EVM User's Guide: UCG28826EVM-093

使用 UCG28826EVM-093 65W 高密度 GaN 集成式准谐振反激式转换器

说明

UCG28826EVM-093 是一款 65W 评估模块 (EVM)，可评估适用于交流/直流适配器、充电器、USB 墙壁插座和其他应用的离线 GaN 集成式准谐振反激式适配器。该 EVM 符合 CoC 第 2 级和 DoE 第 6 级标准的能效要求。该 EVM 的用途是进行评估，不是最终产品。UCG28826EVM-093 将 $90V_{RMS}$ 至 $264V_{RMS}$ 的输入电压向下转换为可选的 USB-C PD 输出电压 $5V_{DC}$、$9V_{DC}$、$15V_{DC}$ 或 $20V_{DC}$。该 EVM 还可以配置来产生 $5V_{DC}$ 至 $24V_{DC}$ 范围内的固定输出电压。该 EVM 设计为：在输出电压最高 $15V_{DC}$ 时，可提供最大 3.00A 输出电流；在输出电压范围为 $15V_{DC}$ 至 $24V_{DC}$ 时，最大输出功率为 65W。该设计采用 UCG28826 作为主器件，该器件集成 650V GaN 功率 FET 与控制器，封装尺寸为 5mm × 5mm。

开始使用

1. 在评估之前，请先完整阅读和学习本用户指南
2. 订购 UCG28826EVM-093 以进行评估（如果符合步骤 1 的要求）
3. 根据用户指南说明设置和测试 UCG28826EVM-093

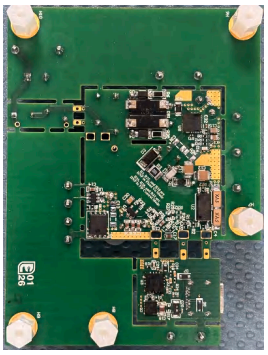
特性

- 整个输入电压范围内满载运行时的效率为 93-95%
- 2.8W/cm^3 (3.9cm x 3.43cm x 1.71cm) 功率密度（通过 140kHz 最大开关频率实现）
- 自偏置和无辅助检测、集成电流检测、集成高压启动和集成 X 电容器放电均可通过集成实现最低 BOM 成本
- 全面的保护特性，包括 OVP、OTP、短路和过流保护以及欠压起动/关断保护
- USB-C 输出可用于对适配器、笔记本电脑充电器、USB 墙壁插座等终端设备进行全面的系统级评估

应用

- USB-C PD 电源适配器
- 交流/直流或直流/直流辅助电源
- 用于笔记本电脑、平板电脑、电视和机顶盒的高密度交流/直流转换器/适配器
- USB-C PPS 电源适配器

图 1-1. UCG28826EVM-093（顶视图）



UCG28826EVM-093（底视图）

1 评估模块概述

1.1 简介

UCG28826EVM-093 评估模块用于在交流-直流准谐振 (QR) 反激式电源转换器中对集成 GaN FET 与控制器的 UCG28826 进行评估。该 EVM 适用于 90VAC 至 264VAC 的通用交流输入范围，并支持 USB PD 3.0 20V/15V/9V/5V 输出协议。本用户指南提供了高压安全概述、推荐的测试设置、得到的效率结果、热特性、波形和传导 EMI 性能。

1.2 套件内容

- 65W USB-C QR 反激式转换器评估模块
- 快速入门指南
- 高压声明

1.3 规格

输入	控制器配置	输出	最大输出功率
90VAC-264VAC 47Hz 至 63Hz	USB-C PD	20V/3.25A、15V/3.00A、9V/3.00A、5V/3.00A	65W
	固定输出电压	5V 至 15V/3A 和 >15V 至 24V/65W	

1.4 器件信息

UCG28826 是一款高频准谐振 (QR) 交流/直流反激式转换器，具有集成式 650V 初级侧 GaN FET，适用于不带 PFC 且功率高达 65W 的电源和带有 PFC 前端且功率高达 120W 的电源。该器件通过 GaN 集成带来优势，能够实现开关频率高达 500kHz 的高功率密度设计。UCG28826 采用业内较早推出的具有自偏置功能的无辅助反激式架构，无需在变压器中使用辅助绕组，即可实现紧凑且成本较低的电源设计。由于无需使用低压降稳压器 (PD) 并消除了生成器件偏置所产生的相关损耗，因此自偏置功能降低了损耗，从而提高了宽输出电压应用（如 USB-LDO 充电器）的效率。UCG28826 支持在低压线路输入条件以及高达 130W（65W 标称输出功率的两倍）的瞬态输出功率条件下，以连续导通模式 (CCM) 运行长达 4ms，而无需使用专为此类瞬态负载条件设计的变压器，从而节省空间和成本。该器件还包含频率折返和突发模式，可分别在轻负载和空载条件下实现更高的运行效率。X 电容器放电电路会在不到 1s 的时间内将输入 EMI 滤波器中的 X 电容器放电至 0V，以防止用户在从壁式插座拔电源时触电。UCG28826 提供可通过电阻器编程的选项，这样用户就能够极其灵活地在所需的工作点优化性能，从而克服集成转换器的系统设计限制。该器件还内置多种保护功能，能够应对输出过压、过流、过载、短路和过热等情况，并具有自动重启和锁存响应功能，从而实现稳健的电源设计，防止在此类故障情况下造成任何损坏。

1.5 通用德州仪器 (TI) 高压评估模块 (TI HV EVM) 用户安全指南

务必遵循 TI 的设置和应用说明，包括在建议的电气额定电压和功率限制范围内使用所有接口元件。务必采取电气安全防护措施，这样有助于确保自身和周围人员的人身安全。如需更多信息，请联系 TI 的产品信息中心，网址为 http://support/ti./com。

保存所有警告和说明以供将来参考。

> **警告**
>
> 务必遵循警告和说明，否则可能引发电击和灼伤危险，进而造成财产损失或人员伤亡。

TI HV EVM 一词是指通常以开放式框架、敞开式印刷电路板装配形式提供的电子器件。EVM *严格用于开发实验室环境，仅供了解开发和应用高压电路相关电气安全风险且接受过专门培训、具有专业知识背景的合格专业用户使用。德州仪器 (TI) 严禁任何其他不合规的使用和/或应用。*如果不满足资格，则立即停止进一步使用 HV EVM。

1. 工作区安全
   a. 保持工作区整洁有序。
   b. 每次电路通电时，都必须由具有资质的观察员在场监督。
   c. TI HV EVM 及接口电子元件通电区域必须设有有效的防护栏和标识；指示可能存在高压操作，以避免意外接触。
   d. 开发环境中使用的所有接口电路、电源、评估模块、仪器、仪表、示波器和其他相关装置如果超过 50Vrms/75VDC，则必须置于紧急断电 EPO 保护电源板内。
   e. 使用稳定且不导电的工作台。
   f. 使用充分绝缘的夹钳和导线来连接测量探针和仪器。尽量不要徒手进行测试。
2. 电气安全
   作为一项预防措施，假定整个 EVM 可能存在用户可完全接触到的高电压是良好的工程实践。
   a. 执行任何电气测量或其他诊断测量之前，需切断 TI HV EVM 及其全部输入、输出和电气负载的电源。再次确认 TI HV EVM 已安全断电。
   b. 确认 EVM 断电后，根据所需的电路配置、接线、测量设备连接和其他应用需求执行进一步操作，同时仍假定 EVM 电路和测量仪器均带电。
   c. EVM 准备就绪后，根据需要将 EVM 通电。

> **警告**
>
> EVM 通电后，请勿触摸 EVM 或电路，因为 EVM 或电路可能存在高压，会造成电击危险。

3. 人身安全
   a. 穿戴人员防护装备（例如乳胶手套或具有侧护板的安全眼镜）或将 EVM 放置于带有联锁装置的透明合成树脂塑料箱中，避免意外接触。

安全使用限制条件：勿将 EVM 作为整体或部分生产单元使用。

2 硬件

2.1 在具有 USB-C PD 通信功能的负载上使用该 EVM

UCG28826EVM-093 配备了 USB-C PD 控制器和板载 USB-C 连接器，可通过 USB-C 线缆连接 USB-C PD 负载进行评估。节 3.2.2 中的部分展示了相应的测试设置图。USB-C PD 控制器可以调整电路板输出以获得 5V、9V、15V 或 20V 电压。为了进行此 EVM 评估，需要 USB-C PD 通信负载。一个此类负载的示例是 USB-C-PD-DUO-EVM。如果没有此类通信负载，电路板输出 USB-C 连接器 (J2) 将不提供可变输出电压。要从 5V、9V 和 15V 获取满载电流 3.00A，可以使用标准 USB-C 电缆。要在 20V 输出下获得 3.25A 电流，必须使用“电子标度”USB-C® 电缆。

2.2 在不具有 USB-C PD 通信功能的负载上使用该 EVM

在配合非 USB-C PD 负载进行评估时，可以将 UCG28826EVM-093 重新配置，使其产生 5V 至 24V 范围内的固定输出电压。节 3.2.2 展示了相应的测试设置图。UCG28826EVM-093 默认配置为 USB-C PD 控制模式。在使用非 USB-C PD 负载进行测试时，必须重新配置控制器电路以启用固定输出电压模式。控制器重新配置指南可在 节 4.1 中找到。在固定输出电压控制模式下，该转换器可在 5V 至 15V 输出时提供额定 3A 电流，在 15V 至 24V 输出时提供额定 45W 功率。

3 实现结果

3.1 电气性能规格

表 3-1. UCC28826EVM-093 电气性能规格

参数		测试条件	最小值	标称值	最大值	单位
输入特性						
V_{IN}	输入线路电压 (RMS)		90	115/230	264	V
f_{LINE}	输入线路频率		47	50/60	63	Hz
P_{STBY}	空载时的输入功率	V_{IN} = 115V/230V_{RMS}，V_{OUT} = 5V 且 I_{OUT} = 0A，已启用 USB-C PD 控制器		10/26		mW
$P_{0.18W}$	0.18W 负载下的输入功率	V_{IN} = 230V_{RMS}，V_{OUT} = 5V，P_{OUT} = 180mW，已启用 USB-C PD 控制器		270		mW
$P_{0.3W}$	0.3W 负载下的输入功率	V_{IN} = 230V_{RMS}，V_{OUT} = 5V，P_{OUT} = 300mW，已启用 USB-C PD 控制器		400		mW
输出特性						
V_{OUT}	输出电压 V_{IN} = 90V 至 264V_{RMS}	I_{OUT} = 0A 至 2.71A，已启用固定 V_{OUT} 控制器		24		V
		I_{OUT} = 0A 至 3.25A，已启用 USB-C PD 控制器		20		
		I_{OUT} = 0A 至 3.00A，已启用 USB-PD 控制器		15		
		I_{OUT} = 0A 至 3.00A，已启用固定 V_{OUT} 控制器		12		
		I_{OUT} = 0A 至 3.00A，已启用 USB-PD 控制器		9		
		I_{OUT} = 0A 至 3.00A，已启用 USB-PD 控制器		5		
I_{OUT}	满载额定输出电流 V_{IN} = 90V 至 264V_{RMS}	V_{OUT} = 24.0V		2.71		A
		V_{OUT} = 20.0V		3.250		
		V_{OUT} = 5.0V、9.0V、12.0V 或 15.0V		3.000		
V_{OUT_pp}	V_{IN} = 115V/230V_{RMS} 时的输出纹波电压	V_{OUT} = 24.0V，I_{OUT} = 0A 至 2.71A		58.62		mV pp
		V_{OUT} = 20.0V，I_{OUT} = 0A 至 3.25A		90.48		
		V_{OUT} = 15.0V，I_{OUT} = 0A 至 3.00A		114		
		V_{OUT} = 12.0V，I_{OUT} = 0A 至 3.00A		99.97		
		V_{OUT} = 9.0V，I_{OUT} = 0A 至 3.00A		87.22		
		V_{OUT} = 5.0V，I_{OUT} = 0A 至 3.00A		87.92		
V_{OUT_Δ}	由于负载升压/降压而产生的输出电压偏差（在 100Hz 速率下，I_{OUT} 阶跃在 0 至 100% 负载之间变化）	V_{OUT} = 24.0V		-463/251		mV pp
		V_{OUT} = 20.0V		-660/500		
		V_{OUT} = 15.0V		-520/480		
		V_{OUT} = 12.0V		-462/261		
		V_{OUT} = 9.0V		-490/460		
		V_{OUT} = 5.0V		-480/450		
P_{OUT_opp}	过功率保护阈值	V_{IN} = 90V 至 264V_{RMS}		100		W

表 3-1. UCC28826EVM-093 电气性能规格（续）

参数		测试条件	最小值	标称值	最大值	单位
系统特性						
η	满载效率 (V_{IN}= 115V/ 230V_{RMS})	V_{OUT} = 24V，I_{OUT} = 2.71A		94.23/94.40		%
		V_{OUT} = 20V，I_{OUT} = 3.25A		94.08/94.63		
		V_{OUT} = 15V，I_{OUT} = 3.00A		93.88/94.31		
		V_{OUT} = 12V，I_{OUT} = 3.00A		94.24/93.06		
		V_{OUT} = 9V，I_{OUT} = 3.00A		93.66/93		
		V_{OUT} = 5V，I_{OUT} = 3.00A		92.8/91.67		
η	4 点平均效率(1) V_{IN} = 115V/ 230V_{RMS}	V_{OUT} = 24V（CoC 2 级，89.0%）		93.67/92.00		%
		V_{OUT} = 20V（CoC 2 级，89.0%）		94.14/93.85		
		V_{OUT} = 15V（CoC 2 级，88.9%）		94.15/92.95		
		V_{OUT} = 12V（CoC 2 级，88.3%）		93.88/91.18		
		V_{OUT} = 9V（CoC 2 级，87.3%）		93.6/91.64		
		V_{OUT} = 5V（CoC 2 级，81.8%）		92.28/89.23		
η	10% 负载时的效率 V_{IN}= 115V/230V_{RMS}	V_{OUT} = 24V（CoC 2 级，79.0%）		91.87/87.66		%
		V_{OUT} = 20V（CoC 2 级，79.0%）		92.04/89.39		
		V_{OUT} = 15V（CoC 2 级，78.9%）		92.4/89.71		
		V_{OUT} = 12V（CoC 2 级，78.3%）		93.47/89.37		
		V_{OUT} = 9V（CoC 2 级，77.3%）		92.6/89.29		
		V_{OUT} = 5V（CoC 2 级，72.5%）		90.6/86.64		
T_{AMB}	环境工作温度范围	V_{IN} = 90V 至 264V_{RMS}，I_{OUT} = 0A 至 3.00A (5V/9V/15V) 或 3.25A (20V)		25		°C

