

REF_5AR4770AG_3W1

About this document

Scope and purpose

This document is a reference design for a 3 W IoT off-line isolated power supply using the latest Infineon fifthgeneration Fixed Frequency (FF) CoolSET[™] ICE5AR4770AG. The power supply is designed with a universal input compatible with most geographic regions, and isolated output (+5 V/0.6 A).

Highlights of the 3 W IoT off-line isolated power supply:

- Very small form-factor design
- Simplified circuitry with good integration of power and protection features
- Auto-restart protection scheme to minimize interruption and enhance end-user experience

Intended audience

This document is intended for power supply design or application engineers, etc. who wish to design low-cost, highly reliable off-line Switched Mode Power Supply (SMPS) systems for:

- Applications related to the Internet of Things (IoT)
 - 1) Standby power supply
 - 2) Power supply for microcontrollers
 - 3) Power supply for standalone sensors operating on a wired/wireless interface bus
- USB-power supply embedded in a wall plug
- Intelligent wall plug switched by wireless (with relay)
- Metering applications
- General applications with small form factor in the power range 1 W to 3 W

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System introduction

1 System introduction

The Internet of Things (IoT) is connecting up ever smarter devices and machines. The fast-growing market around the IoT covers a wide range of applications. All of them have one thing in common, namely the ability to collect and exchange data with each other. The microcontrollers, sensors, actuators, etc. embedded in each of the devices stay connected to the network at all times. They are supplied by an efficient low-power and low-standby power supply, to which the Infineon fifth-generation FF CoolSET[™] family of integrated off-line power supply ICs is ideally suited.



Figure 1 IoT applications

Table 1 lists the system requirements for the IoT, and the corresponding Infineon solution is shown in the right-hand column.

	System requirement for IoT	Infineon solution – ICE5AR4770AG						
1	High efficiency under light-load conditions to meet ENERGY STAR requirements	New FF control and Active Burst Mode (ABM)						
2	Simplified circuitry with good integration of power and protection features	Embedded 700 V MOSFET and controller in DSO-12 package						
3	Robust system and protection features	Input Over Voltage Protection (OVP) and brown-in features						
4	Auto-restart protection scheme to minimize interruption and enhance end-user experience	All protections are in auto-restart						

 Table 1
 System requirements and Infineon solutions



System introduction

1.1 High efficiency under light-load conditions to meet ENERGY STAR requirements

During typical IoT operation, the power requirement fluctuates according to various use cases. Therefore, the efficiency should be optimized across the load range. It is crucial that the IoT power supply operates as efficiently as possible, because it will be in this particular state for most of the period. Under light-load conditions, losses incurred with the power switch are usually dominated by the switching operation. The choice of switching scheme and frequency play a crucial role in ensuring high conversion efficiency.

In this reference design, ICE5AR4770AG was primarily chosen due to its frequency-reduction switching scheme. Compared with a traditional FF flyback, the CoolSET[™] reduces its switching frequency from medium to light load, thereby minimizing switching losses. Therefore, an efficiency of more than 76 percent is achievable under 25 percent loading conditions.

1.2 Simplified circuitry with good integration of power and protection features

To relieve the designer of the complexity of PCB layout and circuit design, the CoolSET[™] is a highly integrated device with both a controller and HV MOSFET integrated into a single, space-saving DSO-12 package. These certainly help the designer to reduce component count as well as simplifying PCB layout for ease of manufacturing and cost.

1.3 Robust system and protection features

Comprehensive protection features are integrated into the FF CoolSET[™] ICE5AR4770AG, such as input line OVP, V_{cc} OV, V_{cc} Under Voltage (UV), over-load/open-loop, over-temperature and Current Sense (CS) short-to-GND. It also has limited charging current for V_{cc} short-to-GND and brown-in protection by utilizing R_{Brown-in} (R16D in Figure 3).

1.4 Auto-restart protection scheme to minimize interruption and enhance end-user experience

For an IoT power supply, it would be annoying for both the end user and the manufacturer if the system were to halt and latch after protection. To minimize interruption, the CoolSET[™] implements auto-restart mode for all abnormal protections.



Reference design board

2 Reference design board

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







Power supply specifications

3 Power supply specifications

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

Table 2 Specifications of REF_5AR4770AG_3W1								
Description	Symbol	Min.	Тур.	Max.	Units	Comments		
Input								
Voltage	V _{IN}	85	-	264	V AC	Two wires (no P.E.)		
Frequency	\mathbf{f}_{LINE}	47	50/60	64	Hz			
No-load input power	P_{stby_NL}	-	-	35	mW	230 V AC		
Output								
Output voltage	V _{OUT}	-	5	-	V	±3%		
Output current	I _{OUT}	0.03	0.3	0.6	А			
Output voltage ripple	V_{RIPPLE}	-	-	250	mV	20 MHz BW		
Max. power output	$P_{\text{OUT}_{Max}}$	-	-	3	W			
Efficiency								
Max. load	η	-	80	-	%	115 V AC/230 V AC		
Average efficiency at 25%, 50%, 75% and 100% of P _{OUT_Max}	$\eta_{\scriptscriptstyle {\mathrm{avg}}}$	79	-	-	%	115 V AC/230 V AC		
Environmental								
Conducted EMI			15		dB	Margin, CISPR 22 class B		
ESD			±8		kV	EN 61000-4-2		
Surge immunity					EN 61000-4-5			
Differential Mode (DM)			±2		kV	See footnote 1 at 11.19		
Common Mode (CM)			±4		kV	See footnote 1 at 11.19		
Ambient temperature	T _{amb}	0	-	50	°C	Free conviction, sea level		
Form factor		50 × 24 ×	× 16		mm ³	L×W×H		

Circuit diagram







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Circuit description

5 Circuit description

In this section, the design circuit for the SMPS unit will be briefly described by the different functional blocks. For details of the design procedure and component selection for the flyback circuitry please refer to the IC design guide [2] and calculation tool [3].

5.1 EMI filtering and line rectification

The input of the power supply unit is taken from the AC power grid, which is in the range of 85 V AC ~ 264 V AC. The fuse F1 is directly connected to the input line to protect the system in case of excess current entering the system circuit due to any fault. Following is the varistor VAR, which is connected across the input to absorb excessive energy during line surge transient. The resistor NTC not only reduces the in-rush current during start-up, but it also helps reduce the voltage increase on the bulk capacitors C13 and C13A during line surge transients. The bridge rectifier BR11 rectifies the AC input into DC voltage, filtered by the bulk capacitors C13 and C13A. Inductor L11 and capacitors C13 and C13A form a π filter to attenuate EMI noise.

5.2 Flyback converter power stage

The flyback converter power stage consists of C13A, transformer TR1, a primary HV MOSFET (integrated into ICE5AR4770AG), secondary rectification diodes D21, and secondary output capacitors and filtering C22, L21 and C24.

When the primary HV MOSFET turns on, some energy is stored in the transformer. When it turns off, the stored energy is released to the output capacitors and the output loading through the output diode D21.

The primary winding has two layers placed back to back for higher winding capacitance. This can reduce EMI by slowing the MOSFET switching. However, this can reduce efficiency. Winding capacitance can be tuned by adding a number of isolation tapes between the layers, depending on the EMI or efficiency need. If efficiency is a priority, interlacing primary and secondary winding is recommended, as it has lower leakage inductance. TR1 has single output windings, the V_{OUT} (5 V). The output rectification of V_{OUT} is provided by the diode D21 through filtering of C22, L21 and C24. All the secondary capacitors must be the low-ESR type, which can effectively reduce the switching ripple. Together with the Y-capacitor C12 across the primary and secondary side, the EMI noise can be further reduced to comply with CISPR 22 specifications.

5.3 Control of flyback converter through fifth-generation FF CoolSET[™] ICE5AR4770AG

5.3.1 Integrated HV power MOSFET

The ICE5AR4770AG CoolSET[™] is a 12-pin device in a DSO-12 package. It has been integrated with the new FF PWM controller and all necessary features and protections, and most importantly the 700 V power MOSFET, Infineon Superjunction (SJ) CoolMOS[™]. Hence the schematic is much simplified and the circuit design is made much easier.

