33 W ultra-wide (three-phase) input-range, off-line isolated power supply using ICE5QR2270AZ and IPD80R2K4P7

EVAL_5QR2270AZ_33W1

About this document

Scope and purpose

This document is an engineering report that describes a 33 W, 24 V ultra-wide (three-phase) input-range off-line flyback converter using the fifth-generation Infineon QR CoolSET™ (ICE5QR2270AZ) and a HV CoolMOS™ P7 series (IPD80R2K4P7). This offers high-efficiency, low-standby power with selectable entry and exit standby power option, wider V_{CC} operating range with fast start-up, robust line protection with input Over Voltage Protection (OVP) and brown-out and various protection modes for a highly reliable system.

Intended audience

This document is intended for power supply design or application engineers, etc. who wish to design low-cost, highly reliable off-line SMPS systems for ultra-wide (three-phase) input ranges.

Table of contents

1 Abstract

This document describes a universal 33 W, 24 V ultra-wide input voltage range power supply module. It is typically used as housekeeping power supply in professional SMPS. Typically driven from the bulk capacitor after any PFC stage or from the bulk after a three-phase rectifier, any DC input voltage from 190 V DC to 790 V DC may be applied to this board. The improved digital frequency reduction with proprietary QR operation offers lower EMI and higher efficiency for a wide AC range by reducing the switching frequency difference between low- and high-line. The enhanced Active Burst Mode (ABM) power enables flexibility in standby power operation range selection and QR operation during ABM. As a result, the system efficiency over the entire load range is significantly improved compared to a conventional free-running QR converter implemented with only maximum switching frequency limitation at light load. In addition, numerous adjustable protection functions have been implemented in ICE5QR2270AZ to protect the system and customize the IC for the chosen application. In case of failure modes, like brown-out or line OV, V_{CC} OV/Under Voltage (UV), open control-loop or over-load, output OV, over-temperature, V_{CC} short-to-ground and Current Sense (CS) short-to-ground, the device enters protection mode. By means of the cycle-by-cycle Peak Current Limitation (PCL), the dimensions of the transformer and current rating of the secondary diode can both be optimized. Thus, a cost-effective solution can easily be achieved.

2 Evaluation board

This document provides complete design details including specifications, schematics, Bill of Materials (BOM), and PCB layout and transformer design and construction information. This information includes performance results pertaining to line/load regulation, efficiency, transient load, thermal conditions, etc.

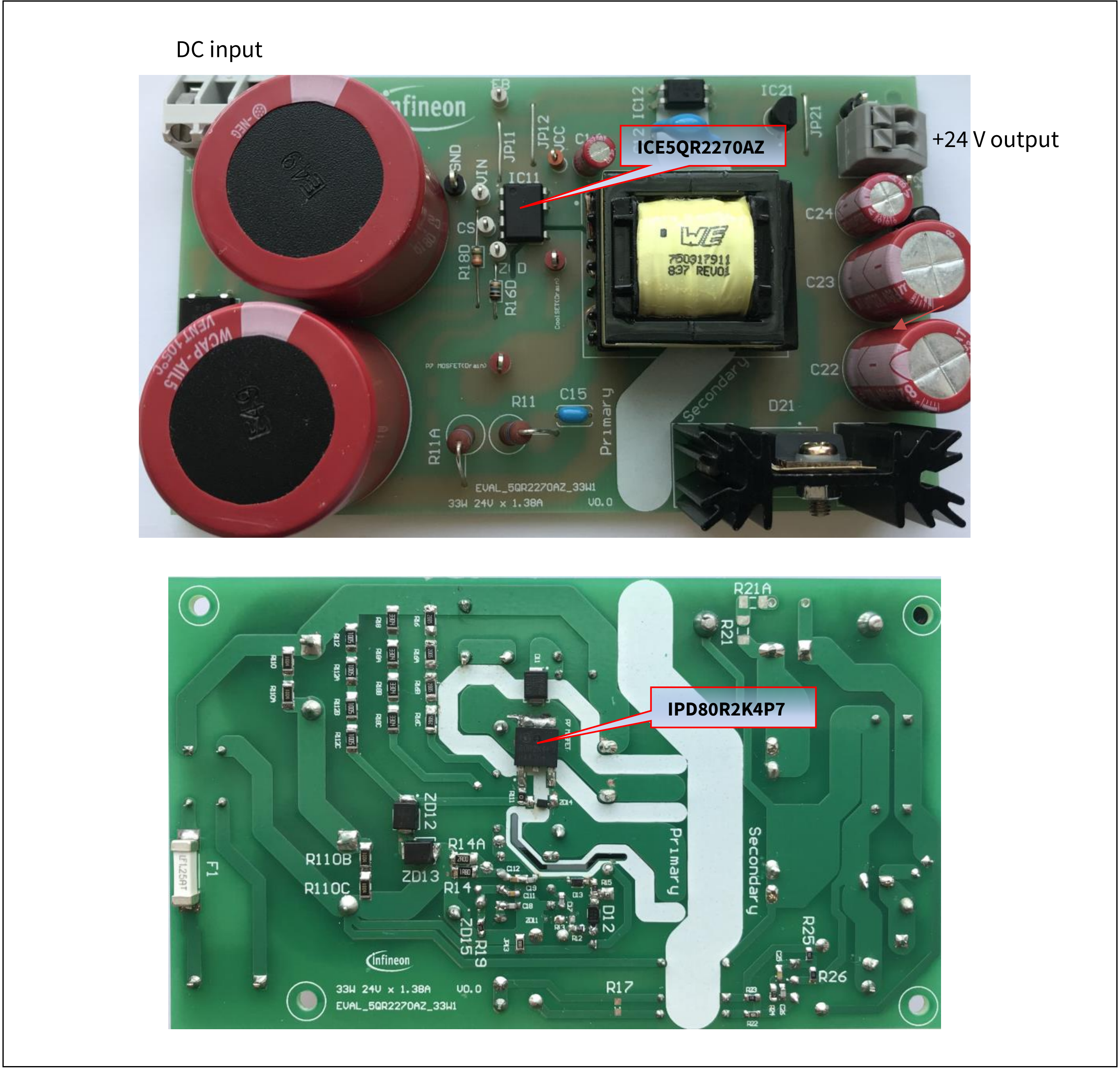


Figure 1 EVAL_5QR2270AZ_33W1

3 Power supply specifications

The table below represents the minimum acceptance performance of the design. Actual performance is listed in the measurements section.

Table 1 Specifications of EVAL_5QR2270AZ_33W1

Description	Symbol	Min.	Typ.	Max.	Units	Comments
Input						
Voltage	V_{IN}	170	–	792	V DC	
No-load input power	P_{stby_NL}	–	–	180	mW	565 V DC
Output						
Output voltage	V_{OUT}	–	24	–	V	±3 percent
Output current	I_{OUT}	0.07	0.69	1.38	A	
Output voltage ripple	V_{RIPPLE}	–	–	250	mV	20 MHz BW
Max. power output	P_{OUT_Max}	–	–	33	W	
Efficiency						
Max. load	η	–	87	–	%	325 V DC/565 V DC
Average efficiency at 25 percent, 50 percent, 75 percent and 100 percent of P_{OUT_Max}	η_{avg}	84	–	–	%	325 V DC/565 V DC
Ambient temperature	T_{amb}	0	–	50	°C	Free conviction, sea level
Form factor	–	70 × 120 × 38			mm^3	L × W × H

4 Circuit diagram

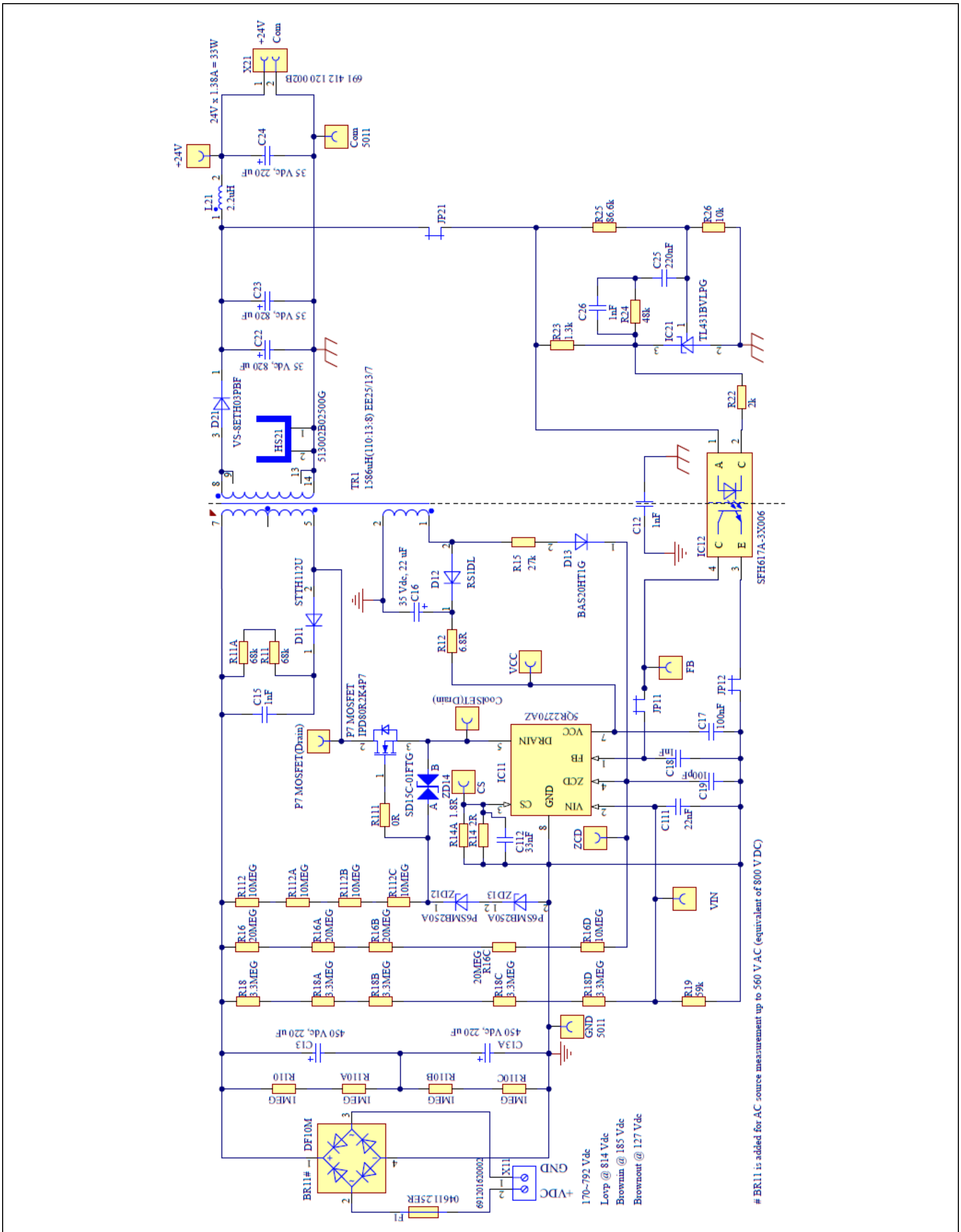


Figure 2 Schematic of EVAL_5QR2270AZ_33W1

5 Circuit description

The input of the SMPS module can be connected to any bulk (after rectification) from 135 V AC single phase up to 560 V AC multi-phase AC front end as well as to the bulk after any PFC stage. Due to the very high maximum input voltage of 800 V DC and the reflected output voltage of approximately 200 V the breakdown capability of the internal switch in the ICE5QR2270AZ is exceeded as well as in its HV version (ICE5QRxx80Ax). A series connection of an 800 V CoolMOS™ transistor with the internal CoolSET™ MOSFET forms a self-driven cascode which is able to handle a maximum drain voltage above 1 kV. The circuit around the CoolSET™ is very similar to the standard application and is therefore not described in this application note. Figure 2 shows the complete schematic of the module. Beside the standard CoolSET™ periphery only a few additional components are required to achieve the HV capability of the power switch.

5.1 Self-driven cascode

The function of the self-driven cascode essentially depends on the chosen Zener diode ZD12 and ZD13. The gate voltage of the P7 MOSFET (across R112 to R112C) tracks the input voltage until it is clamped by ZD12 and ZD13 to approximately 500 V. Due to the source follower circuitry of P7 MOSFET, the maximum drain voltage for IC11 is limited around the voltage across ZD12 and ZD13.

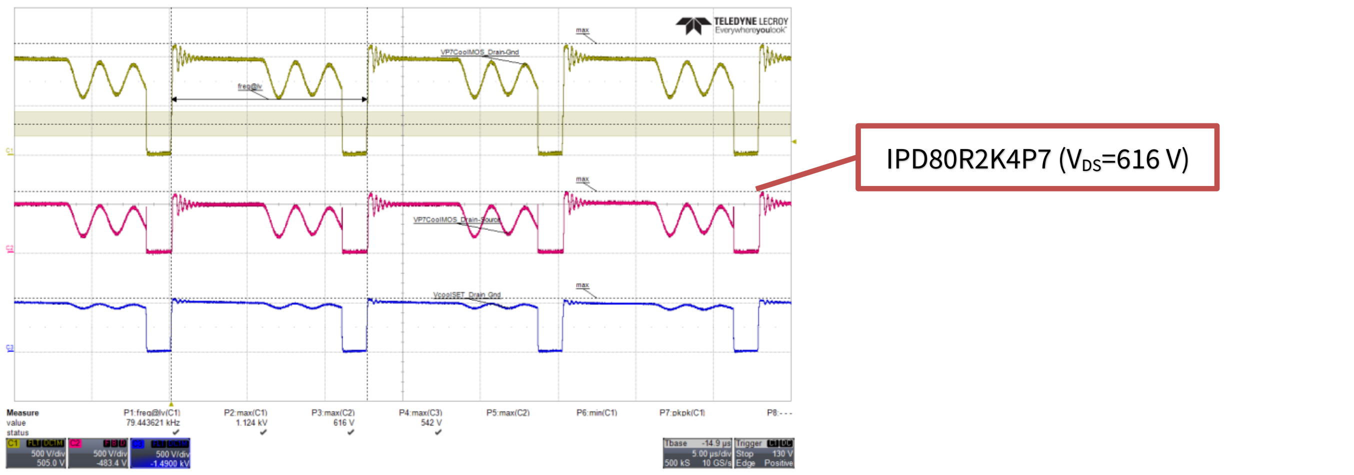
When C16 is charged up to the start voltage of IC11, the internal MOSFET (IC11) will switch on and forces the source of the external MOSFET (P7 MOSFET) close to GND. The charge in the junction of the HV Zener is transferred across R111 to the gate of the P7 MOSFET. ZD14 limits the maximum gate voltage of the P7 MOSFET to 15 V during the switch-on time and it also blocks unnecessary switch-on due to the HV oscillation of the P7 MOSFET during the switch-off time. In this way both MOSFETs switch on nearly simultaneously. The transformer's primary winding is now applied to the input voltage.

When the PWM controller of IC11 switches off, the internal MOSFET (IC11) disconnects the transformer's primary winding from the input. So the voltage across the opened CoolSET™ switch rises (driven by the stored inductive energy) until it is clamped by the source follower P7 MOSFET. Because the source of the P7 MOSFET was held down by IC11 before, the gate voltage of the P7 MOSFET was approximately 15 V. So the fast rising drain voltage of IC11 switches off the P7 MOSFET at nearly the same time (when the voltage is higher than around 12 V). The increasing voltage charges the junction of ZD12 and ZD13 across ZD14. From now the voltage follower P7 MOSFET starts working and stops further increase of the voltage across IC11. So any additional voltage increases across the P7 MOSFET until its maximum value.