(1) 四个负载点的平均效率，I_{OUT} = 每个相应输出电压的额定满载电流的 100%、75%、50% 和 25%。此外，4 点效率值是使用 MP6951 测量的，以获得更好的 9V 和 5V 性能。MP6908 和 MP6951 引脚对引脚兼容，并可在 EVM 上互换使用。

3.2 测试设置

3.2.1 测试设置要求

安全性：此评估模块并未进行封装，电路板中存在超过 $50V_{DC}$ 的可接触电压。

隔离输入变压器：此 EVM 的输入端上应连接额定值合适的 1:1 隔离变压器，该变压器构造为通过增强型绝缘、双重绝缘或连接到保护导体端子的屏蔽将初级绕组与次级绕组隔离开来。

警告

- 如果用户没有接受过安全处理和测试功率电子产品方面的培训，请不要测试此评估模块。
- EVM 通电后，请勿触摸 EVM 或电路，因为 EVM 或电路可能存在高压，会造成电击危险。
- 注意：表面高温。接触会导致烫伤。请勿触摸！
- 在进行测试之前，请仔细阅读本用户指南。

电压源：能够提供 $264V_{RMS}$ 且能够处理 100W 功率级别的隔离式交流电源或可变交流变压器。

电压表：数字电压表

功率分析仪：能够测量 1mW 至 100W 输入功率并能够处理 $264V_{RMS}$ 输入电压。一些功率分析仪可能需要使用精密分流电阻器来测量输入电流，以便测量 5W 或更低的输入功率。请阅读功率分析仪的用户手册，以了解正确测量全功率和待机功率的设置。

示波器：

- 4 通道、500MHz 带宽。
- 能够处理 600V 电压的探针。

输出负载：能够在 20V 条件下处理 130W 的电阻负载或电子负载。

建议线规：绝缘 22AWG 至 18AWG。

警告

注意：在无人看管的情况下，请勿让 EVM 处于通电状态。

3.2.2 测试设置图

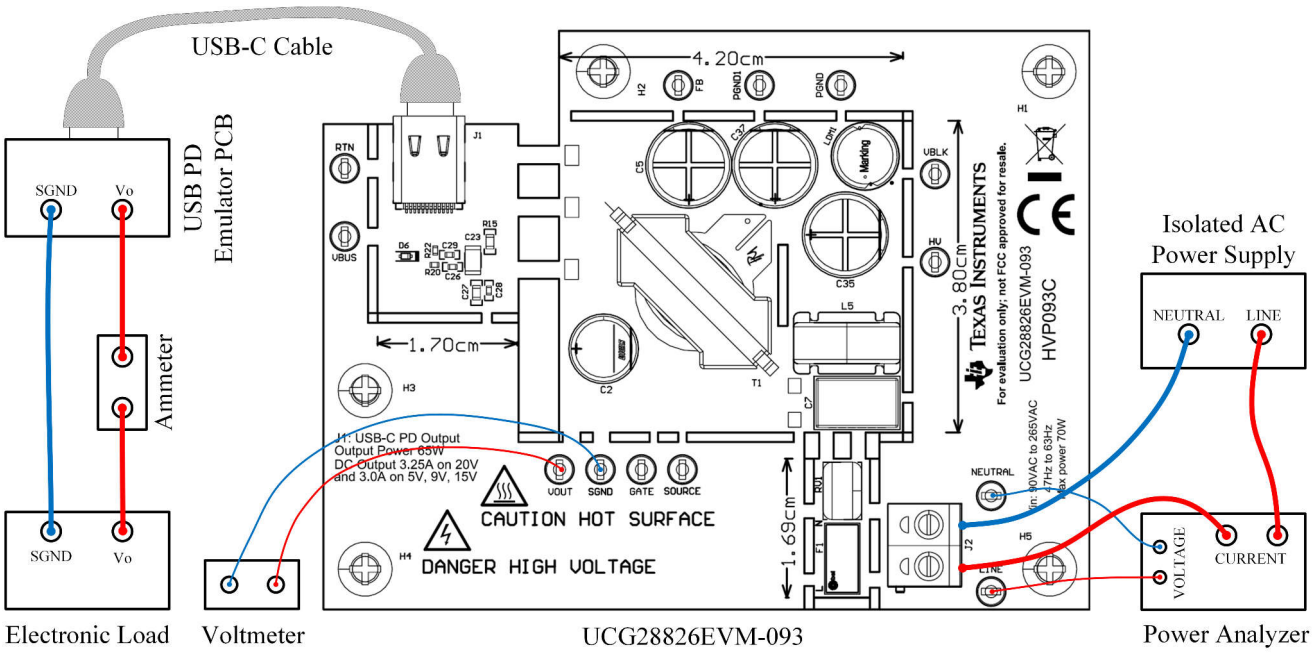


图 3-1. 使用 USB-C PD 负载的 UCG28826EVM-093 测试设置图

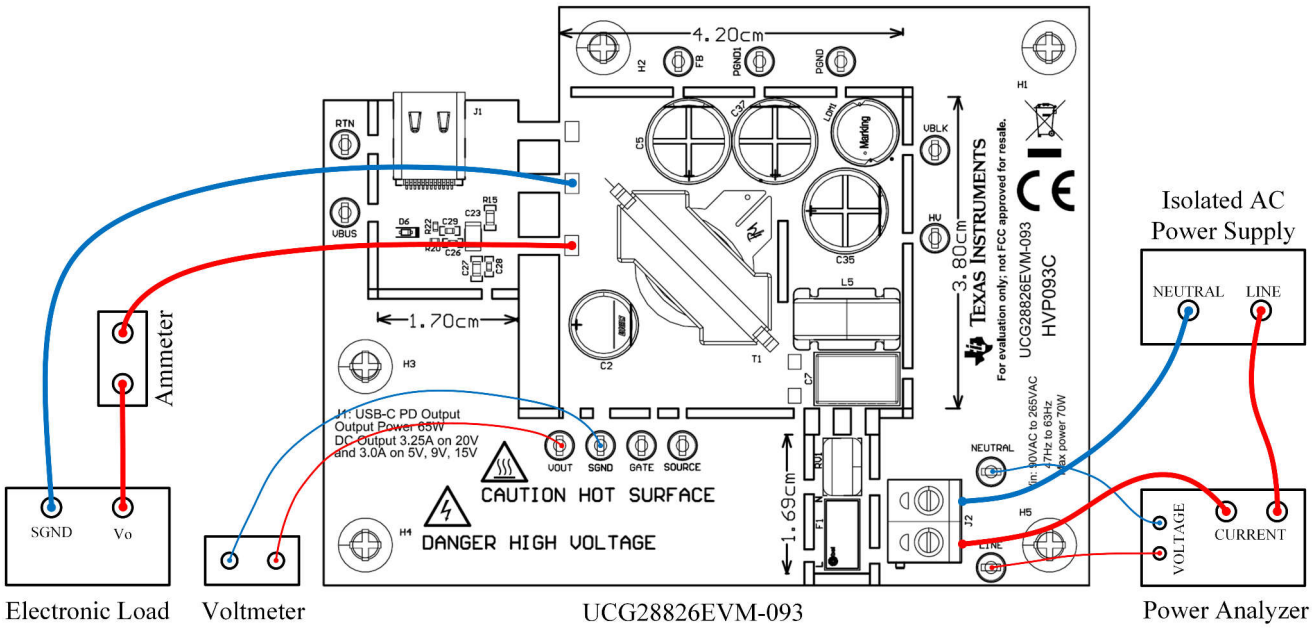
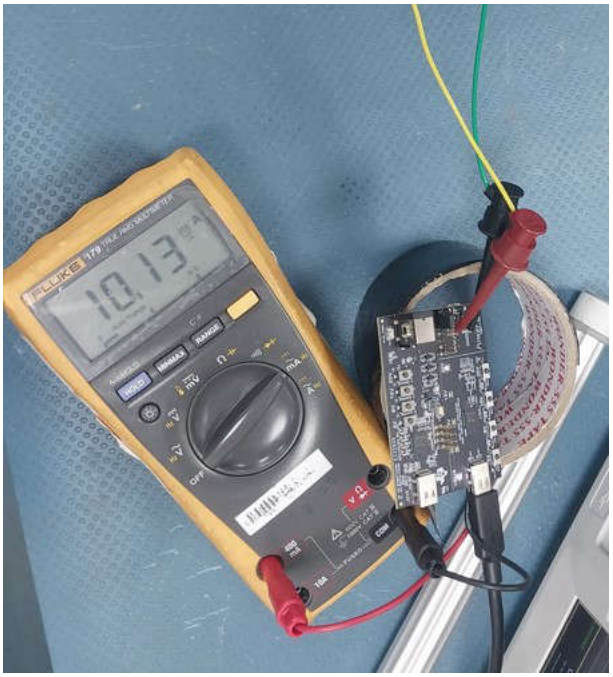


图 3-2. 使用非 USB-C PD 负载的 UCG28826EVM-093 测试设置图

25%-100% 负载下的效率结果是使用上述配置得出的。在待机和 10% 负载条件下，电压测量在电源端/负载端进行，以记录效率数值。



A. 下面的 USB 仿真器“USB-C-DUO EVM”用于评估目的。需要注意的是，该 EVM 的电流消耗接近 10mA，在计算效率时需要考虑到这一点。

图 3-3. USB-C 仿真器

3.2.3 测试点

表 3-2. 输入/输出端子和测试点功能

端子和测试点	说明
J1	USB-C 终端
J2	交流电压输入终端
LINE	交流输入的测试点 – 线路
NEUTRAL	交流输入的测试点 – 中性
PGND、PGND1	初级接地测试点
VBLK	大容量电容器电压的测试点
FB	FB 引脚的测试点
HV	HV 引脚的测试点
SOURCE	SR FET 源极测试点
GATE	SR FET 栅极测试点
SGND	次级接地测试点
VOUT	转换器输出电压测试点
VBUS	输出侧总线电压测试点
RTN	输出侧返回线路的测试点

3.3 性能数据和典型特性曲线

3.3.1 24V_{out} 时的 4 点平均效率结果

V_{IN} (V_{RMS})	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	P_{OUT} (%)	效率 (%)	4 点平均效率
90	69.78	24.02	2.708	65.05	100%	93.22%	
90	51.99	24.02	2.031	48.78	75%	93.84%	
90	34.64	24.03	1.354	32.54	50%	93.93%	93.38%
90	17.39	24.04	0.676	16.25	25%	93.46%	
90	7.05	24.05	0.271	6.52	10%	92.45%	
115	69.03	24.02	2.708	65.05	100%	94.23%	
115	51.72	24.02	2.031	48.78	75%	94.33%	
115	34.45	24.02	1.353	32.50	50%	94.33%	93.67%
115	17.36	24.04	0.676	16.25	25%	93.60%	
115	7.09	24.05	0.271	6.52	10%	91.87%	
230	68.80	24	2.706	64.94	100%	94.40%	
230	51.80	24	2.03	48.72	75%	94.05%	
230	34.90	24.02	1.353	32.50	50%	93.11%	92.00%
230	17.92	24.03	0.677	16.27	25%	90.76%	
230	7.43	24.04	0.271	6.51	10%	87.66%	
264	69.00	24	2.707	64.97	100%	94.16%	
264	52.10	24	2.03	48.72	75%	93.52%	
264	35.19	24.01	1.353	32.49	50%	92.30%	91.08%
264	18.18	24.03	0.676	16.24	25%	89.35%	
264	7.54	24.04	0.27	6.49	10%	86.05%	
CoC 2 级、4 点平均值							89%
CoC 2 级，10% 负载							79%

3.3.2 20V_{out} 时的 4 点平均效率结果

V_{IN} (VRMS)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	P_EMULATOR (W)	P_{out} %	效率	4 点平均效率
89.88	71.2	20.09	3.264	65.64	0.204	100%	92.48%	93.29%
89.91	52.94	20.08	2.451	49.214	0.2	75%	93.34%	
89.94	35.25	20.03	1.636	32.777	0.2	50%	93.55%	
89.98	17.76	20	0.823	16.46	0.2	25%	93.81%	
90.03	7.359	19.99	0.331	6.6193	0.2	10%	92.66%	
114.91	70	20.09	3.265	65.65	0.203	100%	94.08%	94.26%
114.94	52.5	20.08	2.452	449.235	0.203	75%	94.17%	
114.96	34.9	20.03	1.636	32.778	0.2	50%	94.49%	
115	17.68	20	0.824	16.474	0.2	25%	94.31%	
115.04	7.409	19.99	0.331	6.62	0.199	10%	92.04%	
229.98	69.6	20.08	3.265	65.662	0.2	100%	94.63%	93.83%
230.01	52.27	20.07	2.452	49.235.	0.2	75%	94.58%	
230.01	35.06	20.02	1.636	32.778	0.2	50%	94.06%	
230.02	18.11	19.99	0.824	16.471	0.2	25%	92.05%	
230.08	7.63	19.98	0.331	6.6214	0.199	10%	89.39%	
264	69.71	20.08	3.266	65.684	0.2	100%	94.51%	93.29%
264	52.44	20.06	2.452	49235	0.2	75%	94.27%	
264	35.25	20.03	1.636	32.678	0.2	50%	93.53%	
264.02	18.35	20	0.824	16.475	0.2	25%	90.87%	
264.1	7.705	19.98	0.331	6.62	0.199	10%	88.5%	
CoC 2 级、4 点平均值								89.0%
CoC 2 级，10% 负载								79.0%

3.3.3 15V_{out} 时的 4 点平均效率结果

V_{IN} (VRMS)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	P_EMULATOR (W)	P_{out} %	效率	4 点平均效率
89.92	49.08	15.11	3.009	45.525	0.15	100%	93.06%	93.77%
89.95	36.55	15.09	2.259	34.088	0.148	75%	93.67%	
89.97	24.23	15.04	1.512	22.735	0.148	50%	94.44%	
89.99	12.28	15.02	0.758	11.384	0.15	25%	93.93%	
90.03	5.098	15.00	0.305	4.5789	0.148	10%	92.71%	
114.94	48.65	15.12	3.009	45.525	0.148	100%	93.88%	94.16%
114.95	36.32	15.09	2.26	34.105	0.15	75%	94.32%	
114.98	24.23	15.05	1.512	22.737	0.15	50%	94.46%	
115	12.272	15.02	0.758	11.382	0.15	25%	93.97%	
115.04	5.115	15.00	0.305	4.5776	0.149	10%	92.4%	
230	48.43	15.13	3.009	45.527	0.148	100%	94.31%	92.98%
230	36.44	15.08	2.26	34.088	0.148	75%	93.95%	
230	24.61	15.03	1.512	22.742	0.148	50%	93.01%	
230.02	12.72	15.01	0.758	11.382	0.148	25%	90.64%	
230.09	5.268	15.00	0.305	4.5757	0.15	10%	89.71%	
264	48.62	15.11	3.009	45.52	0.15	100%	93.93%	92%
264	36.66	15.08	2.259	34.101	0.148	75%	93.42%	
264.02	24.81	15.04	1.512	22.735	0.148	50%	92.23%	
264.04	13.04	15.02	0.759	11.383	0.148	25%	88.43%	
264.08	5.339	15.00	0.305	4.5779	0.148	10%	88.52%	
CoC 2 级、4 点平均值								88.9%
CoC 2 级，10% 负载								78.9%

