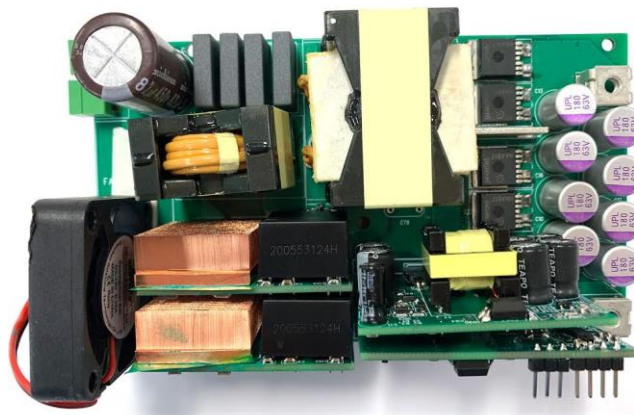


GaN-Based 3KW Full Bridge LLC Resonant Converter Reference Design

Technical Manual



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1. Scope and Purpose

This document provides a general functional description and guideline to designing with the 3KW LLC isolated DC/DC resonant converter reference design (GS-EVB-LLC-3KW-GS) based on the 650V 50mΩ Gallium Nitride (GaN) transistor (Part Number: GS-065-030-2-L) from GaN Systems. It describes the features, system operations, board setup procedure, and GaN-based LLC key parameters.

2. Introduction

The full bridge LLC resonant converter design, integrating GaN Systems' 650V Enhancement mode GaN transistors, exceeds the 80+ Titanium standard for power supply units (PSUs), achieving high power density (AC/DC PSU) above 100W/inch³ and high efficiency of more than 96 percent.

The key benefits and features of this GaN-based LLC include:

- High density: 146W/inch³ (including air-forced cooling)
- High efficiency: Peak efficiency > 98%
- Small size: <30mm height and meets low profile 1U datacenter PSU form factor
- High switching frequency with maximum up to 450 KHz
- Comprehensive system protections such as over current, short circuit, and over voltage

This reference design is applicable to high-density AC/DC SMPS designs with galvanic isolation, for example, data center server, telecom, and industrial power supplies.

2.1 System Block Diagram

The GS-EVB-LLC-3KW-GS reference design includes three main system blocks: the first block is the full bridge LLC power stage; the second block is the digital-based MCU control which includes the signal sensing, algorithm processing, and control signal outputs for the power stage; and the third block is the auxiliary power supply to supply for the whole system such as controller, driver IC, and fan.

Figure 1 illustrates the power stage block diagram for the 3KW LLC resonant converter. On the primary side, there are two half bridge GaN boards (#1 & #2) building up a full bridge topology. Each GaN board implements one 650V, 50mΩ 8x8mm PDFN GaN transistor GS-065-030-2-L on

both high side and low side; the isolated gate drive ICs (Si8271AB) and isolated DC/DC converter are included on the GaN boards to drive the GaN transistor. The isolated DC/DC converter converts 10VP input voltage to +5.8V and -3V for the GaN transistor turn-on and turn-off voltages respectively. The resonant tank (resonant inductor L_r , resonant capacitor C_r , and transformer T_r) are designed to achieve a resonant frequency at 250KHz and maximum switching frequency up to 450KHz. On the output side, the full wave synchronous rectification uses two 150V, 4.4mΩ silicon SR MOSFETs in parallel per switch to rectify the output to 54V.