5.2 Selection of the P7 MOSFET (P7 CoolMOS™)

As mentioned in section 5.1, the self-driven cascode P7 MOSFET and CoolSET™ are switching on and off nearly simultaneously. Otherwise, the self-driven cascode structure won't work smoothly and power losses at switches will be higher, resulting in poor efficiency and higher temperature. During the switch-off time, HV stress (input voltage + reflection voltage) shares the voltage between the P7 MOSFET and CoolSET™ depending on their output capacitance. The lower the output capacitance, the higher the voltage stress. So we should select a proper MOSFET that do not exceed the breakdown voltage of the MOSFET.

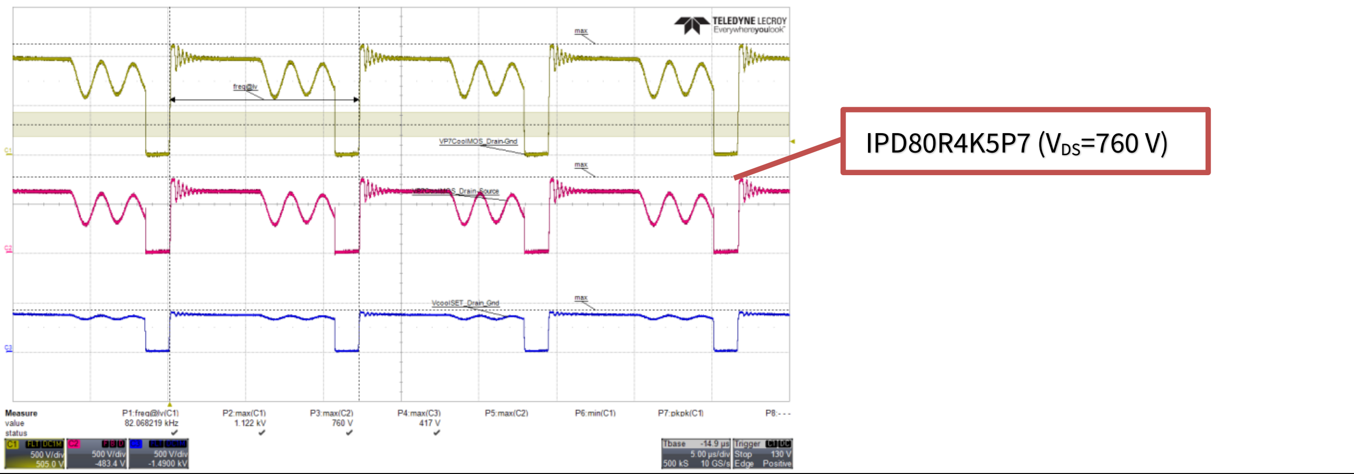
Start with the lowest output capacitance of the P7 MOSFET (IPD80R4K5P7), which shows the highest voltage stress of 760 V (see Figure 4), which is close to the drain-to-source breakdown voltage of the P7 MOSFET. Then select another P7 MOSFET (IPD80R2K4P7) with medium-range output capacitance, and the voltage stress reduces to 616 V (see Figure 3). With a further increase in output capacitance, IPD80R2K0P7 shows the lowest voltage stress of 610 V (see Figure 5). Based on the above three tests, IPD80R2K4P7 is selected to use in this evaluation board. Because it is sharing the suitable voltage stress with the CoolSET™, both switches have a higher than 20 percent margin on breakdown voltage.



V_{IN} = 560 V AC, max. load; $V_{P7Drain\_Source}$: 616 V DC and $V_{CoolSETDrain\_Gnd}$: 542 V DC

C1 (yellow): $V_{P7Drain\_Gnd}$; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$

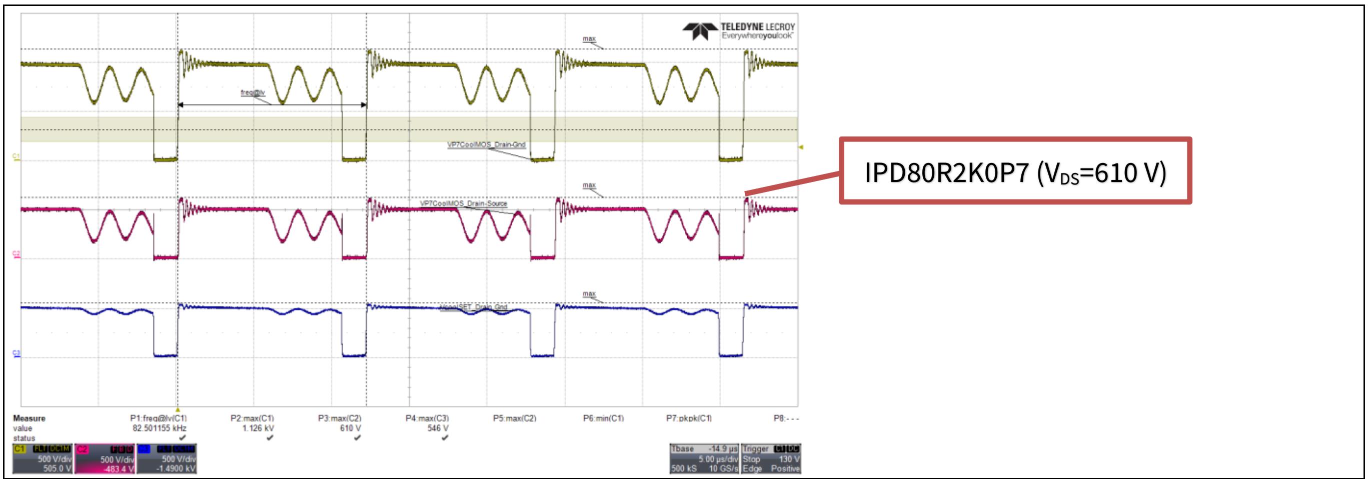
Figure 3 Maximum drain-to-source voltage of P7 CoolMOS™ (with IPD80R2K4P7)



V_{IN} = 560 V AC, max. load; $V_{P7Drain\_Source}$: 760 V DC and $V_{CoolSETDrain\_Gnd}$: 417 V DC

C1 (yellow): $V_{P7Drain\_Gnd}$; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$

Figure 4 Maximum drain-to-source voltage of P7 CoolMOS™ (with IPD80R4K5P7)



V_{IN} = 560 V AC, max. load; $V_{P7Drain\_Source}$: 627 V DC and $V_{CoolSETDrain\_Gnd}$: 541 V DC

C1 (yellow): $V_{P7Drain\_Gnd}$; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$

Figure 5 Maximum drain-to-source voltage of P7 CoolMOS™ (with IPD80R2K0P7)

5.3 System robustness and reliability through protection features

Protection is one of the major factors in determining whether the system is safe and robust. Therefore sufficient protection is necessary. ICE5QR2270AZ provides comprehensive protection to ensure the system is operating safely. The protections include line OV, brown-out, V_{CC} OV and UV, over-load, output OV, over-temperature (controller junction), CS short-to-GND and V_{CC} short-to-GND. When those faults are found, the system will go into the protection mode, until the fault is removed, when the system resumes normal operation. A list of protections and failure conditions are shown in the table below.

Table 2 Protection functions of ICE5QR2270AZ

Protection function	Failure condition	Protection mode
Line OV	V_{VIN} greater than 2.9 V	Non-switch auto-restart
Brown-out	V_{VIN} less than 0.4 V	Non-switch auto-restart
V_{CC} OV	V_{VCC} greater than 25.5 V	Odd-skip auto-restart
V_{CC} UV	V_{VCC} less than 10 V	Auto-restart
Over-load	V_{FB} greater than 2.75 V and lasts for 30 ms	Odd-skip auto-restart
Output OV	V_{ZCD} greater than 2 V and lasts for 10 consecutive pulses	Odd-skip auto-restart
Over-temperature (junction temperature of controller chip only)	T_J greater than 140°C with 40°C hysteresis to reset	Non-switch auto-restart
CS short-to-GND	V_{CS} less than 0.1 V, lasts for 5 µs and three consecutive pulses	Odd-skip auto-restart
V_{CC} short-to-GND (V_{VCC} = 0 V, $R_{StartUp}$ = 50 MΩ and V_{DRAIN} = 90 V)	V_{VCC} less than 1.1 V, $I_{VCC\_Charge1}$ ≈ -0.2 A	Cannot start up

6 PCB layout

6.1 Top side

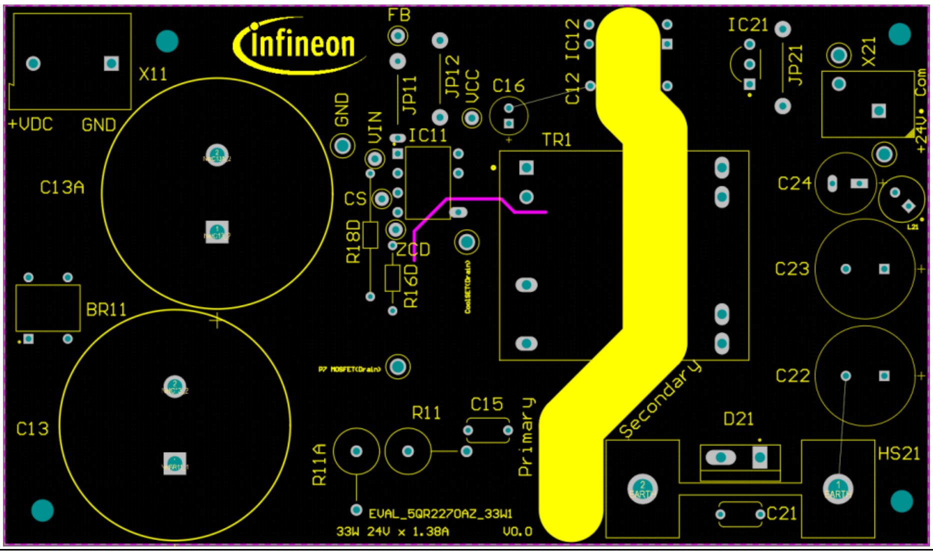


Figure 6 Top-side component legend

6.2 Bottom side

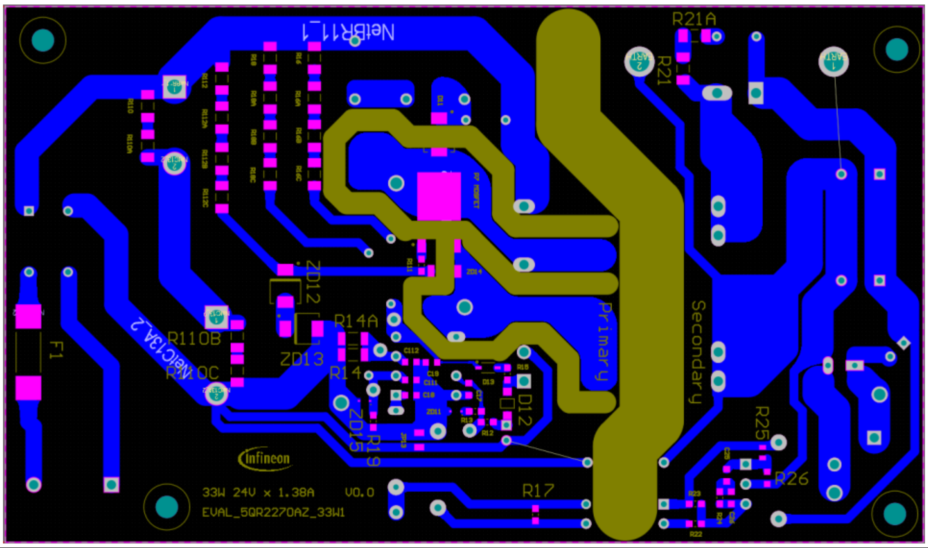


Figure 7 Bottom-side copper and component legend

7 BOM

Table 3 BOM (V 0.2)

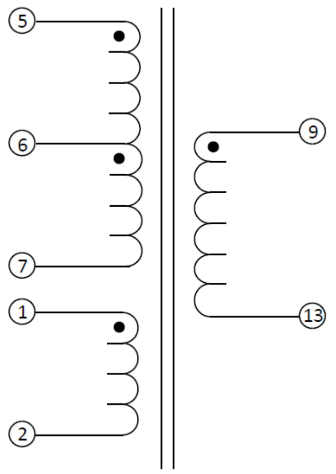
No.	Designator	Description	Part number	Manufacturer	Quantity
1	+24 V, CoolSET™ (drain), P7 MOSFET (drain)	Test point	5010		3
2	BR11	DF10M	DF10M		1
3	C12	1 nF, 500 V	DE1E3RA102MA4BQ01F	Murata	1
4	C13, C13A	450 V DC, 220 µF	861111485027	Würth Electronics	2
5	C15	1 nF, 1 kV	RDE7U3A102J2M1H03A	Murata	1
6	C16	35 V DC, 22 µF	860010572003	Würth Electronics	1
7	C17	100 nF, 50 V	885012206095	Würth Electronics	1
8	C18, C26	1 nF, 50 V	885012206083	Würth Electronics	2
9	C19	100 pF, 50 V	885012006057	Würth Electronics	1
10	C22, C23	35 V DC, 820 µF	860010578016	Würth Electronics	2
11	C24	35 V DC, 220 µF	860010574011	Würth Electronics	1
12	C25	220 nF, 50 V	885012106019	Würth Electronics	1
13	C111	22 nF, 50 V	885012206091	Würth Electronics	1
14	C112	33 nF, 50 V	885012206092	Würth Electronics	1
15	Com, GND	Test point	5011		2
16	CS, FB, V_{IN}, ZCD	Test point	5002		4
17	D11	STTH112U	STTH112U		1
18	D12	RS1DL	RS1DL		1
19	D13	BAS20HT1G	BAS20HT1G		1
20	D21	VS-8ETH03PBF	VS-8ETH03PBF		1
21	F1	1.25 A, 600 V	04611.25ER		1
22	HS21	HS_2p	513002B02500G		1
23	IC11	CoolSET™	ICE5QR2270AZ	Infineon	1
24	IC12	Optocoupler	SFH617A-3X006		1
25	IC21	Shunt regulator	TL431BVLPG		1
26	JP11, JP12, JP21	Jumper			3
27	JP13	0 R (0805)	0 R		1
28	L21	2.2 µH	7447462022	Würth Electronics	1
29	P7 MOSFET	P7 MOSFET	IPD80R2K4P7	Infineon	1
30	R11, R11A	68 k, 500 V	MCF 1W 68K		2
31	R12	6.8 R (0603)			3
32	R14	2 R (1206)	CRCW12062R00FKEA		1
33	R14A	1.8 R (1206)	CRCW12061R80FKEA		1
34	R15	27 k (0603)			1
35	R16, R16A, R16B, R16C	20 M, 200 V (1206)	MCPWR06FTEO2005		8
36	R16D	10 M	MCRE000085		1
37	R18, R18A, R18B, R18C	3.3 M (1206)	AC1206FR-073M3L		4
38	R18D	3.3 M	MCRE000079		1
39	R19	59 k (0603)	CRCW060359K0FKEA		1
40	R22	2 k (0603)	AC0603JR-072KL		1
41	R23	1.3 k (0603)	AC0603FR-071K3L		1