3.3.4 12V_{out} 时的 4 点平均效率结果

V_{IN} (V_{RMS})	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	P_{OUT} (%)	效率	4 点平均效率
90	38.46	12.01	3.000	36.03	100%	93.66%	93.68%
90	28.85	12.01	2.250	27.03	75%	93.69%	
90	19.18	12.02	1.500	18.02	50%	93.97%	
90	9.61	12.02	0.750	9.01	25%	93.82%	
90	3.87	12.02	0.300	3.61	10%	93.23%	
115	38.23	12.01	3.001	36.03	100%	94.24%	93.88%
115	28.67	12.01	2.250	27.02	75%	94.26%	
115	19.14	12.01	1.500	18.02	50%	94.12%	
115	9.66	12.02	0.750	9.01	25%	93.30%	
115	3.86	12.02	0.300	3.61	10%	93.47%	
230	38.70	12.00	3.001	36.02	100%	93.06%	91.18%
230	29.22	12.01	2.250	27.02	75%	92.45%	
230	19.65	12.01	1.500	18.02	50%	91.69%	
230	10.09	12.02	0.750	9.01	25%	89.35%	
230	4.03	12.02	0.300	3.61	10%	89.37%	
264	39.07	12.00	3.001	36.01	100%	92.16%	89.83%
264	29.61	12.00	2.250	27.00	75%	91.20%	
264	19.94	12.01	1.500	18.01	50%	90.31%	
264	10.28	12.01	0.750	9.01	25%	87.64%	
264	4.12	12.02	0.301	3.62	10%	87.83%	
CoC 2 级、4 点平均值							88.3%
CoC 2 级，10% 负载							78.3%

3.3.5 9V_{out} 时的 4 点平均效率结果

V_{IN} (VRMS)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	P_EMULATOR (W)	P_{out} %	效率	4 点平均效率
89.96	29.4	9.1	3.002	27.316	0.087	100%	93.21%	93.41%
89.98	21.98	9.08	2.249	20.424	0.087	75%	93.32%	
89.99	14.64	9.05	1.504	13.607	0.087	50%	93.54%	
90.0	7.368	9.01	0.755	6.8052	0.088	25%	93.56%	
90.03	3.043	8.99	0.305	2.7394	0.087	10%	92.89%	
114.98	29.25	9.09	3.001	27.307	0.087	100%	93.66%	93.62%
114.99	21.85	9.07	2.25	20.432	0.088	75%	93.92%	
115.0	14.59	9.05	1.503	13.601	0.087	50%	93.82%	
115.01	7.407	9.01	0.756	6.8077	0.088	25%	93.10%	
115.03	3.051	9.00	0.304	2.7368	0.088	10%	92.6%	
230.06	29.47	9.1	3.002	27.319	0.087	100%	93.0%	91.86%
230.06	22.13	9.08	2.249	20.42	0.089	75%	92.67%	
230.06	14.92	9.05	1.503	13.604	0.088	50%	91.77%	
230.06	7.66	9.01	0.755	6.8056	0.088	25%	90.0%	
230.08	3.165	8.99	0.305	2.739	0.087	10%	89.29%	
264.07	29.7	9.09	3.001	27.309	0.087	100%	92.24%	90.9%
264.07	22.34	9.06	2.249	20.42	0.087	75%	91.8%	
264.05	15.11	9.03	1.503	13.606	0.087	50%	90.62%	
264.05	7.747	9.01	0.755	6.803	0.087	25%	88.94%	
264.07	3.206	9.00	0.305	2.739	0.087	10%	88.15%	
CoC 2 级、4 点平均值								87.3%
CoC 2 级，10% 负载								77.3%

3.3.6 5V_{out} 时的 4 点平均效率结果

V_{IN} (VRMS)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	P_EMULATOR (W)	P_{out} %	效率	4 点平均效率
89.99	16.63	5.09	2.994	15.242	0.048	100%	91.94%	92.26%
90	12.38	5.05	2.254	11.382	0.049	75%	92.33%	
90	8.223	5.01	1.51	7.5643	0.049	50%	92.58%	
90.02	4.151	4.99	0.757	3.7775	0.049	25%	92.17%	
90.03	1.723	4.97	0.306	1.5192	0.049	10%	90.99%	
115	16.55	5.09	2.995	15.243	0.048	100%	92.39%	92.28%
115	12.349	5.05	2.256	11.395	0.048	75%	92.66%	
115.01	8.251	5.01	1.51	7.5648	0.048	50%	92.26%	
115.01	4.167	4.99	0.757	3.7773	0.048	25%	91.18%	
115.03	1.731	4.97	0.306	1.5204	0.048	10%	90.6%	
230.04	16.77	5.08	2.994	15.242	0.049	100%	91.18%	89.23%
230.05	12.72	5.04	2.256	11.395	0.049	75%	89.97%	
230.06	8.62	5.01	1.512	7.5737	0.048	50%	88.42%	
230.06	4.381	4.99	0.757	3.7791	0.048	25%	87.35%	
230.08	1.811	4.97	0.306	1.5205	0.049	10%	86.64%	
264.04	16.96	5.08	2.998	15.258	0.048	100%	90.25%	87.82%
264.05	12.91	5.03	2.257	11.397	0.049	75%	88.66%	
264.07	8.79	5.01	1.51	7.5673	0.048	50%	86.64%	
264.07	4.462	4.99	0.757	3.777	0.048	25%	85.72%	
264.09	1.842	4.97	0.306	1.5192	0.048	10%	85.08%	
CoC 2 级、4 点平均值								81.8%
CoC 2 级，10% 负载								72.5%