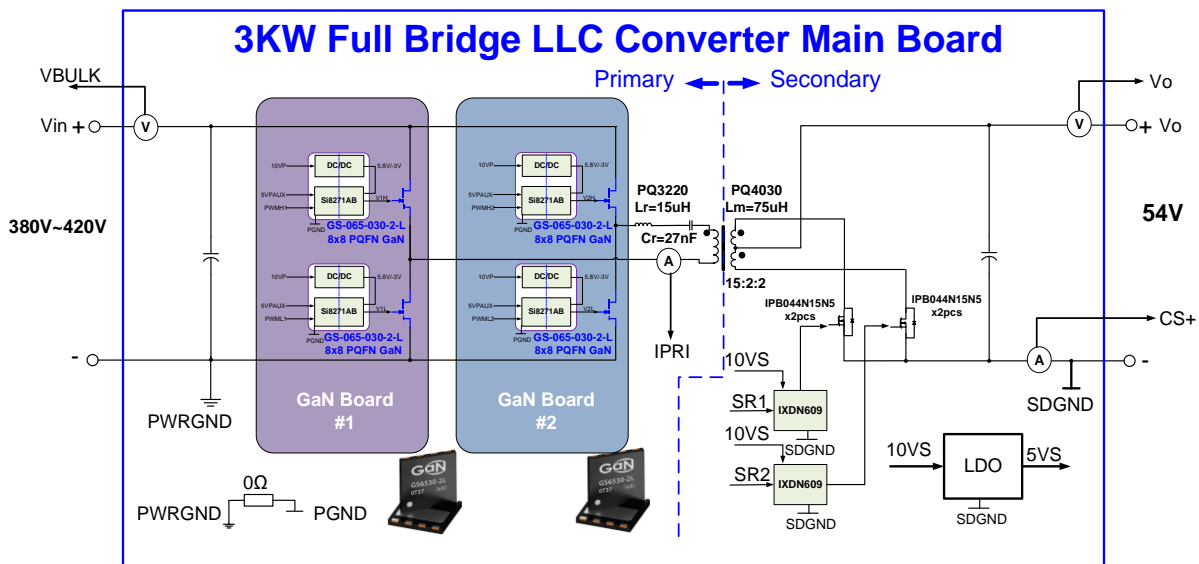


Figure 1. Simplified power stage block diagram for the GS-EVB-LLC-3KW-GS reference design

As shown in Figure 2, the STM32F334C8 MCU is placed on the secondary side which includes three key functional sections:

- 1) Feedback signal sensing and sampling from power stage
- 2) Digital control algorithm process
- 3) Output signal generations for power stage

The feedback signal sensing and sampling circuits have the following sections:

1. Output voltage sense (V_o sample) for control feedback loop algorithm;
2. Primary input voltage sense (VBULK) with an optocoupler isolation from the primary side to the secondary side, which acts as input voltage brown-out protection. The LLC

resonant converter will not operate until the input DC voltage V_{in} is above 370V and shut down when the input voltage is below 340V;

3. Primary current through the resonant tank (IPRI) senses for overcurrent protection (OCP) with an optocoupler isolation to secondary side signal, OCP_pri. When the primary current is above 18A, the primary OCP is triggered, and LLC resonant converter will shut down;
4. Secondary side current on the output (CS+) is sensed to MCU (OCP_sec) for the output OCP. When the output current is above 60A, the output OCP is triggered, and the LLC resonant converter will shut down.

The digital control algorithm processing includes the state machine for the output load regulation and system protection. The control feedback algorithm regulates output voltage at 54V with input voltage range from 380V to 400V and load range from 0A to 55A. It also integrates the protection with the input voltage brown-out, primary OCP, and output OCP.

The output drive signals (PWMH1/PWML1 and PWMH2/PWML2) are generated after the signal isolation (ISO7740) to drive the primary side's GaN boards. The SR1 and SR2 are the secondary drive signals for SR MOSFETs.