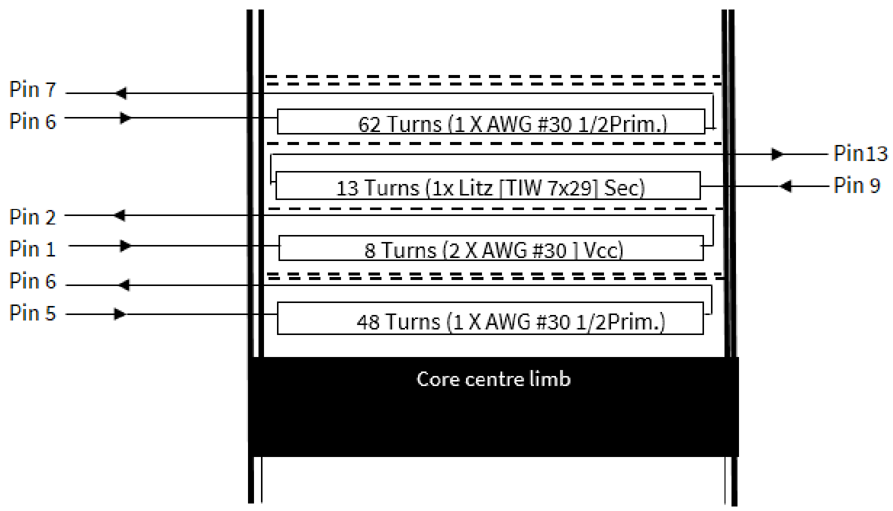
No.	Designator	Description	Part number	Manufacturer	Quantity
42	R24	48 k (0603)			1
43	R25	86.6 k (0603)	CRCW060386K6FK		1
44	R26	10 k (0603)	MCR03EZPJ103		1
45	R110, R110A, R110B, R110C	1 M, 500 V	KTR18EZPF1004		4
46	R111	0 R (0603)			1
47	R112, R112A, R112B, R112C	10 M, 200 V (1206)	RC1206FR-0710ML		8
48	TR1	1586 µH (110:13:8) EE25/13/7	750317911 rev. 01	Würth Electronics	1
49	V_{CC}	Test point	5003		1
50	X11	Connector	691201620002	Würth Electronics	1
51	X21	Connector	691 412 120 002B	Würth Electronics	1
52	ZD12, ZD13	250 V TVS diode	P6SMB250A		2
53	ZD14	15 V bi-directional TVS diode	SD15C-01FTG		1
54	PCB	120 mm x 60 mm (L x W), single-layer, 2 oz., FR-4			1
55	D21 accessories	M3 screw and nut			1
56	D21 accessories	Insulating kit	MK3306		1

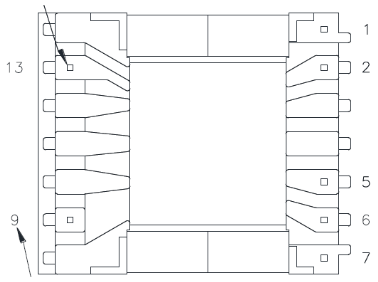
8 Transformer specification

(Refer to Appendix A for transformer design and Appendix B for WE transformer specifications.)

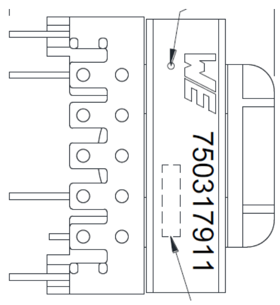
- Core and materials: EE25/13/47 TP4A (TDG)
- Bobbin: 070-5644 (14-pin, THT, horizontal version)
- Primary inductance: L_p = 1.59 mH (±10 percent), measured between pin 5 and pin 7
- Manufacturer and part number: Würth Electronics Midcom (750317911) rev. 01







Bottom view



Side view

Start	Stop	No. of turns	Wire size	Layer
5	6	48	1 x AWG#30	1/2 Primary
1	2	8	2 x AWG#30	Auxiliary
9	13	13	1 x Litz [TIW 7 x 29]	1/2 Secondary
6	7	62	1 x AWG#30	1/2 Primary

Figure 8 Transformer structure

9 Measurement data and graphs

All measurements are done by AC source with bridge diode BR11 (Chroma AC Source Model 61504 and Chroma AC Transform Unit A615003 with Yokogawa Power Meter WT310HC), as the maximum DC output from a single DC power supply is limited to 600 V DC. Thus, measurement data from an actual source may differ from the results below.

Table 4 Measurement data

Input (V AC/Hz)	Description	P_{IN} (W)	V_{OUT} (V_{DC})	I_{OUT} (A)	P_{OUT} (W)	η (%)	$η_{avg}$ (%)	P_{IN_OLP} (W)	I_{OUT_OLP} (A)
	No load	0.08	23.93	0.000					
	Min. load	2.07	23.92	0.069	1.65	79.73			
	1/10 load	4.07	23.92	0.138	3.30	81.10			
135/50	1/4 load	9.73	23.92	0.345	8.25	84.81		50.00	1.85
	Typ. load	19.11	23.92	0.690	16.50	86.37	86.56		
	3/4 load	28.24	23.92	1.035	24.76	87.67			
	Max. load	37.77	23.92	1.380	33.01	87.40			
	No load	0.10	23.93	0.000					
	Min. load	2.15	23.92	0.069	1.65	76.77			
	1/10 load	4.20	23.92	0.138	3.30	78.59			
230/50	1/4 load	9.93	23.92	0.345	8.25	83.11		62.00	2.32
	Typ. load	19.08	23.92	0.690	16.50	86.50	86.14		
	3/4 load	28.38	23.92	1.035	24.76	87.23			
	Max. load	37.63	23.92	1.380	33.01	87.72			
	No load	0.17	23.93	0.000					
	Min. load	2.27	23.92	0.069	1.65	72.71			
	1/10 load	4.33	23.92	0.138	3.30	76.23			
400/50	1/4 load	10.25	23.92	0.345	8.25	80.51		64.00	2.40
	Typ. load	19.35	23.92	0.690	16.50	85.30	84.74		
	3/4 load	28.77	23.92	1.035	24.76	86.05			
	Max. load	37.89	23.92	1.380	33.01	87.12			
	No load[1]	0.30	23.93	0.000					
	Min. load	2.43	23.92	0.069	1.65	67.92			
	1/10 load	4.52	23.92	0.138	3.30	73.03			
560/50	1/4 load	10.70	23.92	0.345	8.25	77.13		70.00	2.60
	Typ. load	19.80	23.92	0.690	16.50	83.36	82.71		
	3/4 load	29.22	23.92	1.035	24.76	84.73			
	Max. load	38.54	23.92	1.380	33.01	85.65			

- No-load condition (no load) : 24 V at 0 A
- Minimum load condition (min. load) : 24 V at 69 mA
- 1/10 load condition (1/10 load) : 24 V at 138 mA

[1] Add ZD15 (2.7 V Zener) to disable LOVP.

- 1/4 load condition (1/4 load) : 24 V at 0.345 A
- Typical load condition (typ. load) : 24 V at 0.69 A
- 3/4 load condition (3/4 load) : 24 V at 0.1.035 A
- Maximum load condition (max. load) : 24 V at 1.38 A

