC Input: Conn Term Block 3Pos 5.08mm	PHOENIX CONTACT	1888690
51	1	J4		Header 5X2: Box Header,0.050 10 POS	CNC Tech	3220-10-0100-00
52	1	J5		Header 2x1: 2.54 mm Pitch Berg Stick Male	ANY	ANY
53	1	J6	PWM Input	Terminal Blocks 2Pos 2.54mm	ANY	ANY
54	1	J7	0-10V Input	Terminal Blocks 2Pos 2.54mm	ANY	ANY
55	1	J8	Do not mount	Header 5x1: 2.54 mm Pitch Berg Stick Male		
56	1	J9	Do not mount	Header 4x1: 2.54 mm Pitch Berg Stick Female		

Item	Q.ty	Ref.	Part / Value	Description	Manufacturer	Order code
57	2	L1, L3	560μH	Inductor	WURTH ELECTRONICS	750343567r03
58	1	L2	33mH, 1A	Common Mode Choke	KEMET	SS26V-R100330
59	1	L4	10μH - BEAD, 150mA, ±10%	Fixed Inductor	TAIYO YUDEN	LBR2012T100K
60	6	MH1, MH2, MH3, MH4, MH5, MH6		Mounting Holes Diameter=3.5mm: Screws and Nuts	ANY	ANY
61	1	RT1	2.5E, 230 V AC	Inrush Current Limiters	EPCOS / TDK	B57364S259M54
62	1	RT2	Do not mount	Header 2x1: 2.54 mm Pitch Berg Stick Male		
63	5	R25, R26, R90, R99, R100	Do not mount	Thick Film Resistors		
64	12	R2, R14, R17, R21, R29, R62, R67, R71, R74, R83, R86, R88	10K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
65	2	R40, R51	10K, 1/4 W, ±1%	Thick Film Resistors	ANY	ANY
66	1	RT3	30V/0.12A	Fuse	BOURNS INC.	MF-NSMF012-2
67	1	RV1	DISC 10mm, 320V AC	Varistor	ANY	ANY
68	6	R1, R6, R9, R36, R38, R39	200K, 1/4 W, ±1%	Thick Film Resistors	ANY	ANY
69	2	R78, R79	200K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
70	1	R5	1M, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
71	6	R3, R4, R7, R8, R11, R13	1M, 1/4 W, ±1%	Thick Film Resistors	ANY	ANY
72	3	R10, R30, R37	47E, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
73	1	R12	22K, 1/8W, ±5%	Thick Film Resistors	ANY	ANY
74	1	R15	5.6K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
75	1	R16	12K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
76	18	R18, R19, R31, R47, R48, R49, R54, R60, R61, R63, R64, R66, R68, R80, R81, R82, R84, R98	1K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
77	7	R20, R57, R77, R101, R102, R103, R104	4.7K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
78	5	R22, R27, R28, R34, R45	10E, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
79	1	R53	10E, 1/2W, ±1%	Thick Film Resistors	STACKPOLE ELECTRONICs INC.	RNCP1206FTD10R0

Item	Q.ty	Ref.	Part / Value	Description	Manufacturer	Order code
80	2	R23, R41	0.68E, 1W, ±1%	Thick Film Resistors	PANASONIC ELECTRONIC COMPONENTS	ERJ-1TRQFR68U
81	2	R32, R33	0.47E, 1W, ±1%	Thick Film Resistors	PANASONIC ELECTRONIC COMPONENTS	ERJ-1TRQFR47U
82	1	R35	4.2K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
83	1	R43	1.5K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
84	9	R44, R46, R56, R69, R70, R92, R93, R95, R96	100E, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
85	1	R50	220K, 1/4W, ±1%	Thick Film Resistors	PANASONIC INDUSTRIAL DEVICES	ERJ-8ENF2203V
86	2	R52, R76	560E, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
87	1	R55	470E, 1/8W, ±5%	Thick Film Resistors	ANY	ANY
88	1	R58	47K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
89	1	R59	91K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
90	1	R65	510E, 1/8W, ±5%	Thick Film Resistors	ANY	ANY
91	1	R72	11K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
92	1	R73	24K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
93	1	R75	18K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
94	1	R85	680E, 1/8W, ±5%	Thick Film Resistors	ANY	ANY
95	1	R87	9.1K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
96	1	R89	6.8K, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
97	1	R91	22E, 1/8W, ±1%	Thick Film Resistors	ANY	ANY
98	3	SW1, SW2, SW3	0.05A/24VDC	SW PUSHBUTTON: Switch Tactile SPST	TE Connectivity ALCOSWITCH SWITCHES	FSM4JSMATR
99	1	SW4	0.05A/12VDC	SPST: Tactile Switches	WURTH ELECTRONICS	732-7047-1-ND
100	3	SW5, SW6, SW7	12 VDC	SW KEY-SPDT: Slide Switches	EAO	09.03290.01
101	1	T1	760µH	PFC Transformer	WURTH ELECTRONICS	750343861r02
102	1	T2	0-10V	Isolation Transformer	WURTH ELECTRONICS	750510642r00
103	1	T3	2.5mH	Flyback Transformer	AQ Magnetica Italy	1155.0005

16 References

The following reference documents are freely available on www.st.com.

1. AN2928 – Modified buck converter for LED applications
2. AN3009 – How to design a transition mode PFC pre-regulator using the L6564
3. AN4776 – General-purpose timer cookbook

Revision history

Table 13. **Document revision history**

Date	Version	Changes
28-Nov-2018	1	Initial release.

Contents

List of figures

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