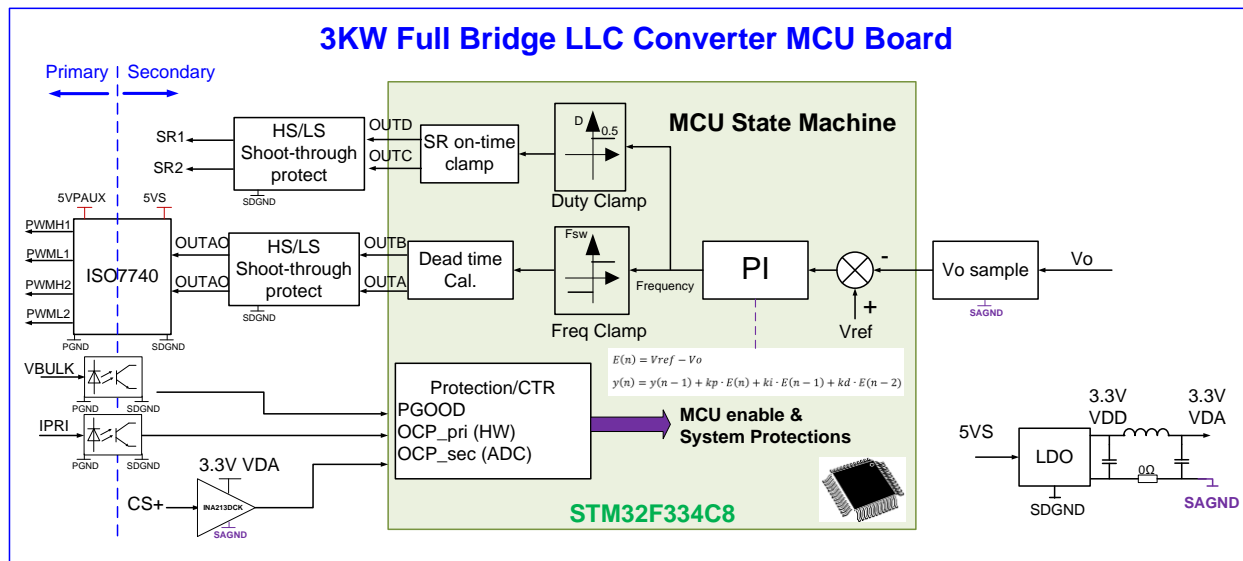


Figure 2. MCU control block diagram for the GS-EVB-LLC-3KW-GS reference design

The auxiliary power supply block in Figure 3 uses a QR flyback topology with GaN Systems 650V 450mΩ GaN transistor (GS-065-004-1-L), which gets 10VP output for primary supply voltage, 10VS output for secondary supply voltage, and 12VSFAN output for air-forced fan.

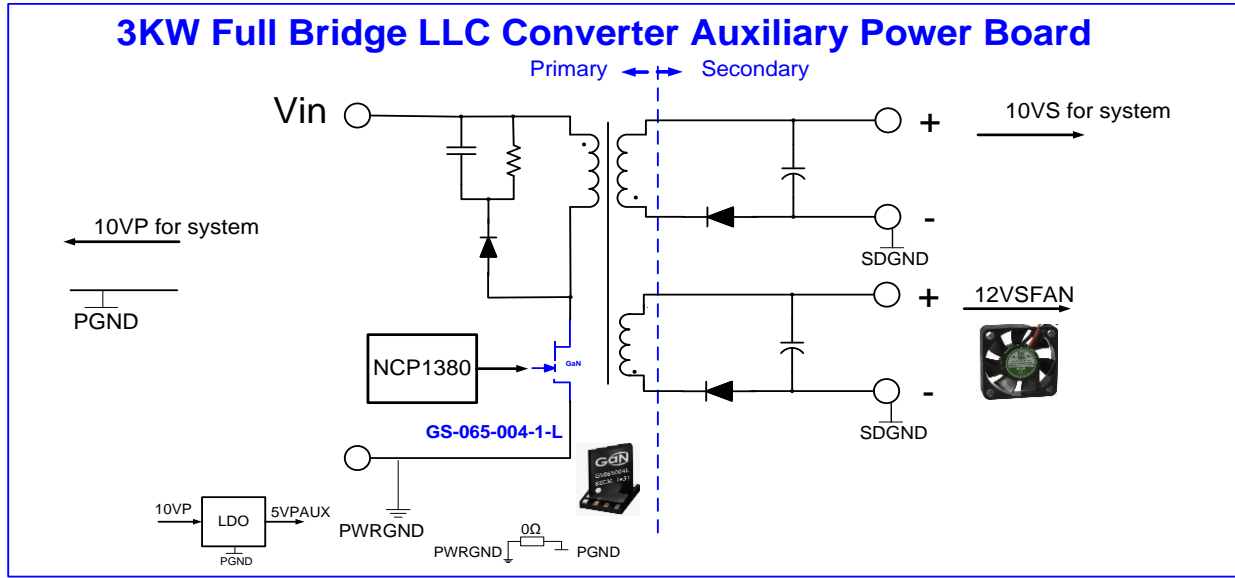


Figure 3. Auxiliary power supply block diagram for the GS-EVB-LLC-3KW-GS reference design

2.2 System Specifications

Table 1 summarizes the key parameters and performance for the GS-EVB-LLC-3KW-GS reference design.