9.1 Load regulation

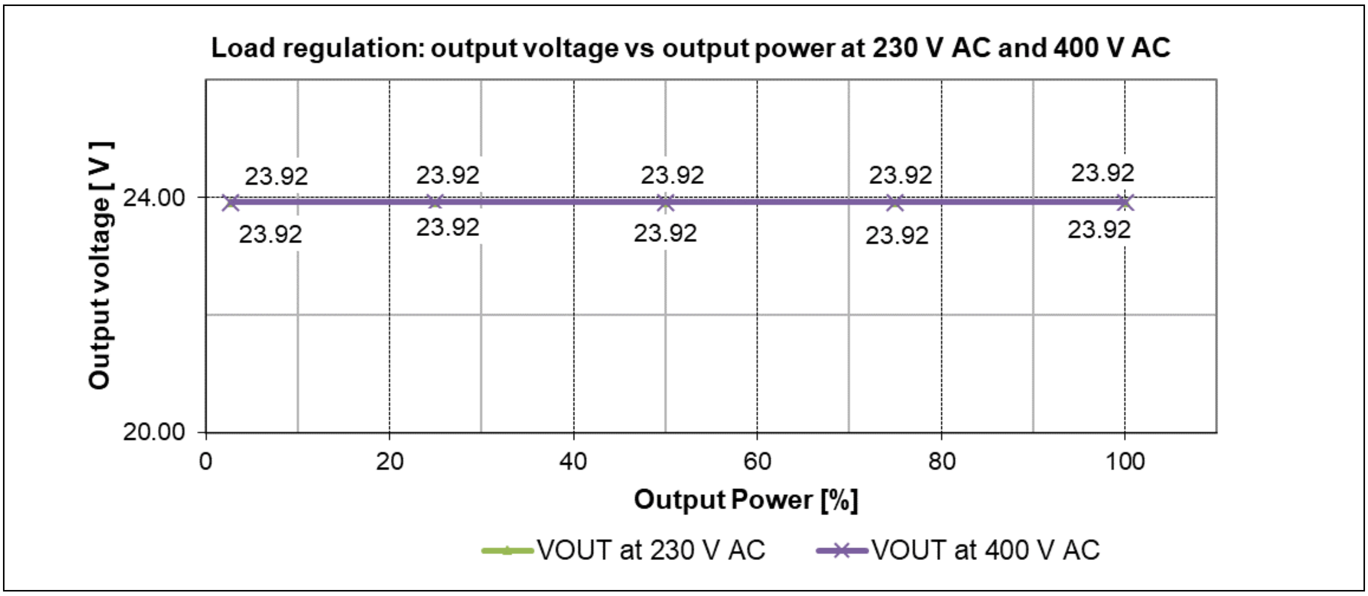


Figure 9 Load regulation VOUT vs output power

9.2 Line regulation

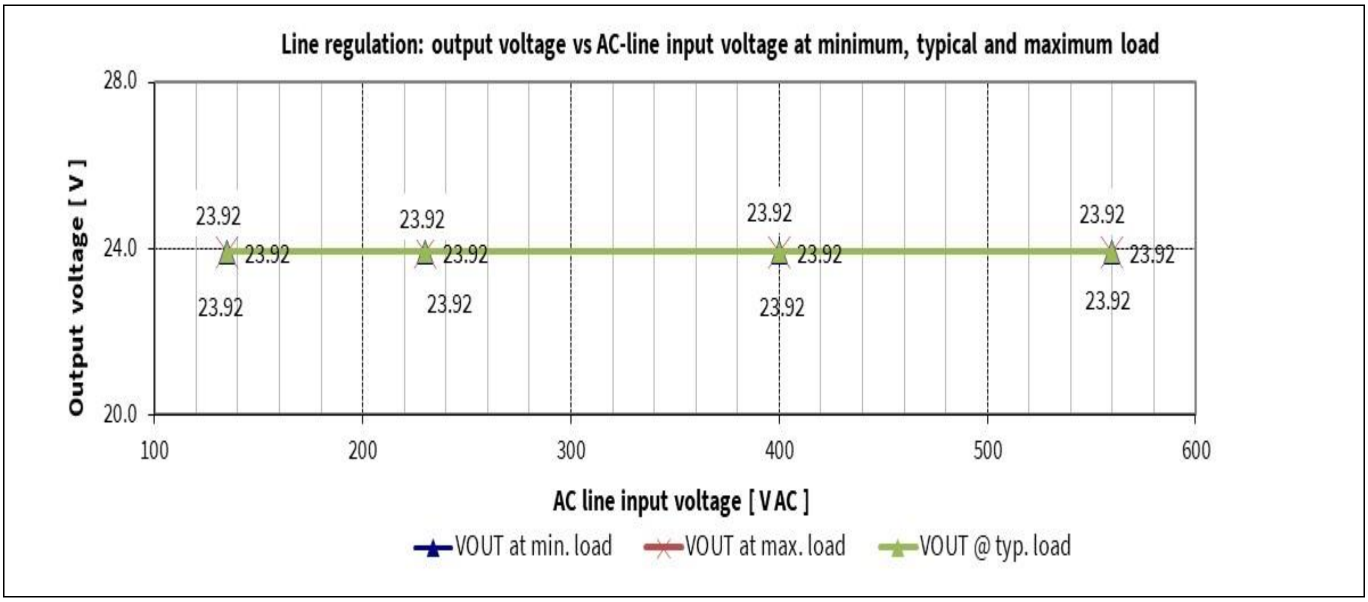


Figure 10 Line regulation: VOUT vs AC-line input voltage

9.3 Efficiency vs AC-line input voltage

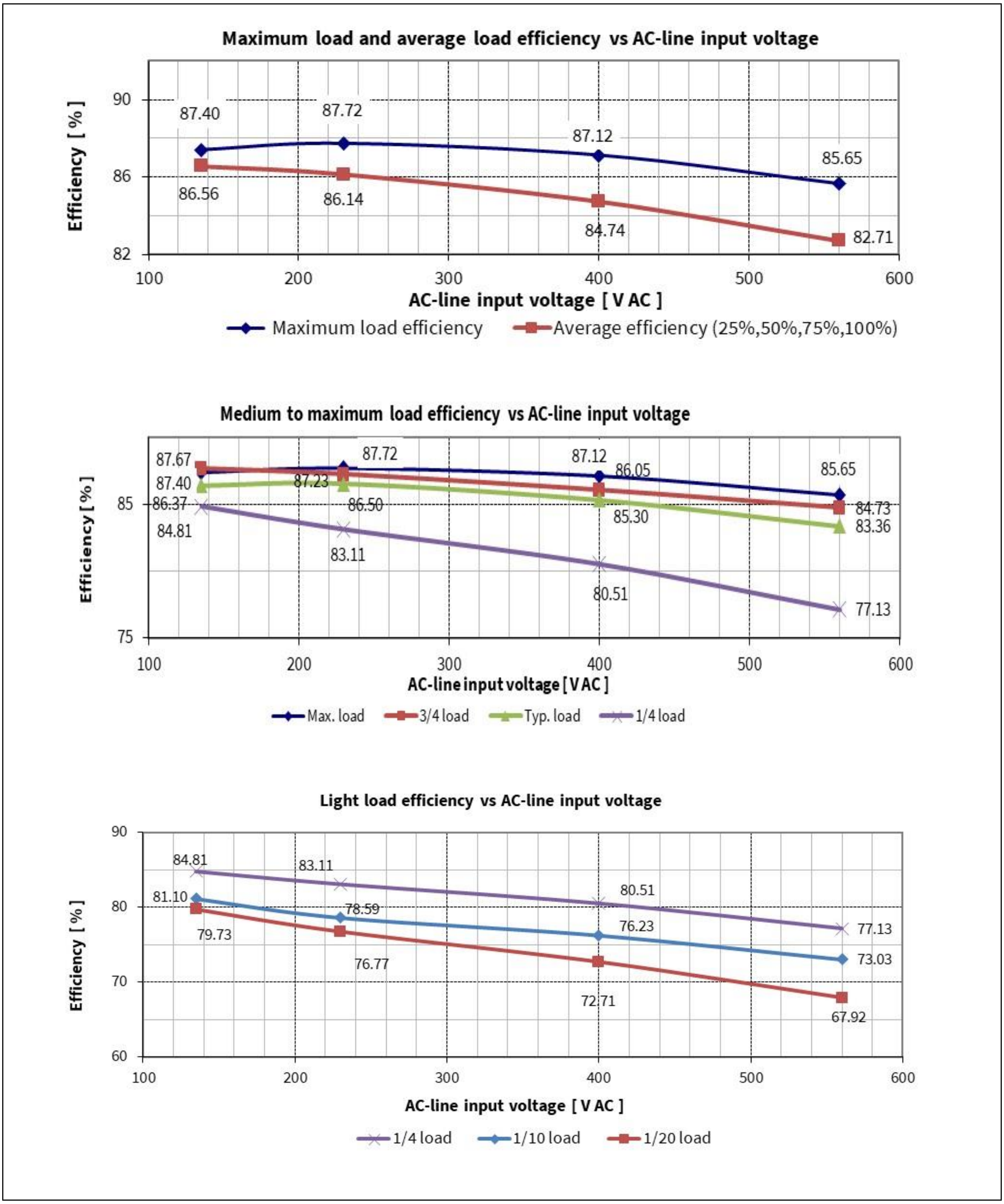


Figure 11 Efficiency vs AC-line input voltage

9.4 Standby power

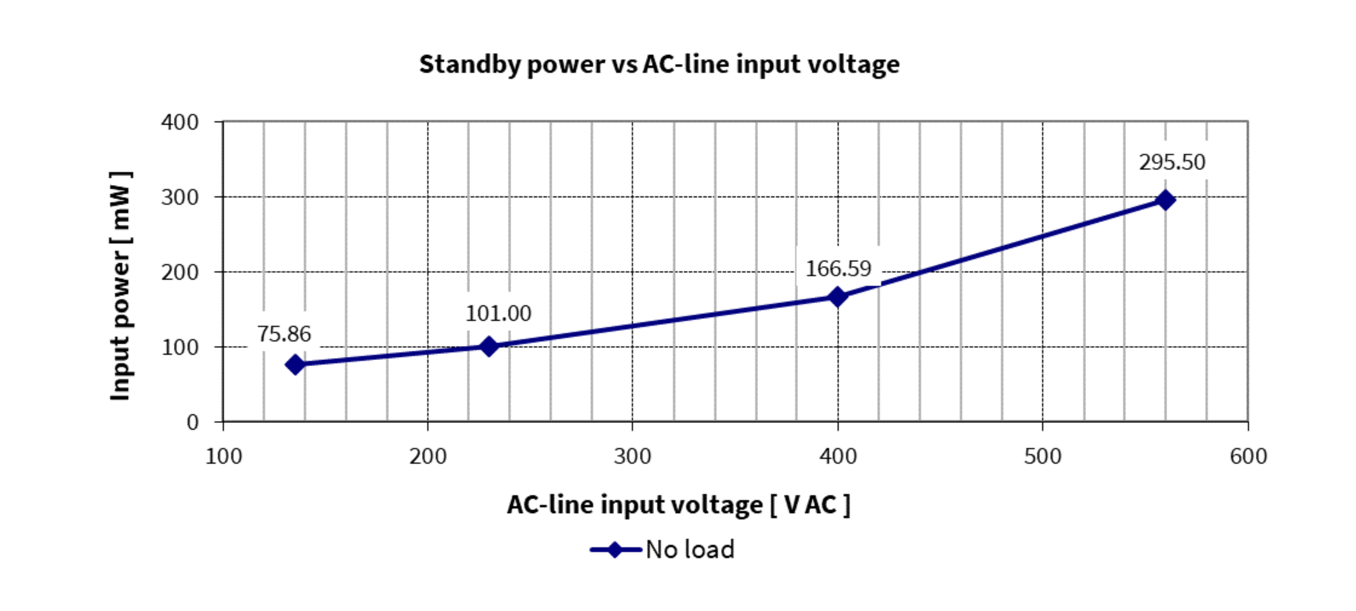


Figure 12 Standby power at no load vs AC-line input voltage (measured by Yokogawa WT210 power meter – integration mode)

9.5 Maximum output current

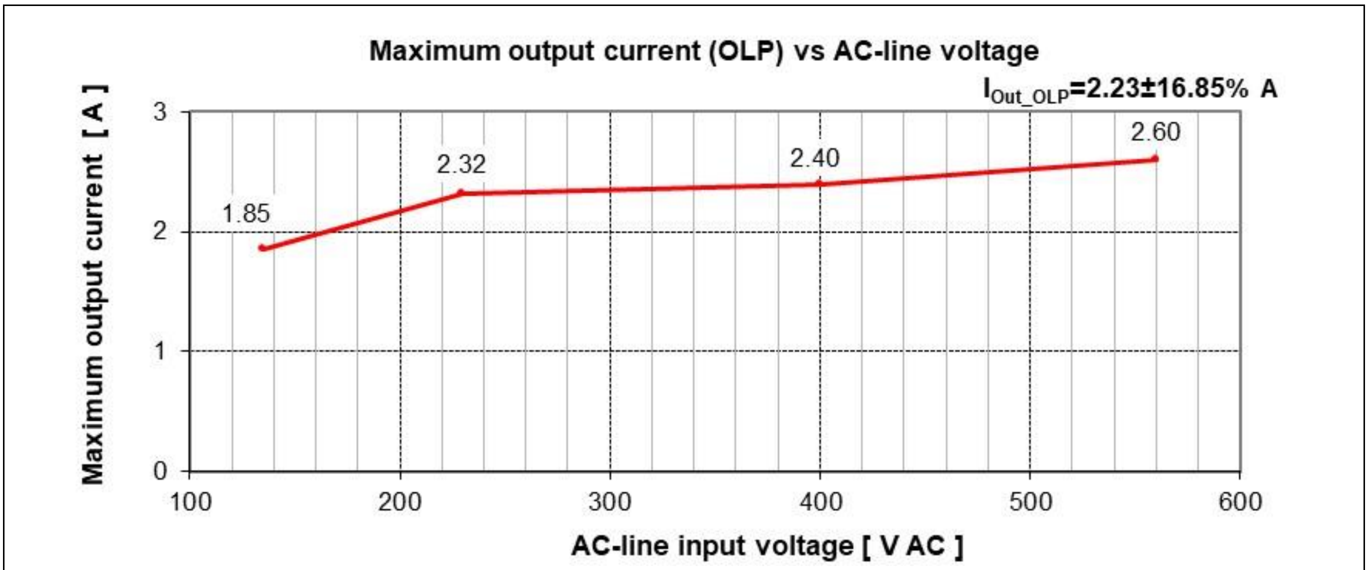


Figure 13 Maximum output current (before over-load protection) vs AC-line input voltage

10 Thermal measurement

The thermal testing of the evaluation board was done in the open air without forced ventilation at an ambient temperature of 25°C. An infrared thermography camera (FLIR-T62101) was used to capture the thermal reading of particular components. The measurements were taken at the maximum load running for one hour. The tested input voltage was 135 V AC and 560 V AC.

Table 5 Component temperature at full load (24 V, 1.38 A) under T_{amb} = 25°C

Circuit code	Major component	135 V AC (°C)	560 V AC (°C)
IC11	ICE5QR2270AZ	55.8	66.3
TR1	Transformer	53.5	67.9
D21	+24 V output diode	46.2	46.7
P7MOSFET	IPD80R2K4P7	54.1	58.8
ZD12	Clamper diode for IC11 drain pin	34.6	50.8
	Ambient	25.0	25.0

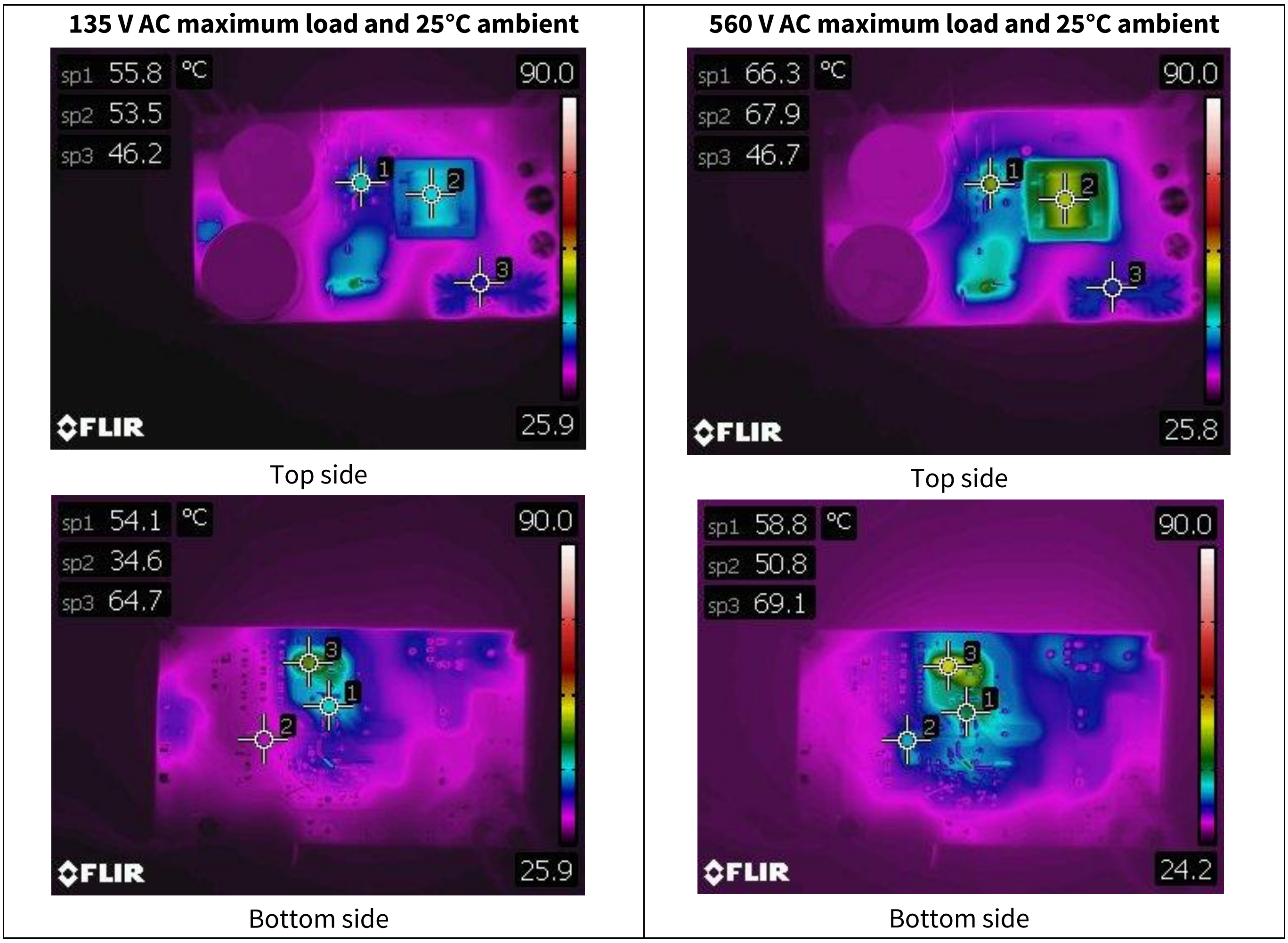


Figure 14 Infrared thermal image of EVAL_5QR2270AZ_33W1

11 Waveforms

All waveforms and scope plots were recorded with a Teledyne LeCroy 606Zi oscilloscope.

11.1 Switching waveform at maximum load

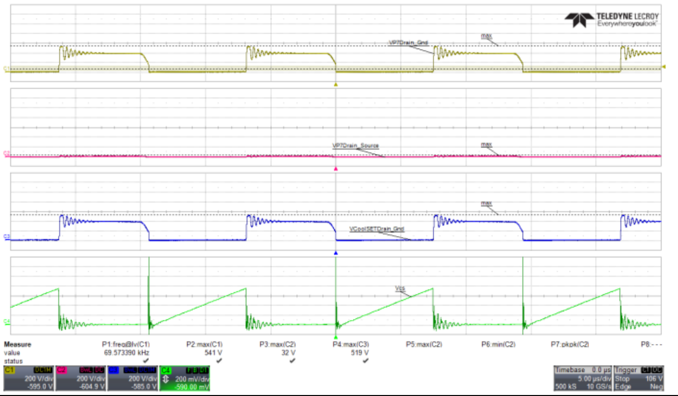
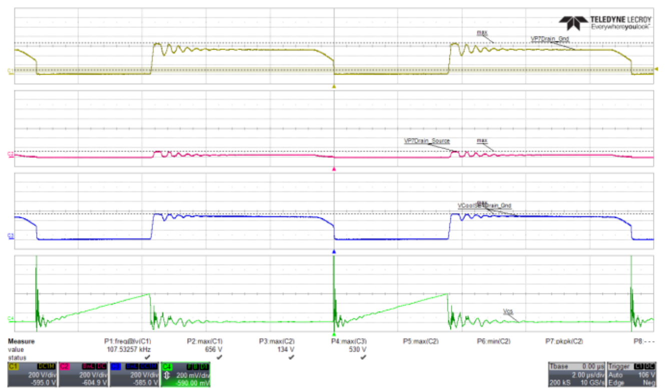
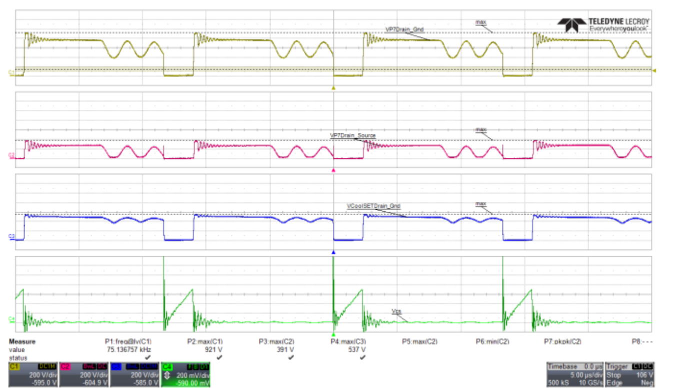
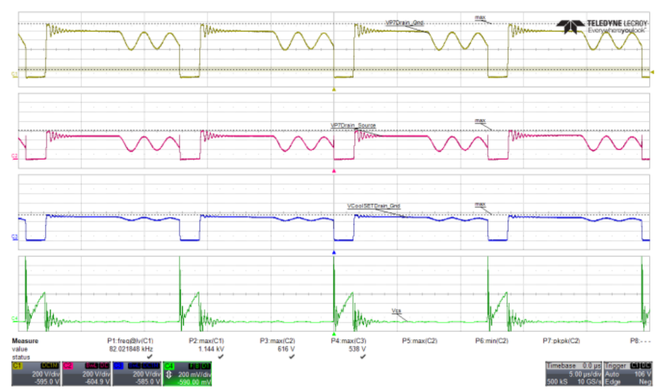
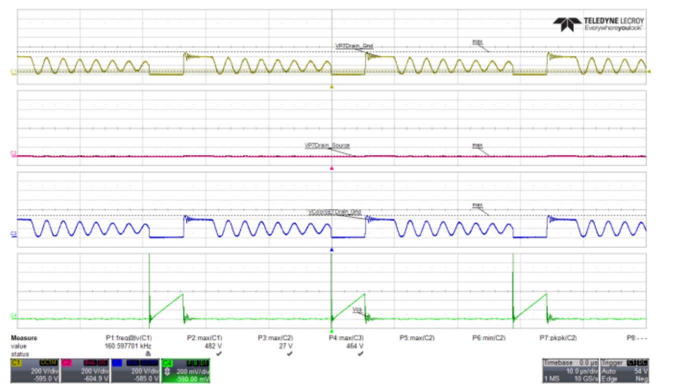
	