5.3.2 Current Sensing (CS)

The ICE5AR4770AG is a current mode controller. The peak current is controlled cycle-by-cycle through the CS resistors R14 in the CS pin (pin 4) and so transformer saturation can be avoided and the system is more robust and reliable.



Circuit description

5.3.3 Feedback and compensation network

Resistor R25 is used to sense the V_{OUT} and feedback (FB) to the reference pin (pin 1) of error amplifier IC21 with reference to the voltage at resistor R26. A type 2 compensation network C25, C26 and R24 is connected between the output pin (pin 3) and the reference pin (pin 2) of the IC21 to stabilize the system. The IC21 further connects to pin 2 of the optocoupler, and IC12 with a series resistor R22 to convert the control signal to the primary side through the connection of pin 4 of the IC12 to the ICE5AR4770AG FB pin (pin 3) and complete the control loop. Both the optocoupler IC12 and the error amplifier IC21 are biased by V_{OUT}; IC12 is a direct connection while IC21 is through an R23 resistor.

The FB pin of ICE5AR4770AG is a multi-function pin which is used to select the entry burst power level (there are three levels available) through the resistor at the FB pin (R17) and also the burst-on/burst-off sense input during ABM.

5.4 Unique features of the fifth-generation FF CoolSET[™] ICE5AR4770AG to support the requirements of IoT power supply

5.4.1 Fast self-start-up and sustaining of V_{cc}

The IC uses a cascode structure to fast-charge the V_{cc} capacitor. Pull-up resistors R16, R16A, R16B and R16C connected to the gate pin (pin 10) are used to initiate the start-up phase. At first, 0.2 mA is used to charge the V_{cc} capacitor from 0 V to 1.1 V. This is a protection which reduces the power dissipation of the IC during V_{cc} short-to-GND condition. Thereafter, a much higher charging current of 3.2 mA will charge the V_{cc} capacitor until the V_{cc_ON} is reached. Start-up time of less than 80 ms is achievable with a V_{cc} capacitor of 4.7 μ F.

After start-up, the IC V_{cc} supply is sustained by the auxiliary winding of transformer TR1, which needs to support the V_{cc} to be above Under Voltage Lockout (UVLO) voltage (10 V typ.) through the rectifier circuit D12, R12 and C16.

5.4.2 CCM, DCM operation with frequency reduction

ICE5AR4770AG can be operated in either Discontinuous Conduction Mode (DCM) or Continuous Conduction Mode (CCM) with frequency-reduction features. This reference board is designed to operate in DCM. When the system is operating at maximum power, the controller will switch at the fixed frequency of 100 kHz. In order to achieve a better efficiency between light load and medium load, frequency reduction is implemented, and the reduction curve is shown in Figure 4. The V_{cs} is clamped by the current limitation threshold or by the PWM op-amp while the switching frequency is reduced. After the maximum frequency reduction, the minimum switching frequency is f_{OSC2_MIN} (43 kHz).



Circuit description



Figure 4 Frequency-reduction curve

5.4.3 Frequency jittering with modulated gate drive

The ICE5AR4770AG has a frequency jittering feature with modulated gate drive to reduce the EMI noise. The jitter frequency is internally set at 100 kHz (±4 kHz), and the jitter period is 4 ms.

5.4.4 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. ICE5AR4770AG provides comprehensive protection to ensure the system is operating safely. This includes V_{IN} LOVP, brown-in, V_{cc} OV and UV, over-load, over-temperature (controller junction), CS short-to-GND and V_{cc} short-to-GND. When those faults are found, the system will enter protection mode. Once the fault is removed, the system resumes normal operation. A list of protections and failure conditions is shown in the table below.

Protection function	Failure condition	Protection mode					
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					
V _{IN} LOVP	V_{VIN} greater than 2.85 V	Non-switch auto-restart					
Over-load	$V_{\mbox{\tiny FB}}$ greater than 2.75 V and lasts for 54 ms	Odd-skip auto-restart					
Over-temperature (junction temperature of controller chip only)	TJ greater than 140°C	Non-switch auto-restart					
CS short-to-GND	V_{cs} less than 0.1 V, lasts for 0.4 μs and three consecutive pulses	Odd-skip auto-restart					
V _{cc} short-to-GND	V_{VCC} less than 1.1 V, $I_{VCC_Charge1} \approx -0.2$ mA	Cannot start up					
(V_{VCC} = 0 V, start-up = 50 M Ω and V_{DRAIN} = 90 V)							
Brown-in	V _{GATE} less than 20 V	Cannot start up					

Table 3 Protection functions of ICE5AR4770AG



Circuit description

5.5 Clamper circuit

A clamper RCD network normally added in parallel to the primary inductance of the transformer (pins 1 and 2 of TR1) is removed in this reference board to save on the BOM and increase efficiency. Without a clamper RCD, maximum drain voltage of the CoolMOS[™] is still less, and 650 V in worst-case conditions, which gives a 7 percent margin from maximum drain-source breakdown voltage of 700 V.

5.6 PCB design tips

For a good PCB design layout, there are several points to note.

- The power loop needs to be as small as possible (see Figure 5). There are two power loops in the demo design; one from the primary side and one from the secondary side. For the primary side, it starts from the bulk capacitor (C13A) positive to the bulk capacitor negative. The power loop components include C13, the main primary transformer winding (pin 1 and pin 2 of TR1), the drain pin and the CS pin of the CoolSET[™] IC11 and CS resistor. For the secondary side, the 5 V output starts from the secondary transformer windings (pin 9 of TR1), output diode D21 and output capacitors C22, L21 and C24.
- Star-ground concept should be used to avoid unexpected HF noise coupling affecting control. The ground of the small-signal components, e.g. C17, C18 and C111, and the emitter of the optocoupler (pin 3 of IC12) etc. should connect directly to the IC ground (pin 12 of IC11). Then it connects to the negative terminal of the C13A capacitor directly.



Figure 5 PCB layout tips

- Separating the HV components and LV components, e.g. V_{BUS} and CoolSET[™] drain at the top part of the PCB (see Figure 5) and the other LV components at the lower part of the PCB, can reduce the spark-over chance of the high-energy surge during ESD or a lightning surge test.
- Pour the PCB copper on the drain pin of the CoolSET[™] over as wide an area as possible to act as a heatsink.

5.7 EMI reduction tips

EMI compliance is always a challenge for the power supply designer. There are several critical points to consider in order to achieve satisfactory EMI performance:

• A proper transformer design can significantly reduce EMI. Low leakage inductance can incur a low switching spike and HF noise. Interlaced winding technique is the most common practice to reduce leakage inductance.¹ Winding shield, core shield and whole transformer shield are also some of the techniques that can be used to reduce EMI.

¹ Not implemented with this reference design.



Circuit description

- Input CMC and X-capacitor greatly reduces EMI but it is costly and impractical, especially for low-power applications.¹
- Using a short power loop design in the PCB (as described in section 5.6) and terminating to the low-ESR capacitor such as C13A for primary-side loop and C22 for the secondary-side loop can help to reduce the switching ripple which comes out to the input terminals V_{IN}. In addition, adding a low-ESR ceramic capacitor in parallel to the C13A/C22 can help to further reduce the switching ripple.
- The Y-capacitor C12 has a function to return the HF noise to the source (negative of C13A) and reduce the overall HF noise going out to the input terminals. The larger capacitance is more effective. However, larger values would introduce larger leakage current and may fail the safety requirements.
- Adding a drain to the CS pin capacitor for the MOSFET of the CoolSET[™] can reduce the high switching noise. However, it also reduces efficiency.¹
- Adding a ferrite bead to the critical nodes of the circuit can help to reduce the HF noise, such as on the connecting path between the transformer and the drain pin, output diode D21, Y-capacitor C12, etc.¹
- Adding additional output CMC can also help to reduce the HF noise.¹

 $^{^{\}rm 1}$ Not implemented with this reference design.



_ ...