3.3.7 效率典型结果

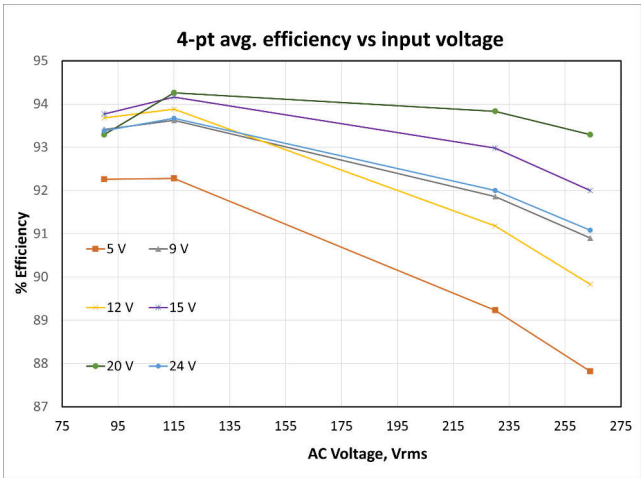


图 3-4. 4 点平均效率与输入电压间的关系

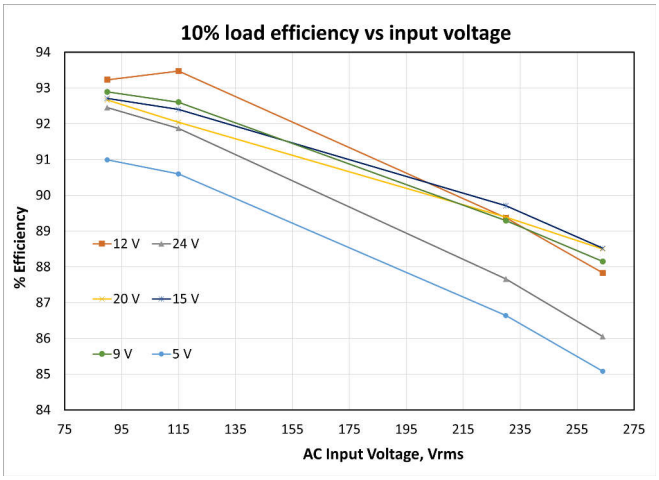


图 3-5. 10% 负载效率与输入电压间的关系

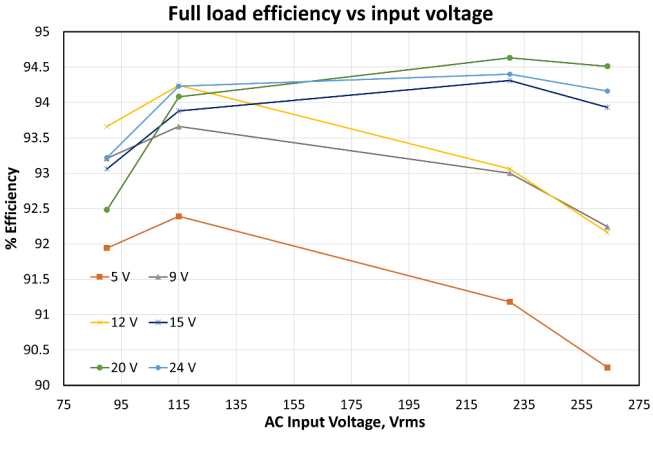


图 3-6. 满负载效率与输入电压

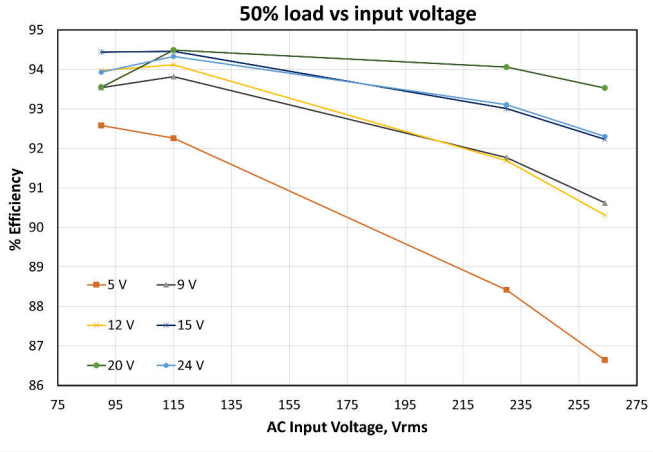


图 3-7. 50% 负载效率与输入电压

3.3.8 输出特性

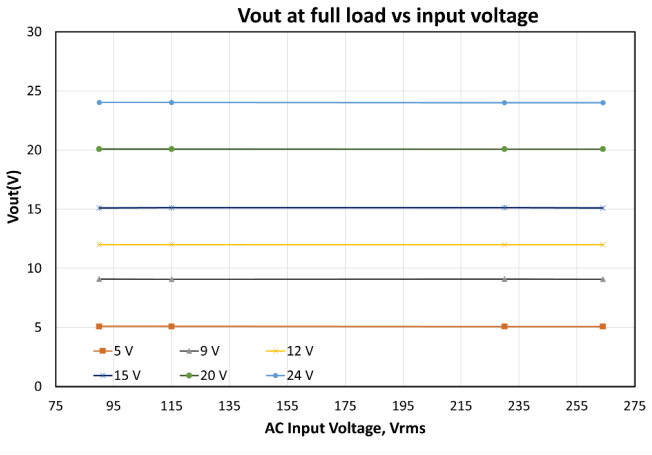


图 3-8. 满载条件下的 V_{OUT} 与输入电压间的关系

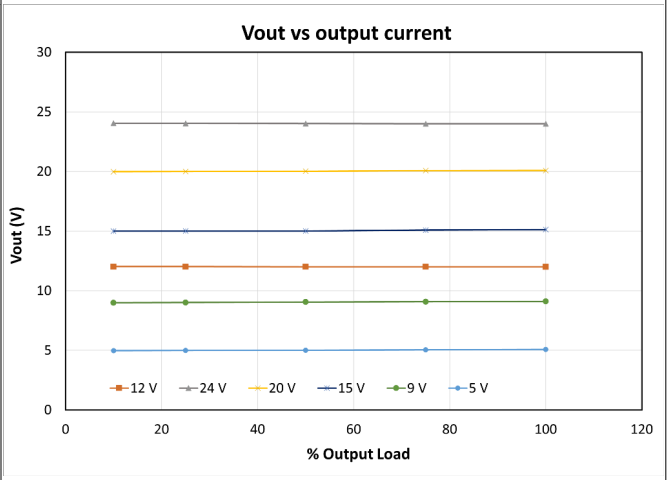


图 3-9. V_{OUT} 与输出电流间的关系

3.3.9 启动波形

此部分展示了 12V 和 24V 输出在无负载和满负载启动时的波形。黄色 = 输出电压，蓝色 = Vbulk，红色 = 开关节点电压，绿色 = FB 引脚电压

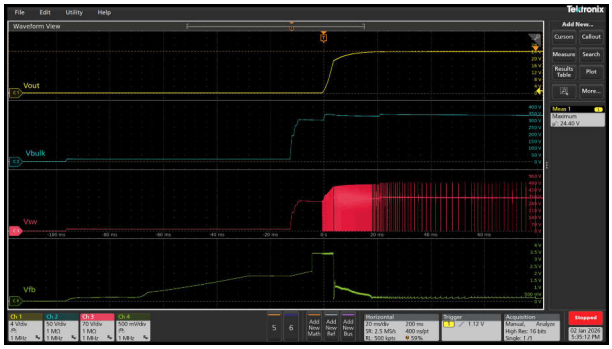


图 3-10. 无负载条件下 24V 输出的启动波形

图 3-11. 满负载条件下 24V 输出的启动波形

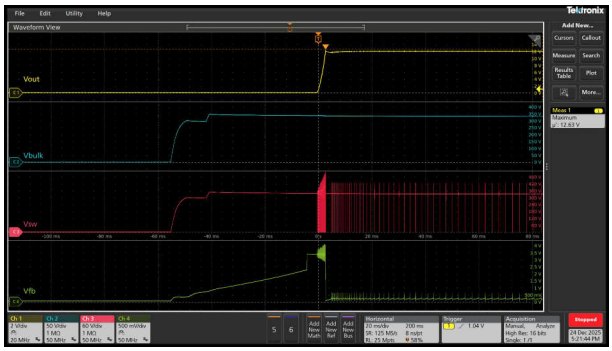


图 3-12. 无负载条件下 12V 输出的启动波形

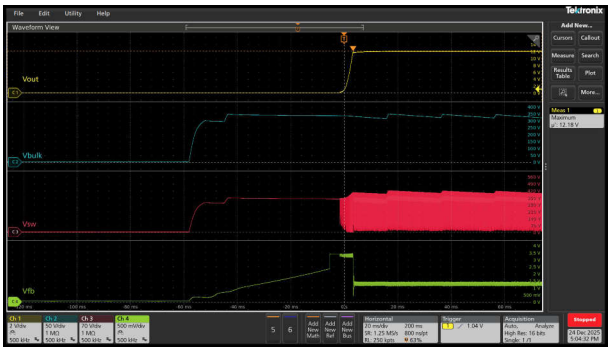


图 3-13. 满负载条件下 12V 输出的启动波形

3.3.10 重要开关波形

此部分展示了在 5V、9V、15V 和 20V 输出条件下满负载时的典型开关波形。

黄色 = 开关节点，蓝色 = 输出电压，棕色 = SR 栅极电压，红色 = FB 引脚电压

图 3-14. Vin = 90Vac，Vout = 20V

图 3-15. Vin = 115Vac，Vout = 20V

图 3-16. Vin = 230Vac，Vout = 20V

图 3-17. Vin = 264Vac，Vout = 20V

图 3-18. Vin = 90Vac，Vout = 15V

图 3-19. Vin = 115Vac，Vout = 15V

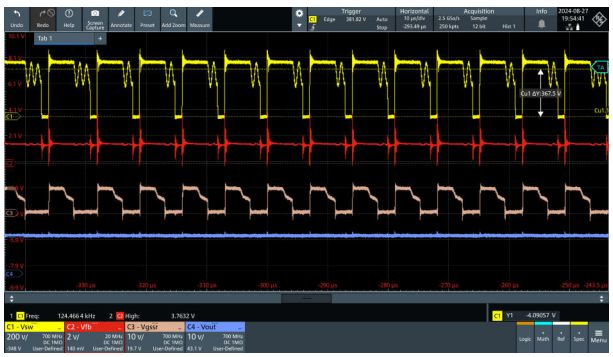


图 3-20. Vin = 230Vac，Vout = 15V

图 3-21. Vin = 264Vac，Vout = 15V

图 3-22. Vin = 90Vac，Vout = 9V

图 3-23. Vin = 115Vac，Vout = 9V

图 3-24. Vin = 230Vac，Vout = 9V

图 3-25. Vin = 264Vac，Vout = 9V

图 3-26. Vin = 90Vac，Vout = 5V

图 3-27. Vin = 115Vac，Vout = 5V

图 3-28. Vin = 230Vac，Vout = 5V

图 3-29. Vin = 264Vac，Vout = 5V

此部分展示了 24V 和 12V 输出，满负载时的典型开关波形。

黄色 = 输出电压，蓝色 = SR 栅极电压，红色 = SR 栅极电压，绿色 = FB 引脚电压

图 3-30. Vin = 90Vac，Vout = 24V

图 3-31. Vin = 115Vac，Vout = 24V

图 3-32. Vin = 230Vac，Vout = 24V

图 3-33. Vin = 264Vac，Vout = 24V

图 3-34. Vin = 90Vac，Vout = 12V

图 3-35. Vin = 115Vac，Vout = 12V

图 3-36. Vin = 230Vac，Vout = 12V

图 3-37. Vin = 264Vac，Vout = 12V

3.3.11 开关频率与负载

本节展示了不同负载条件下的典型开关波形。黄色 = 输出电压，蓝色 = Vbulk，红色 = 开关节点电压，绿色 = FB 引脚电压

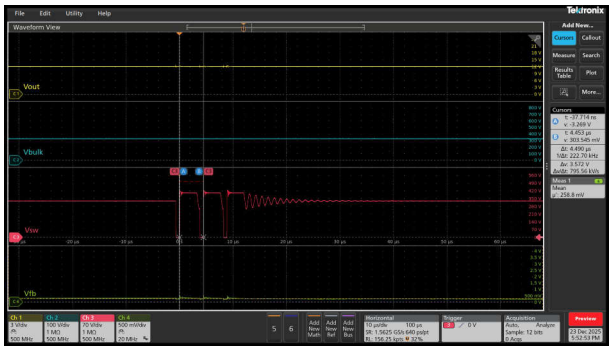


图 3-38. 230Vac/0.6W（222khz 突发频率/VFB - 0.258V）

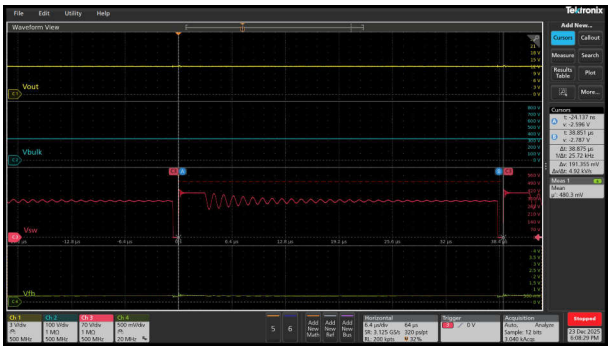


图 3-39. 230Vac/2.94W（25kHz 频率 -折返/Vfb - 0.48V）

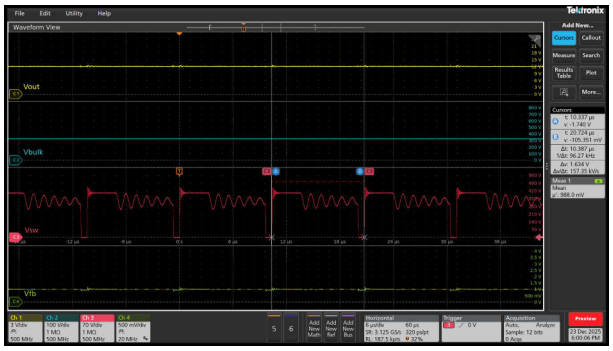


图 3-40. 230Vac/12W（96kHz 频率/Vfb - 0.988V）

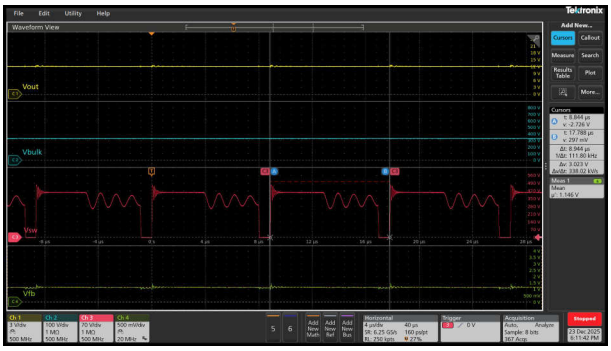


图 3-41. 230Vac/20.4W（111kHz 频率/Vfb - 1.146V）

图 3-42. 230Vac/27.6W（121kHz 频率/Vfb - 1.252V）

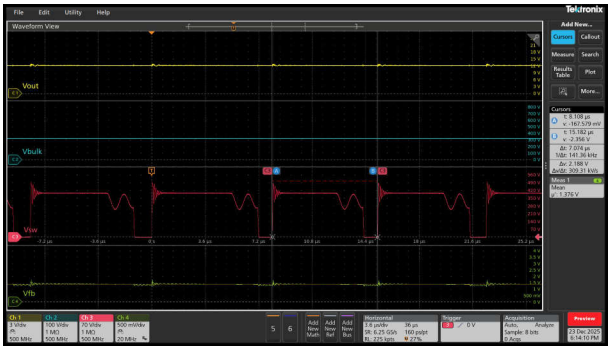


图 3-43. 230Vac/36W（141kHz 频率/Vfb - 1.376V）

3.3.12 输出纹波电压

此部分展示了 230Vac 条件下输出电压的纹波。黄色 = 输出电压纹波，示波器通道带宽 = 20MHz。

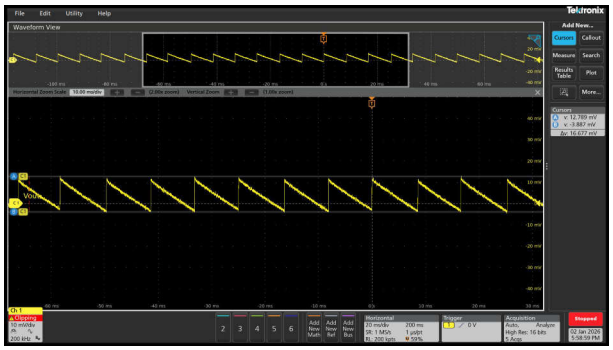


图 3-44. V_{OUT} = 24V 且无负载时的典型纹波电压 (16.67mVpp)

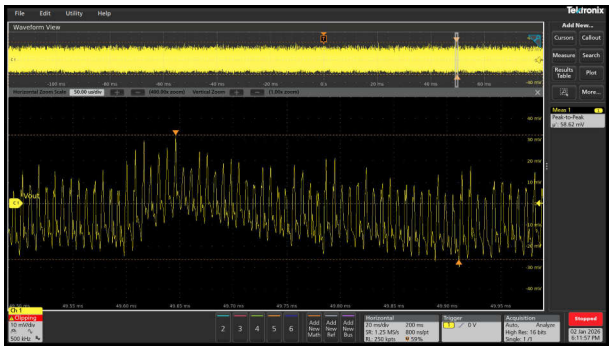


图 3-45. V_{OUT} = 20V 且满负载时的典型纹波电压 (58.62mVpp)

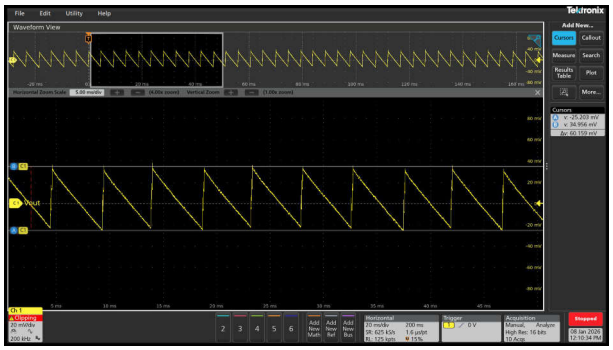


图 3-46. V_{OUT} = 20V 且无负载时的典型纹波电压 (60.16mVpp)

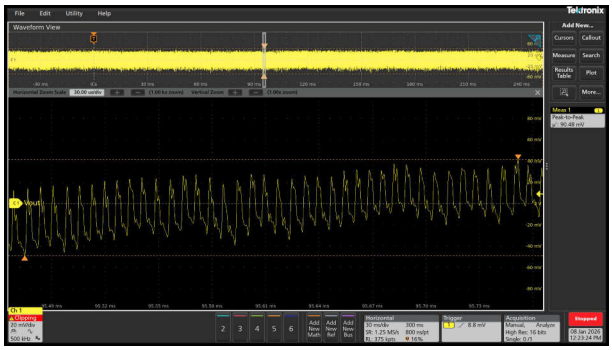


图 3-47. V_{OUT} = 20V 且满负载时的典型纹波电压 (90.48mVpp)

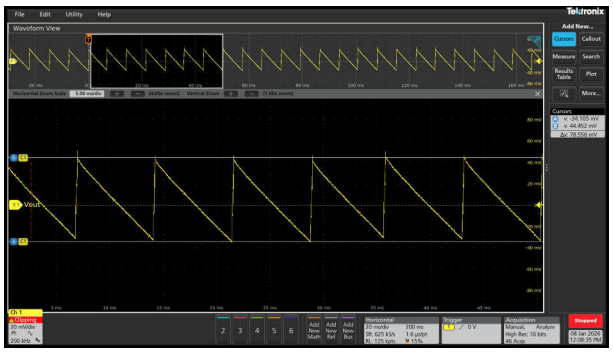


图 3-48. V_{OUT} = 15V 且无负载时的典型纹波电压 (78.56mVpp)

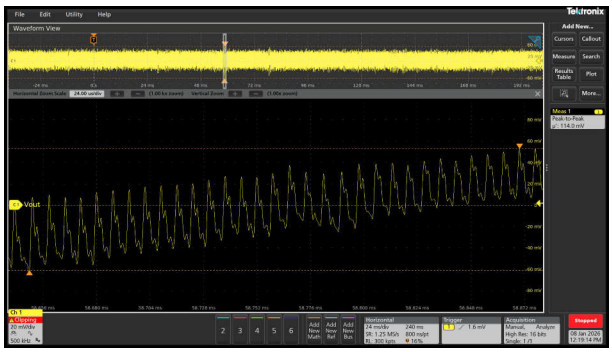


图 3-49. V_{OUT} = 15V 且满负载时的典型纹波电压 (114mVpp)

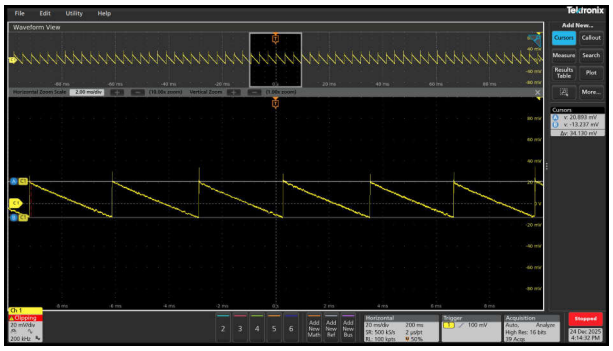


图 3-50. V_{OUT} = 12V 且无负载时的典型纹波电压 (34.13mVpp)

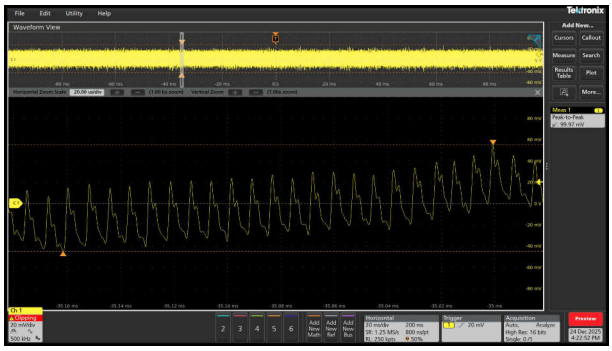


图 3-51. V_{OUT} = 12V 且满负载时的典型纹波电压 (99.97mVpp)