C1 (yellow): $V_{P7Drain\_Gnd}$; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$; C4 (green): V_{CS}	C1 (yellow): $V_{P7Drain\_Gnd}$; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$; C4 (green): V_{CS}
V_{IN} = 135 V AC, max. load; $V_{P7Drain\_Source}$: 32 V DC and $V_{CoolSETDrain\_Gnd}$: 519 V DC	V_{IN} = 230 V AC, max. load; $V_{P7Drain\_Source}$: 134 VDC and $V_{CoolSETDrain\_Gnd}$: 530 V DC
	
C1 (yellow): $V_{P7Drain\_Gnd}$; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$; C4 (green): V_{CS}	C1 (yellow): $V_{P7Drain\_Gnd}$; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$; C4 (green): V_{CS}
V_{IN} = 400 V AC, max. load; $V_{P7Drain\_Source}$: 391 V DC and $V_{CoolSETDrain\_Gnd}$: 537 V DC	V_{IN} = 560 V AC, max. load; $V_{P7Drain\_Source}$: 616 V DC and $V_{CoolSETDrain\_Gnd}$: 538 V DC

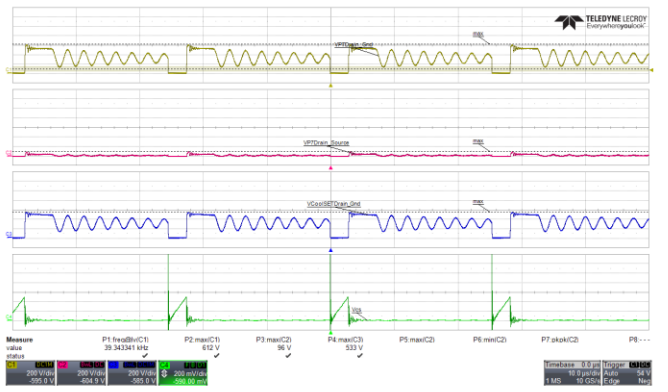
Figure 15 Drain and CS voltage at maximum load

11.2 Switching waveform at 25 percent load



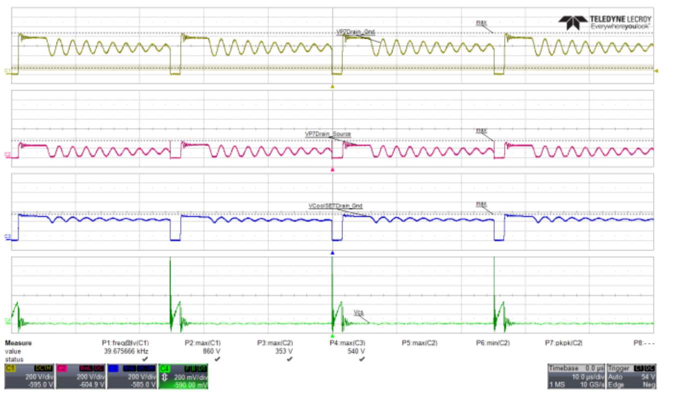
C1 (yellow): $V_{P7Drain\_Gnd}$; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$; C4 (green): V_{CS}

V_{IN} = 135 V AC, 25% load; 8th zero crossing (zero crossing varies from 1~8)



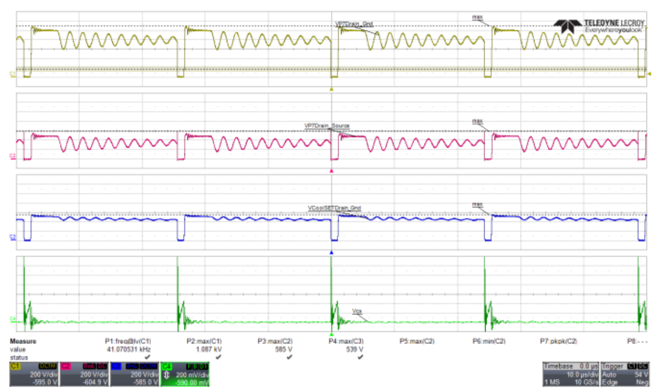
C1 (yellow): $V_{P7Drain\_Gnd}$; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$; C4 (green): V_{CS}

V_{IN} = 230 V AC, max. load; 8th zero crossing (zero crossing varies from 1~8)



C1 (yellow): $V_{P7Drain\_Gnd}$; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$; C4 (green): V_{CS}

V_{IN} = 400 V AC, max. load; 10th zero crossing (zero crossing varies from 3~10)



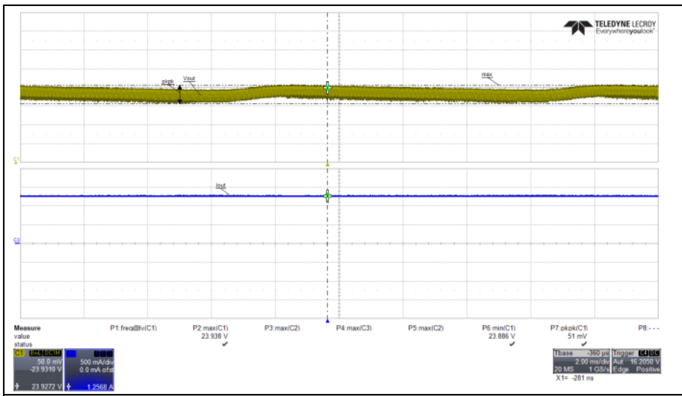
C1 (yellow): $V_{P7Drain\_Gnd}$; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$; C4 (green): V_{CS}

V_{IN} = 560 V AC, max. load; 10th zero crossing (zero crossing varies from 3~10)

Figure 16 Drain and CS voltage at 25 percent load

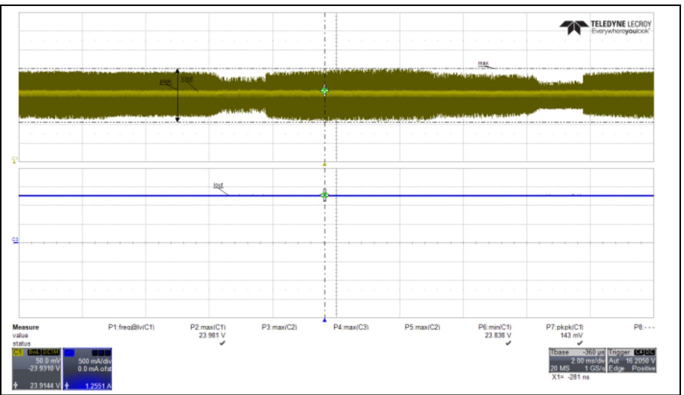
11.3 Output ripple voltage at maximum load

- Probe terminal end with decoupling capacitor of 0.1 µF (ceramic) and 1 µF (electrolytic), 20 MHz BW



C2 (purple): V_{OUT}; C3 (blue): I_{OUT}

V_{IN} = 135 V AC, max. load; V_{OUT_Ripple} (24 V): 51 mV



C2 (purple): V_{RIPPLE} (5 V)

V_{IN} = 560 V AC, max. load; V_{OUT_Ripple} (24 V): 143 mV

Figure 17 Output ripple voltage at maximum load

11.4 Output ripple voltage in ABM (1.7 W load)

- Probe terminal end with decoupling capacitor of 0.1 µF (ceramic) and 1 µF (electrolytic), 20 MHz BW
- Load: 1.7 W (24 V, 70 mA)

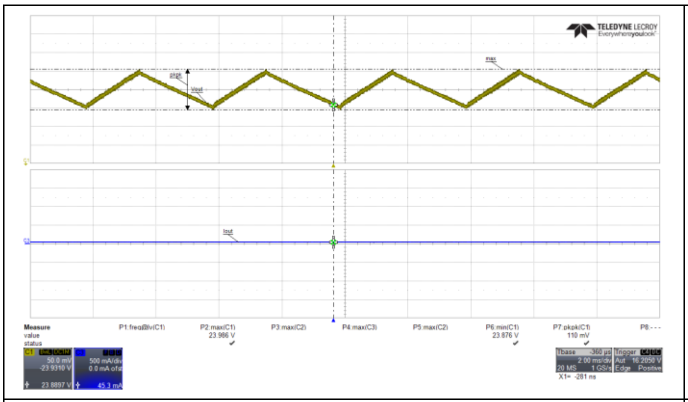
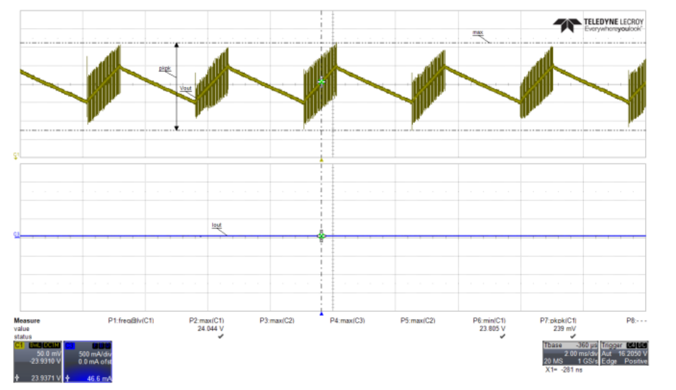
	
C2 (purple): V_{OUT}; C3 (blue): I_{OUT}	C2 (purple): V_{OUT}; C3 (blue): I_{OUT}
V_{IN} = 135 V AC, min. load; V_{OUT_Ripple} (24 V): 110 mV	V_{IN} = 560 V AC, min. load; V_{OUT_Ripple} (24 V): 239 mV

Figure 18 Output ripple voltage in ABM (1.7 W load)

11.5 Load transient response (dynamic load from 10 percent to 100 percent)

- Probe terminal end with decoupling capacitor of 0.1 µF (ceramic) and 1 µF (electrolytic), 20 MHz BW
- 24 V load change from 10 percent to 100 percent, 100 Hz, 0.4 A/µs slew rate

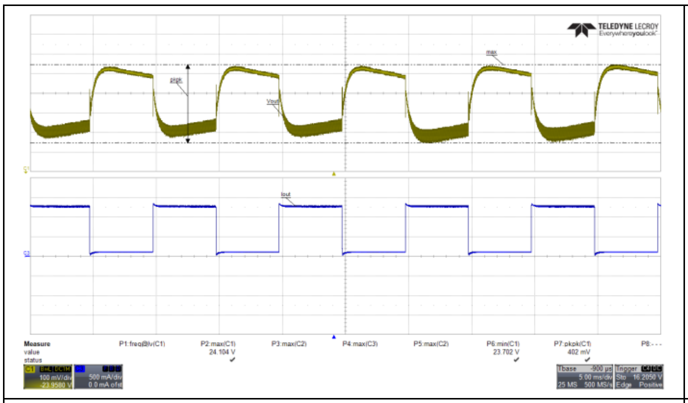
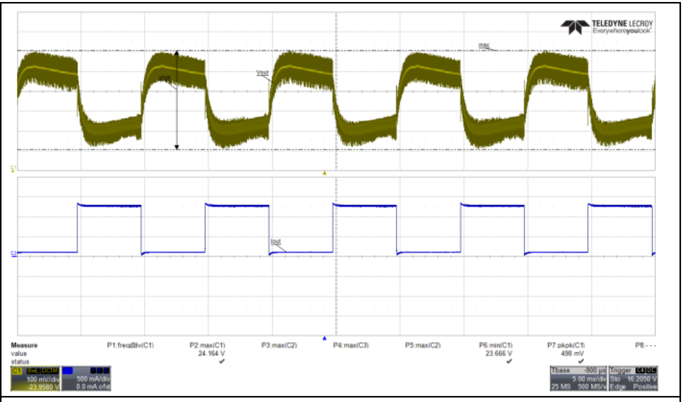
	
C2 (purple): V_{RIPPLE} (5 V)	C2 (purple): V_{RIPPLE} (5 V)
V_{IN} = 85 V AC, 10 percent to 100 percent load; V_{RIPPLE} (5 V): 402 mV	V_{IN} = 264 V AC, 10 percent to 100 percent load; V_{RIPPLE} (5 V): 500 mV

Figure 19 Load transient response

11.6 Entering ABM

- Load change from 8.25 W (24 V, 0.35 A) to 1 W (24 V, 0.04 A)

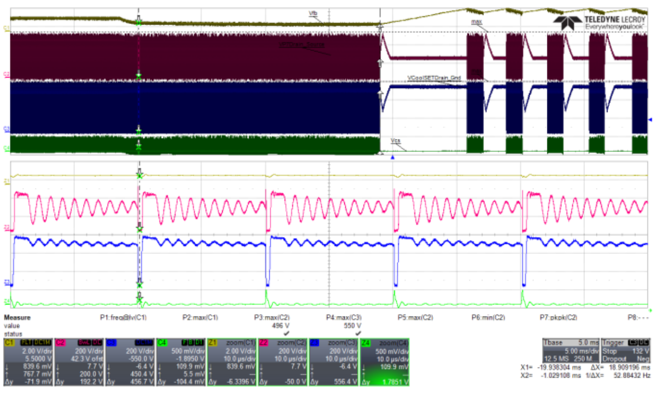
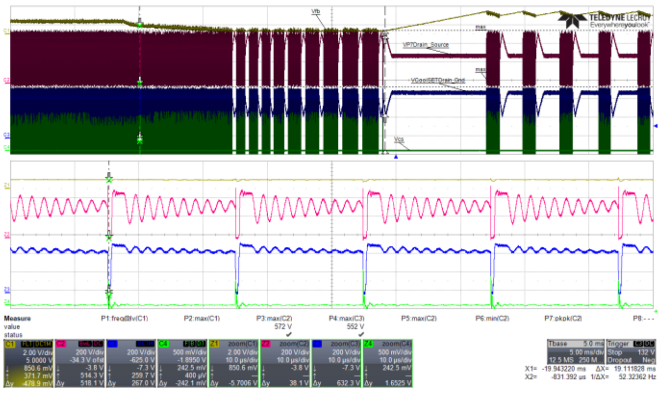
	
C1 (yellow): V_{FB}; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$; C4 (green): V_{CS}	C1 (yellow): V_{FB}; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$; C4 (green): V_{CS}
V_{IN} = 135 V AC; system enters burst mode option 1: V_{FB} less than 0.9 V, 8 ZC and $t_{blanking}$ = 20 ms	V_{IN} = 560 V AC; system enters burst mode option 1: V_{FB} less than 0.9 V, 10 ZC and $t_{blanking}$ = 20 ms

Figure 20 Entering ABM

11.7 During ABM

- Load: 1.68 W (24 V, 0.07 A)