6.1 Top side

Figure 6 Top-side copper and component legend

6.2 Bottom side



Infineon

5V x 0.0

Figure 7 Bottom-side copper and component legend



Figure 8 Top and bottom side copper



7 BOM

BOM (V 0.2)

Table 4

No.	Designator	Description	Part number	Manufacturer	Quantity
1	+5 V	KEY_PN5000	5000		1
2	BR11	D1UBA80-7062	D1UBA80-7062	Shindengen	1
3	C12	1 nF, 500 V	DE1E3RA102MA4BQ01F	Murata	1
4	C13, C13A	4.7 μF, 400 V	860021374008	Wurth Electronic	2
5	C16	4.7 μF, 50 V	GRM31CR71H475KA12	Murata	1
6	C17, C25	100 nF, 50 V	885012206095	Wurth Electronic	2
7	C18	1 nF, 50 V	885012206083	Wurth Electronic	1
8	C22	820 μF, 6.3 V	875075155009	Wurth Electronic	1
9	C24	10 μF, 25 V	885012208069	Wurth Electronic	1
10	C26	68 pF, 50 V	885012006056	Wurth Electronic	1
11	C111	22 nF, 50 V	885012206091	Wurth Electronic	1
12	Com, N	KEY_PN5001	5001		2
13	D12	200 V, 0.8 A	RS1DL		1
14	D21	50 V, 8 A	V8PAN50-M3/I		1
15	F1	0.5 A, 250 V	MCPMP 0.5 A 250 V		1
16	IC11	ICE5AR4770AG	ICE5AR4770AG	Infineon Technologies	1
17	IC12	VOL618A-3X001T	VOL618A-3X001T		1
18	IC21	TL431BQDBZR	TL431BQDBZR		1
19	L	KEY_PN5002	5002		1
20	L11	1000 μH	7447462102	Wurth Electronic	1
21	L21	2.2 μΗ	DFE201610E-2R2M=P2	Murata	1
22	NTC	4.7 R	B57153S0479M0	Epcos	1
23	R12	27 R (0603)	AC0603FR-0727RL		1
24	R14	3.9 R (1206)	ERJ8RQF3R9V		1
25	R16, R16A, R16B, R16C, R16D	15 MEGR/150 V (0805)	RC0805JR-0715ML		5
26	R17	750 kR (0603)	CRCW0603750KFK		1
27	R18, R18A	8.2 MEGR/400 V (0805)	WK08V825 JTL		2
28	R19	121 kR (0603)	ERJ3EKF1213V		1
29	R22	120 R (0603)	RC0603FR-07120RL		1
30	R23	1.2 kR (0603)	RC0603FR-071K2L		1
31	R24, R25, R26	10 k (0603)	RC0603FR-0710KL		3
32	R25A	0 R(0603)	RC0603JR-070RL		1
33	TR1	1.96 mH (126:10:28) (EE13 7 4)	750344058 (Rev. 02)	Wurth Electronic	1
34	VAR	300 V	B72650M0301K072	Epcos	1
35	РСВ	50 mm × 24 mm (L × W), single layer, 1 Oz., FR-4			1

infineon



Transformer specification

8 Transformer specification

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

- Core and materials: EE13/7/4, TP4A (TDG)
- Bobbin: 070-6258 (9-terminal, SMD, horizontal version)
- Primary inductance: L_p = 1.96 mH (±10 percent), measured between pin 1 and pin 2
- Manufacturer and part number: Wurth Electronics Midcom (750344058) Rev. 02







9 Measurement data and graphs

Table 5Measurement data

Input (V AC/Hz)	Description	P _{IN} (W)	V _{о∪т} (V _{DC})	І _{оυт} (А)	Р _{оυт} (W)	η (%)	η _{avg} (%)	P _{in_OLP} (W)	I _{out_OLP} (A)
	No load	0.019	5.01	0.000					
	Min. load	0.22	5.00	0.030	0.15	68.18			
	1/10 load	0.39	5.00	0.059	0.30	75.64			
85/60	1/4 load	0.93	4.99	0.150	0.75	80.48		4.89	0.79
	Typ. load	1.83	4.98	0.300	1.49	81.64	01.24		
	3/4 load	2.74	4.96	0.451	2.24	81.64	81.24		
	Max. load	3.65	4.94	0.600	2.96	81.21			
	No load	0.020	5.01	0.000					
	Min. load	0.21	5.00	0.030	0.15	71.43			
	1/10 load	0.40	5.00	0.061	0.31	76.25			
115/60	1/4 load	0.93	4.97	0.150	0.75	80.16		4.93	0.81
	Typ. load	1.82	4.98	0.300	1.49	82.09	91 50		
	3/4 load	2.72	4.96	0.451	2.24	82.24	01.59		
	Max. load	3.62	4.94	0.600	2.96	81.88			
	No load	0.029	5.01	0.000					
	Min. load	0.23	5.00	0.030	0.15	65.22			
	1/10 load	0.43	5.00	0.061	0.31	70.93			
230/50	1/4 load	0.96	4.99	0.150	0.75	77.97		5.30	0.87
	Typ. load	1.86	4.98	0.300	1.49	80.32	70.00		
	3/4 load	2.78	4.96	0.451	2.24	80.47	19.00		
	Max. load	3.67	4.94	0.600	2.96	80.76			
	No load	0.032	5.01	0.000					
	Min. load	0.24	5.00	0.030	0.15	62.50			
	1/10 load	0.45	5.00	0.061	0.31	67.78			
264/50	1/4 load	0.98	4.99	0.150	0.75	76.38		5.50	0.90
	Typ. load	1.89	4.98	0.300	1.49	79.05	78.86		
	3/4 load	2.80	4.96	0.451	2.24	79.89	10.00		
	Max. load	3.70	4.94	0.600	2.96	80.11			
 No-load 	d condition (no	load)		:5V	at 0 A				
Minimum load condition (min. load) : 5 V at 30 m A									
 1/10 loa 	ad condition (1	/10 load)		:5 V	at 60 mA				
 1/4 load 	d condition (1/4	4 load)		:5V	at 0.15 A				
• Typical load condition (typ. load) : 5 V at 0.3 A									

- 3/4 load condition (3/4 load) : 5 V at 0.45 A
- Maximum load condition (max. load) : 5 V at 0.6 A

9.1 Load regulation





9.2 Line regulation























9.5 Maximum output current







Thermal measurement

10 Thermal measurement

The thermal testing of the demo 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 85 V AC and 264 V AC.

Table 0	component temperature at fut toad (5 v, 0.0 Å) under Tamb – 25 C						
Circuit code	Major component	85 V AC (°C)	264 V AC (°C)				
IC11	ICE5AR4770AG	39.3	46.6				
TR1	Transformer	42.0	44.6				
BR1	Bridge diode	34.9	31.3				
D21	+5 V output diode	47.8	48.1				
	Ambient	25.0	25.0				

Table 6Component temperature at full load (5 V, 0.6 A) under Tamb = 25°C





Waveforms

11.1

Waveforms 11

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

TELEDYNE LECRO Everywhereyourook X1= -10.4** 10.0 ms/dw Stop 6 80 MS/s Edge Pos C1 (yellow): V AC; C2 (purple): Vvcc; C3 (blue): Vout (5 V) C1 (yellow): V AC; C2 (purple): V_{VCC}; C3 (blue): V_{OUT} (5 V) V_{IN} = 85 V AC, max. load; start-up time: ≈ 71 ms V_{IN} = 264 V AC, max. load; start-up time: ≈ 62 ms

Start-up at low/high AC-line input voltage with maximum load



11.2 Soft-start







wavefor

11.3 Switching waveform at maximum load



Figure 18 Drain and CS voltage at maximum load

11.4 Frequency jittering and modulated gate drive



Figure 19 Frequency jittering and modulated gate drive



Waveforms

11.5 Output ripple voltage at maximum load

• Probe terminal end with decoupling capacitor of 0.1 μ F (ceramic) and 1 μ F (electrolytic), 20 MHz BW



Figure 20 Output ripple voltage at maximum load

11.6 Output ripple voltage in ABM 50 mW load

- Probe terminal end with decoupling capacitor of 0.1 μ F (ceramic) and 1 μ F (electrolytic), 20 MHz BW
- Load: 50 mW (5 V, 10 mA)







