

Introduction

This document describes the design and performance of a 63W auxiliary power supply with wide input voltage for industrial and solar applications using 1.7 kV Silicon Carbide (SiC) MOSFETs. The evaluation board is designed to evaluate the performance of MSC750SMA170B for ease of use.

This document is for the users of MSC750SMA170B who want to create low-cost and high-performance off-line Switch Mode Power Supply (SMPS) for auxiliary power supply. This document provides the design details, including device selection, control parameter determination, and transformer and hardware designs.

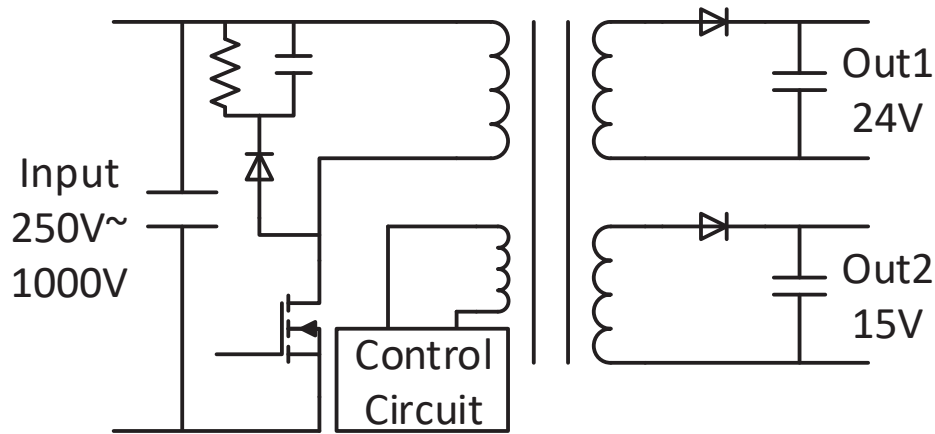
Auxiliary power supply is an essential part of a power converter that converts the electric power from High Voltage (HV) DC bus to a Low Voltage (LV) source for powering control circuits, sensing circuits, cooling fans, and so on. A low power (<100W) power converter with galvanic isolation is one of the most important components in industrial and Photovoltaic (PV) applications. Due to DC link voltage variation, many of these auxiliary power supplies must operate from a wide input voltage range, typically ranging from 250V to 1000V. To ensure the overall reliability of the power converter system, this converter must have a simple topology and a low component count.

Due to its simple structure, low component count, and low cost, the single switch flyback topology is a popular choice for such low power DC-DC converters. However, due to the high peak voltage seen on the power switching device, using silicon MOSFETs in the auxiliary power supply applications presents many challenges. For example, at the highest input voltage of 1 kV, the peak voltage on the switching device can easily exceed 1.2 kV due to secondary side reflected voltage and voltage across transformer leakage inductance, forcing the user to use 1.5 kV–2 kV devices.

The options for the HV silicon MOSFETs are limited, and the specific on-state resistance is much higher than for LV MOSFETs, reducing the converter efficiency and complicating the cooling design. Furthermore, due to limited resources, the cost of the HV silicon MOSFETs is significantly higher. To utilize the lower rated voltage silicon MOSFETs, two-switch flyback or other topologies can be used, but the design complexity and component count increase significantly, reducing reliability and increasing design cost.

The following figure shows the topology of a single switch flyback converter with a 1.7 kV SiC MOSFET for the auxiliary power supply applications.

Figure 1. Single Switch Flyback Converter for Auxiliary Power Supply Applications



1.7 kV SiC MOSFET is an excellent choice for using a single switch flyback topology in an auxiliary power supply application that requires a wide input voltage range. The 1.7 kV breakdown voltage provides sufficient voltage margin for the 1 kV input voltage. The specific on-resistance of 1.7 kV SiC MOSFET is much lower than that of HV silicon MOSFET, allowing for a smaller die size and lower on-resistance in the same package. The smaller die size also significantly reduces switching loss. This option allows to increase the switching frequency of the auxiliary power supply in order to reduce transformer size and weight.

Features

The evaluation board has the following key hardware features:

- Single Switch Flyback Topology
- 250V-1000V Wide Input Voltage
- +24V/2A and +15V/1A Dual Outputs, and Total 63W Output Power
- High-Power Conversion Efficiency Over Wide Power Range
- Current-Mode Pulse-Width Modulation (PWM) Controller-Based Closed Loop Control

Applications

The evaluation board has the following applications:

- Industrial motor drives
- Solar inverters
- Uninterruptible power supplies
- General purpose inverters
- Cascaded H-bridge converters
- Modular multilevel converters

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1. Electrical Specification

The following table lists the electrical specification of the evaluation board.

Table 1-1. Electrical Specification—Evaluation Board

Symbol	Parameter	Ratings	Unit
V_{in_min}	Minimum input voltage	250	V
V_{in_max}	Maximum input voltage	1000	
V_{out1}	Output voltage 1	24	
I_{out_max1}	Maximum output current 1	2	A
V_{out2}	Output voltage 2	15	V
I_{out_max2}	Maximum output current 2	1	A
P_{out_max}	Maximum output power	63	W
f_s	Switching frequency	45	kHz
—	Efficiency at >25% load	>80	%
E_{ff_max}	Peak efficiency	89	