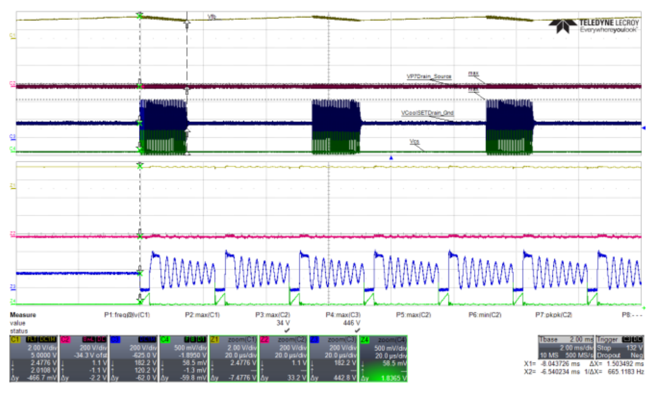
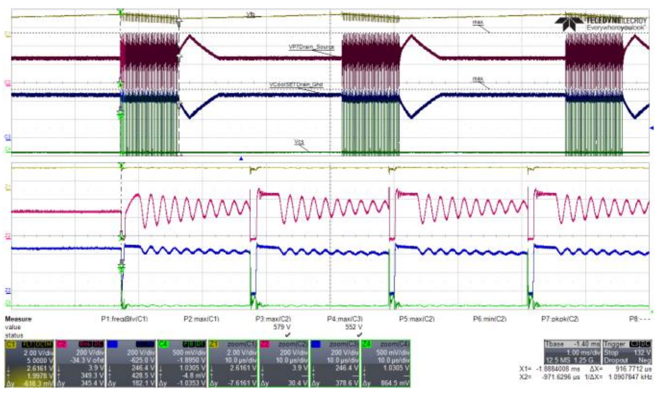
	
C1 (yellow): V_{FB}; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$; C4 (green): V_{CS}	C1 (yellow): V_{FB}; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$; C4 (green): V_{CS}
V_{IN} = 135 V AC; burst mode option 1: V_{FB_BOn} = 2.4 V, V_{FB_BOff} = 2.0 V, V_{CSBL1} = 0.31 V, 8 ZC	V_{IN} = 560 V AC; burst mode option 1: V_{FB_BOn} = 2.4 V, V_{FB_BOff} = 2.0 V, V_{CSBL1} = 0.31 V, 10 ZC

Figure 21 During ABM

11.8 Leaving ABM

- Load change from 0.1 W (24 V, 0.7 A) to maximum load

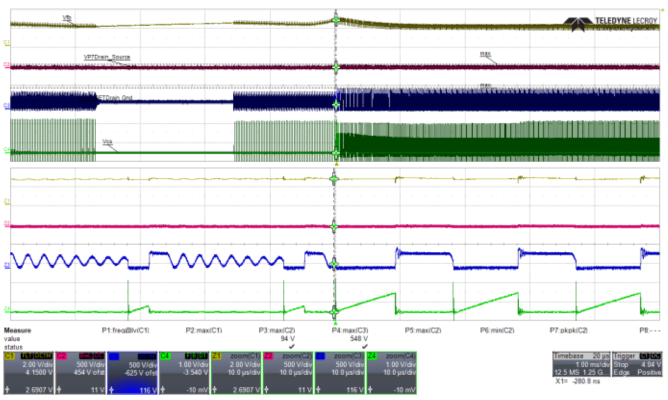
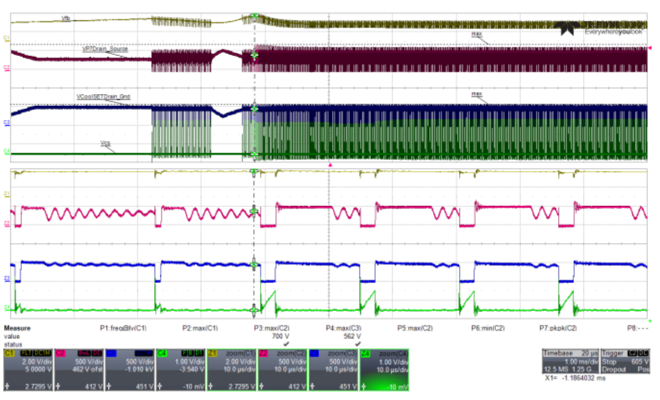
	
C1 (yellow): V_{FB}; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$; C4 (green): V_{CS}	C1 (yellow): V_{FB}; C2 (purple): $V_{P7Drain\_Source}$; C3 (blue): $V_{CoolSETDrain\_Gnd}$; C4 (green): V_{CS}
V_{IN} = 135 V AC; system leaves burst mode: V_{FB} greater than 2.75 V	V_{IN} = 560 V AC; system leaves burst mode: V_{FB} greater than 2.75 V

Figure 22 Leaving ABM

11.9 Line OV Protection (OVP) (non-switch auto-restart)

- Increase AC-line voltage gradually at maximum load until line OVP is detected, and then decrease the AC-line until line OVP reset is detected

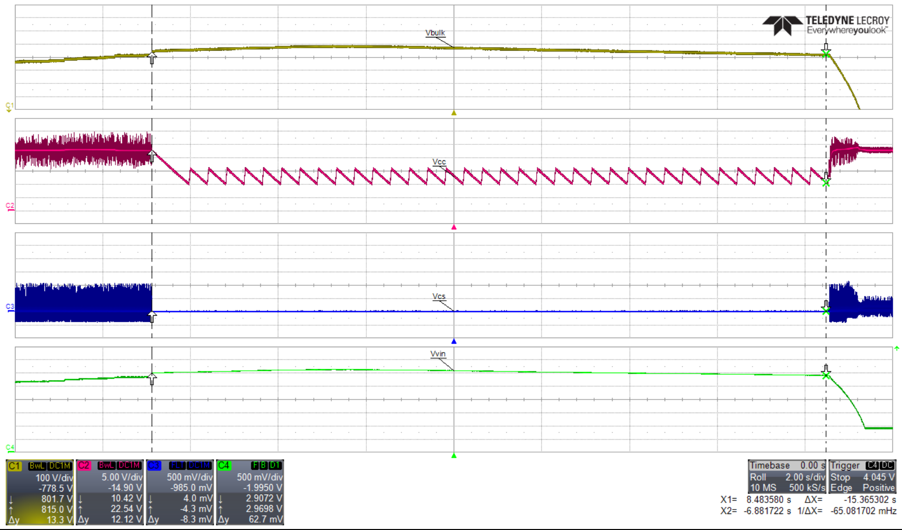
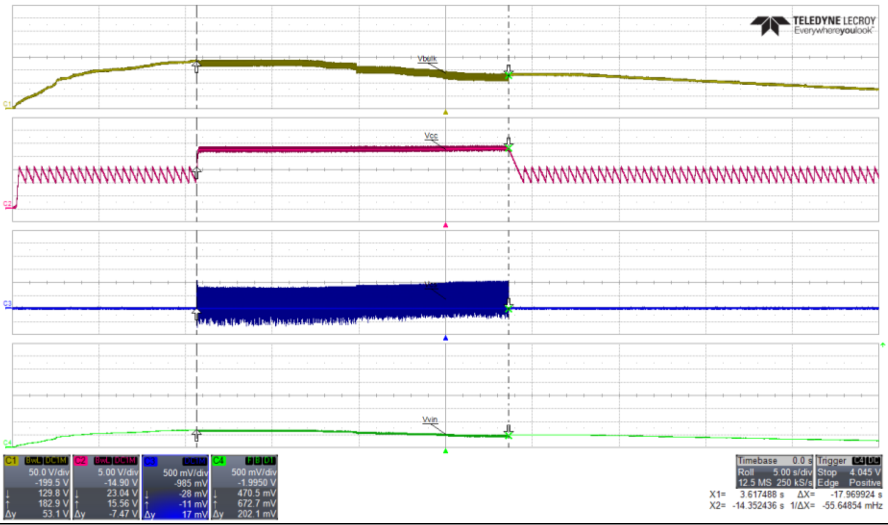

C1 (yellow): V_{Bulk}; C2 (purple): V_{VCC}; C3 (blue): V_{CS}; C4 (green): V_{VIN}
Max. load; line OVP triggered: V_{BUS} greater than 810 V DC or V_{VIN} greater than 2.9 V); line OVP reset: V_{BUS} less than 810 V DC or V_{VIN} less than 2.9 V)

Figure 23 Line OVP

11.10 Brown-in/out protection

- Increase AC-line voltage gradually at full load until the system starts up (brown-in) and reduce the line until brown-out detection.

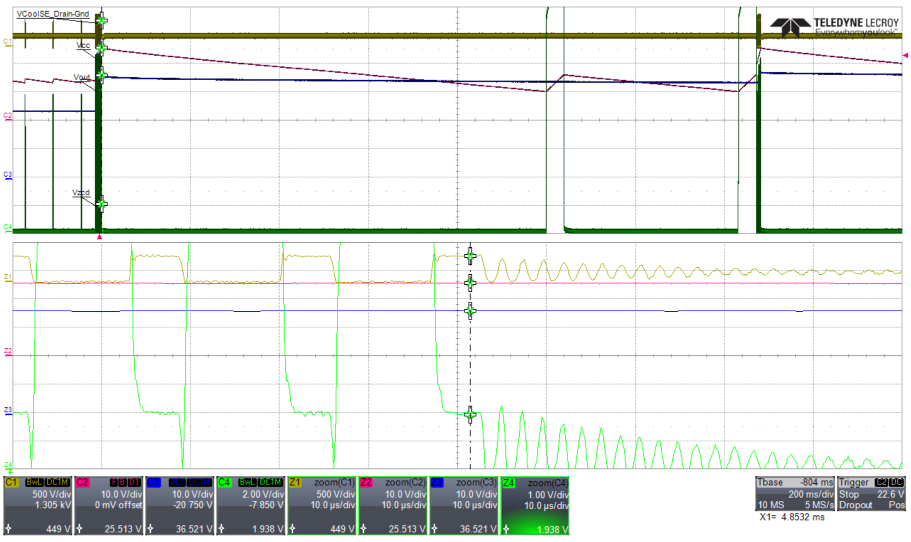


C1 (yellow): V_{Bulk}; C2 (purple): V_{VCC}; C3 (blue): V_{CS}; C4 (green): V_{VIN}
Full load; brown-in: V_{VIN} greater than 0.66 V (V_{BULK} greater than 183 V DC) and brown-out: V_{VIN} less than 0.4 V (V_{BULK} less than 129 V DC)

Figure 24 Brown-in/out protection

11.11 V_{CC} OVP (odd-skip auto-restart)

- Short R26 resistor during system operation at no load (change R15 to 36 kΩ)

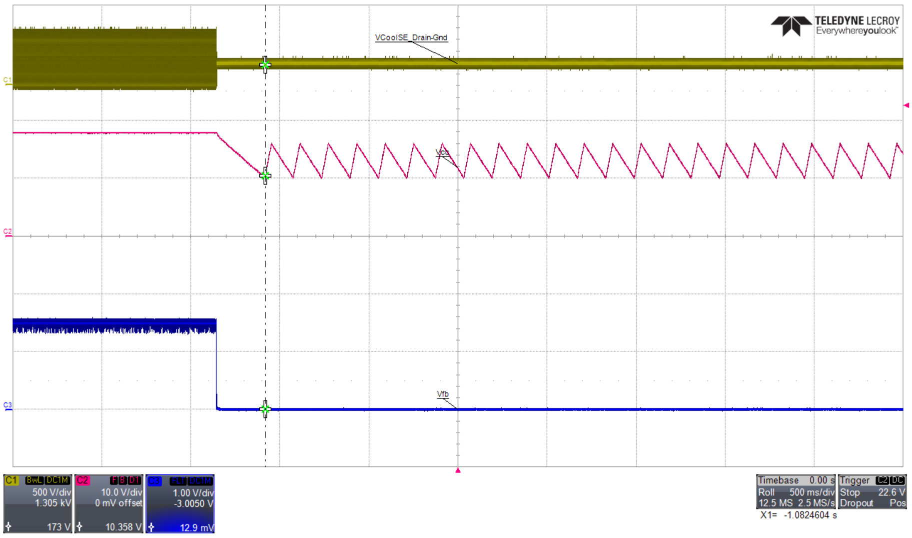


C1 (yellow): $V_{CoolSETDrain\_Gnd}$; C2 (purple): V_{CC}; C3 (blue): V_{OUT} (24 V); C4 (green): V_{ZCD}
V_{IN} = 135 V AC; system enters V_{CC} OVP: V_{CC} greater than 25.5 V

Figure 25 V_{CC} OVP

11.12 V_{CC} UVP (auto-restart)

- Short R17 while the system is operating at 25 percent load (24 V, 345 A)



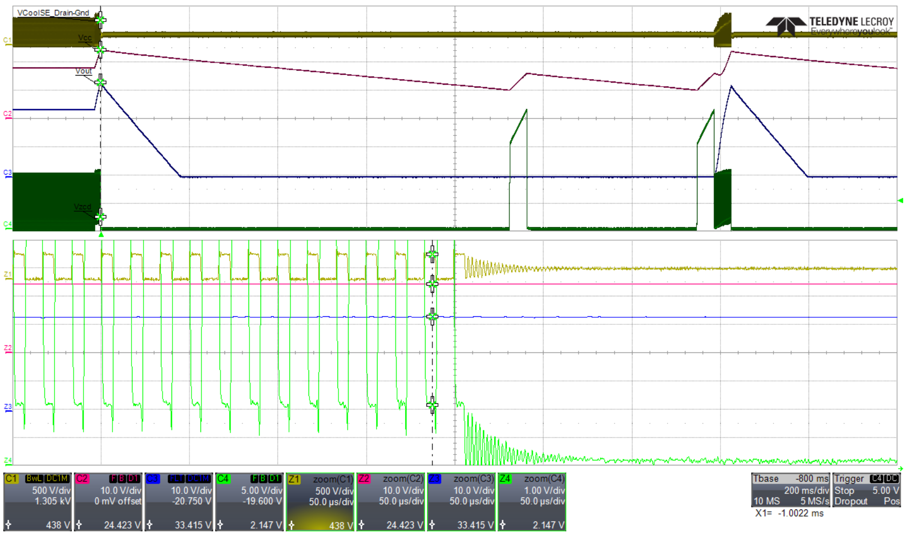
C1 (yellow): $V_{CoolSETDrain\_Gnd}$; C2 (purple): V_{VCC}; C3 (blue): V_{FB}

V_{IN} = 135 V AC; system enters V_{CC} UVP: V_{CC} less than 10 V

Figure 26 V_{CC} UVP

11.13 Output OVP

- Short R26 resistor during system operation at 25 percent load (24 V, 0.345 A)



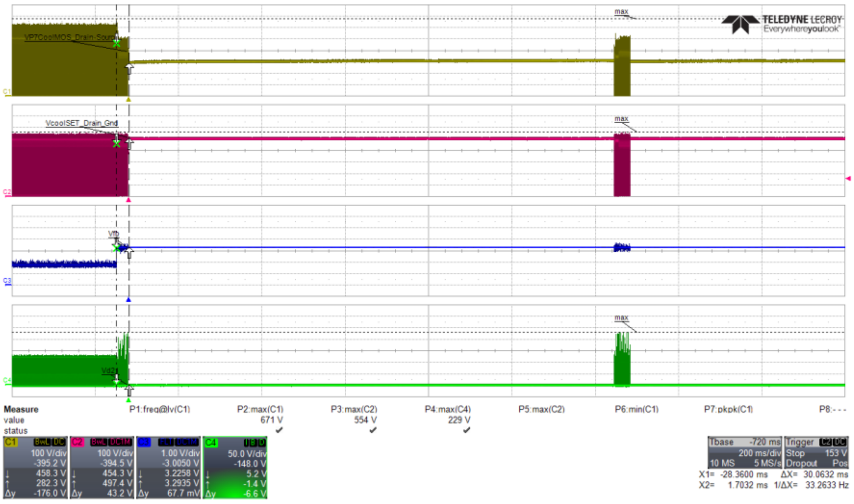
C1 (yellow): $V_{CoolSETDrain\_Gnd}$; C2 (purple): V_{VCC}; C3 (blue): V_{OUT} (24 V); C4 (green): V_{ZCD}