Waveforms

11.7 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
- 5 V load change from 10 percent to 100 percent, 100 Hz, 0.4 A/μs slew rate



Figure 22 Load transient response

11.8 Entering ABM

• Load change from 3 W (5 V, 0.6 A) to 0.1 W (5 V, 0.02 A)







Waveforms

11.9 During ABM

• Load: 0.11 W (5 V, 0.022 A)





11.10 Leaving ABM

• Load change from 0.1 W (5 V, 0.02 A) to full load







Waveforms

11.11 Line 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



Figure 26 Line OVP

11.12 Brown-in protection by utilizing R_{Brown-in} (R16D in Figure 3)

• Increase AC-line voltage gradually at full load until the system starts up







Waveforms

11.13 Output OVP by utilizing V_{cc} OVP (odd-skip auto-restart)

• Short R26 resistor during system operation at no load



Figure 28 V_{cc} OVP

11.14 V_{cc} UVP (auto-restart)

• Short R17 while the system is operating at full load







Waveforms

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

• V_{OUT} (5 V) short-to-GND at 264 V AC



Figure 30 Over-load protection and max. voltage stress for MOSFET and output diode (D21)

11.16 V_{cc} short-to-GND protection

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



Figure 31 V_{cc} short-to-GND protection

11.17 Conducted emissions (EN 55022 class B)

Equipment: Schaffner SMR4503 (receiver); standard: EN 55022 (CISPR 22) class B; test conditions: V_{IN} = 115 V AC and 230 V AC; load: 3 W (5 V, 8.3 Ω).

• Pass conducted emissions EN 55022 (CISPR 22) class B with greater than 16 dB margin for quasi-peak measurement.



0.2

Level Pk

42.0

39.6

N

Ν

0.15 MHz

Ν

Ν

Frequency

0.7140

0.9060

NNB41.trd EN 55022 class B CE

Transducer Limit Line

3 W flyback IoT off-line isolated power supply reference board using 5th generation fixed frequency CoolSET™ (ICE5AR4770AG)



Waveforms





AV



_ _ _ _ _ _

24.7 N

19.5 N

Level AV

Level QP

_ _ _ _ _ _ _ _ _

34.7

32.5

20

Limit AV

_ _ _ _ _ _ _ _ _ _ _

46.0

46.0

30 MHz

Limit QP

56.0

56.0



Waveforms



Figure 34 Conducted emissions at 230 V AC-line and 3 W load – greater than 16 dB margin



Figure 35 Conducted emissions at 230 V AC-neutral and 3 W load – greater than 20 dB margin



Waveforms

11.18 ESD immunity (EN 61000-4-2)

This system was subjected to a ±8 kV ESD test according to EN 61000-4-2 for both contact and air discharge. A test failure was defined as non-recoverable.

• Air discharge: pass ±8 kV; contact discharge: pass ± 8 kV.

Description	ESD		Number	of strikes	
Description	test	Level	+ V out	-V _{out}	l'est result
	Contact	+8 kV	10	10	Pass
115 V AC, 3 W	Contact	-8 kV	10	10	Pass
(5 V, 8.3 Ω)	٨٠	+8 kV	10	10	Pass
	All	-8 kV	10	10	Pass
	Contact	+8 kV	10	10	Pass
230 V AC, 3 W	Contact	-8 kV	10	10	Pass
(5 V, 8.3 Ω)	٨٠	+8 kV	10	10	Pass
	All	-8 kV	10	10	Pass

Table 7System ESD test result

11.19 Surge immunity (EN 61000-4-5)

This system was subjected to a surge immunity test (±2 kV DM and ±4 kV CM) according to EN 61000-4-5. A test failure was defined as a non-recoverable.

• DM: pass ±2 kV¹; CM: pass ±4 kV¹.

Table 8System surge immunity test result

Description	Teet	Level -		Number of strikes				Toot recult
Description	Test			0°	90°	180°	270°	rescresult
	DM	+2 kV	$L \rightarrow N$	3	3	3	3	Pass ¹
	DM	-2 kV	$L \rightarrow N$	3	3	3	3	Pass ¹
115 V AC, 3 W		+4 kV	$L \rightarrow G$	3	3	3	3	Pass ¹
(5 V, 8.3 Ω)	СМ	+4 kV	$N \to G$	3	3	3	3	Pass ¹
		-4 kV	L→G	3	3	3	3	Pass ¹
		-4 kV	$N \to G$	3	3	3	3	Pass ¹
	DM	+2 kV	$L \rightarrow N$	3	3	3	3	Pass ¹
		-2 kV	$L \rightarrow N$	3	3	3	3	Pass ¹
230 V AC, 3 W	СМ	+4 kV	L→G	3	3	3	3	Pass ¹
(5 V, 8.3 Ω)		+4 kV	$N \to G$	3	3	3	3	Pass ¹
		-4 kV	$L \rightarrow G$	З	3	3	3	Pass ¹
		-4 kV	$N \to G$	3	3	3	3	Pass ¹

 $^{^{\}scriptscriptstyle 1}\,$ 1. Change F1 to 36911600000 (300 V, 1.6 A time-lag fuse).

^{2.} Change VAR to B72207S2301K101 (300 V, 0.25 W varistor).

^{3.} Disable line OVP by clamping V_{IN} pin voltage less than 2.75 V (add 2.4 V Zener diode at V_{IN} pin to GND pin).



Appendix A: Transformer design and spreadsheet [3]

12 Appendix A: Transformer design and spreadsheet [3]

Design procedure for FF flyback converter using CoolSET[™] 5xRxxxxAG/BZS (version 1.0) Project ICE5AR4770AG Application 85 ~ 264 V AC and 3 W (5 V, 0.6 A) single-output, isolated flyback CoolSET™ ICE5AR4770AG Date 18 June 2018 Revision 0.2 Enter design variables in orange-colored cells Read design results in green-colored cells Equation numbers are according to the Design Guide. Select component values based on standard values available. Voltage/current rating does not include design margin, voltage spikes and transient currents. In "Output regulation", only fill in either isolated or non-isolated, whichever is applicable. Description Eq.# Parameter Unit Value Input, output, CoolSET[™] specs Line input Minimum AC input voltage V AC_{Mir} Input [V] 85 Maximum AC input voltage Input V AC_{Max} [V] 264 Line frequency **f**_{AC} [Hz] Input 60 V DC_{Ripple} Bus capacitor DC ripple voltage [V] 27 Input **Output 1 specs** Input Output voltage 1 V_{Out1} [V] 5 Input Output current 1 lout1 [A] 0.6 Input Forward voltage of output diode 1 [V] 0.6 V_{FOut1} Input Output ripple voltage 1 [V] 0.1 V_{OutRipple1} [W] 3 Result Output power 1 P_{Out1} Eq. 001 Auxiliary Vcc voltage Input Vvcc [V] 15 Input Forward voltage of Vcc diode (D2) VFVC [V] 0.6 Power Input Efficiency 0.8 PoutNom Result Nominal output power Eq. 003 [W] 3.00 Maximum output power for over-load protection [W] 3.3 Input POUT May PInMax [W] Result Maximum input power for over-load protection Eq. 006 4.13 Minimum output power Input POUT_Mi [W] 0.3 **Controller/CoolSET™** CoolSET[™] -ICE5AR4770AG [Hz] Input Switching frequency fe 100000 Input Targeted max. drain source voltage [V] 600 **V**_{DSMax} Input Max. ambient temperature Tama [°C 50 Diode bridge and input capacitor **Diode bridge** Power factor 0.6 Input cosø Result Maximum AC input current Eq. 007 [A] 0.081 ACRMS Peak voltage at V AC_{Max} Eq. 008 V DC_{MaxPk} [V] 373.35 Result Input capacitor V DC_{MinPk} Result Peak voltage at V AC_{Min} Eq. 009 [V] 120.21 Result Selected minimum DC input voltage Eq. 010 V DC_{MinSet} [V] 93.21 Result Discharging time at each half-line cycle 6.52 Eq. 011 TD [ms] Result Required energy at discharging time of input capacitor Eq. 012 Win [Ws] 0.03 CINCal Result Calculated input capacitor Eq. 013 [µF] 9.34 Select input capacitor (C1) Ci [μF] Input 9.4