Table 1. Key parameters & performance of GS-EVB-LLC-3KW-GS reference design

Parameter	Value
Input DC Voltage (V_{in})	380-420 V
Output Voltage (V_o)	54 V
Max. Output Power (P_o)	3000 W
Full Load Output Current (I_o)	55 A
Resonant frequency (f_r)	250 KHz
Max. Switching frequency (f_{max})	450 KHz
Performance	Specification
Power Density	146 W/in ³
PCBA Board Size	80 mmx140 mmx30 mm (with air-forced cooling fan)
Peak Efficiency	>98%
System Protections	Input voltage brown-out, output short, output OCP, primary OCP

2.3 Reference Design Board

Figure 4 shows the PCBA photo of this reference design which has a main power stage, two GaN boards (#1 & #2), one MCU board, and one auxiliary power board. A 15000 RPM fan is used to cool the heatsinks.

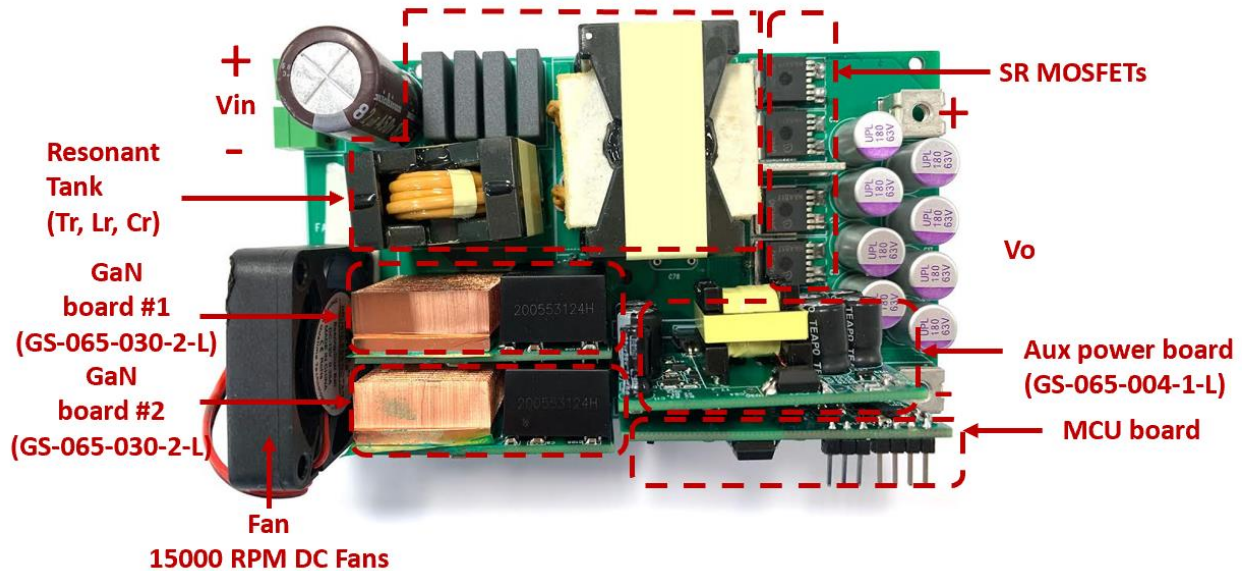


Figure 4. PCBA photos for GS-EVB-LLC-3KW-GS reference design

2.4 Test Setup Procedure

The reference design board test setup procedure is as follows:

1. Insert daughter boards (auxiliary power board, MCU control board, and GaN boards (#1)) on the main board and make sure they are tightly connected with the main power board;
2. Connect a DC source on the input side and an Electronic Load (E-load) on the output side;
3. Apply a 300V DC at the input side, the fan will operate, and a Red LED on the MCU board will turn on, which means the auxiliary board is working;
4. Set the E-load to CR (Resistor load) Mode and power up the board with light load around 300W-500W;
5. Increase the input voltage from 300Vdc to 400V; the output voltage will be about 54V;
6. The board works and can be tested with the load increasing or decreasing.