V_{IN} = 135 V AC; system enters output OVP: V_{OUT} greater than 30 V (V_{ZCD} greater than 2 V)

Figure 27 V_{CC} OVP

11.14 Over-load protection (odd-skip auto-restart)

- V_{OUT} (24 V) short-to-GND at 560 V AC



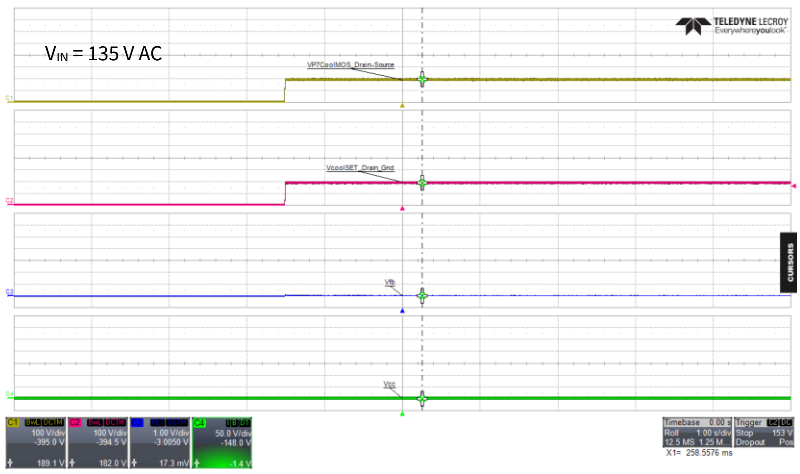
C1 (yellow): $V_{P7Drain\_Source}$; C2 (purple): $V_{CoolSETDrain\_Gnd}$; C3 (blue): V_{FB}; C4 (green): V_{D21}

V_{IN} = 264 V AC; system enters over-load protection: V_{FB} greater than 2.75 V and lasts for ≈ 30 ms blanking time: $V_{P7Drain\_Source\_max}$: 671 V DC, $V_{CoolSETDrain\_Gnd\_max}$: 554 V DC and V_{D21_max}: 229 V DC

Figure 28 Over-load protection and max. voltage stress for MOSFETs and output diode (D21)

11.15 V_{CC} short-to-GND protection

- Short V_{CC} pin-to-GND with current meter before system start-up



C1 (yellow): $V_{P7Drain\_Source}$; C2 (purple): $V_{CoolSETDrain\_Gnd}$; C3 (blue): V_{FB}; C4 (green): V_{VCC}

V_{IN} = 135 V AC; system enters V_{CC} short-to-GND: V_{CC} less than V_{VCC_SCP} ➔ I_{VCC} = 270 µA (input power ≈ 70 mW)
V_{IN} = 560 V AC; system enters V_{CC} short-to-GND: V_{CC} less than V_{VCC_SCP} ➔ I_{VCC} = 560 µA (input power ≈ 680 mW)

Figure 29 V_{CC} short-to-GND protection

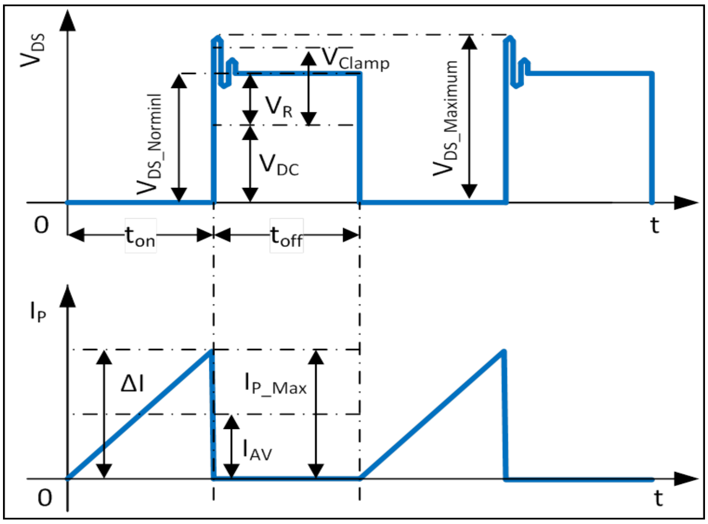
12 Appendix A: Transformer design and spreadsheet [3]

Design procedure for QR flyback converter using Gen5 QR 5QRxxxxAx (version 1.1)

Project:	**EVAL_5QR2270AZ_33W1**
Application:	**135~560 V AC and (24 V x 1.38 A = 33 W)**
CoolSET™:	**ICE5QR2270AZ**
Date:	
Revision:	

Enter design variables in orange colored cells
Read design results in green colored cells
Equation numbers are according to the application note

			Unit	Value
Input	**Minimum AC input voltage**	**V AC_{Min}**	[V]	135
Input	**Maximum AC input voltage**	**V AC_{Max}**	[V]	560
Input	**Line frequency**	**f_{AC}**	[Hz]	50
Input	**Bus capacitor (C13) DC ripple voltage**	**V DC_{RIPPLE}**	[V]	18
Input	**Output voltage 1**	**V_{OUT1}**	[V]	24
Input	**Output current 1**	**I_{OUT1}**	[A]	1.38
Input	**Forward voltage of output diode (D21)**	**$V_{FDiode1}$**	[V]	0.6
Input	**Output voltage 2**	**V_{OUT2}**	[V]	0
Input	**Output current 2**	**I_{OUT2}**	[A]	0
Input	**Forward voltage of output diode (D22)**	**$V_{FDiode2}$**	[V]	0
Input	**Maximum output power for start-up, transient response and OLP**	**P_{OUTMax}**	[W]	0.24
Input	**Nominal output power**	**P_{OUTNor}**	[W]	36
Input	**Minimum output power**	**P_{OUTMin}**	[W]	33.00
Input	**Efficency**	**η**		3.6
Result	**Drain-to-source capacitance of MOSFET (including $Co_{(er)}$ of MOSFET)**	**C_{DS}+$Co_{(er)}$**	[pF]	0.86



Input	**Reflection voltage**	**V_R**	[V]	208.15
Input	**V_{CC} voltage**	**V_{VCC}**	[V]	15
Input	**Forward voltage of V_{CC} diode (D12)**	**$V_{FDiodeVCC}$**	[V]	0.6
Input	**CoolSET™**	**Gen5 QR**		ICE5QR2270AZ
Input	**Low-line min. switching frequency**	**f_S**	[Hz]	65000
Input	**Targeted max. drain-source voltage**	**V_{DSMax}**	[V]	1200
Input	**Max. ambient temperature**	**T_a**	[°C]	50
Diode bridge (BR1)				
Result	**Eq 1**	P_{INMax}	[W]	41.86
Result	**Eq 2**	I_{AC_RMS}	[A]	0.517
Result	**Eq 3**	V DC_{Max_Pk}	[V]	791.96
Result	**Eq 4**	V DC_{Min_Pk}	[V]	190.92
Result	**Eq 10**	V DC_{Min}	[V]	172.91

Result	**Eq 6**	T_D	[ms]	8.61
Result	**Eq 7**	W_{IN}	[Ws]	0.36
Result	**Eq 11**	D_{Max}		0.5462
Input capacitor (C13)				
Result	**Eq 8**	C_{IN} (C13)	[µF]	110.02
Input	**Select input capacitor**	**C_{IN} (C13)**	[µF]	**110**
Transformer (TR1)				
Result	**Eq 12**	L_P	[H]	1.557E-03
Result	**Eq 13**	I_{AV}	[A]	0.44
Result	**Eq 14**	ΔI	[A]	0.933
Result	**Eq 15**	I_{P_Max}	[A]	0.91
Result	**Eq 16**	I_{Valley}	[A]	0.0
Result	**Eq 17**	I_{P_RMS}	[A]	0.38
Select core type				
Input	**Select core type**			**2**
		Core type		**E25/13/7**
		Core material		**TP4A(TDG)**
	Maximum flux density	B_{Max}	[T]	**0.26**
	Effective magnetic cross-section	A_e	[mm²]	**51.4**
	Bobbin width	BW	[mm]	**15.6**
	Winding cross-section	A_N	[mm²]	**61**
	Average length of turn	l_N	[mm]	**50**
Winding calculation				
Result	**Eq 18**	N_P	Turns	108.08
Input	**Choose number of primary turns**	**N_P**	Turns	**110**
Result	**Eq 19**	N_{S1}	Turns	13.00
Input	**Choose number of secondary turns**	**N_{S1}**	Turns	**13**
Result	**Eq 19**	N_{S2}	Turns	0.00
Input	**Choose number of secondary turns**	**N_{S2}**	Turns	**0**
Result	**Eq 20**	N_{VCC}	Turns	8.24
Input	**Choose number of auxiliary turns**	**N_{VCC}**	Turns	**8**
Result	**Auxiliary supply voltage (Eq 21)**	V_{VCC}	[V]	**14.54**
Post calculation				
Result	**Eq 23**	V_R	[V]	**208.15**
Result	**Eq 24**	D_{Max}		**0.55**
Result	**Eq 25**	D_{Max}'		**0.45**
Result	**Eq 26**	B_{Max}	[T]	**0.251**
CS resistor(R14)				
Input	**CS threshold value from datasheet**	**V_{csth}**	[V]	**1**
Result	**Eq 21**	R_{Sense} (R14)	[Ω]	1.10
Result	**Eq 22**	P_{SR}	[W]	**0.16**
Input	**PWM-OP gain from datasheet**	**G_{PWM}**		**2.05**
Result	**Eq 94**	Z_{PWM}	[V/A]	**2.3**
Transformer winding design				
Input	**Margin according to safety standard**	**M**	[mm]	**0**
Input	**Copper space factor**	**f_{cu}**		**0.3**
Primary				
Input	**Insulation thickness**	**INS**	[mm]	**0.02**
Result	**Eq 32**	A_p (area of primary wire)	[mm²]	0.08
Result	**Eq 36**	Dia. (diameter of primary wire)	[mm]	0.33
Result	**Eq 35**	AWG		28
Input	**Selected wire size**	**AWG**		**30**
Input	**Number of parallel wires**	**Np**		**1**
Result	**Eq 37**	Dia. (diameter of primary wire)	[mm]	0.26
Result	**Eq 38**	(Eff. copper area of primary)	[mm²]	0.0517
Result	**Eq 39**	Sp (primary current density)	[A/mm²]	7.41
Result	**Eq 30**	BW_e (effective bobbin width)	[mm]	15.6
Result	**Eq 40**	Od_p (diameter of primary wire including insulation)	[mm]	0.30
Result	**Eq 41**	NL_P (max. primary turns/layer)	Turns/layer	52
Result	**Eq 42**	Ln_P (primary layers)	Layers	3

Secondary				
Input	**Insulation thickness**	**INS**	[mm]	**0.02**
Result	**Eq 33**	A_S (area of secondary wire)	[mm²]	0.63
Result	**Eq 36**	Dia. (diameter of secondary wire)	[mm]	0.90
Result	**Eq 35**	AWG		19
Input	**Selected wire size**	**AWG**		**29**
Input	**Number of parallel wires**	**Np**		**7**
Result	**Eq 37**	Dia. (diameter of secondary wire)	[mm]	0.29
Result	**Eq 38**	(Eff. copper area of secondary)	[mm²]	0.4562
Result	**Eq 39**	S_S (secondary current density)	[A/mm²]	6.48
Result	**Eq 30**	BW_E (effective bobbin width)	[mm]	15.6
Result	**Eq 40**	Od_S (diameter of secondary wire including insulation)	[mm]	0.33
Result	**Eq 41**	NL_S (max. secondary turns/layer)	Turns/layer	6
Result	**Eq 42**	Ln_S (secondary layers)	Layers	3
Leakage inductance				
Input		**Leakage Inductance in percent of L_P**	[%]	**2.15**
Result	**Eq 45**	L_{LK}	[H]	3.35E-06
RCD clamper circuit (D11, R11 and C15)				
Result	**Eq 44**	V_{clamp}	[V]	199.89
Result	**Eq 46**	C_{clamp} (C15)	[nF]	0.3
Input	**Selected C_{clamp} capacitor value**	**C_{clamp} (C15)**	[nF]	**1**
Result	**Eq 47**	R_{clamp} (R11)	[kΩ]	136.8
Input	**Selected R_{clamp} value**	**R_{clamp} (R11)**	[kΩ]	**138**
Output and V_{CC} diodes (D21, D22 and D12)				
Result	**Eq 27**	K_{L1} (load factor)		1.00
Result	**Eq 43a**	$V_{RDiode1}$ (for output diode D21)	[V]	117.60
Result	**Eq 28**	I_{S_Max1}	[A]	7.70
Result	**Eq 29**	I_{S_RMS1}	[A]	2.96
Result	**Eq 43a**	$V_{RDiode2}$ (for output diode D22)	[V]	0.00
Result	**Eq 27**	K_{L2} (load factor)		0.00
Result	**Eq 28**	I_{S_Max2}	[A]	
Result	**Eq 29**	I_{S_RMS2}	[A]	
Result	**Eq 43b**	V_{RDiode} (for V_{CC} diode)	[V]	72.60
Output capacitors (C22 and C23)				
Input	**Max. voltage overshoot at output capacitor (C22, C23)**	**ΔV_{OUT1}**	[V]	**0.5**
Input	**Number of clock periods**	**n_{cp}**		**20**
Result	**Eq 49**	$I_{RIPPLE1}$	[A]	2.62
Result	**Eq 50**	C_{OUT1}	[µF]	846
Zero frequency of output capacitors (C22 and C23) and associated ESR				
Input	**Selected output capacitor value**	**C22**	[µF]	**820**
Input	**ESR (Z_{Max}) value from datasheet at 100 kHz**	**ESR**	[Ω]	**0.028**
Input	**I_{ACMax} value from datasheet at 100 kHz**	**I_{ACMax}**	[Arms]	**1.045**
Input	**Number of parallel capacitors**	**n_c**		**2**
Result	**Eq 51**	f_{ZCOUT1}	[kHz]	6.93
Ripple voltage first stage				
Result	**Eq 52**	$V_{RIPPLE1}$	[V]	0.11
Input	**Selected LC filter inductor value**	**L_{OUT1} (L21)**	[µH]	**2.2**
Calculating the necessary capacitance for the output LC-filter (C24)				
Result	**Eq 53**	C_{LC1} (C24)	[µF]	239.6
Input	**Selected output inductance value**	**C_{LC1} (C24)**	[µF]	**220**
Result	**Eq 54**	f_{LC1}	[kHz]	7.23
Ripple voltage 2nd stage				
Result	**Eq 55**	$V_{RIPPLE2}$	[mV]	1.321
Soft-Start Time				
Input	**Selected soft-start time from datasheet**	**$t_{softstart}$**	[ms]	**12**
V_{CC} capacitor (C16) and start-up time				
Input	**Selected $I_{VCC,Charge3}$ from datasheet**	**$I_{VCC,Charge3}$**	[mA]	**3**
Input	**Selected V_{VCChys} from datasheet**	**V_{VCChys}**	[mV]	**6**
Result	**Eq 56A**	C_{VCC}	[µF]	6.00
Input	**Selected V_{CC} capacitor**	**C_{VCC} (C16)**	[µF]	**22**