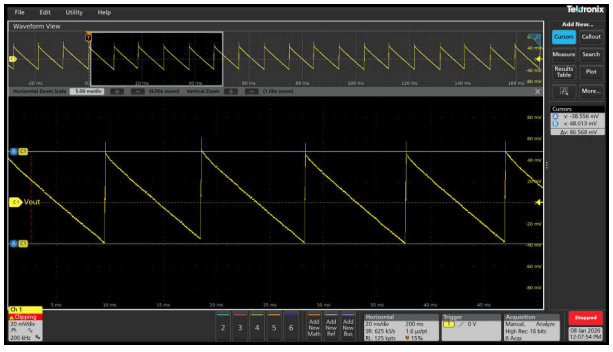


图 3-52. V_{OUT} = 9V 且无负载时的典型纹波电压 (86.57mVpp)

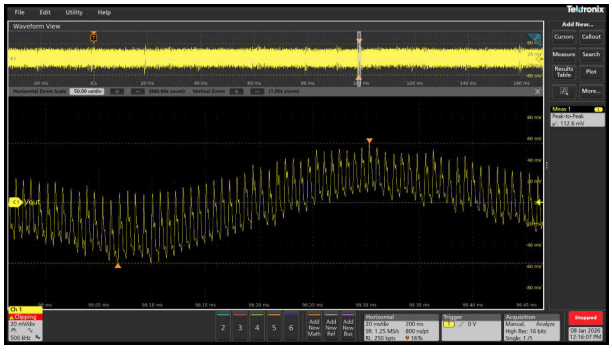


图 3-53. V_{OUT} = 9V 且满负载时的典型纹波电压 (112.6mVpp)

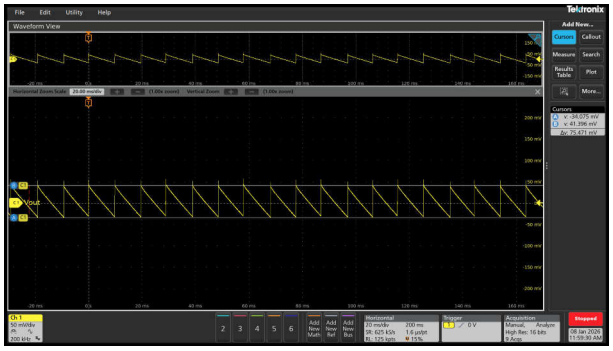


图 3-54. V_{OUT} = 5V 且无负载时的典型纹波电压 (75.47mVpp)

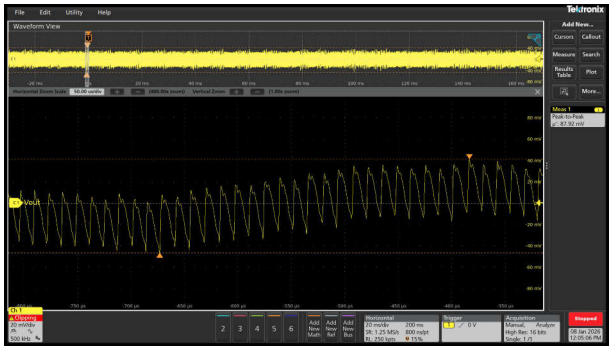


图 3-55. V_{OUT} = 5V 且满负载时的典型纹波电压 (87.92mVpp)

3.3.13 负载瞬态响应

下方示波器截图显示了在负载电流以 100Hz 频率在 0% 至 100% 之间进行阶跃变化，且电流变化斜率为 2.5A/µs 时，输出电压 V_{OUT} 的偏差。请注意，捕获的阶跃负载电流是反向的。

绿色（交流耦合）= V_{OUT}，粉色 = 负载电流。

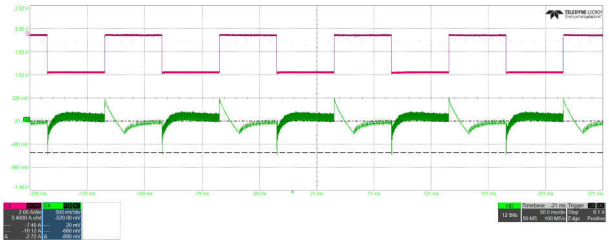


图 3-56. V_{OUT} = 20V 过冲/下冲= 495mV/-680mV 条件下的负载瞬态响应

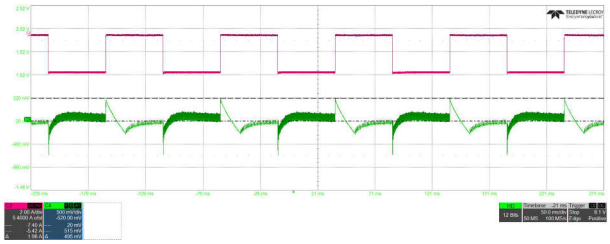


图 3-57. V_{OUT} = 15V 过冲/下冲= 485mV/-630mV 条件下的瞬态响应

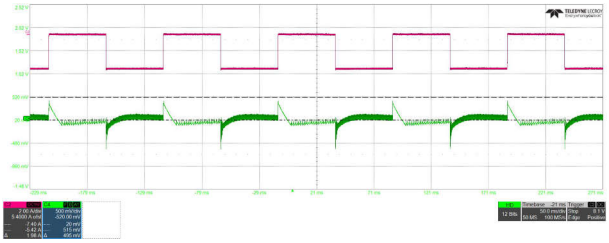


图 3-58. V_{OUT} = 9V 过冲/下冲= 460mV/-500mV 条件下的瞬态响应

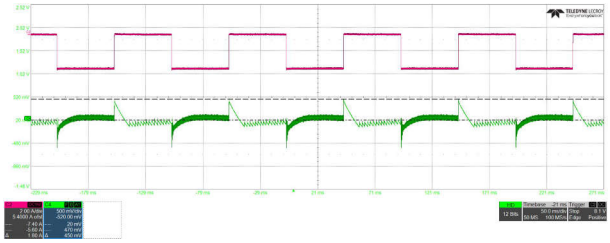


图 3-59. V_{OUT} = 5V 过冲/下冲= 440mV/-480mV 条件下的瞬态响应

下方示波器截图显示了在负载电流以 100Hz 频率在 0% 至 100% 之间进行阶跃变化，且电流变化斜率为 2.5A/µs 时，输出电压 V_{OUT} 的偏差。下方截图的阶跃负载电流未进行反相处理。

黄色（交流耦合）= V_{OUT}，蓝色 = 负载电流。

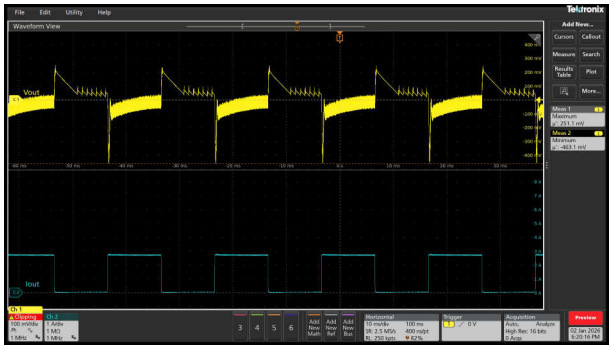


图 3-60. V_{OUT} = 24V 过冲/下冲= 251.1mV/-463.1mV 条件下的瞬态响应

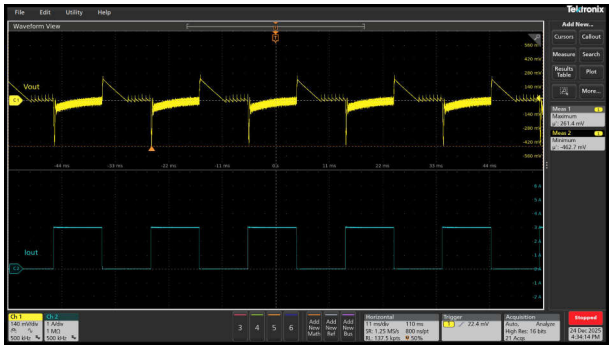


图 3-61. V_{OUT} = 12V 过冲/下冲= 261.4mV/-462.7mV 条件下的瞬态响应

3.3.14 线路瞬态响应

此部分展示了空载和满负载条件下，当在 90Vac 至 264Vac 之间发生线路瞬变时的输出电压。红色 = 输出电压，黑色 = 交流输入，蓝色 = 开关节点

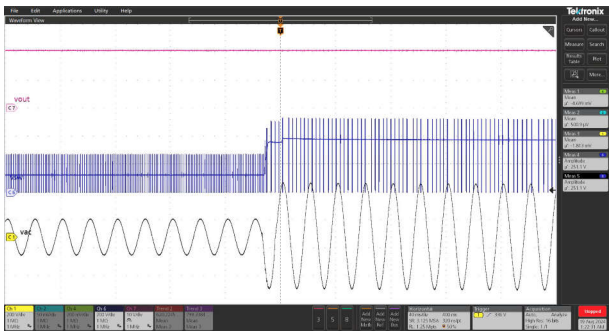


图 3-62. 20V 空载条件下从 90Vac 到 264Vac 的线路瞬态

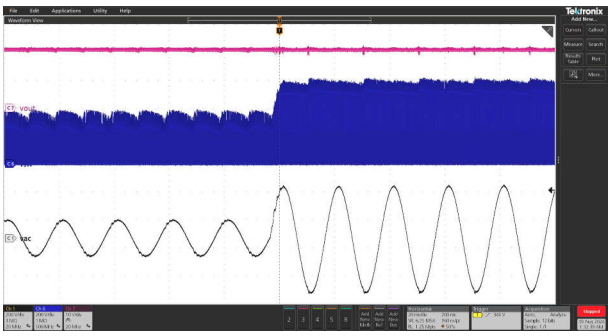


图 3-63. 20V 满负载条件下从 90Vac 到 264Vac 的线路瞬态

3.3.15 浪涌测试

以下部分展示了在对 EVM 施加 2KV 和 1KV 浪涌冲击（单次正向脉冲，相位角为 90°）时的响应结果。黄色 = 体电压，紫色 = 开关节点电压

图 3-64. 230Vac 输入电压时的 2KV 浪涌

图 3-65. 230Vac 输入电压时的 1KV 浪涌

3.3.16 短期过载运行

该 EVM 能够支持短期过载运行，而不会造成损坏、安全问题或触发保护功能。当施加 6.5A 的峰值短期过载持续 2ms 时，输出电压会降至 17.8V，施加 7.32A 持续 1ms 时，输出电压会降至 18.2V。这些结果已在 100Vac 条件下进行检查。粉色 = 开关节点电压，绿色 = 负载电流，蓝色 = 输出电压，黄色 = FB 引脚电压

输出电压降至约 17.8V

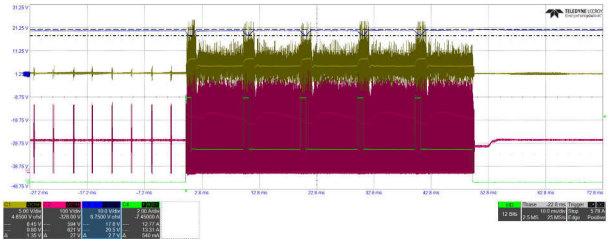


图 3-66. VIN = 100Vac（2.25 倍额定电流持续 1ms，0.9 倍额定电流持续 9ms）

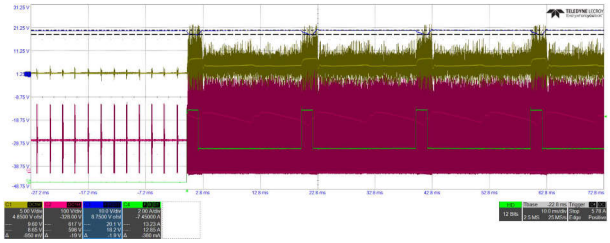


图 3-67. VIN = 100Vac（2 倍额定电流并持续 2ms，0.9 倍额定电流并持续 18ms）

3.3.17 CCM 运行

此部分展示了在 90Vac、6.5A 负载下的 CCM 运行情况；该负载电流是 20V 输出下额定电流 3.25A 的 2 倍。粉色 = 开关节点电压，绿色 = 负载电流，蓝色 = 输出电压