Calculated minimum DC input voltage

Result

Eq. 015

V DC_{Mir}

93.42

[V]



Appendix A: Transformer design and spreadsheet [3]





Primary inductance and winding currents							
Input	Reflection voltage		V _{RSET}	[V]	70.56		
Result	Maximum duty cycle	Eq. 016	D _{Max}		0.43		
Input	Select current ripple factor		K _{RF}		1		
Result	Primary inductance	Eq. 017	Lp	[H]	1.96E-03		
Result	Primary turn-on average current	Eq. 018	I _{AV}	[A]	0.10		
Result	Primary peak-to-peak current	Eq. 019	ΔI	[A]	0.21		
Result	Primary peak current	Eq. 020	I _{PMax}	[A]	0.21		
Result	Primary valley current	Eq. 021	Ivalley	[A]	0.00		
Result	Primary RMS current	Eq. 022	I _{PRMS}	[A]	0.078		
Select core ty	pe						
Input	Select core type				1		
Result	Core type				EE13/7/4		
Result	Core material				TP4A (TDG)		
Result	Maximum flux density		B _{Max}	[T]	0.26		
Result	Cross-sectional area		A _e	[mm²]	12.4		
Result	Bobbin width		BW	[mm]	7.49		
Result	Winding cross-section		A _N	[mm ²]	13.48		
Result	Average length of turn		l _N	[mm]	27.4		
Winding calcu	lation						
Result	Calculated minimum number of primary turns	Eq. 023	N _{PCal}	Turns	124.68		
Input	Select number of primary turns		N _P	Turns	126		
Result	Calculated number of secondary 1 turns	Eq. 024	N _{S1Cal}	Turns	10.00		
Input	Select number of secondary 1 turns		N _{S1}	Turns	10		
Result	Calculated number of auxiliary turns	Eq. 026	NvccCal	Turns	27.86		
Input	Select number of auxiliary turns		Nvcc	Turns	28		



Appendix A: Transformer design and spreadsheet [3]

Result	Calculated V _{CC} voltage	Eq. 027	V _{VccCal}	[V]	15.08
Post calculati	on				
Result	Primary to secondary 1 turns ratio	Eq. 028	N _{PS1}		12.60
Result	Post calculated reflected voltage	Eq. 030	V _{RPost}	[V]	70.56
Result	Post calculated maximum duty cycle	Eq. 031	D _{MaxPost}		0.43
Result	Duty cycle prime	Eq. 032	D _{Max} '		0.57
Result	Actual flux density	Eq. 033	B _{MaxAct}	[T]	0.257
Result	Maximum DC input voltage for CCM operation	Eq. 034	V DC _{maxCCM}	[V]	93.42
Transformer	winding design			r 1	
Input	Margin according to safety standard		M	[mm]	0
Input	Copper space factor	Ex 025		[mm]	0.4
Result	Effective bobbin window	Eq. 035	BVVE	[mm]	1.5
Result	Effective winding cross-section	Eq. 036	A _{Ne}	[mm ⁻]	13.5
Input	Primary winding area factor				0.50
Input	Secondary 1 winding area factor		AF _{NS1}		0.45
Input Drimory wind	Auxiliary winding area factor		AF _{NVcc}		0.05
Primary wind	Calculated wire conner cross sectional area	Eq. 027	Angl	[mm ²]	0.0214
Posult		Eq. 039		[]	24
Input		Lq. 030			25
Input	Select number of parallel wire		AWGp		1
Rosult	Wire copper diameter	Eq. 039	d-	[mm]	0.14
Result	Wire copper cross sectional area	Eq. 040	Δp	[mm ²]	0.14
Posult	Wire current density	Eq. 040	Ap Sa	[///mm ²]	4 77
Input		Eq. 041		[A/IIIII]	4.11
Rocult		Eq. 042	NI -	Turns/lavor	0.01
Posult	Number of layers	Eq. 042			40
Secondary 1	winding	Lq. 043	LIIP	Layers	3
Result	Calculated wire copper cross-sectional area	Fa 044	ANSICAL	[mm ²]	0 2426
Result	Calculated maximum wire size	Eq. 045	AWGs1cal	[]	23
Input	Select wire size	_q, o to	AWG _{S1}		25
Input	Select number of parallel wire		nws1		1
Result	Wire copper diameter	Ea. 046	dsi	[mm]	0.4572
Result	Wire copper cross-sectional area	Ea. 047	Ası	[mm ²]	0.1642
Result	Peak current	Ea. 048	IS1Max	[A]	2.5859
Result	RMS current	Eq. 049	Isirms	[A]	1.1269
Result	Wire current density	Eq. 050	S _{S1}	[A/mm ²]	6.86
Input	Insulation thickness		INS ₅₁	[mm]	0.01
Result	Turns per layer	Eq. 051	NL _{S1}	Turns/layer	10
Result	Number of layers	Eq. 052	Ln _{S1}	Layers	1
RCD clamper	and CS resistor				
RCD clamper	circuit				
Input	Leakage inductance percentage		L _{LK%}	[%]	0.36
Result	Leakage inductance	Eq. 062	Llk	[H]	7.05E-06
Result	Clamping voltage	Eq. 063	V _{Clamp}	[V]	156.09
Result	Calculated clamping capacitor	Eq. 064		[nF]	0.01
Input	Select clamping capacitor value (C2)		C _{clamp}	[nF]	1
Result	Calculated clamping resistor	Eq. 065	RclampCal	[kΩ]	3123.9
Input	Select clamping resistor value (R4)		R _{clamp}	[kΩ]	3000
CS resistor					
Input	CS threshold value from datasheet		V _{cs_N}	[V]	0.8
Result	Calculated CS resistor (R8A, R8B)	Eq. 066	R _{sense}	[Ω]	3.90
Ouput rectifie	er				

Secondary 1 output rectifier



Appendix A: Transformer design and spreadsheet [3]