2. Evaluation Board

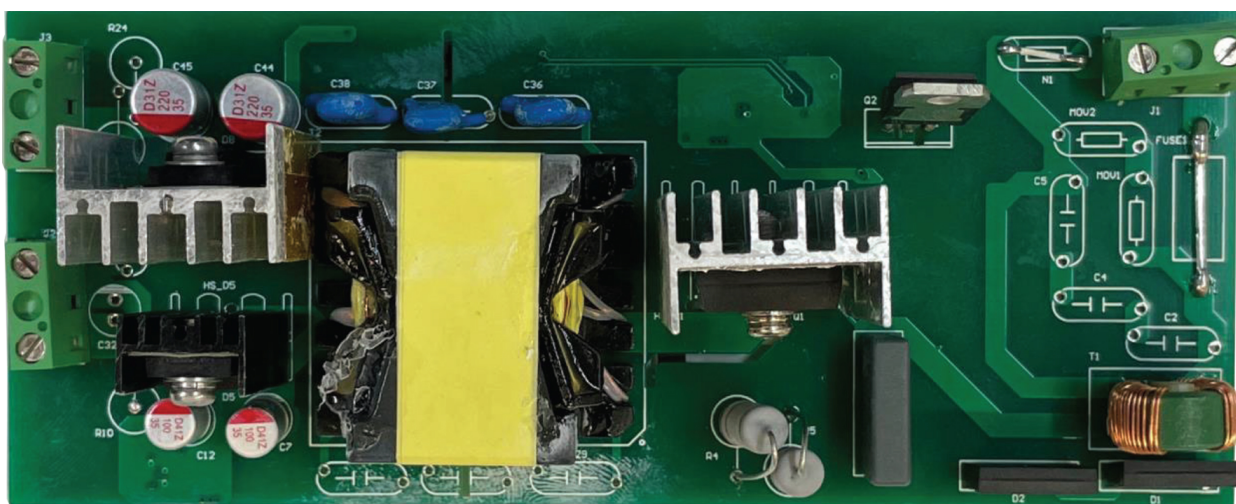
This chapter describes the evaluation board hardware, schematics, circuit, and Printed Circuit Board (PCB) layout.

2.1 Evaluation Board Hardware

The main components of the evaluation board include input and output power connectors, input and output capacitors, SiC MOSFET, isolation transformer, output rectifier, driver IC, and analog closed-loop circuits.

The following figure shows the picture of the evaluation board hardware.

Figure 2-1. Evaluation Board Hardware



2.2 Schematic

The following components are included in the main power stage circuit:

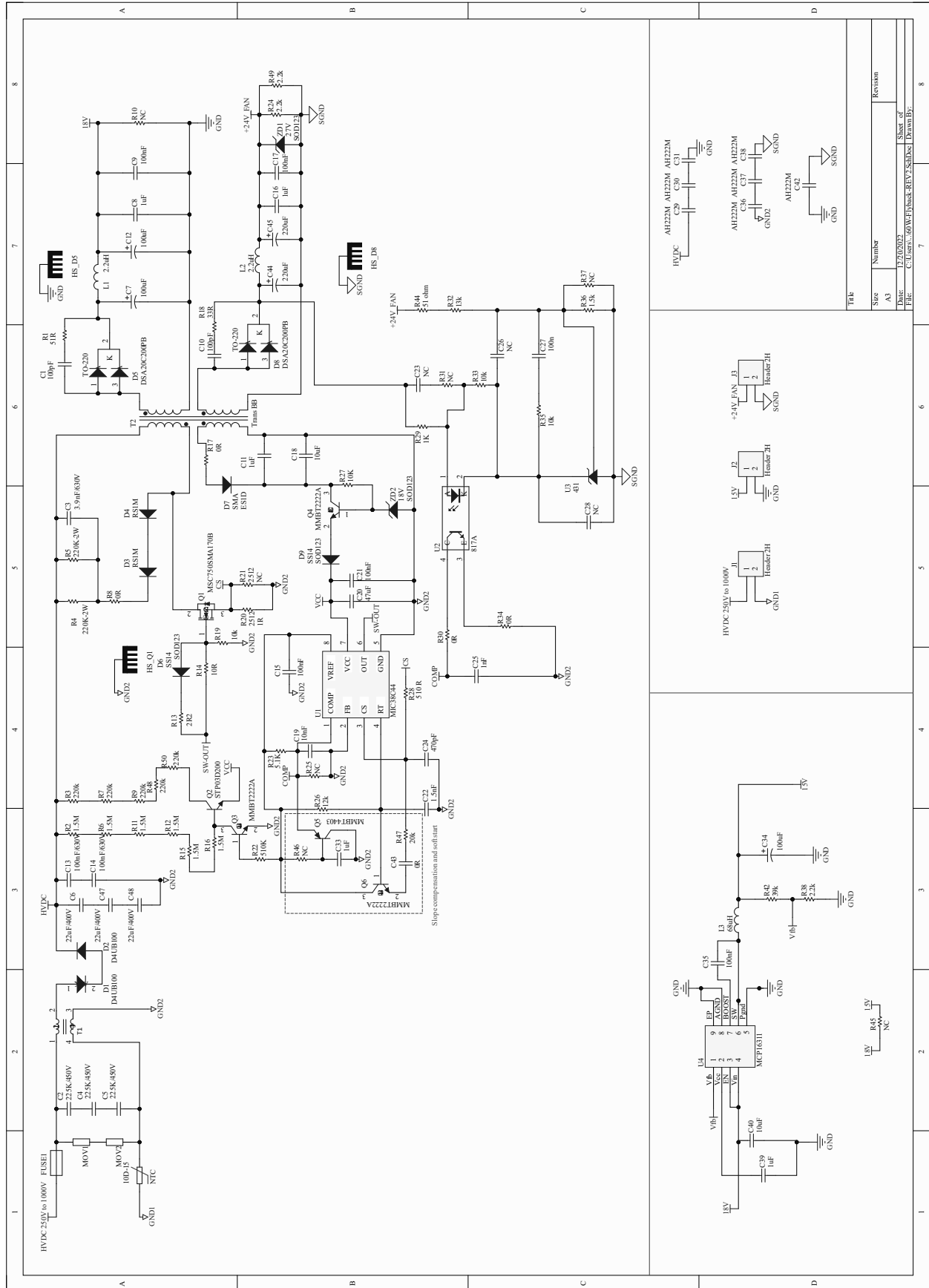
- A DC input fuse and a Metal Oxide Varistor (MOV) (optional)
- An input capacitor
- A loss reduction startup circuit
- A Resistor Capacitor Diode (RCD) snubber circuit
- An isolation transformer
- SiC MOSFET
- A gate driving circuit
- An output rectification circuit
- An isolated output voltage feedback circuit
- An analog control circuit

The control circuit is based on a fixed frequency, high performance, and current-mode PWM controller Integrated Circuit (IC) MIC38C44. The following section describes the detailed design and parameter selection method. To download the actual design files (schematic and gerber files), go to microchip.com/sic.

The following figure shows the schematic of the evaluation board.

Note: The resistance units denoted by k, M, and R in the following figure are k Ω , M Ω , and Ω respectively.

Figure 2-2. Schematic of the Evaluation Board



2.3 Circuit Description

The design of a SiC-based single switch flyback converter can be similar to the traditional design of a flyback converter using MIC38C4x controllers. However, some special considerations are discussed in the following sections.