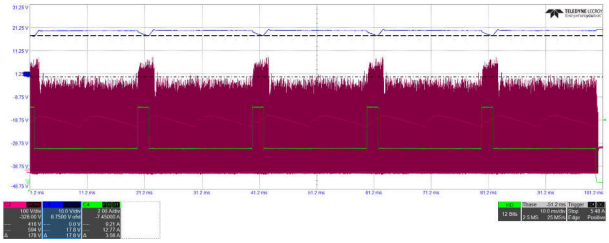


图 3-68. VIN = 90Vac（2 倍额定电流并持续 2ms，0.9 倍额定电流并持续 18ms）

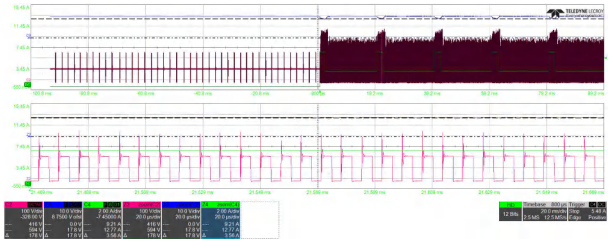


图 3-69. VIN = 90Vac（2 倍额定电流并持续 2ms，0.9 倍额定电流并持续 18ms）- 缩放版本

3.3.18 满负载条件下的热图像（20V 和 3.25A）

下方的热成像图展示了在不同线路电压下，满负载运行时的最高温度。

图 3-70. V_{IN} = 90V_{AC}，顶面

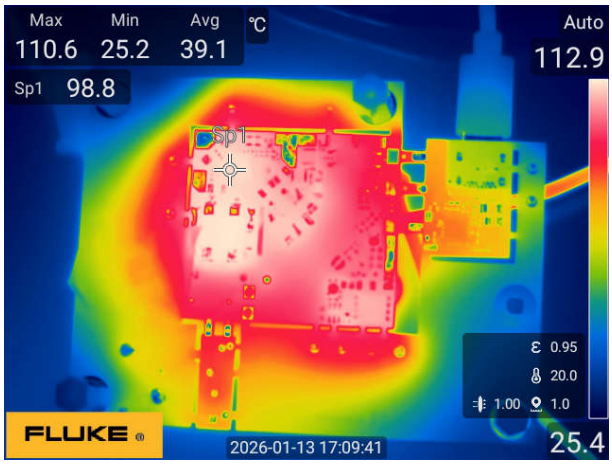


图 3-71. V_{IN} = 90V_{AC}，底面

图 3-72. V_{IN} = 115V_{AC}，顶面

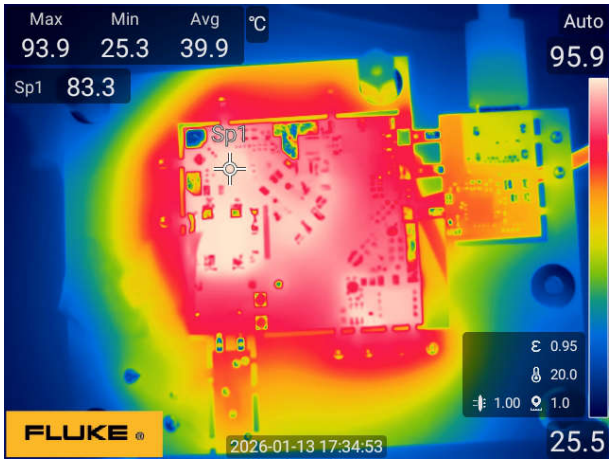


图 3-73. V_{IN} = 115V_{AC}，底面

图 3-74. V_{IN} = 230V_{AC}，顶面

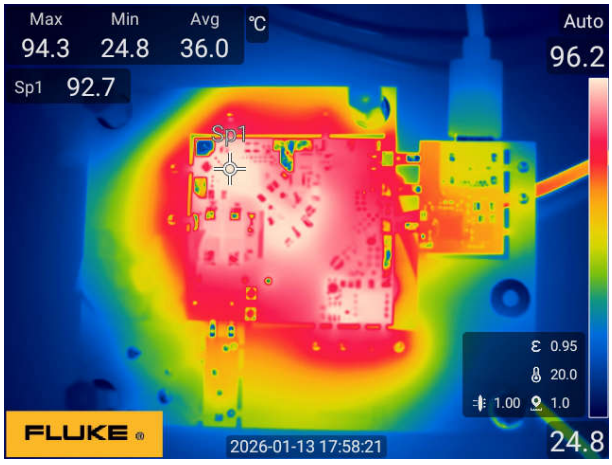


图 3-75. V_{IN} = 230V_{AC}，底面

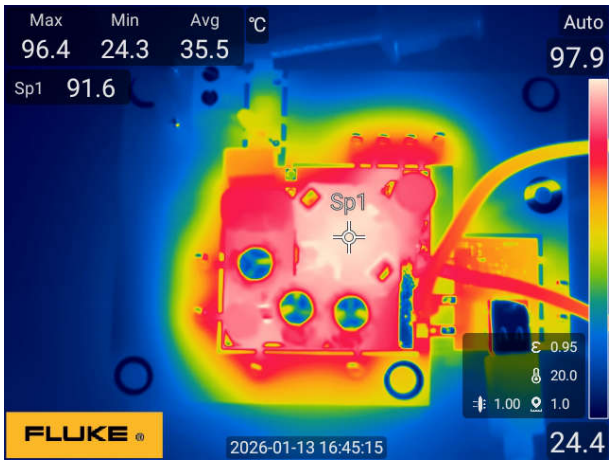


图 3-76. V_{IN} = 264V_{AC}，顶面

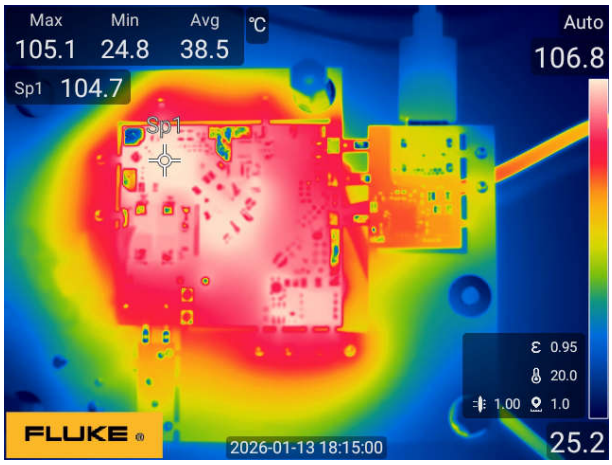


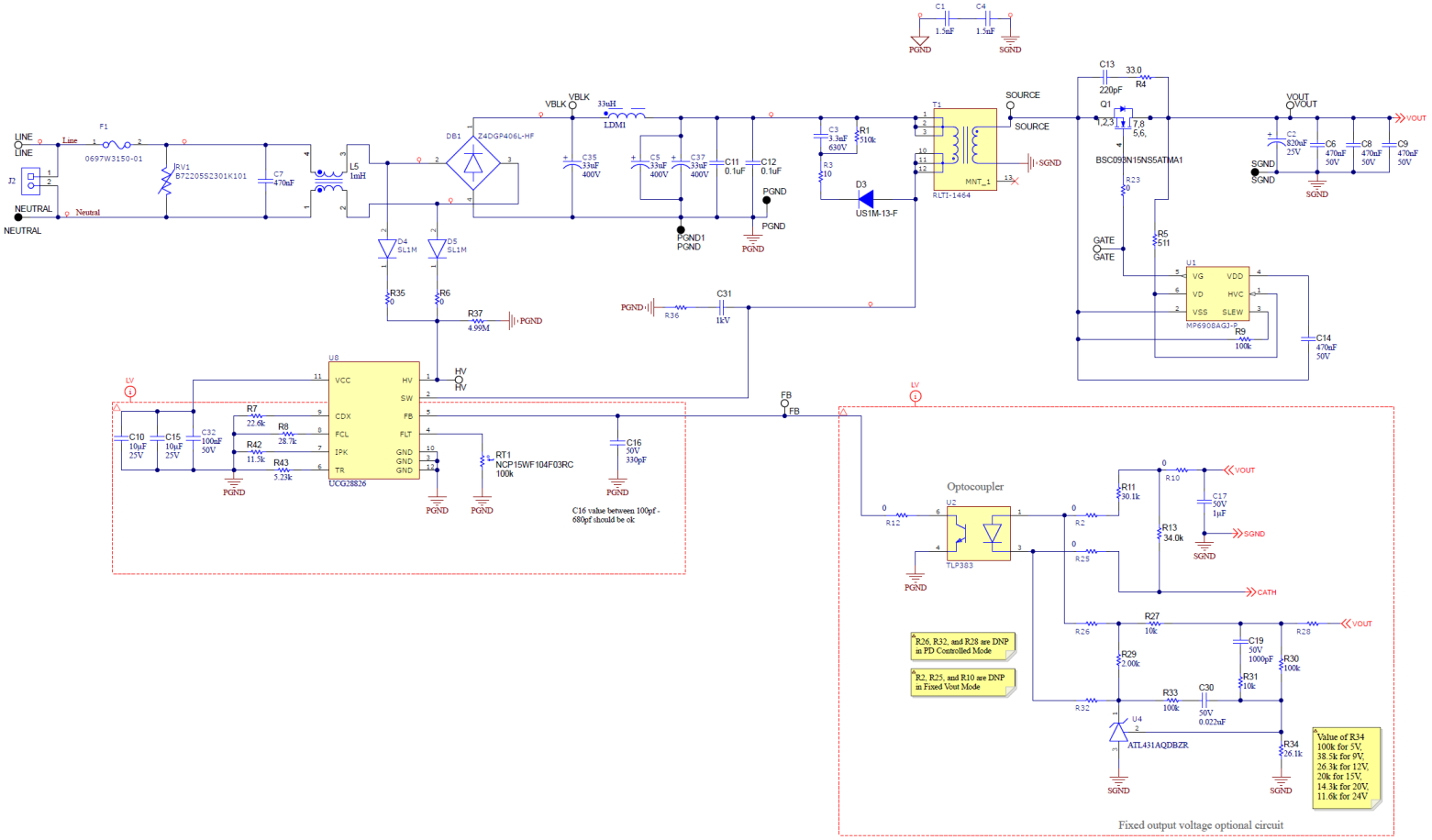
图 3-77. V_{IN} = 264V_{AC}，底面

4 硬件设计文件

4.1 原理图

UCG28826EVM-093 的原理图如下所示。该 EVM 已配置为启用 USB-PD 控制器，以便使用 USB-PD 负载进行评估。此 EVM 还可以重新配置以产生固定输出电压，用于使用非 USB-EVM PD 负载进行测试。为启用固定输出电压控制器，需先通过移除零欧姆电阻 R2、R25、R10 和 R19 来禁用 USB-C PD 控制器。然后通过安装零欧姆电阻 R26、R32 和 R28 来启用固定输出电压控制器。随后可以通过调节 R34 的阻值来设置输出电压，计算公式为：