WARNING NOTES:

- **DO NOT APPLY DC INPUT VOLTAGE WITHOUT MCU BOARD AND AUX POWER BOARD**
- **OUTPUT CONNECTORS' SCREWS SHOULD NOT TOUCH or DAMAGE THE PCB BOARD'S TOP SIDE AS SHOWN IN THE BELOW FIGURE**



3. System Design Considerations

3.1 GaN-based LLC Value Proposition

This GaN-based LLC resonant converter has several benefits due to its full resonant behavior allowing soft switching turn-on over the entire range from no load to full load, which intrinsically helps to minimize losses in both power transistors and magnetic components. In Figure 5, the LLC primary side current, I_{Lr} , consists of a superposition of the secondary side current, divided by the transformer turns ratio n and the magnetizing current I_{Lm} . The magnetizing current does not transfer to the output but is required to discharge the parasitic output capacitance of the transistors as well as a combination of the transformer intra-winding and inter-winding capacitance, hence achieving Zero Voltage Switching (ZVS) for transistor turn-on without

switching turn-on loss. In order to achieve the ZVS for turn-on, the parasitic output capacitance of the transistor should be fully discharged by using this magnetizing current during each dead time. However, the magnetizing current will contribute an additional circulating loss on the primary during the dead time. Minimizing magnetizing current is thus a goal for improving an LLC converter.

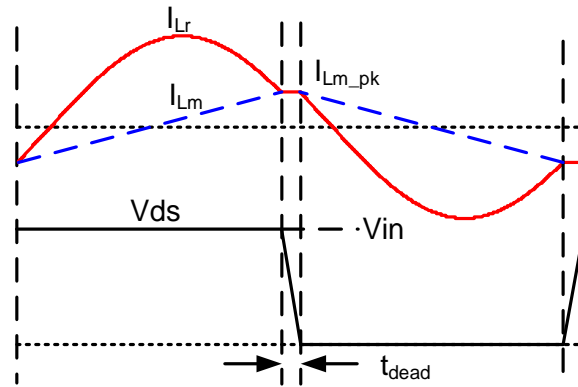





Figure 5. The primary current and voltage waveform for the LLC resonant converter

The minimum dead time $t_{deadmin}$ for a full bridge LLC's ZVS achievement condition can be derived from equation (1) as the reference of [2]. Here, L_m is the magnetizing inductance of the main transformer and f_s is the switching frequency. From equation (1), the transistor parameter $C_{o(tr)}$, which describes the output capacitance needed to transition the drain to source voltage passively, is a key parameter for high efficiency and high-density LLC converters. The lower the value of the effective $C_{o(tr)}$, the less magnetizing current is required for a given drain to source transition time, and this allows a higher value of magnetizing inductance for the transformer and a shorter dead time, lowering the circulating losses on the primary side. Meanwhile, for a given L_m and t_{dead} , the lower value of effective $C_{o(tr)}$, the higher switching frequency f_s can be used with ZVS condition to make a higher density.

$$t_{deadmin} = 8 \cdot C_{o(tr)} \cdot L_m \cdot f_s \quad (1)$$

Table 2. Key primary side transistors' parameters for the LLC resonant converter

Parameters		GS-065-030-2-L	Superjunction MOSFET	SiC MOSFET	GaN's value
					
Blocking voltage	V_{ds} ; V	650	600	650	
On resistance	$R_{DS(on),typ}$; m Ω	50	48	55	Almost same typical $R_{DS(on)}$
Time related effective output capacitance	$C_{o(tr)}$; pF	150	1171	210	Shorter dead time for LLC, low circulating loss
Gate to drain charge	Q_{gd} ; nC	2	28	27	Lower switching turn-off loss
Turn-off time @5A 400V	t_{off} ; ns	2.52	15.1	11.0	Lower switching turn-off loss
Total gate charge	Q_g ; nC	6.7	79	73	Lower gate drive loss
Reverse Recovery charge	Q_{rr} ; nC	0	720	85	No hard commutation failure