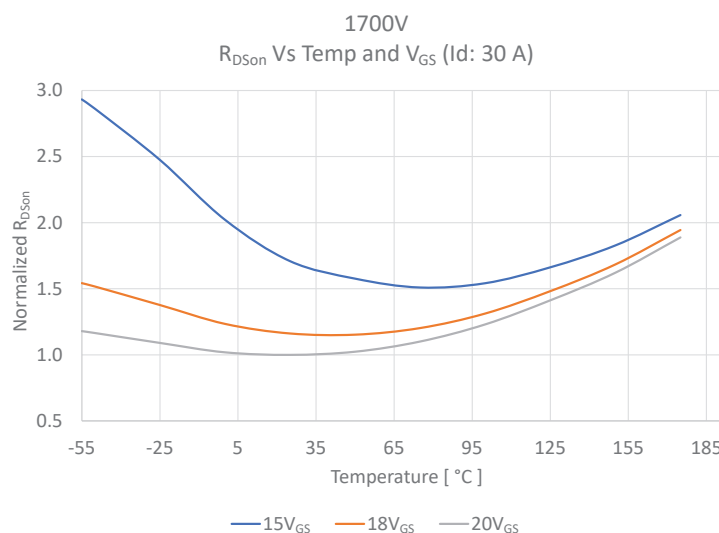
2.3.1 Primary Side SiC Switching Device Selection

For a 1 kV maximum input voltage and the reflected voltages at the transformer from the secondary side 24V output voltage, the peak voltage on the primary side switching device can exceed 1.2 kV; thus, 1.7 kV SiC MOSFETs are selected. The Root Mean Square (RMS) current through the primary side switching device is very low for the rated 63W power, so 750 mΩ SiC MOSFET is more than enough for such applications, while the smaller die size of the 750 mΩ SiC MOSFET can also help to reduce switching loss. Because the peak current through the device is also relatively small, the 3L-TO247 package was chosen for better thermal performance, allowing natural convection cooling to eliminate the need for a fan. Therefore, a 1.7 kV, 750 mΩ SiC MOSFET in an industry standard 3L-TO247 package from Microchip (part number MSC750SMA170B) is selected as the primary side switching power device.

2.3.2 Gate Driving Voltage and Gate Resistance Selection

The ultra low gate capacitance of the 1.7 kV, 750 mΩ SiC MOSFET enables direct driving from the controller IC, eliminating the need for an additional gate driver. It is recommended that the gate driving voltage for MSC750SMA170B be +20V/-5V. However, as shown in the following figure, the device works well at +18V with only a slight increase in on-state resistance; even at +15V, the on-state resistance increase is less than 25% at higher junction temperatures. The conduction loss in this application is very low due to the low RMS current through the primary side switch.

Figure 2-3. Normalized On-State Resistance (R_{DSon}) under Different Gate Voltages



Furthermore, because MSC750SMA170B is a normally off device, a negative voltage is not required to keep the device off in a steady state; the recommended negative voltage is to avoid false turn on, which can cause shoot through failure in a half-bridge circuit. There is no risk of shoot through failure in a single switch flyback topology. Therefore, the negative off voltage is not required.

Meanwhile, the controller IC MIC38C44 has an absolute maximum supply voltage of +20V, with special precautions required for operations at $\geq 18V$. To ensure the controller IC safe operation, the driving voltage of the SiC MOSFET is set to +17V/0V.

The selection of suitable gate resistance is determined by optimizing switching losses, Electromagnetic Interference (EMI) noise emission, and driving IC capability. A lower gate resistance

increases power MOSFET switching speed and reduces switching loss, while a higher gate resistance reduces converter EMI noise emission. A turn on resistance of 10Ω is selected based on the internal gate resistance of the SiC MOSFET, the peak output current capability, and the output impedance of the PWM controller.

The Undervoltage Lockout (UVLO) of the controller MIC38C44 is relatively low when compared to the optimal gate voltage of the SiC MOSFETs. During the startup process, the controller begins to operate once the supply voltage exceeds the UVLO threshold. When the gate voltage is low, the SiC MOSFET may operate in linear mode, and the maximum current through the device may be less than the current required if the load is heavy. The UVLO can be bypassed, and the threshold voltage can be set through an external circuit. For more information on detailed implementation, contact Microchip technical support.

2.3.3 Control Power Supply and Active Startup

In steady-state operation, the control voltage is generated from the auxiliary winding of the transformer through an 18V zener diode and an NPN transistor. During the startup process, the control voltage is drawn directly from the DC bus. To reduce converter loss and protect the controller from the high DC link voltage, a HV N-channel MOSFET (part number CS3N150AHR) with a high resistance branch is designed for control voltage during startup. Once the voltage on the auxiliary winding of the transformer is built up, the circuit cuts the connection to the HV DC bus to reduce power loss.

It is critical to optimize the gate loop layout design after determining the gate driving parameters. To reduce gate ringing and avoid high peak gate voltage, the key consideration is to reduce gate loop inductance and avoid near-field coupling.

2.3.4 Switching Frequency

The switching frequency of the power converter is one of the most important design parameters because it influences switching losses, transformer losses, overall converter size/weight, and converter level EMI. SiC MOSFETs have low switching loss energy and ultra-low gate charge when compared to Silicon (Si) switches, allowing for higher switching frequency and a more compact transformer design with lower power loss. For this evaluation board, a switching frequency of $f_s = 45$ kHz is selected considering the overall optimization of the converter loss.

2.3.5 Output Voltage Regulation

This demonstration hardware is designed for industrial and solar applications and has two output voltages: 24V/2A for fan loads and 15V/1A for main converter level control circuits. The 24V/2A output is directly regulated by feeding the output voltage back to the controller through an analog compensation network and an opto isolator. The 15V/1A output has an optional second stage power conversion based on the fixed frequency PWM/PFM synchronous buck regulator (MCP16311). If a high precision 15V output is required, the secondary winding of the transformer outputs 18V and feeds it into the buck regulator, which converts it to a precision 15V output. The buck regulator can also be bypassed for cost reduction. In this configuration, the transformer secondary winding is redesigned for 15V output to comply with the 24V regulation; this transformer design is also available.