$$R34 = R30 \times \frac{2.5V}{(Vout - 2.5V)}$$



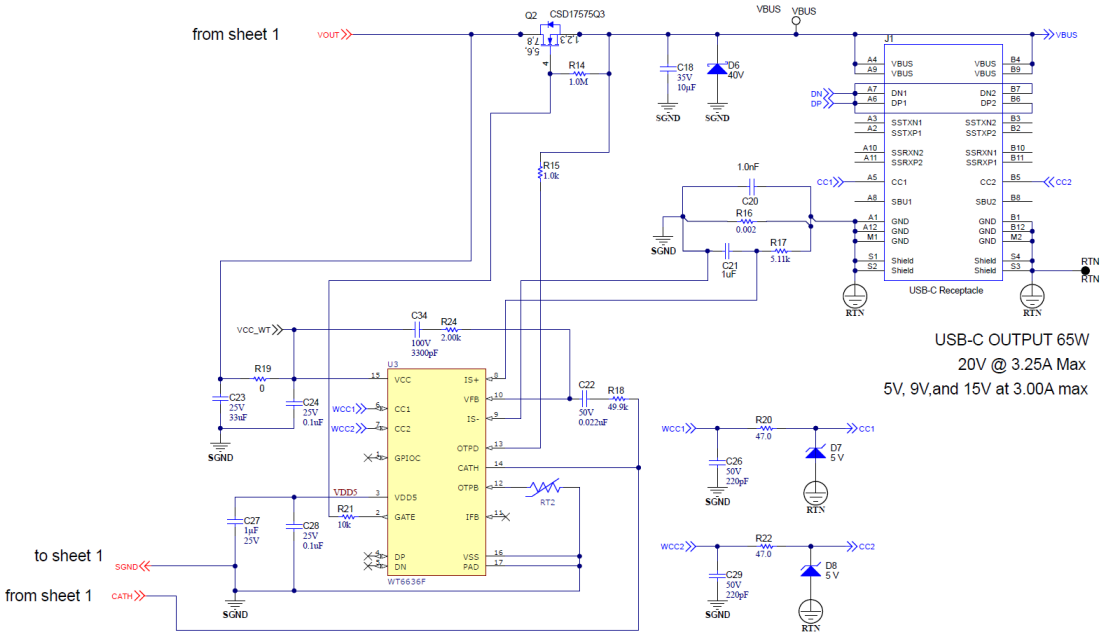


图 4-1. UCG28826EVM-093 原理图

4.2 PCB 布局

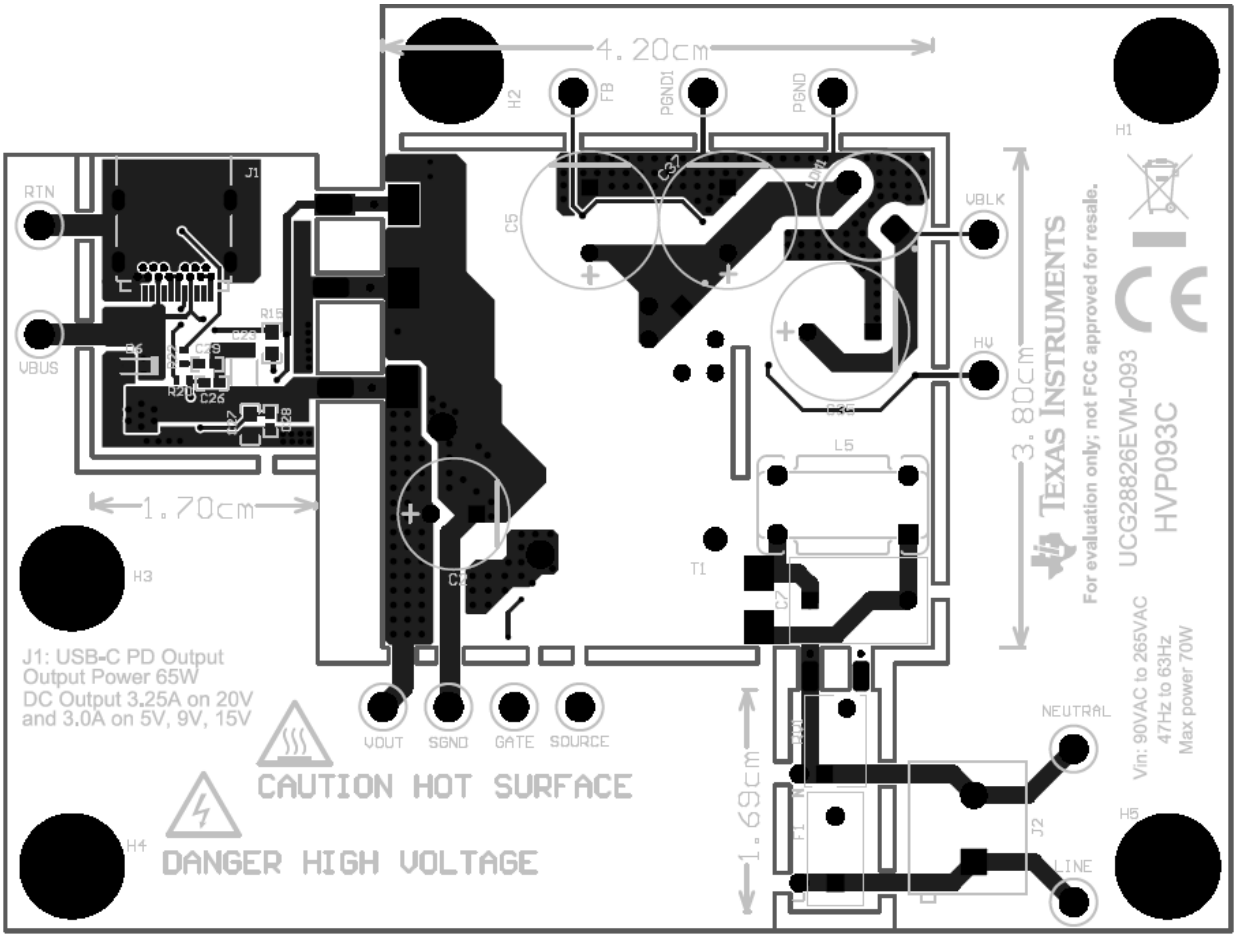


图 4-2. EVM 装配图（顶视图）

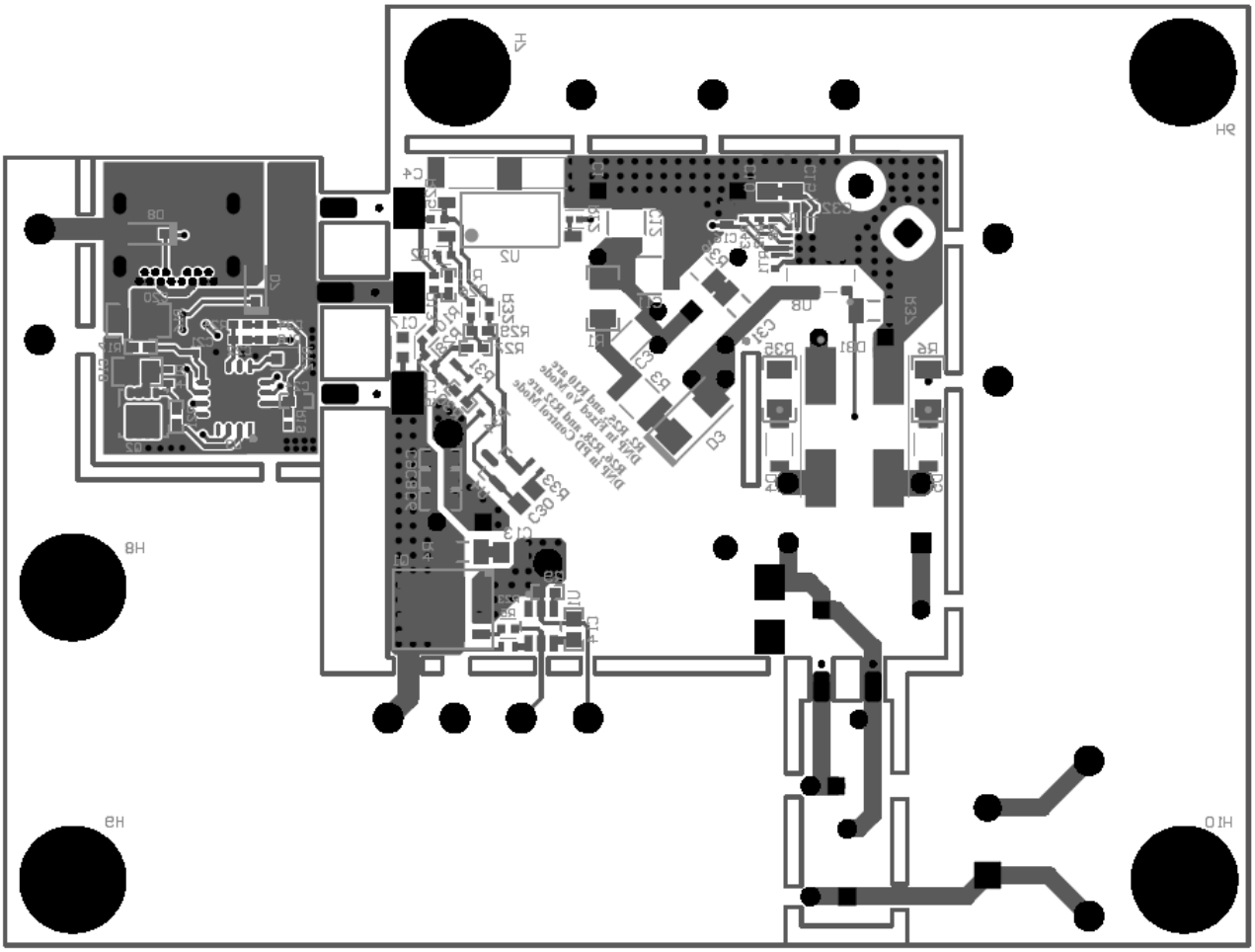


图 4-3. EVM 装配图（底视图）

4.3 变压器详细信息

本设计使用 Renco 的变压器，规格如下所述。

4.3.1 RLTI-1464 (RENCO)

此变压器是此设计中的出色选择，能够满足效率规格要求。这可以在泄漏能量（提高效率）与绕组间电容（有助于改善 UCG28826 热性能）之间实现良好的平衡。

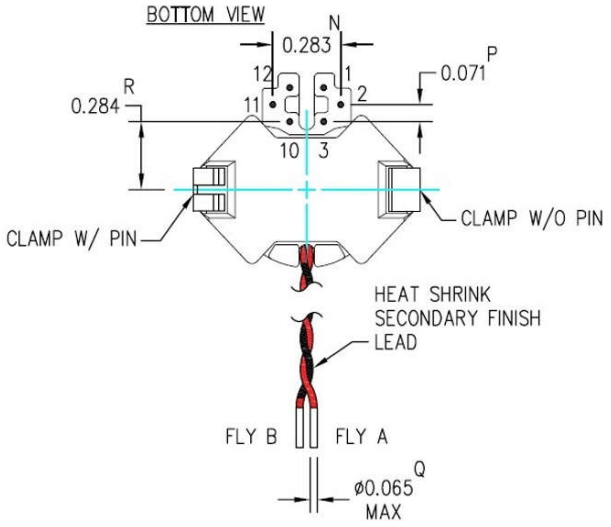


图 4-4. RLTI-1464 引脚配置

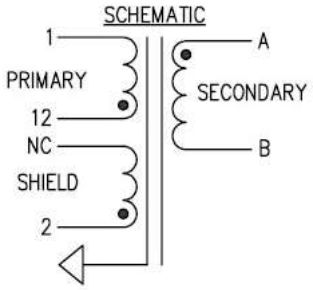


图 4-5. RLTI-1464 原理图

表 4-1. 25°C 时的变压器规格

参数	值	引脚/引线	测试条件
电感 (µH)	200，±5%	1 – 12	所有其他引脚均为开路，100kHz/0.1Vac
漏电感 (µH)	3.5（最大值）	1 – 12	短接 A - B，100kHz/0.1Vac
直流电阻 (Ω)	0.220，±15%	1 – 12	
直流电阻 (Ω)	0.007（最大值）	A – B	
电介质（VAC，60Hz）	3000Vac	1 – A	1mA，60Hz，1s
匝数比	6:1	(1-12):(A-B)	施加：1.0V @ 10kHz 至 (12 - 1) 输出电压：(A-B) 0.167V

4.4 物料清单

下表列出了 UCG28826EVM-093 的物料清单。

表 4-2. 物料清单

位号	值	数量	说明	器件型号	制造商
C1, C4	1500pF	2	1500pF ±10% 250VAC 陶瓷电容器 X7R 1808（公制 4520）	1808YA250152KJTSYX	Knowles Syfer
C2	820µF	1	820µF 25V 铝聚合物电容器，径向引脚罐式封装，22mΩ，在 105°C 条件下寿命为 5000 小时	RPF0816821M025K	KYOCERA AVX
C3	3.3nF	1	陶瓷电容 3.3nF 630V C0G 5% 焊盘 SMD 1206 +125°C 汽车级 T/R	CGA5L4C0G2J332J160AA	TDK
C5、C35、C37	33µF	3	33uF 400V 500mΩ@100kHz 370mA@100kHz ±20% 插件式 D10xL15mm 铝电解电容器 - 引脚型，符合 ROHS	87EC0493	KNSCHA
C6、C8、C9、C14	0.47µF	4	电容，陶瓷，0.47µF，50V，+/-20%，X7R，AEC-Q200 1 级，0603	CGA3E3X7R1H474M080AE	TDK
C7	470nF	1	470nF ±10% X2 插件式，P = 7.5mm 抑制电容器，符合 ROHS	MPX474K31B9KN20600	KNSCHA
C10，C15	10µF	2	电容，陶瓷，10uF，25V，+/-10%，X7R，0805	GRM21BZ71E106KE15L	Murata
C11，C12	0.1µF	2	电容，陶瓷，0.1µF，630V，+/-10%，X7R，1210	C1210C104KBRAC7800	KEMET
C16	330pF	1	电容，陶瓷，330pF，50V，+/-5%，C0G/NP0，0603	885012006060	Wurth Elektronik
C17	1µF	1	1µF ±10% 50V 陶瓷电容器 X7R 0603（公制 1608）	CC0603KRX7R9BB105	Yageo Group
C18	10µF	1	电容，陶瓷，10µF，35V，+/-10%，X5R，0805	GMK212BBJ106KG-T	TAIYO YUDEN（太阳诱电）
C19	1000pF	1	电容，陶瓷，1000pF，50V，+/-5%，C0G/NP0，0603	C0603C102J5GAC	Kemet
C20	1000pF	1	电容，陶瓷，1000pF，50V，+/-10%，X7R，0402	885012205061	Wurth Elektronik
C21	1µF	1	电容，陶瓷，1µF，6.3V，+/-20%，X7R，0402	GRM155R70J105MA12D	Murata
C22	0.022µF	1	电容，陶瓷，0.022µF，50V，+/-10%，X7R，AEC-Q200 1 级，0402	CGA2B3X7R1H223K050BB	TDK
C23	33µF	1	电容，陶瓷，33µF，25V，+/-20%，X5R，1206	C3216X5R1E336M160AC	TDK
C24、C28	0.1µF	2	电容，陶瓷，0.1µF，25V，+/-10%，X7R，0402	GRM155R71E104KE14D	Murata
C26，C29	220pF	2	电容，陶瓷，220pF，50V，+/-10%，X7R，0402	GRM155R71H221KA01D	Murata
C27	1µF	1	电容，陶瓷，1µF，25V，+/-10%，X7R，AEC-Q200 1 级，0603	GCM188R71E105KA64D	Murata
C30	0.022µF	1	电容，陶瓷，0.022µF，50V，+/-1%，C0G/NP0，0805	C0805C223F5GACTU	KEMET
C32	100nF	1	多层陶瓷电容器，100nF，50V，X7R ±10%，0402，纸质 T/R	GRT155R71H104KE01D	Murata
C34	3300µF	1	电容，陶瓷，3300pF，100V，+/-10%，X7R，0402	GRM155R72A332KA01D	Murata
D3	1000V	1	二极管，超快速，1000V，1A，SMA	US1M-13-F	Diodes Inc.
D4，D5	800V	2	二极管 800V 1A 表面贴装 SOD-123FL	SL1K	Diotec

表 4-2. 物料清单（续）

位号	值	数量	说明	器件型号	制造商
D6	40V	1	二极管，肖特基，40V，0.2A，SOD-523	RB521SM-40T2R	ROHM
D7，D8	5.6V	2	二极管，齐纳，5.6V，400mW，SOD-323F	D3Z5V6BF-7	Diodes Inc.
DB1		1	桥接整流器、单相标准、600V 表面贴装 Z4-D	Z4DGP406L-HF	Comchip
F1	3.15A	1	微型慢断保险丝，3.15A，350V，径向引脚，8.35 × 4 × 7.8mm，热塑性盒装	0697W3150-01	百富电子 (Bel Fuse)
FB，GATE，HV，LINE，SOURCE，VBLK，VBUS，VOUT		8	测试点，通用，白色，TH	5012	Keystone
H1、H2、H3、H4、H5		5	#4-40 平头机用螺钉十字螺丝刀，尼龙	NY PMS 440 0038 PH	结构紧固件
H6、H7、H8、H9、H10		5	六角螺柱，0.5"L #4-40，尼龙	1902C	Keystone
J1		1	连接器，插口，USB Type C，R/A	632723300011	Würth Elektronik
J2		1	端子块，5.08mm，2x1，黄铜，TH	ED120/2DS	On Shore Technology Inc.
L5	1mH	1	耦合电感器，1mH，2A，0.045Ω，TH	744821201	Wurth Elektronik
LDM1	33µH	1	WE-TI 径向引脚绕线电感，尺寸 8095，33uH，2.5A，0.066Ω	7447720330	Wurth Elektronik
NEUTRAL，PGND，PGND1，RTN，SGND		5	测试点，多用途，黑色，TH	5011	Keystone
Q1	150V	1	MOSFET，N 沟道，150V，87A，PG-TDSON-8	BSC093N15NS5ATMA1	Infineon Technologies
Q2	30V	1	MOSFET，N 沟道，30V，60A，DQG0008A (VSON-CLIP-8)	CSD17575Q3	德州仪器 (TI)
R1	510kΩ	1	电阻，510k，5%，0.25W，AEC-Q200 0 级，1206	CRCW1206510KJNEA	Vishay/Dale
R2、R10、R12、R23、R25	0Ω	5	电阻厚膜，0Ω，0.2W，0402	CRCW04020000Z0EDHP	Vishay
R3	10Ω	1	10Ω ±5% 0.5W 1210 厚膜片上电阻，符合 AEC-Q200 标准	RMCF1210JT10R0	Stackpole Electronics
R5	511Ω	1	电阻，511，1%，0.063W，AEC-Q200 0 级，0402	CRCW0402511RFKED	Vishay/Dale
R6，R35	0Ω	2	电阻，0，5%，0.25W，AEC-Q200 0 级，1206	CRCW12060000Z0EA	Vishay/Dale
R7	22.6kΩ	1	电阻，22.6k，1%，0.063W，AEC-Q200 0 级，0402	CRCW040222K6FKED	Vishay/Dale
R8	28.7kΩ	1	电阻，28.7kΩ，1%，0.063W，AEC-Q200 0 级，0402	CRCW040228K7FKED	Vishay/Dale
R9，R30	100kΩ	2	电阻，100k，1%，0.1W，0402	ERJ-2RKF1003X	Panasonic
R11	30.1kΩ	1	电阻，30.1k，1%，0.063W，0402	CRCW040230K1FKED	Vishay/Dale
R13	34kΩ	1	电阻，34.0kΩ，1%，0.063W，AEC-Q200 0 级，0402	CRCW040234K0FKED	Vishay/Dale
R14	1MΩ	1	电阻，1.0MΩ，5%，0.063W，AEC-Q200 0 级，0402	CRCW04021M00JNED	Vishay/Dale
R15	1kΩ	1	电阻，1.0k，5%，0.25W，AEC-Q200 0 级，0603	ESR03EZPJ102	ROHM
R16	0.002Ω	1	电阻，0.002，1%，1W，AEC-Q200 0 级，1206	PMR18EZPFV2L00	ROHM
R17	5.11kΩ	1	电阻，5.11k，1%，0.063W，0402	CRCW04025K11FKED	Vishay/Dale