As shown in the Table 2, compared to Si and SiC, the GaN transistor with similar $R_{DS(on)}$ has lower values of $C_{o(tr)}$, Q_{gd} , t_{off} , and Q_g , resulting in better performance of the LLC converter. Designed for high efficiency and high power density, especially with lower $C_{o(tr)}$, the shorter dead time is achieved with lower primary side circulation loss. In this 3KW LLC reference design, 100ns dead time can be used with lower loss and maximum frequency up to 450KHz. On the contrary, a Si-based LLC should use longer dead time ~200ns in order to achieve ZVS operation with typical frequency around 100KHz.

3.2 LLC Resonant Tank Design

Using the FHA (First Harmonic Approximation) method, the voltage DC gain can be theoretically calculated with reference to the equivalent resonant circuit, shown in Figure 6. This equivalent circuit represents a transformation of the circuit, in which the output transformer and rectifier + filter are reflected by an equivalent load R_e , which is the output loading R_o of the converter transformed back through the converter transformer and can be expressed in equation (2).

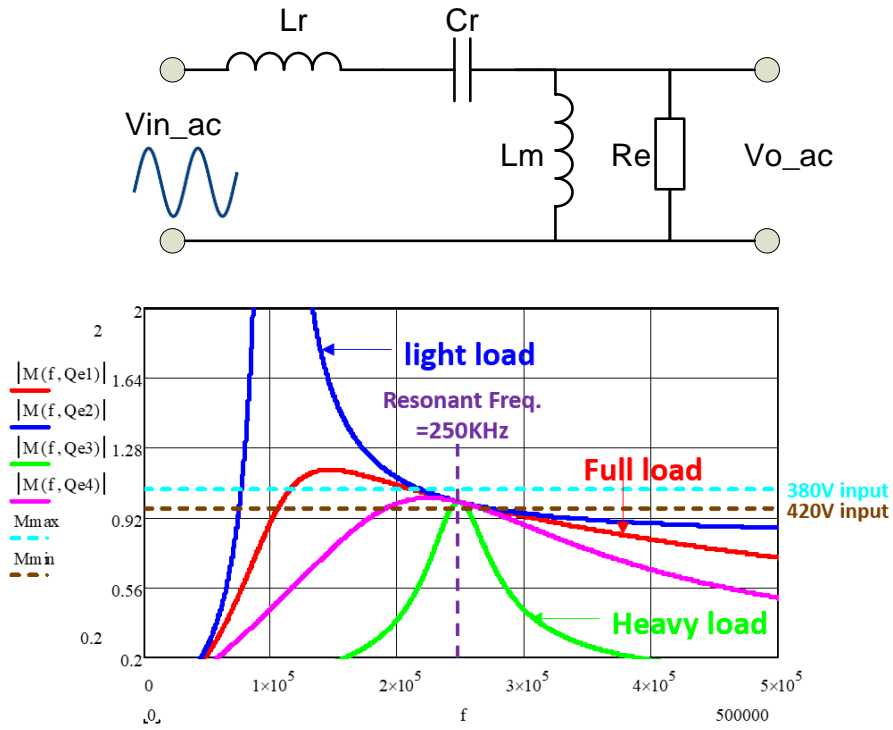


Figure 6. FHA equivalent resonant circuit and the DC gain M curve with frequency

$$Re(Ro) := \frac{8}{\pi^2} \cdot Nps^2 \cdot Ro \quad (2)$$

Where R_o is the output load, Nps is the transformer's turns ratio from primary to secondary.