2.3.6 Transformer Design

The transformer is the key passive component in the circuit for providing correct output voltages and galvanic isolation. The transformer power loss and temperature rise are determined by the core material and winding wire selection. The leakage inductance, which is determined directly by the winding structure, influences the voltage ringing and peak voltage on the power MOSFET, as well as the RCD clamping circuit design. The isolation capacitance effects the Common Mode (CM) noise emission of the system.

The following table lists the transformer key parameters.

Table 2-1. Transformer Design Specification

Parameter	Specification
Core material	PQ3528
Turns ratio (Np-Ns1-Ns2-Na, Pri:Sec1:Sec2:Aux)	60:7:5:5
Primary side inductance (L_p)	3.5 mH
Isolation rating (pri-sec)	3000 VAC, 3s, 2.0 mA
Isolation resistance (Np-Ns)	100 M Ω
Working temperature	-25 °C-125 °C

2.3.7 RCD Clamping

To avoid excessive voltage on the primary side switching devices, the flyback topology requires an RCD clamping circuit to absorb the energy in the transformer leakage inductance. When the device drain source voltage is higher than the input plus reflected output voltage, the RCD snubber circuit absorbs the energy from the leakage inductance resonance by forward biasing the diode. The voltage can be assumed constant during one switching period if the snubber capacitance is large enough. To absorb the energy from the transformer leakage inductance, two high power 2W resistors are connected in parallel with one HV 630V/3.9 nF film capacitor.

2.3.7.1 Closed Loop Control Parameter

Closed loop control is used to eliminate steady-state error and reduce the sensitivity of system parametric change. The gain and phase margin of the converter are optimized over a specific frequency range to reduce the influence of small signal load disturbances and improve system load dynamic performance. The closed loop control has minimal influence on the steady state performance. Because the drive IC is configured as a peak current mode PWM controller, an external voltage feedback loop is required to stabilize the converter.

The compensation loop is a typical dual loop design with TL431, the phototransistor optocoupler FOD817A, and the error amplifier inside the controller IC. A detailed RC value calculation for the voltage compensation loop design is not included in this user guide because the purpose of this evaluation board is to demonstrate the power stage performance. For more details, contact the Microchip support team.

2.4 PCB Layout

To reduce system costs, a two-layer PCB configuration is selected. The power loop on the primary side and the gate loop on the secondary side are both minimized for the improved device switching performance and the overall converter performance.

The following figures show the PCB layout design of the demo hardware.