Result	Diode reverse voltage Eq. 067 V _{RDiode}		V _{RDiode1}	[V]	34.63
Result	Diode RMS current Is 1RMS		I _{S 1RMS}	[A]	1.13
Input	Max. voltage undershoot at output capacitor		ΔV _{Out1}	[V]	0.15
Input	Number of clock periods		n _{cp1}		20
Result	Output capacitor ripple current	Eq. 068	I _{Ripple1}	[A]	0.95
Result	Calculated minimum output capacitor	Eq. 069	Cout1Cal	[μF]	800
Input	Select output capacitor value (C152)		C _{Out1}	[μF]	820
Input	ESR (Z _{max}) value from datasheet at 100 kHz		R _{esr1}	[Ω]	0.008
Input	Number of parallel capacitors		NC _{COut1}		1
Result	Zero frequency of output capacitor	Eq. 070	f _{ZCOut1}	[kHz]	24.26
Result	First-stage ripple voltage	Eq. 071	V _{Ripple1}	[V]	0.020687
Input	Select LC filter inductor value (L151)		Lout1	[µH]	2.2
Result	Calculated LC filter capacitor	Eq. 072	CLCCal1	[μF]	19.6
Input	Select LC filter capacitor value (C153)		C _{LC1}	[µF]	20
Result	LC filter frequency	Eq. 073	f _{LC1}	[kHz]	23.99
Result	Second-stage ripple voltage	Eq. 074	V _{2ndRipple1}	[mV]	1.13
Vcc diode and	capacitor		•		
Result	Auxiliary diode reverse voltage (D2)	Eq. 083	VRDiodeVCC	[V]	98.05
Input	Soft-start time from datasheet		t _{ss}	[ms]	12
Input	Ivcc,Charge3 from datasheet		Ivcc_charge3	[mA]	3
Input	Vcc on-threshold		Vvcc_on	[V]	16
Input	V _{cc} off-threshold		V _{VCC_OFF}	[V]	10
Result	Calculated Vcc capacitor	Eq. 084	Cvcccal	[µF]	6.00
Input	Select Vcc capacitor (C3)		Cvcc	[µF]	4.7
Input	V _{cc} short threshold from datasheet		V _{VCC_SCP}	[V]	1.1
Input	Ivcc_Charge1 from datasheet		Ivcc_Charge1	[mA]	0.2
Result	Start-up time	Eq. 085	t _{StartUp}	[ms]	49.193
Calculation o	flosses				
Calculation o Input diode b	f losses ridge				
Calculation o Input diode b Input	f losses ridge Diode bridge forward voltage		V _{FBR}	[V]	1
Calculation of Input diode b Input Result	f losses ridge Diode bridge forward voltage Diode bridge power loss	Eq. 086	V _{FBR} P _{DIN}	[V] [W]	1 0.16
Calculation o Input diode b Input Result Transformer	f losses ridge Diode bridge forward voltage Diode bridge power loss copper	Eq. 086	V _{FBR} P _{DIN}	[V] [W]	1 0.16
Calculation o Input diode b Input Result Transformer Result	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance	Eq. 086	V _{FBR} P _{DIN} Rpcu	[V] [W] [mΩ]	1 0.16 3642.43
Calculation o Input diode b Input Result Transformer Result Result	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Secondary 1 winding copper resistance	Eq. 086 Eq. 087 Eq. 088	V _{FBR} P _{DIN} R _{PCu} R _{S1Cu}	[V] [W] [mΩ] [mΩ]	1 0.16 3642.43 28.71
Calculation o Input diode b Input Result Transformer Result Result	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Secondary 1 winding copper resistance Primary winding copper loss	Eq. 086 Eq. 087 Eq. 088 Eq. 090	V _{FBR} P _{DIN} R _{PCu} P _{PCu}	[V] [W] [mΩ] [mΩ] [mW]	1 0.16 3642.43 28.71 22.01
Calculation o Input diode b Input Result Transformer Result Result Result	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Secondary 1 winding copper resistance Primary winding copper loss Secondary 1 winding copper loss	Eq. 087 Eq. 087 Eq. 088 Eq. 090 Eq. 091	VFBR PDIN RPCu RS1Cu PPCu PS1Cu	[V] [W] [mΩ] [mΩ] [mW]	1 0.16 3642.43 28.71 22.01 36.46
Calculation o Input diode b Input Result Transformer Result Result Result Result	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Secondary 1 winding copper resistance Primary winding copper loss Secondary 1 winding copper loss	Eq. 087 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093	VFBR PDIN RPCU RSICU PPCU PSICU PCU	[V] [W] [mΩ] [mΩ] [mW] [mW] [W]	1 0.16 3642.43 28.71 22.01 36.46 0.0585
Calculation o Input diode b Input Result Transformer Result Result Result Result Output rectif	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Secondary 1 winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Total transformer copper loss	Eq. 086 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093	V _{FBR} P _{DIN} R _{PCu} R _{SICu} P _{PCu} P _{SICu} P _{Cu}	[V] [W] [mΩ] [mΩ] [mW] [mW] [W]	1 0.16 3642.43 28.71 22.01 36.46 0.0585
Calculation o Input diode b Input Result Transformer Result Result Result Result Output rectif Result	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Secondary 1 winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Total transformer copper loss ier diode Secondary 1 diode loss	Eq. 087 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093	VFBR PDIN RPCu RS1Cu PPCu PS1Cu PCu PDiode1	[W] [WΩ] [mΩ] [mW] [mW] [W]	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.68
Calculation o Input diode b Input Result Transformer Result Result Result Result Output rectif Result RCD clamper	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Secondary 1 winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Secondary 1 winding copper loss ier diode Secondary 1 diode loss circuit	Eq. 086 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093 Eq. 094	VFBR PDIN RPCu RS1Cu PPCu PS1Cu PCu PCu PDiode1	[V] [W] [mΩ] [mΩ] [mW] [W] [W]	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.68
Calculation o Input diode b Input Result Transformer Result Result Result Result Output rectif Result RCD clamper Result CS register	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Primary winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Secondary 1 winding copper loss Total transformer copper loss ier diode Secondary 1 diode loss circuit RCD clamper loss	Eq. 086 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093 Eq. 094 Eq. 096	V _{FBR} P _{DIN} R _{PCu} R _{SICu} P _{PCu} P _{SICu} P _{Cu} P _{Cu} P _{Diode1}	[V] [W] [mΩ] [mΩ] [mW] [W] [W] [W]	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.68 0.68
Calculation o Input diode b Input Result Transformer Result Result Result Result Output rectif Result RCD clamper Result CS resistor Result	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Primary winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Secondary 1 winding copper loss Total transformer copper loss Total transformer copper loss ier diode Secondary 1 diode loss circuit RCD clamper loss	Eq. 086 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093 Eq. 094 Eq. 096	V _{FBR} P _{DIN} R _{PCu} R _{SICu} P _{PCu} P _{SICu} P _{Cu} P _{Cu} P _{Diode1} P _{Clamper}	[V] [W] [mΩ] [mΩ] [mW] [W] [W] [W]	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.68 0.68
Calculation o Input diode b Input Result Transformer Result Result Result Result Output rectif Result RCD clamper Result CS resistor Result MOSFET	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Secondary 1 winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Secondary 1 winding copper loss ier diode Secondary 1 diode loss circuit RCD clamper loss	Eq. 087 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093 Eq. 094 Eq. 094	VFBR PDIN RPCu RS1Cu PPCu PS1Cu PCu PCu PCu PCu PCu PCu PCu PClamper	[V] [W] [mΩ] [mW] [mW] [W] [W] [W]	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.68 0.02
Calculation o Input diode b Input Result Transformer Result Result Result Result Output rectif Result RCD clamper Result CS resistor Result MOSFET	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Secondary 1 winding copper loss Total transformer copper loss Total transformer copper loss ier diode Secondary 1 diode loss circuit RCD clamper loss CS resistor loss	Eq. 086 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093 Eq. 094 Eq. 096 Eq. 097	V _{FBR} P _{DIN} R _{PCu} R _{SICu} P _{PCu} P _{SICu} P _{Cu} P _{Diode1} P _{Clamper} P _{Cs} R _{DSON} at T _J =	[V] [W] [mΩ] [mΩ] [mW] [W] [W] [W] [W]	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.68 0.68 0.02
Calculation o Input diode b Input Result Transformer Result Result Result Result Output rectif Result RCD clamper Result CS resistor Result MOSFET Input	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Secondary 1 winding copper loss Secondary 1 winding copper loss Secondary 1 winding copper loss Total transformer copper loss ier diode Secondary 1 diode loss circuit RCD clamper loss CS resistor loss RDSON from datasheet	Eq. 087 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093 Eq. 094 Eq. 094 Eq. 096 Eq. 097	V _{FBR} P _{DIN} RPCu RSICu PPCu PSICu PCu PCu PCu PCu PCu PCu PCu RDSON at TJ = 125°C	[V] [W] [mΩ] [mΩ] [mW] [W] [W] [W] [W] [Ω] [Ω]	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.68 0.02 0.02 0.02 8.73 3.4