The mathematical expression (3) of the DC gain M is given in terms of switching frequency f and quality factor Q_e :

$$M(f, Q_e) := \frac{1}{\sqrt{\left[1 + \frac{L_r}{L_m} \cdot \left[1 - \left(\frac{f_r}{f}\right)^2\right]^2\right]^2 + Q_e^2 \cdot \left(\frac{f}{f_r} - \frac{f_r}{f}\right)^2}} \quad (3)$$

Where:

$$f_r := \frac{1}{2\pi\sqrt{L_r \cdot C_r}} \quad \left| \quad Q_e := \frac{\sqrt{\frac{L_r}{C_r}}}{\text{Re}(R_o)} \right. \quad (4)$$

The f_r is resonant frequency and Q_e is quality factor. Here, the Q_{e1} , Q_{e2} , Q_{e3} , and Q_{e4} in Figure 6 represent the quality factors at 100% full load, 10% load, 10x load, and 2x load respectively. The LLC converter with wide load range is regulated to 54V with an input voltage range from 380V to 420V. The resonant frequency is set at 250KHz. At 100% full load, the switching frequency operates from 220KHz to 280KHz. At light load or soft start-up conditions, the max frequency is up to 450KHz.

The passive resonant tank values are designed with the following key parameters:

- **Transformer T_r** (ITG Electronics Inc. Part number: T301373SP-04)
 - Core: PQ4030 3C96 $L_m=75\mu\text{H}$
 - Turns: 15:2:2Ts
- **Resonant Inductor L_r** (ITG Electronics Inc. Part number: L101374SP-03)
 - Core: PQ3220 3C96 $L_r=15\mu\text{H}$
 - Winding: 0.1mm*200 15Ts
 - Distributed air-gap
- **Resonant Capacitor C_r**
 - $C_r=27\text{nF}$

4. Test Results

This section illustrates the testing equipment and experimental results of the reference design.

4.1 Test Equipment

The input power is measured by Power Meter (WT310E), output voltage is measured by Multi Meter (Fluke 179), and output current is measured by E-load (Chroma 63211).

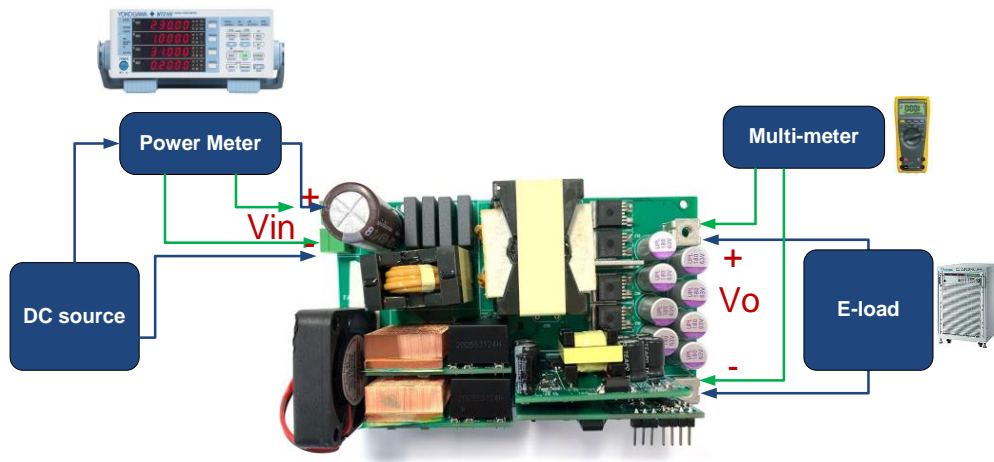


Figure 7. Test setup and equipment for GS-EVB-LLC-3KW-GS reference design

4.2 Efficiency

The efficiency curve and data are shown in the below figure and table. The efficiency data point is measured after 10min soak time, and the auxiliary power loss and the fan loss are excluded. The efficiency result shows ~98.2% peak efficiency at a half load 400V input. The average efficiency (10%, 20%, 50%, and 100% loading) is above 95.4%.