Figure 2-4. PCB Layout Design

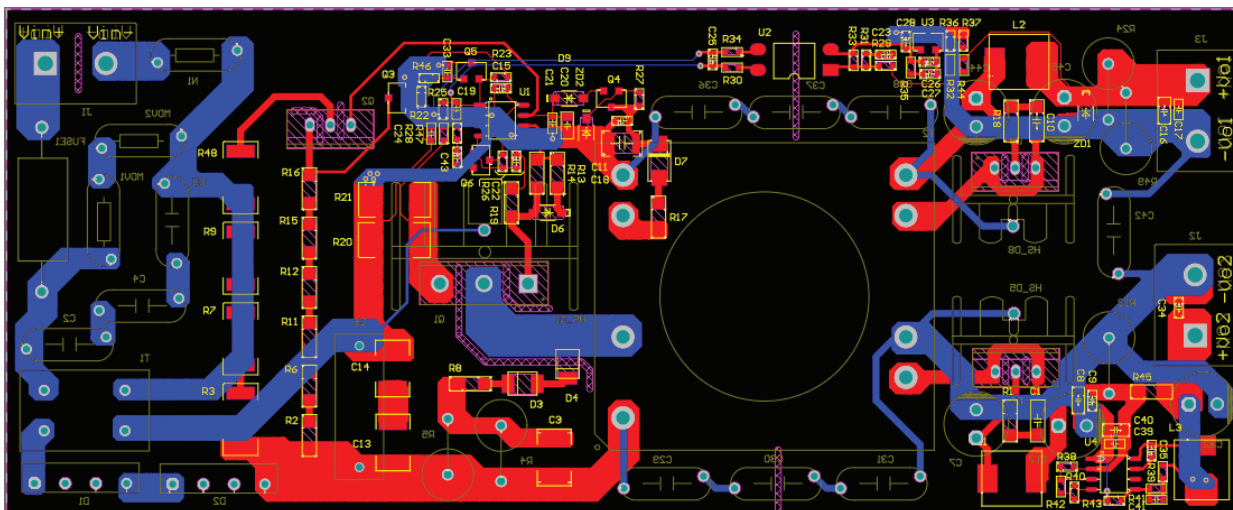


Figure 2-5. PCB Layout Design—Top Layer Copper and Top Side Component Placement

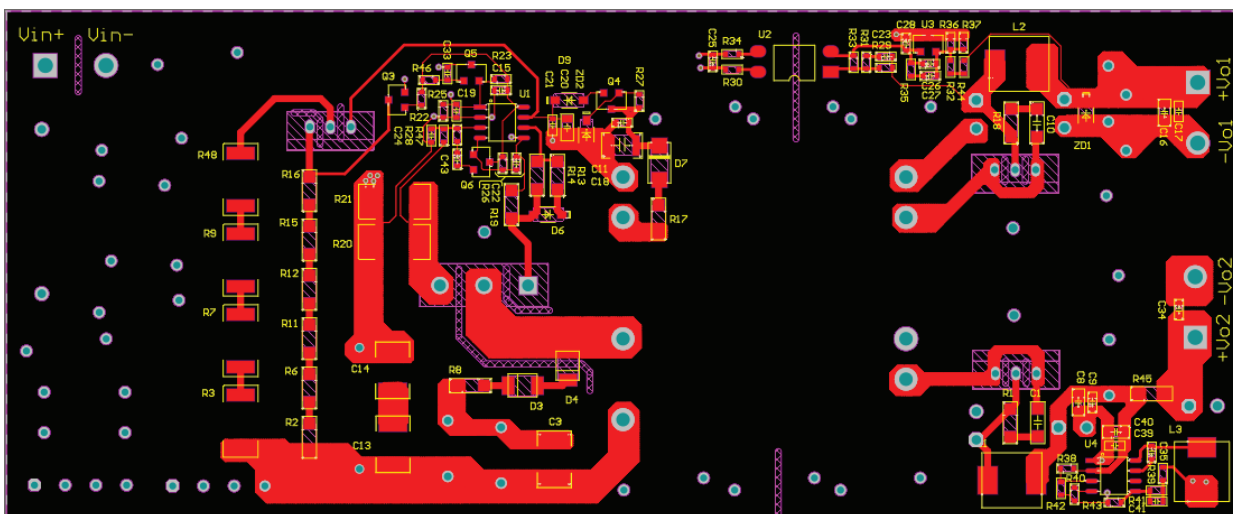
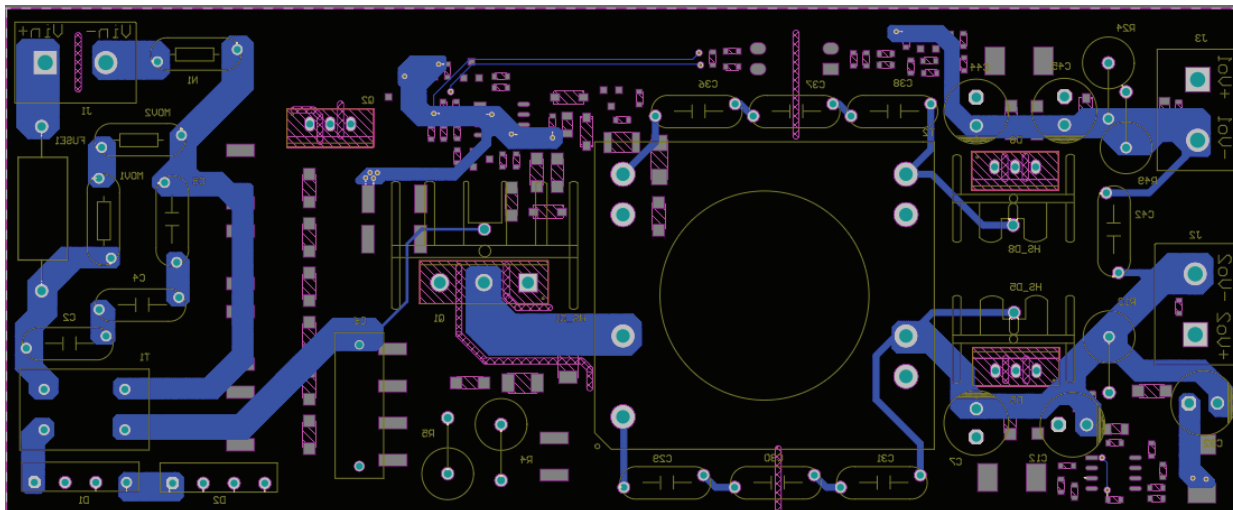


Figure 2-6. PCB Layout Design—Bottom Layer Copper and Bottom Side Component Placement



3. Bill Of Materials (BOM)

The following table lists BOM of the evaluation board.

Table 3-1. BOM of the Evaluation Board

Type	Ratings/Part Number	Designator	Footprint	Description	Quantity
Capacitor	3.9 nF/630V	C3	1812	TDK, 'X7R, ±10%	1
	100 nF/630V	C13, C14	1812	TDK, 'X7R, ±10%	2
	100 µF/35V	C7, C12, C32	C 8*11-3.5	AIHUA	3
	220 µF/35V	C44, C45	C 8*11-3.5	AIHUA	2
	1 µF	C8, C11, C16	C0603	TDK, 'X7R, ±10%, 35V	3
	100 nF	C9, C15, C17, C21	C0603	TDK, 'X7R, ±10%, 35V	4
	10 nF	C19	C0603	TDK, 'X7R, ±10%, 35V	1
	1 nF	C22	C0603	TDK, 'X7R, ±10%, 35V	1
	100 nF	C23	C0603	TDK, 'X7R, ±10%, 35V	1
	200 pF	C24, C34, C35, C39, C41	C0603	TDK, 'X7R, ±10%, 35V	5
	22 nF	C25	C0603	TDK, 'X7R, ±10%, 35V	1
	NC	C26, C28, C33, C43	C0603	TDK, 'X7R, ±10%, 35V	4
	10 nF	C27	C0603	TDK, 'X7R, ±10%, 35V	1
	10 µF	C20, C40	C0805	TDK, 'X7R, ±10%, 35V	2
	100 pF	C1, C10	C1206	TDK, 'X7R, ±10%, 35V	2
	10 µF	C18	C1210	TDK, 'X7R, ±10%, 35V	1
	3 µF/1100V	C6	C-18*6-15P	HJC	1
	2.2 µF/450V	C2, C4, C5	CY-222-4.5X14	±10%	3
	2200 pF	C29, C30, C31, C36, C37, C38, C42	CY-222-4.5X14	KEMET	7

.....continued

Type	Ratings/Part Number	Designator	Footprint	Description	Quantity
Resistor	510 k Ω	R22, R38	R0603	YAGEO, $\pm 1\%$	2
	5.1 k Ω	R23	R0603	YAGEO, $\pm 1\%$	1
	NC	R25, R37, R46, R47	R0603	YAGEO, $\pm 1\%$	4
	23 k Ω	R26	R0603	YAGEO, $\pm 1\%$	1
	10 k Ω	R27	R0603	YAGEO, $\pm 1\%$	1
	1 k Ω	R28, R29, R33	R0603	YAGEO, $\pm 1\%$	3
	0 Ω	R30, R34, R39	R0603	YAGEO, $\pm 1\%$	3
	5.6 k Ω	R31	R0603	YAGEO, $\pm 1\%$	1
	21.5 k Ω	R32	R0603	YAGEO, $\pm 1\%$	1
	14.3 k Ω	R35	R0603	YAGEO, $\pm 1\%$	1
	2.43 k Ω	R36	R0603	YAGEO, $\pm 1\%$	1
	68 k Ω	R40, R42	R0603	YAGEO, $\pm 1\%$	2
	230 k Ω	R41	R0603	YAGEO, $\pm 1\%$	1
	20 k Ω	R43	R0603	YAGEO, $\pm 1\%$	1
	51 Ω	R44	R0603	YAGEO, $\pm 1\%$	1
	2.2 Ω	R13	R0805	YAGEO, $\pm 1\%$	2
	10 Ω	R14	R0805	YAGEO, $\pm 1\%$	2
	NC	R45	R1206	YAGEO, $\pm 1\%$	1
	51 Ω	R1	R1206	YAGEO, $\pm 1\%$	1
	1.5 M Ω	R2, R6, R11, R12, R15, R16	R1206	YAGEO, $\pm 1\%$	6
	0 Ω	R8	R1206	YAGEO, $\pm 1\%$	1
	NC	R10	R-6.8-LS	YAGEO, $\pm 1\%$	1
	10 Ω	R17	R1206	YAGEO, $\pm 1\%$	1
	33 Ω	R18	R1206	YAGEO, $\pm 1\%$	1
	10 k Ω	R19	R1206	YAGEO, $\pm 1\%$	1
	150 k Ω	R3, R7, R9, R48	R2512	YAGEO, $\pm 1\%$	4
	1 Ω	R20, R21	R2512	YAGEO, $\pm 1\%$	2
	68 k Ω /2W	R4, R5	R-6.8-LS	YAGEO, $\pm 1\%$	2
	200 Ω /5W	R24, R49	R-6.8-LS	YAGEO, $\pm 1\%$	2
	Diode	ES1D	D7	SMA	ON, ST
RS1M		D3, D4	SMB	ON, ST	2
SS14		D6, D9	SOD123	ON, ST	2
27V		ZD1	SOD123	UMZ27K	1
18V		ZD2	SOD123	BZT52C18	1
D4UB100		D1, D2	D3K	YJ	2
DSA20C200PB		D5, D8	TO-220AB	Littelfuse	2