Calculation o Input diode b Input Result Transformer Result Result Result Result Output rectif Result CS resistor Result CS resistor Result MOSFET Input	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Secondary 1 winding copper loss Total transformer copper loss Total transformer copper loss ier diode Secondary 1 diode loss circuit RCD clamper loss CS resistor loss Rosow from datasheet Co(er) from datasheet	Eq. 086 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093 Eq. 094 Eq. 096 Eq. 097	V _{FBR} P _{DIN} RPCu RSICu PPCu PSICu PCu PCu PCu PCu PCu PCu PCu PCu RDSON at TJ = 125°C Co(er)	[V] [W] [mΩ] [mΩ] [mW] [W] [W] [W] [W] [V] [Ω] [Ω] [Ω]	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.68 0.02 0.02 0.02 8.73 3.4
Calculation o Input diode b Input Result Transformer Result Result Result Result Output rectif Result CS resistor Result CS resistor Result MOSFET Input Input Input Result	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Primary winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Total transformer copper loss Total transformer copper loss ier diode Secondary 1 diode loss circuit RCD clamper loss CS resistor loss RDSON from datasheet Co(er) from datasheet External drain-to-source capacitance Switch-on loss at minimum 4C input voltage	Eq. 086 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093 Eq. 094 Eq. 096 Eq. 096 Eq. 097	V _{FBR} P _{DIN} R _{PCu} R _{SICu} P _{PCu} P _{SICu} P _{Cu} P _{Cu} P _{Cu} P _{Cu} P _{Cu} R _{DSON} at T _J = 125°C C _{o(er)} C _{DS} P _{Cu}	[V] [W] [mΩ] [mΩ] [mW] [W] [W] [W] [V] [V] [V] [V] [V]	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.68 0.02 0.02 8.73 3.4 0 0.0046
Calculation o Input diode b Input diode b Input Result Transformer Result Result Result Result Output rectif Result RCD clamper Result CS resistor Result MOSFET Input Input Result Result Result Result Result	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Primary winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Secondary 1 winding copper loss Total transformer copper loss ier diode Secondary 1 diode loss circuit RCD clamper loss CS resistor loss Roson from datasheet Co(er) from datasheet External drain-to-source capacitance Switch-on loss at minimum AC input voltage Conduction loss at minimum AC input voltage	Eq. 086 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093 Eq. 093 Eq. 094 Eq. 094 Eq. 096 Eq. 097	VFBR PDIN RPCU RSICU PPCU PSICU PCU PCU PCU PCU PCU PCU PCU P	[V] [W] [mΩ] [mW] [mW] [W] [W] [W] [V] [V] [V] [V] [V] [V]	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.68 0.02 0.02 0.02 8.73 3.4 0 0.0046 0.0046
Calculation o Input diode b Input diode b Input diode b Input Result Transformer Result Result Result Cutput rectif Result RCD clamper Result CS resistor Result MOSFET Input Input Input Result Result Result Result Result Result Result Result Result Result	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Secondary 1 winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Total transformer copper loss Total transformer copper loss ier diode Secondary 1 diode loss circuit RCD clamper loss CS resistor loss Rosow from datasheet External drain-to-source capacitance Switch-on loss at minimum AC input voltage Conduction loss at minimum AC input voltage	Eq. 086 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093 Eq. 094 Eq. 094 Eq. 096 Eq. 097	V _{FBR} P _{DIN} R _{PCu} R _{S1Cu} P _{PCu} P _{S1Cu} P _{Cu} P _{Cu}	[V] [W] [mΩ] [mΩ] [mW] [W] [W] [W] [W] [W] [V] [Ω] [Ω] [PF] [PF] [W] [W]	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.68 0.0585 0.02 0.02 8.73 3.4 0 0.0046 0.00527 0.0527
Calculation o Input diode b Input Result Transformer Result Result Result Result Output rectif Result CS resistor Result CS resistor Result MOSFET Input Input Result Result Result Result Result Result Result Result Result Result Result	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Secondary 1 winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Total transformer copper loss Total transformer copper loss ier diode Secondary 1 diode loss circuit RCD clamper loss CS resistor loss RDSON from datasheet Co(er) from datasheet External drain-to-source capacitance Switch-on loss at minimum AC input voltage Conduction loss at minimum AC input voltage	Eq. 086 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093 Eq. 094 Eq. 094 Eq. 096 Eq. 096 Eq. 097 Eq. 097 Eq. 097	V _{FBR} P _{DIN} R _{PCu} R _{S1Cu} P _{PCu} P _{S1Cu} P _{Cu} P _{Cu} P _{Cu} P _{Cu} P _{Cu} R _{DSON} at T _J = 125°C C _{o(er)} C _{DS} P _{soNMinAC} P _{MOSMinAC} P _{MOSMinAC}	[V] [W] [mΩ] [mΩ] [mW] [W] [W] [W] [W] [W] [V] [V] [V] [V] [V] [V] [V] [V	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.0585 0.068 0.02 0.02 8.73 3.4 0 0.0046 0.0046 0.0527 0.0573 0.0335
Calculation o Input diode b Input diode b Input diode b Result Result Result Result Result Output rectif Result CS resistor Result CS resistor Input Input Input Result Result Result Result Result Result Result Result Result Result Result Result Result Result Result Result	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Secondary 1 winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Total transformer copper loss Total transformer copper loss ier diode Secondary 1 diode loss circuit RCD clamper loss CS resistor loss Roson from datasheet Co(er) from datasheet External drain-to-source capacitance Switch-on loss at minimum AC input voltage Conduction loss at minimum AC input voltage Switch-on loss at maximum AC input voltage Switch-on loss at maximum AC input voltage	Eq. 086 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093 Eq. 093 Eq. 094 Eq. 096 Eq. 096 Eq. 097 Eq. 097 Eq. 097 Eq. 097	VFBR PDIN RPCu RSICu PPCu PSICu PCu PCu PDiode1 PClamper PCS RDSON at TJ = 125°C Co(er) CDS PSONMinAC PMOSMInAC PSONMAXAC Proventer for	[V] [W] [mΩ] [mΩ] [mW] [W] [W] [W] [W] [V] [V] [V] [V] [V] [V] [V] [V	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.68 0.0585 0.68 0.02 8.73 3.4 0 0.02 8.73 3.4 0 0.0046 0.00527 0.0573 0.0335
Calculation o Input diode b Input Result Transformer Result Result Result Result Output rectif Result CS resistor Result CS resistor Result Input Input Input Result Result Result Result Result Result Result Result Result Result Result Result Result Result Result Result Result Result Result	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Secondary 1 winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Total transformer copper loss Total transformer copper loss ier diode Secondary 1 diode loss circuit RCD clamper loss CS resistor loss Rosow from datasheet Co(er) from datasheet External drain-to-source capacitance Switch-on loss at minimum AC input voltage Conduction loss at minimum AC input voltage Switch-on loss at maximum AC input voltage Conduction loss at maximum AC input voltage	Eq. 086 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093 Eq. 093 Eq. 094 Eq. 094 Eq. 096 Eq. 097 Eq. 097 Eq. 097 Eq. 097 Eq. 097	VFBR PDIN RPCu RS1Cu PPCu PSICu PCu PCS Roson at TJ= 125°C Cofer) CDS PsonMinAC PuosMinAC PcondMaxAC PuosMeuxic	[V] [W] [mΩ] [mW] [mW] [W]	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.0585 0.02 0.02 0.02 8.73 3.4 0 0.002 8.73 3.4 0 0.0046 0.00527 0.0573 0.0335 0.0132 0.0467
Calculation o Input diode b Input Result Transformer Result Result Result Result Output rectif Result CS resistor Result CS resistor Result MOSFET Input Input Input Result	f losses ridge Diode bridge forward voltage Diode bridge power loss copper Primary winding copper resistance Secondary 1 winding copper resistance Primary winding copper loss Secondary 1 winding copper loss Total transformer copper loss ier diode Secondary 1 diode loss circuit RCD clamper loss CS resistor loss Roson from datasheet External drain-to-source capacitance Switch-on loss at minimum AC input voltage Conduction loss at minimum AC input voltage Total MOSFET loss at maximum AC input voltage Conduction loss at maximum AC input voltage Conduction loss at maximum AC input voltage Total MOSFET loss at maximum AC input voltage	Eq. 087 Eq. 087 Eq. 088 Eq. 090 Eq. 091 Eq. 093 Eq. 094 Eq. 094 Eq. 096 Eq. 096 Eq. 097 Eq. 097 Eq. 097 Eq. 098 Eq. 099 Eq. 100 Eq. 101 Eq. 102 Eq. 103	V _{FBR} P _{DIN} R _{PCu} R _{S1Cu} P _{PCu} P _{S1Cu} P _{Cu} P _{Cu} P _{Cu} P _{Cu} P _{Cu} R _{DSON} at T _J = 125°C C _{o(er)} C _{DS} P _{SONMinAC} P _{SONMin}	[V] [W] [mΩ] [mΩ] [mW] [W] [W]	1 0.16 3642.43 28.71 22.01 36.46 0.0585 0.0585 0.0585 0.058 0.02 0.02 8.73 3.4 0 0.02 8.73 3.4 0 0.0046 0.0527 0.0573 0.0335 0.0132 0.0467 0.0573