表 4-2. 物料清单（续）

位号	值	数量	说明	器件型号	制造商
R18	49.9kΩ	1	电阻，49.9k，1%，0.063W，AEC-Q200 0 级，0402	CRCW040249K9FKED	Vishay/Dale
R19	0Ω	1	电阻，0，5%，0.063W，AEC-Q200 0 级，0402	CRCW04020000Z0ED	Vishay / Dale
R20，R22	47Ω	2	电阻，47.0，1%，0.063W，0402	RK73H1ETTP47R0F	KOA Speer
R21、R27、R31	10kΩ	3	电阻，10k，5%，0.063W，0402	CRCW040210K0JNED	Vishay / Dale
R24	2kΩ	1	电阻，2.00k，0.1%，0.063W，0402	RG1005P-202-B-T5	Susumu
R29	2kΩ	1	电阻，2.00k，1%，0.063W，AEC-Q200 0 级，0402	CRCW04022K00FKED	Vishay / Dale
R33	100kΩ	1	电阻，100k，1%，0.063W，AEC-Q200 0 级，0402	CRCW0402100KFKED	Vishay / Dale
R34	26.1kΩ	1	电阻，26.1kΩ，1%，0.063W，AEC-Q200 0 级，0402	CRCW040226K1FKED	Vishay / Dale
R37	4.99MΩ	1	电阻，4.99M，1%，0.25W，AEC-Q200 0 级，1206	CRCW12064M99FKEA	Vishay/Dale
R42	11.5kΩ	1	电阻，11.5k，1%，0.063W，AEC-Q200 0 级，0402	CRCW040211K5FKED	Vishay / Dale
R43	5.23kΩ	1	电阻，5.23k，1%，0.063W，AEC-Q200 0 级，0402	CRCW04025K23FKED	Vishay / Dale
RT1	100kΩ	1	热敏电阻 NTC，100kΩ，1%，0402	NCP15WF104F03RC	Murata
RT2	220kΩ	1	热敏电阻 NTC，220KΩ，5%，2 引脚，0603，表面贴装，焊盘，4450K，卷带	ERT-J1VT224J	Panasonic
RV1		1	470V 800A 压敏电阻 1 电路穿孔圆盘 5mm	B72205S2301K101	EPCOS
T1		1	反激式变压器	RLTI-1464	RENCO
U1		1	快速关断智能整流器	MP6908GJ-Z	Monolithic Power Systems
U2		1	光耦合器晶体管输出 5000Vrms 1 通道 6-SO	TLP383(GR-TPL,E	Toshiba Semiconductor and Storage
U3		1	USB PD/QC4/QC4+ 控制器	WT6636F	Weltrend
U4		1	电压基准，可调/精密型，2.5V 至 36V，100mA，3 引脚，SOT-23，T/R	ATL431AQDBZR	德州仪器 (TI)
U8		1	具有集成式 GaN 的自偏置高频 QR 反激式转换器	UCG28826-1REZR	德州仪器 (TI)

5 其他信息

商标

所有商标均为其各自所有者的财产。

6 修订历史记录

注：以前版本的页码可能与当前版本的页码不同

Changes from Revision B (May 2025) to Revision C (November 2025)	Page
• 更新了 表 3-1。	5
• 更新了 节 3.2.2 部分中的图像	8
• 更新了表 3-2	10

Changes from Revision A (February 2025) to Revision B (May 2025)	Page
• 更新了*测试设置图*部分中的图像	8
• 更新了*线路瞬态响应*部分中的图注释的输入电压范围	27
• *满负载（20V 和 3.25A）条件下热图像*部分中已更新的图像	29
• 更新了*硬件设计文件*部分中的图像	31
• 更新了*变压器详细信息*部分中变压器设计的详细信息	35
• 在*物料清单*部分中根据当前 BOM 更新了表	36

Changes from Revision * (October 2024) to Revision A (February 2025)	Page
• *满负载（20V 和 3.25A）条件下热图像*部分中已更新的图像	29

STANDARD TERMS FOR EVALUATION MODULES

1. *Delivery:* TI delivers TI evaluation boards, kits, or modules, including any accompanying demonstration software, components, and/or documentation which may be provided together or separately (collectively, an “EVM” or “EVMs”) to the User (“User”) in accordance with the terms set forth herein. User's acceptance of the EVM is expressly subject to the following terms.

   1.1 EVMs are intended solely for product or software developers for use in a research and development setting to facilitate feasibility evaluation, experimentation, or scientific analysis of TI semiconductors products. EVMs have no direct function and are not finished products. EVMs shall not be directly or indirectly assembled as a part or subassembly in any finished product. For clarification, any software or software tools provided with the EVM (“Software”) shall not be subject to the terms and conditions set forth herein but rather shall be subject to the applicable terms that accompany such Software

   1.2 EVMs are not intended for consumer or household use. EVMs may not be sold, sublicensed, leased, rented, loaned, assigned, or otherwise distributed for commercial purposes by Users, in whole or in part, or used in any finished product or production system.

2 *Limited Warranty and Related Remedies/Disclaimers*:

   2.1 These terms do not apply to Software. The warranty, if any, for Software is covered in the applicable Software License Agreement.

   2.2 TI warrants that the TI EVM will conform to TI's published specifications for ninety (90) days after the date TI delivers such EVM to User. Notwithstanding the foregoing, TI shall not be liable for a nonconforming EVM if (a) the nonconformity was caused by neglect, misuse or mistreatment by an entity other than TI, including improper installation or testing, or for any EVMs that have been altered or modified in any way by an entity other than TI, (b) the nonconformity resulted from User's design, specifications or instructions for such EVMs or improper system design, or (c) User has not paid on time. Testing and other quality control techniques are used to the extent TI deems necessary. TI does not test all parameters of each EVM. User's claims against TI under this Section 2 are void if User fails to notify TI of any apparent defects in the EVMs within ten (10) business days after delivery, or of any hidden defects with ten (10) business days after the defect has been detected.

   2.3 TI's sole liability shall be at its option to repair or replace EVMs that fail to conform to the warranty set forth above, or credit User's account for such EVM. TI's liability under this warranty shall be limited to EVMs that are returned during the warranty period to the address designated by TI and that are determined by TI not to conform to such warranty. If TI elects to repair or replace such EVM, TI shall have a reasonable time to repair such EVM or provide replacements. Repaired EVMs shall be warranted for the remainder of the original warranty period. Replaced EVMs shall be warranted for a new full ninety (90) day warranty period.

WARNING

Evaluation Kits are intended solely for use by technically qualified, professional electronics experts who are familiar with the dangers and application risks associated with handling electrical mechanical components, systems, and subsystems.

User shall operate the Evaluation Kit within TI’s recommended guidelines and any applicable legal or environmental requirements as well as reasonable and customary safeguards. Failure to set up and/or operate the Evaluation Kit within TI’s recommended guidelines may result in personal injury or death or property damage. Proper set up entails following TI’s instructions for electrical ratings of interface circuits such as input, output and electrical loads.

NOTE:

EXPOSURE TO ELECTROSTATIC DISCHARGE (ESD) MAY CAUSE DEGREDATION OR FAILURE OF THE EVALUATION KIT; TI RECOMMENDS STORAGE OF THE EVALUATION KIT IN A PROTECTIVE ESD BAG.

3 *Regulatory Notices:*

3.1 *United States*

3.1.1 *Notice applicable to EVMs not FCC-Approved:*

FCC NOTICE: This kit is designed to allow product developers to evaluate electronic components, circuitry, or software associated with the kit to determine whether to incorporate such items in a finished product and software developers to write software applications for use with the end product. This kit is not a finished product and when assembled may not be resold or otherwise marketed unless all required FCC equipment authorizations are first obtained. Operation is subject to the condition that this product not cause harmful interference to licensed radio stations and that this product accept harmful interference. Unless the assembled kit is designed to operate under part 15, part 18 or part 95 of this chapter, the operator of the kit must operate under the authority of an FCC license holder or must secure an experimental authorization under part 5 of this chapter.

3.1.2 *For EVMs annotated as FCC – FEDERAL COMMUNICATIONS COMMISSION Part 15 Compliant:*

CAUTION

This device complies with part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) This device may not cause harmful interference, and (2) this device must accept any interference received, including interference that may cause undesired operation.

Changes or modifications not expressly approved by the party responsible for compliance could void the user's authority to operate the equipment.

FCC Interference Statement for Class A EVM devices

NOTE: This equipment has been tested and found to comply with the limits for a Class A digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference when the equipment is operated in a commercial environment. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instruction manual, may cause harmful interference to radio communications. Operation of this equipment in a residential area is likely to cause harmful interference in which case the user will be required to correct the interference at his own expense.

FCC Interference Statement for Class B EVM devices

NOTE: This equipment has been tested and found to comply with the limits for a Class B digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates, uses and can radiate radio frequency energy and, if not installed and used in accordance with the instructions, may cause harmful interference to radio communications. However, there is no guarantee that interference will not occur in a particular installation. If this equipment does cause harmful interference to radio or television reception, which can be determined by turning the equipment off and on, the user is encouraged to try to correct the interference by one or more of the following measures:

- *Reorient or relocate the receiving antenna.*
- *Increase the separation between the equipment and receiver.*
- *Connect the equipment into an outlet on a circuit different from that to which the receiver is connected.*
- *Consult the dealer or an experienced radio/TV technician for help.*

3.2 *Canada*

3.2.1 *For EVMs issued with an Industry Canada Certificate of Conformance to RSS-210 or RSS-247*

Concerning EVMs Including Radio Transmitters:

This device complies with Industry Canada license-exempt RSSs. Operation is subject to the following two conditions:

(1) this device may not cause interference, and (2) this device must accept any interference, including interference that may cause undesired operation of the device.

Concernant les EVMs avec appareils radio:

Le présent appareil est conforme aux CNR d'Industrie Canada applicables aux appareils radio exempts de licence. L'exploitation est autorisée aux deux conditions suivantes: (1) l'appareil ne doit pas produire de brouillage, et (2) l'utilisateur de l'appareil doit accepter tout brouillage radioélectrique subi, même si le brouillage est susceptible d'en compromettre le fonctionnement.

Concerning EVMs Including Detachable Antennas:

Under Industry Canada regulations, this radio transmitter may only operate using an antenna of a type and maximum (or lesser) gain approved for the transmitter by Industry Canada. To reduce potential radio interference to other users, the antenna type and its gain should be so chosen that the equivalent isotropically radiated power (e.i.r.p.) is not more than that necessary for successful communication. This radio transmitter has been approved by Industry Canada to operate with the antenna types listed in the user guide with the maximum permissible gain and required antenna impedance for each antenna type indicated. Antenna types not included in this list, having a gain greater than the maximum gain indicated for that type, are strictly prohibited for use with this device.

Concernant les EVMs avec antennes détachables

Conformément à la réglementation d'Industrie Canada, le présent émetteur radio peut fonctionner avec une antenne d'un type et d'un gain maximal (ou inférieur) approuvé pour l'émetteur par Industrie Canada. Dans le but de réduire les risques de brouillage radioélectrique à l'intention des autres utilisateurs, il faut choisir le type d'antenne et son gain de sorte que la puissance isotrope rayonnée équivalente (p.i.r.e.) ne dépasse pas l'intensité nécessaire à l'établissement d'une communication satisfaisante. Le présent émetteur radio a été approuvé par Industrie Canada pour fonctionner avec les types d'antenne énumérés dans le manuel d'usage et ayant un gain admissible maximal et l'impédance requise pour chaque type d'antenne. Les types d'antenne non inclus dans cette liste, ou dont le gain est supérieur au gain maximal indiqué, sont strictement interdits pour l'exploitation de l'émetteur

3.3 *Japan*

3.3.1 *Notice for EVMs delivered in Japan:* Please see http://www.tij.co.jp/lsds/ti_ja/general/eStore/notice_01.page 日本国内に輸入される評価用キット、ボードについては、次のところをご覧ください。

https://www.ti.com/ja-jp/legal/notice-for-evaluation-kits-delivered-in-japan.html

3.3.2 *Notice for Users of EVMs Considered "Radio Frequency Products" in Japan:* EVMs entering Japan may not be certified by TI as conforming to Technical Regulations of Radio Law of Japan.

If User uses EVMs in Japan, not certified to Technical Regulations of Radio Law of Japan, User is required to follow the instructions set forth by Radio Law of Japan, which includes, but is not limited to, the instructions below with respect to EVMs (which for the avoidance of doubt are stated strictly for convenience and should be verified by User):

1. Use EVMs in a shielded room or any other test facility as defined in the notification #173 issued by Ministry of Internal Affairs and Communications on March 28, 2006, based on Sub-section 1.1 of Article 6 of the Ministry's Rule for Enforcement of Radio Law of Japan,
2. Use EVMs only after User obtains the license of Test Radio Station as provided in Radio Law of Japan with respect to EVMs, or
3. Use of EVMs only after User obtains the Technical Regulations Conformity Certification as provided in Radio Law of Japan with respect to EVMs. Also, do not transfer EVMs, unless User gives the same notice above to the transferee. Please note that if User does not follow the instructions above, User will be subject to penalties of Radio Law of Japan.

【無線電波を送信する製品の開発キットをお使いになる際の注意事項】 開発キットの中には技術基準適合証明を受けていないものがあります。 技術適合証明を受けていないもののご使用に際しては、電波法遵守のため、以下のいずれかの措置を取っていただく必要がありますのでご注意ください。

1. 電波法施行規則第6条第1項第1号に基づく平成18年3月28日総務省告示第173号で定められた電波暗室等の試験設備でご使用いただく。
2. 実験局の免許を取得後ご使用いただく。
3. 技術基準適合証明を取得後ご使用いただく。

なお、本製品は、上記の「ご使用にあたっての注意」を譲渡先、移転先に通知しない限り、譲渡、移転できないものとします。

上記を遵守頂けない場合は、電波法の罰則が適用される可能性があることをご留意ください。 日本テキサス・インスツルメンツ株式会社

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西新宿三井ビル

3.3.3 *Notice for EVMs for Power Line Communication:* Please see http://www.tij.co.jp/lsds/ti_ja/general/eStore/notice_02.page

電力線搬送波通信についての開発キットをお使いになる際の注意事項については、次のところをご覧ください。https://www.ti.com/ja-jp/legal/notice-for-evaluation-kits-for-power-line-communication.html

3.4 *European Union*

3.4.1 *For EVMs subject to EU Directive 2014/30/EU (Electromagnetic Compatibility Directive)*:

This is a class A product intended for use in environments other than domestic environments that are connected to a low-voltage power-supply network that supplies buildings used for domestic purposes. In a domestic environment this product may cause radio interference in which case the user may be required to take adequate measures.

4 *EVM Use Restrictions and Warnings:*

4.1 EVMS ARE NOT FOR USE IN FUNCTIONAL SAFETY AND/OR SAFETY CRITICAL EVALUATIONS, INCLUDING BUT NOT LIMITED TO EVALUATIONS OF LIFE SUPPORT APPLICATIONS.

4.2 User must read and apply the user guide and other available documentation provided by TI regarding the EVM prior to handling or using the EVM, including without limitation any warning or restriction notices. The notices contain important safety information related to, for example, temperatures and voltages.

4.3 *Safety-Related Warnings and Restrictions:*

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最后更新日期：2025 年 10 月