.....continued

Type	Ratings/Part Number	Designator	Footprint	Description	Quantity
Integrated Circuit (IC)	MIC38C44	U1	SOIC8	Microchip	1
	MCP16311	U4	SOIC8	Microchip	1
	817A	U2	OPTO-SMT	TI	1
	TL431	U3	SOT23	TI	1
NPN transistor	STN0214	Q2	SOT223	ST	1
	MMBT2222A	Q3, Q4, Q6	SOT23	ON, ST	3
PNP transistor	MMBT4403	Q5	SOT23	ON, ST	1
MOSFET	MSC750SMA170B	Q1	TO-247	MC	1
Fuse	FUSE	FUSE1	AXIAL0.8	Littelfuse	1
Header	Header 2H	J1, J2, J3	HDR1X2-7.5	TE	3
Heat sink	Heat sink	HS_D5, HS_D8	HS-TO220-1	—	2
	Heat sink	HS_Q1	HS-TO247-1	—	1
Inductance	2.2 μ H	L1, L2	IN-L	3A	2
	10 μ H	L3	IN-L	2A	1
	70 m Ω /2A	T1	LL	PDMCAT1386-472ML	1
MOV	—	MOV1, MOV2	MOV	Placeholder	2
Negative Temperature Coefficient (NTC)	NTC	N1	NTC	Placeholder	1
Transformer	Trans BB	T2	PQ3528	—	1

4. Quick Startup and Test Procedure

Perform the following steps to quickly boot up and test the evaluation board:

1. Visually inspect any damage to the board and the components. Examine for bending, breaking, or a change in shape.
2. Connect the DC input to the DC power supply and the two DC outputs to passive or electronic loads, making sure to match the positive/negative connections.
3. Connect all the measurement equipment, such as oscilloscope probes and Digital Multimeter (DMM).
4. Start with a DC input of 10V/0.1A and monitor the DC source current. Make sure the DC source current is close to 0 to ensure there is no short circuit in the system. If the DC source current is 0.1A, there is a short circuit in the input. Stop the system and look for problems.
5. Set the DC source to 250V/0.5A for normal testing, and the outputs setups after 0.5s.

5. Experimental Testing Results

This chapter describes the results of tests performed on SiC MOSFET.

5.1 Operation Waveforms

The converter operates at Continuous Conduction Mode (CCM) with a 250V input voltage at 50% and 100% load and at Discontinuous Conduction Mode (DCM) with a 1 kV input voltage at 50% and 100% load. The drain-to-source peak voltage on the MOSFET is well below the 1.7 kV device rated voltage. The RCD circuit well clamps the device drain-to-source voltage, but there is still some V_{DS} ringing after device turn-off due to the relatively large leakage inductance of the transformer. Because of the relatively large gate resistance and good PCB layout design, the gate voltage has small voltage overshoot and undershoot during device switching transient. The gate signal V_{GS} is clean during both the turn-on and turn-off transients. The measured gate voltage on the device is 16.5V, and works well with 0V gate voltage during turn-off.

The following figures show the operation waveforms for SiC MOSFET at different input voltages and steady-state output power levels.

Note: In the following operation waveforms, drain-to-source voltage (V_{DS}) is blue, gate-to-source voltage (V_{GS}) is red, and device current (I_{DS}) is green.