Input	Selected $V_{VCC,STG}$ from datasheet	$V_{VCC,STG}$	[V]	1.1
Input	Selected $I_{VCC,Charge1}$ from datasheet	$I_{VCC,Charge1}$	[mA]	0.2
Input	Selected $V_{VCC,ON}$ from datasheet	$V_{VCC,ON}$	[V]	16
Result	Eq 56B	$t_{StartUp}$	[ms]	238.33
Calculation of losses				
Input diode bridge				
Result	Eq 57	P_{DIN}	[W]	1.03
Transformer copper losses				
Result	Eq 58	R_{PCu}	[mΩ]	1828.64
Result	Eq 58	R_{SCu1}	[mΩ]	24.51
Result	Eq 58	R_{SCu2}	[mΩ]	268.71
Result	Eq 59	P_{PCu}	[mW]	214.19
Result	Eq 60	P_{SCu1}	[mW]	0.4829
Result	Eq 60	P_{SCu2}	[mW]	1828.64
Result	Eq 61	P_{Cu}	[W]	24.51
Output rectifier diode				
Result	Eq 62	P_{OUT_DIODE1} (D21)	[W]	1.77
RCD clamper circuit				
Result	Eq 63	P_{clamp}	[W]	1.84
MOSFET				
Input	R_{DSON} from datasheet	R_{DSON} at T_J = 125°C	[Ω]	4.31
Input	$C_{O(er)}$ from datasheet	Co(er)	[pF]	10
Input	External drain-to-source capacitance of MOSFET	C_{DS}	[pF]	0
MOSFET losses at V AC_{Min} + P_{Max}				
Result	Eq 65	P_{SON}	[W]	0.000403586
Result	Eq 66	Pcond	[W]	0.6333
Result	Eq 67	MOSFET losses	[W]	0.6337
MOSFET losses at V AC_{Max} + P_{Max}				
Result	Eq 68	P_{SON}	[W]	0.1440
Result	Eq 69	P_{cond}	[W]	0.1798
Result	Eq 70	MOSFET losses	[W]	0.3238
Temperature calculation				
Input	Enter MOSFET losses	MOSFET losses	[W]	0.63
Input	Enter thermal resistance junction – ambient	R_{th}	[°K/W]	100.0
Result	Eq 74	ΔT	[°K]	63.4
Result	Eq 75	T_{jmax}	[°C]	113.4
Controller				
Result	$I_{VCC,Normal}$xV_{VCC}	Controller losses	[W]	0.0131
Sum of losses				
Result	Eq 77	P_{Losses}	[W]	5.78
Efficiency after losses				
Result	Eq 78	η_L		0.8617
Calculation of the regulation loop (R22, R23, R24, R25, R25A, R26, C25, C26)				
Input	Minimum current for TL431 reference	I_{KAmin}	[mA]	1
Input	Optocoupler gain	G_C (200 percent)		2
Input	Maximum current for optocoupler diode	I_{Fmax}	[mA]	10
Input	Second resistor of TL431 voltage divider	R26	[kΩ]	10
Input	0 db crossover frequency	fg	[kHz]	1.2
Result	Eq 81	R25	[kΩ]	1.20
Input	Selected value of R25	R25	[kΩ]	86.6
Result	Eq 82	R22	[kΩ]	2.0250
Input	Selected value of R22	R22	[kΩ]	2
Input	V_{REF} from datasheet	V_{REF}	[V]	3.3
Input	$V_{FB,OLP}$ from datasheet (over-load/open-loop detection limit at FB pin)	$V_{FB,OLP}$	[V]	2.75
Input	R_{FB} from datasheet	R_{FB}	[kΩ]	15
Result	Eq 83	R23	[kΩ]	1.29
Input	Selected value of R23	R23	[kΩ]	1.3
Result	Eq 84	V_{OUT1_RL}	[V]	24.2
Result	Eq 85	K_{FB}		15.00
Result	Eq 86	G_{FB}	[db]	23.52

Result	**Eq 87**	K_{VD}		0.10
Result	**Eq 88**	G_{VD}	[db]	-19.70
Result	**Eq 89**	R_{LH}	[Ω]	16.00
Result	**Eq 90**	R_{LL}	[Ω]	160.00
Result	**Eq 91**	f_{OH}	[Hz]	12.13
Result	**Eq 92**	f_{OL}	[Hz]	1.21
Result	**Eq 93**	f_{OM}	[Hz]	3.84
Result	**Eq 95**	F_{PWR} (fg)		0.118
Result	**Eq 96**	G_{PWR} (fg)	[db]	-18.53
Result	**Eq 99**	Gr	[db]	14.712
Result	**Eq 100**	R24	[kΩ]	48.77
Input	**Selected value of R24**	**R24**	[kΩ]	**48**
Result	**Eq 101**	C26	[nF]	2.763
Input	**Selected value of C26**	**C26**	[nF]	**1**
Result	**Eq 102**	C25	[nF]	863.36
Input	**Selected value of C25**	**C25**	[nF]	**220**
ZCD and output OVP calculation				
Input	**Designed V_{OUT_OVP}**	V_{OUT_OVP}	[V]	**30**
Input	**$V_{ZC\_OVP\_MIN}$ from datasheet**	$V_{ZC\_OVP\_MIN}$	[V]	**1.9**
Input	**R_{ZCD_MIN} from datasheet**	R_{ZCD}	[kΩ]	**3**
Result	**Eq 103**	R_{ZC} (R15)	[kΩ]	26.73
Input	**Selected value of R15**	**R_{ZC} (R15)**	[kΩ]	**27**
Input	**f_{OSC2} by measurement**	f_{OSC2}	[kHz]	**915**
Result	**Eq 104**	C_{ZC} (C19)	[pF]	100
Input	**Selected value of C_{ZC} (C19)**	C_{ZC} (C19)	[pF]	100
Line OVP is the first priority and its associated brown-out, brown-in and line selection				
Input		**R_{I1} (R18)**	[Ω]	**16,500,000**
Input		Line OV (V_{OVP_AC})	[V AC]	**576**
Input		**V DC_{RIPPLE}**	[V]	**18**
Result	**Eq 105A**	R_{I2} (R19)	[Ω]	58,951
Input	**Selected value of R19 (R_{I2})**	**R_{I2} (R19)**	[Ω]	**59,000.0**
Result	**Eq 106**	Brown-in voltage ($V_{Brownin\_AC}$)	[V AC]	131
Result	**Eq 107**	Brown-out voltage for full load which considers V DC_{RIPPLE} ($V_{Brownout\_AC}$)	[V AC]	92
Result	**Eq 107**	Brown-out voltage for light load which neglects V DC_{RIPPLE} ($V_{Brownout\_AC}$)	[V AC]	79
Result	**Eq 108**	Line selection threshold with V DC_{RIPPLE} (V_{VIN} = 1.52 V)	[V AC]	314
Result	**Eq 108**	Line selection threshold without V DC_{RIPPLE} (V_{VIN} = 1.52 V)	[V AC]	302
Brown-out is the first priority and its associated line OVP and line selection				
Input		**R_{I1} (R18)**	[Ω]	**16,500,000**
Input		Brown-in voltage (V_{OVP_AC})	[V AC]	**131**
Input		**V DC_{RIPPLE}**	[V]	**18**
Result	**Eq 105B**	R_{I2} (R19)	[Ω]	58,992
Input	**Selected value of R19 (R_{I2})**	**R_{I2} (R19)**	[Ω]	**59,000**
Result	**Eq 107**	Brown-out voltage for full load which considers V DC_{RIPPLE} ($V_{Brownout\_AC}$)	[V AC]	92
Result	**Eq 107**	Brown-out voltage for light load which neglect V DC_{RIPPLE} ($V_{Brownout\_AC}$)	[V AC]	79
Result	**Eq 114**	Line OV (V_{OVP_AC})	[V AC]	576
Result	**Eq 108**	Line selection threshold with V DC_{RIPPLE} (V_{VIN} = 1.52 V)	[V AC]	314
Result	**Eq 108**	Line selection threshold without V DC_{RIPPLE} (V_{VIN} = 1.52 V)	[V AC]	302

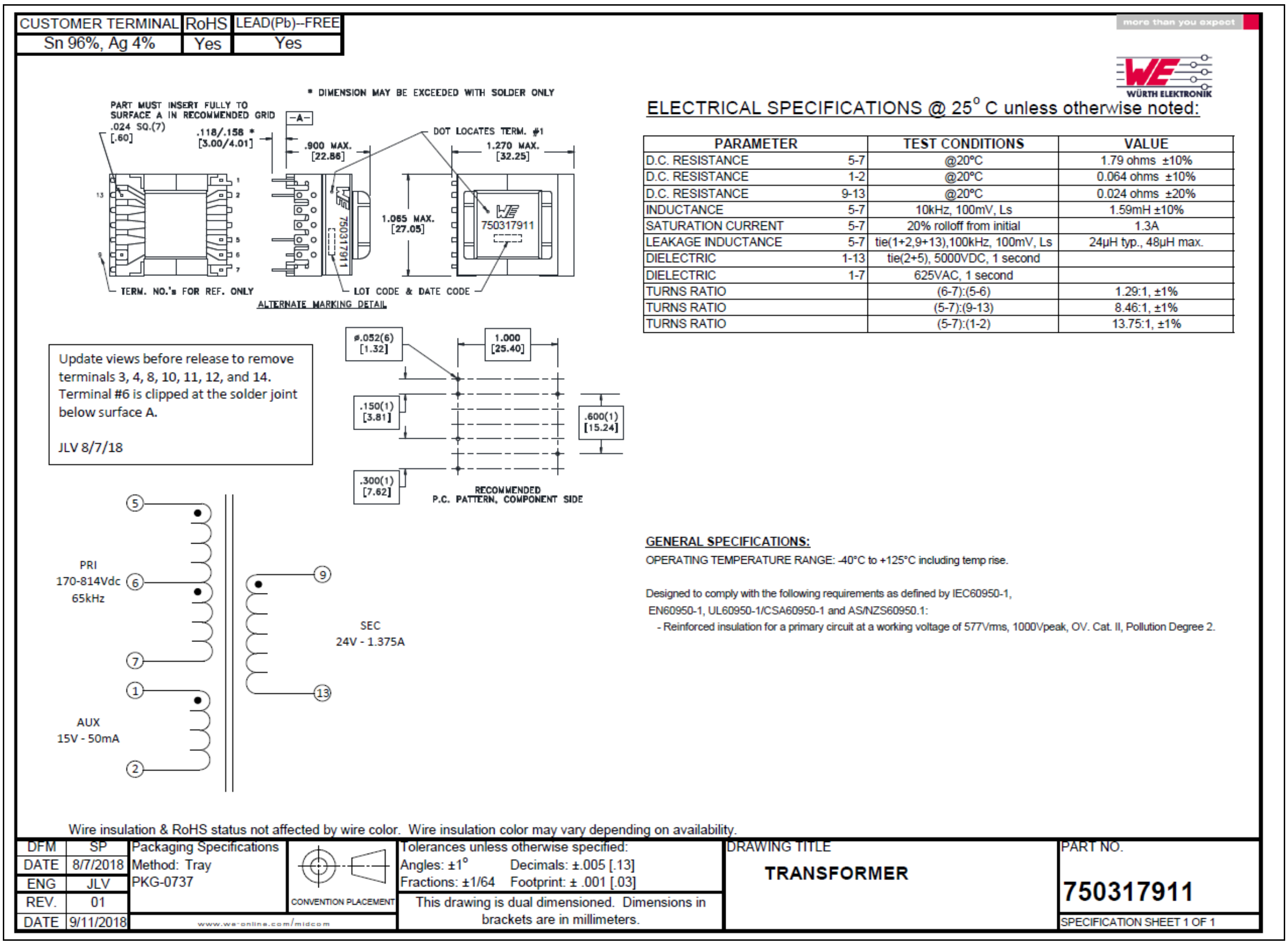
Electrical			
Minimum AC voltage		[V]	**135**
Maximum AC voltage		[V]	**560**
Maximum input current		[A]	**0.31**
Minimum DC voltage		[V]	**173**

Maximum DC voltage		[V]	**792**
Maximum output power		[W]	**36.0**
Output voltage		[V]	**24.0**
Output ripple voltage		[mV]	**1.3**
Inductor peak current		[A]	**0.91**
Maximum duty cycle			**0.55**
Reflected output voltage		[V]	**208**
Copper losses		[W]	**0.48**
MOSFET losses		[W]	**0.63**
Sum losses		[W]	**5.78**
Efficiency			**0.86**

Transformer			
Core type			**E25/13/7**
Core material			**TP4A(TDG)**
Effective core area		[mm²]	**51.4**
Maximum flux density		[mT]	**251**
Inductance		[µH]	**1557**
Margin		[mm]	**0**
Primary turns		Turns	**110**
Primary copper wire size		AWG	**30**
Secondary turns (N_{S1})		Turns	**13**
Secondary copper wire size		AWG	**29**
Number of parallel secondary wires			**7**
Secondary turns (N_{S2})		Turns	**0**
Auxiliary turns		Turns	**8**
Leakage inductance		[µH]	**33.5**
Turns ratio			**8.46**
Primary layers		Layer	**3**
Secondary layers		Layer	**3**

Components			
Input capacitor	C13	[µF]	**110.0**
Output capacitor	C22	[µF]	**820.0**
LC filter capacitor	C24	[µF]	**220.0**
Output capacitor	C28	[µF]	**0.0**
LC filter capacitor	C210	[µF]	**0.0**
LC filter inductor	L21	[µH]	**2.2**
LC filter inductor	L22	[µH]	**0.0**
V_{CC} capacitor	C16	[µH]	**22.0**
ZC capacitor	C19	[pF]	**100**
ZC resistor	R15	[kΩ]	**27**
Sense resistor	R14	[Ω]	**1.10**
Clamping resistor	R11	[kΩ]	**138.0**
Clamping capacitor	C15	[nF]	**1**
Voltage divider	R25	[kΩ]	**1.2**
Voltage divider	R26	[kΩ]	**10.0**
Regulator component	R22	[kΩ]	**2.00**
Regulator component	R23	[kΩ]	**1.3**
Regulator component	R24	[kΩ]	**48.0**
Regulator component	C25	[nF]	**220.0**
Regulator component	C26	[nF]	**1.00**

13 Appendix B: WE transformer specification



PARAMETER		TEST CONDITIONS	VALUE
D.C. RESISTANCE	5-7	@20°C	1.79 ohms ±10%
D.C. RESISTANCE	1-2	@20°C	0.064 ohms ±10%
D.C. RESISTANCE	9-13	@20°C	0.024 ohms ±20%
INDUCTANCE	5-7	10kHz, 100mV, Ls	1.59mH ±10%
SATURATION CURRENT	5-7	20% rolloff from initial	1.3A
LEAKAGE INDUCTANCE	5-7	tie(1+2,9+13),100kHz, 100mV, Ls	24µH typ., 48µH max.
DIELECTRIC	1-13	tie(2+5), 5000VDC, 1 second	
DIELECTRIC	1-7	625VAC, 1 second	
TURNS RATIO		(6-7):(5-6)	1.29:1, ±1%
TURNS RATIO		(5-7):(9-13)	8.46:1, ±1%
TURNS RATIO		(5-7):(1-2)	13.75:1, ±1%

Figure 30 WE transformer specification

14 References

[1] ICE5QRxxxxAx datasheet, Infineon Technologies AG

[2] AN-201609_PL83_026 – 5th Generation Quasi-Resonant Design Guide

[3] Calculation Tool Quasi-Resonant CoolSET™ Generation 5

[4] Ultra Wide Input Range, HV-BIAS Supply for SMPS with ICE2B265 and SPA02N80

Revision history

Document version	Date of release	Description of changes
V1.0	10 Oct 2018	First release

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