Appendix A: Transformer design and spreadsheet [3]

Controller					
Input	Controller current consumption Ivcc_Normal		[mA]	0.9	
Result	Controller loss	Eq. 104	P _{Ctrl}	[W]	0.0136
Efficiency aft	er losses				
Result	Total power loss	Eq. 105	P _{Losses}	[W]	1.01
Result	Post calculated efficiency	Eq. 106	η_{Post}	[%]	76.52
CoolSET™/MC	OSFET temperature				
Input	Enter thermal resistance junction-ambient (include copper pour)		R _{thJA_As}	[°K/W]	104.0
Result	Temperature rise	Eq. 107	ΔΤ	[°K]	6.0
Result	Junction temperature at T _{amax}		T _{jmax}	[°C]	56.0
Line OVP					
Input	Select AC input LOVP		V _{OVP_AC}	[V AC]	275
Input	High side DC input voltage divider resistor (R3A, R3B, R3C)		R ₁₁	[MΩ]	16
Input	Controller LOVP threshold		V _{VIN_LOVP}	[V]	2.85
Result	Low side DC input voltage divider resistor	Eq 109	R _{I2Cal}	[kΩ]	121.07
Input	Select low-side DC input voltage divider resistor (R7)		R ₁₂	[kΩ]	121
Result	Post calculated LOVP	Eq 110	V _{OVP_ACPost}	[V _{AC}]	275.16
Output regulation (isolated using TI 431 and ontocounler)					

Output regulation (isolated using TL431 and optocoupler)





Output regulation

Input	TL431 reference voltage		V _{REF_TL}	[V]	2.5
Input	Current for voltage divider resistor R26		I _{R26}	[mA]	0.25
Result	Calculated voltage divider resistor	Eq. 111	R26 _{Cal}	[kΩ]	10
Input	Select voltage divider resistor value		R26	[kΩ]	10
Result	Calculated voltage divider resistor	Eq. 112	R25 _{Cal}	[kΩ]	10.00
Input	Select voltage divider resistor value		R25	[kΩ]	10.0
Optocoupler	and TL431 bias				
Input	Current Transfer Ratio (CTR)		Gc	[%]	100
Input	Optocoupler diode forward voltage		V _{FOpto}	[V]	1.25
Input	Maximum current for optocoupler diode		I _{Fmax}	[mA]	10
Input	Minimum current for TL431		I _{KAmin}	[mA]	1
Result	Calculated minimum optocoupler bias resistance	Eq. 114	R22 _{Cal}	[kΩ]	0.1250
Input	Select optocoupler bias resistor		R22	[kΩ]	0.12
Input	FB pull-up reference voltage V _{REF} from datasheet		V _{REF}	[V]	3.3
Input	V _{FB_OLP} from datasheet		V _{FB_OLP}	[V]	2.75
Input	R _{FB} from datasheet		R _{FB}	[kΩ]	15
Result	Calculated maximum TL431 bias resistance	Eq. 115	R23 _{Cal}	[kΩ]	1.25
Input	Selected TL431 bias resistor		R23	[kΩ]	1.2



Appendix A: Transformer design and spreadsheet [3]

Regulation loop					
Result	FB transfer characteristic Eq. 116 K _{FB}			125.00	
Result	Gain of FB transfer characteristicEq. 117GFB[db]		[db]	41.94	
Result	Voltage divider transfer characteristic	Eq. 118	Kvd		0.500000
Result	Gain of voltage divider transfer characteristic	Eq. 119	G _{VD}	[db]	-6.02
Result	Resistance at maximum load pole	Eq. 120	R _{LH}	[Ω]	7.58
Result	Resistance at minimum load pole	Eq. 121	RLL	[Ω]	83.33
Result	Poles of power stage at maximum load pole	Eq. 122	foн	[Hz]	51.24
Result	Poles of power stage at minimum load pole	f power stage at minimum load pole Eq. 123 fol [Hz]		[Hz]	4.66
Result	Zero frequency of the compensation network Eq. 124 for [Hz]		[Hz]	15.45	
Input	Zero dB crossover frequency		fg	[kHz]	3
Input	PWM-OP gain from datasheet		Av		2.03
Result	Transient impedanceEq. 117ZPWM[V/A]		[V/A]	9.9	
Result	Power stage at crossover frequency Eq. 118 F _{PWR} (fg)			0.042	
Result	Gain of power stage at crossover frequency Eq. 119 G _{PWR} (fg) [db		[db]	-27.52	
Result	Gain of the regulation loop at fg	Eq. 120	Gs(ω)	[db]	8.396
Result	Separated components of the regulator Eq. 12		Gr(ω)	[db]	-8.396
Result	Calculated resistance value of compensation network Eq. 12		R24 _{Cal}	[kΩ]	1.90
Input	Select resistor value of compensation network		R24	[kΩ]	10
Result	Calculated capacitance value of compensation network	Eq. 123	C26 _{Cal}	[nF]	5.305
Input	Select capacitor value of compensation network		C26	[nF]	0.068
Result	Calculated capacitance value of compensation network	Eq. 124	C25 _{Cal}	[nF]	1030.10
Input	Select capacitor value of compensation network		C25	[nF]	100

Output regulation (non-isolated)

Final design Electrical

Minimum AC voltage	[V]	85
Maximum AC voltage	[V]	264
Maximum input current	[A]	0.05
Minimum DC voltage	[V]	93
Maximum DC voltage	[V]	373
Maximum output power	[W]	3.3
Output voltage 1	[V]	5.0
Output ripple voltage 1	[mV]	1.1
Transformer peak current	[A]	0.21
Maximum duty cycle		0.43
Reflected voltage	[V]	71
Copper losses	[W]	0.06
MOSFET losses	[W]	0.06
Sum losses	[W]	1.01
Efficiency	[%]	76.52

Transformer

Core type		EE13/7/4
Core material		TP4A(TDG)
Effective core area	[mm ²]	12.4
Maximum flux density	[mT]	257
Inductance	[μH]	1959
Margin	[mm]	0
Primary turns	Turns	126
Primary copper wire size	AWG	35
Number of primary copper wires in parallel		1
Primary layers	Layer	3
Secondary 1 turns (N _{S1})	Turns	10
Secondary 1 copper wire size	AWG	25
Number of secondary 1 copper wires in parallel		1
Secondary 1 layers	Layer	1
Auxiliary turns	Turns	28
Leakage inductance	[μH]	7.1



Appendix A: Transformer design and spreadsheet [3]

Component	S			
	Input capacitor (C1)		[μF]	9.4
	Secondary 1 output capacitor (C152)		[μF]	820.0
	Secondary 1 output capacitor in parallel			1.0
	Secondary 1 LC filter inductor (L151)		[μH]	2.2
	Secondary 1 LC filter capacitor (C153)		[μF]	10.0
	V _{cc} capacitor (C3)		[μF]	4.7
	Sense resistor (R8A, R8B)		[Ω]	3.90
	Clamping resistor (R4)		[kΩ]	3000.0
	Clamping capacitor (C2)		[nF]	1
	High-side DC input voltage divider resistor (R3A, R3B, R3C)		[MΩ]	16
	Low-side DC input voltage divider resistor (R7)		[kΩ]	121
Regulation	components (isolated using TL431 and optocoupler)			
	Voltage divider	R26	[kΩ]	10.0
	Voltage divider (V _{OUT1} sense)	R25	[kΩ]	10.0
	Optocoupler bias resistor	R22	[kΩ]	0.12
	TL431 bias resistor	R23	[kΩ]	1.2
	Compensation network resistor	R24	[kΩ]	10.0
	Compensation network capacitor	C26	[nF]	0.07
	Compensation network capacitor	C25	[nF]	100.0



Appendix B: WE transformer specification

13 Appendix B: WE transformer specification



Figure 36 WE transformer specification



14 References

- [1] ICE5AR4770AG datasheet, Infineon Technologies AG
- [2] <u>5th-Generation Fixed-Frequency Design Guide</u>
- [3] <u>CalculationTool ICE5xSAG ICE5xRxxxAG</u>
- [4] <u>AN-REF-3W-IOT-COOLSET^M</u>



References

Revision history

Document version	Date of release	Description of changes
V1.0	28 August 2018	First release

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