Figure 5-1. Operation Waveform at $V_{in} = 250V$ and 50% Load

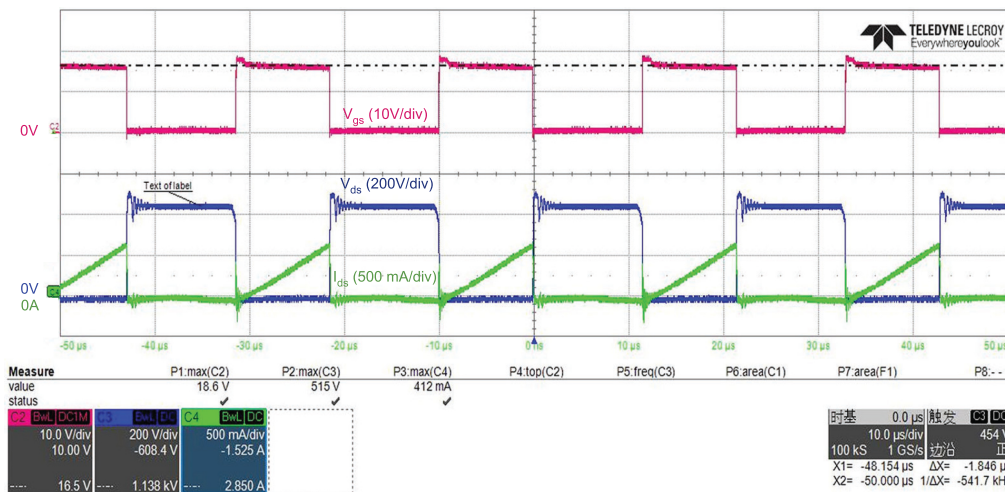


Figure 5-2. Operation Waveform at $V_{in} = 250V$ and 100% Load

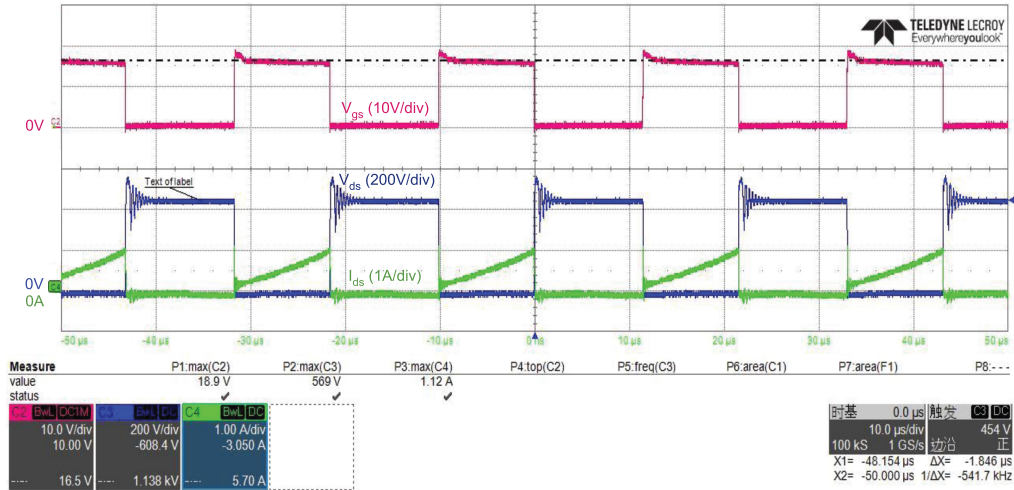


Figure 5-3. Operation Waveform at $V_{in} = 1000V$ and 50% Load

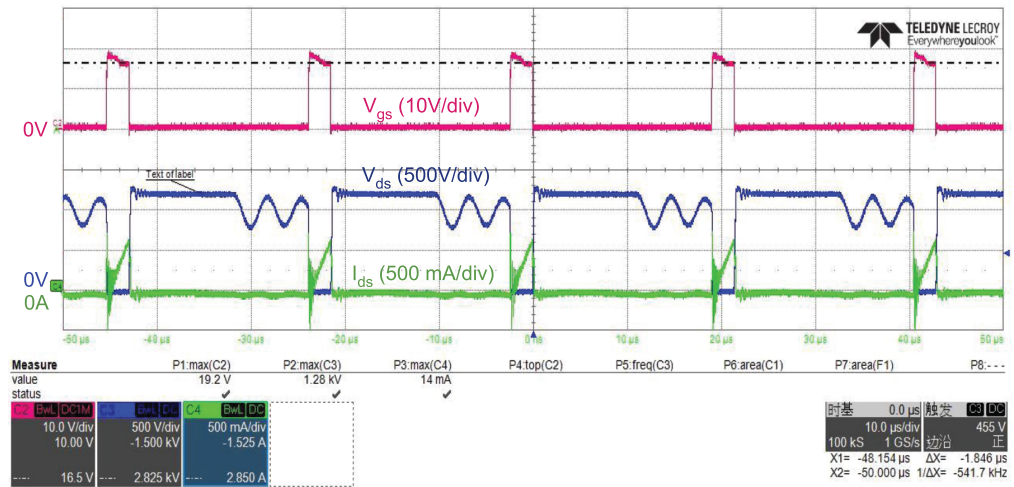
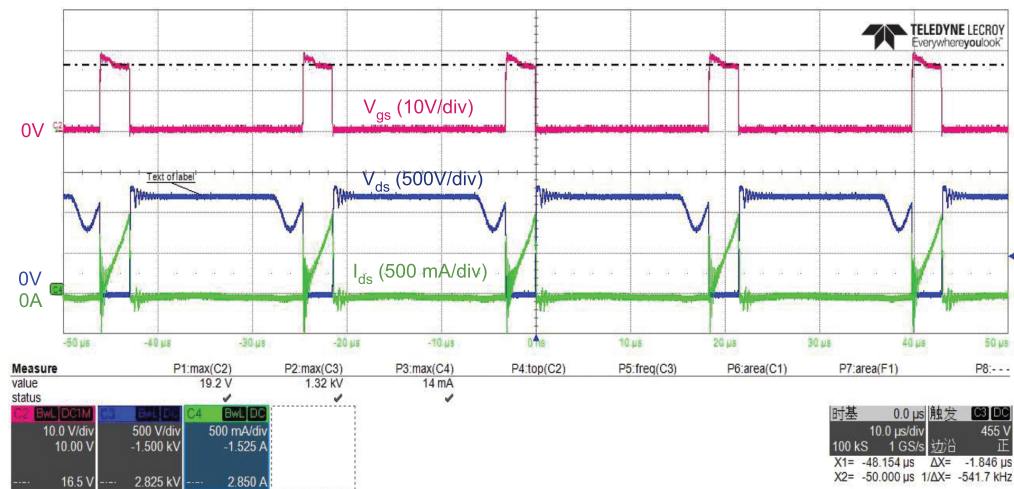


Figure 5-4. Operation Waveform at $V_{in} = 1000V$ and 100% Load

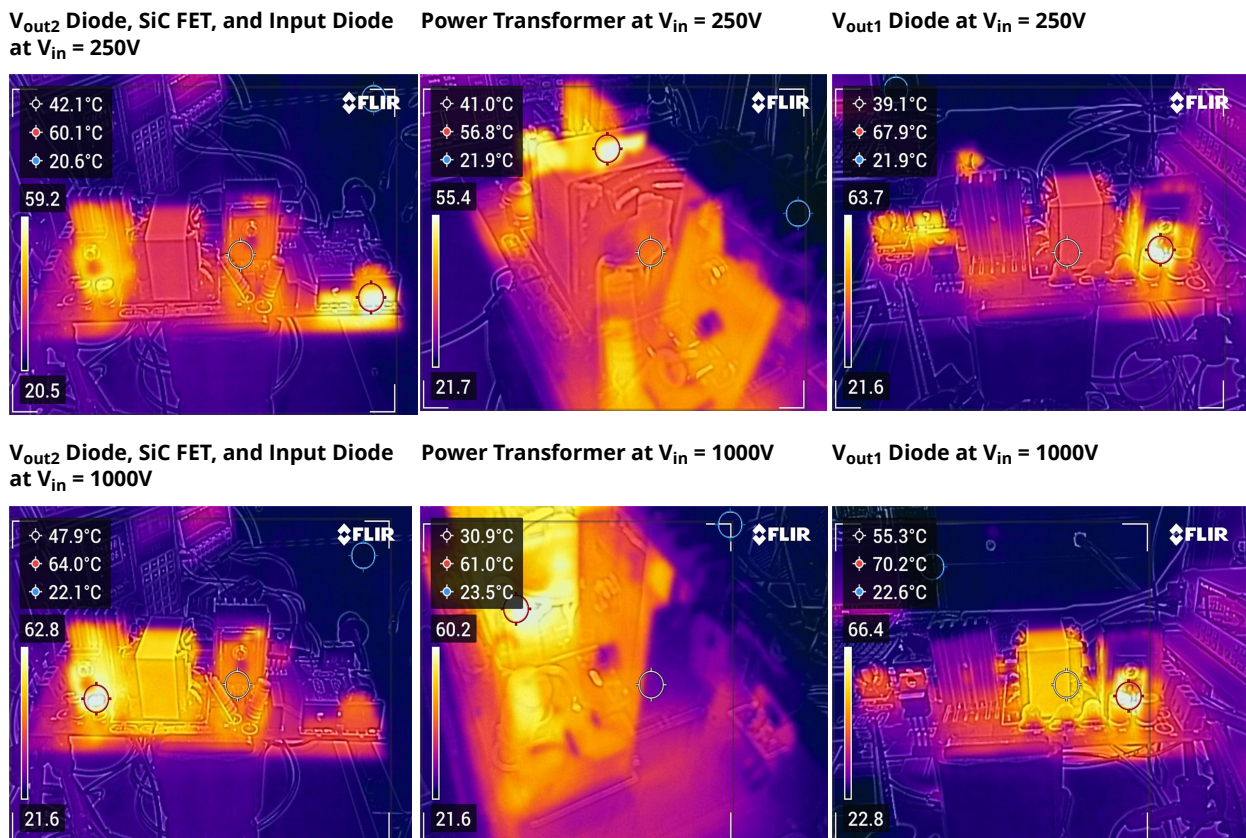


5.2 Thermal Performance

With only a small heatsink and no fan cooling, the primary side MOSFET temperature rise is only 25.8 °C in the worst case, demonstrating that the MOSFETs can process much higher power and that the heatsink is not required in some applications. The maximum temperature rise of the power transformer is 37.5 °C, which validates its effectiveness. At full load, the highest temperature rise (47.6 °C) is measured on the rectifier diode of output 1. The output diodes are connected to a small heatsink, and natural convection cooling is used. The results validate the design effectiveness and show that the temperature rise of all the major components in the converter design is relatively low due to the small heatsink and natural convection cooling.

The following figure shows the thermal performance of the converter at full load under different input voltage conditions.

Figure 5-5. Temperature Measurement Results

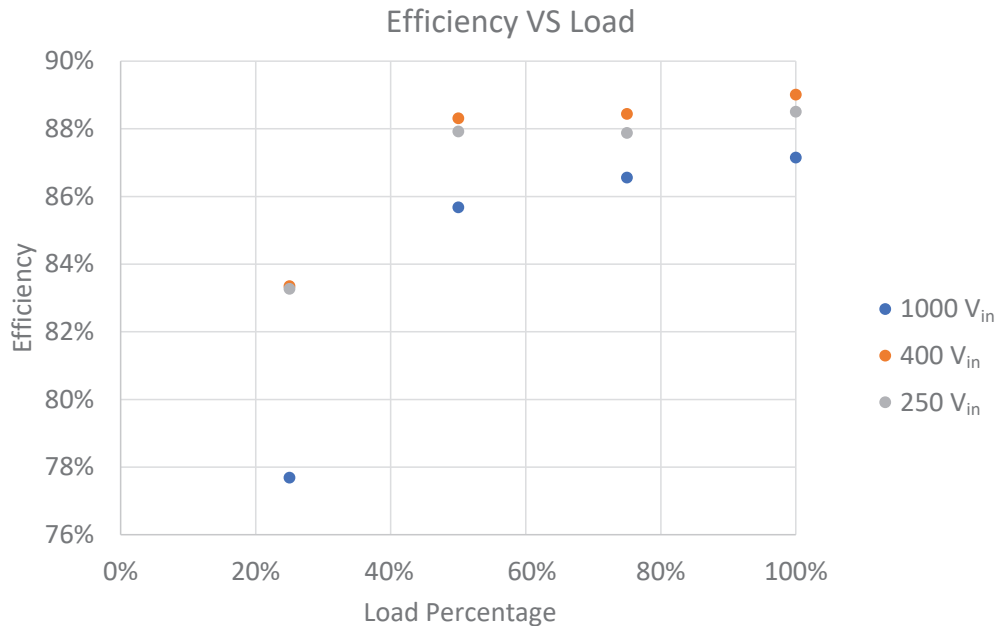


5.3 Power Loss and Efficiency

The switching loss of the converter increases significantly with high input voltage, so the efficiency at 1 kV is lower than the efficiency at 400V and 250V. Above 25% load, the converter efficiency is more than 80% for 250V and 400V input voltages, with a peak efficiency of 89% at 100% load and 400V input voltage.

The following figure shows the efficiency measurement results for the demo converter at different input voltage and load conditions.

Figure 5-6. Measured Efficiency vs. Output Power Load Under Different Input Voltage



More test results are available, including the steady state output voltage ripple. For more information on load and line regulations, start-up time, hold-up time, and short circuit protection results for various working conditions, contact the Microchip technical support team.

6. Reference Documents

The following document is referred in this user guide:

- [MIC38C42/43/44/45 BiCMOS Current-Mode PWM Controllers Data Sheet](#)

7. Revision History

The revision history describes the changes that were implemented in the document. The changes are listed by revision, starting with the most current publication.

Revision	Date	Description
B	06/2023	Replaced HV SiC MOSFETs with HV silicon MOSFETs and lower rated voltage SiC MOSFETs with lower rated voltage silicon MOSFETs in Introduction .
A	02/2023	Initial revision

Microchip Information

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