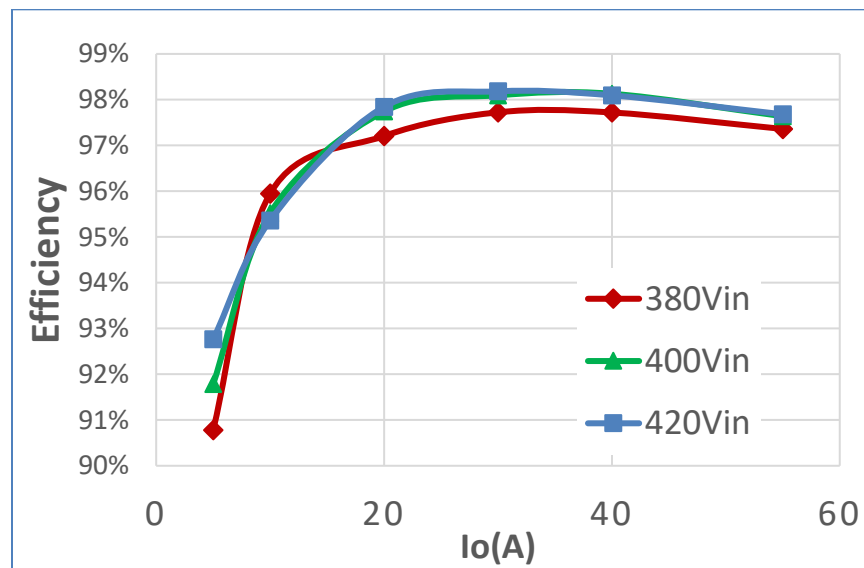


Figure 8. Efficiency curve with output current

Table 3. Efficiency table with 380V, 400V and 420V

	Vo (V)	Io (A)	Po (W)	Pin (W)	Eff
380Vin	54.38	4.908	266.89704	294.006	90.78%
	54.38	9.916	539.23208	562	95.95%
	54.324	19.767	1073.82251	1104.7	97.20%
	54.341	29.667	1612.13445	1649.7	97.72%
	54.3	39.61	2150.823	2201	97.72%
	54.268	55.056	2987.77901	3068.8	97.36%
	10%, 20%, 50%, 100% Average Eff.				
400Vin	54.382	4.908	266.906856	290.8	91.78%
	54.326	9.9168	538.740077	564	95.52%
	54.32	19.748	1072.71136	1097.5	97.74%
	54.306	29.66	1610.71596	1642	98.09%
	54.296	39.623	2151.37041	2192.4	98.13%
	54.278	55.056	2988.32957	3060.6	97.64%
	10%, 20%, 50%, 100% Average Eff.				
420Vin	54.4	4.908	266.9952	287.826	92.76%
	54.34	9.9168	538.878912	565.1	95.36%
	54.316	19.725	1071.3831	1095	97.84%
	54.297	29.662	1610.55761	1640.4	98.18%
	54.275	39.581	2148.25878	2190	98.09%
	54.273	55.05	2987.72865	3058.7	97.68%
	10%, 20%, 50%, 100% Average Eff.				

5.1 Load Regulation

The load regulation is within 54.0V~54.4V with wide load range and input voltage from 380V to 420V.

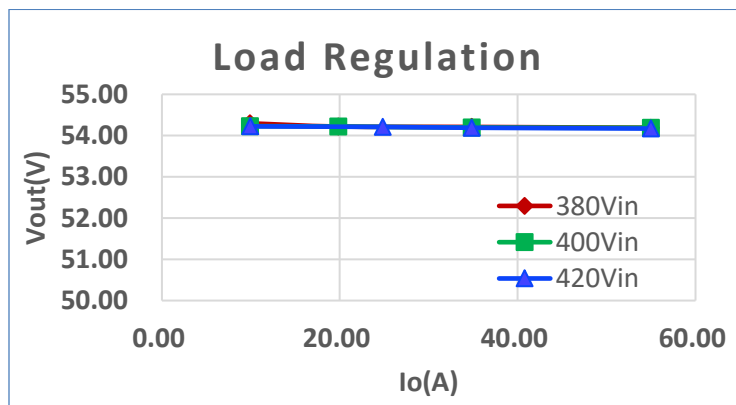


Figure 9. Load regulation curve with output current

5.2 Thermal

The thermal IR camera pictures and component temperatures are measured for 400V input and a full load operating condition after more than 0.5hr bake time. It shows that the GaN transistors' case temperature is below 80°C.

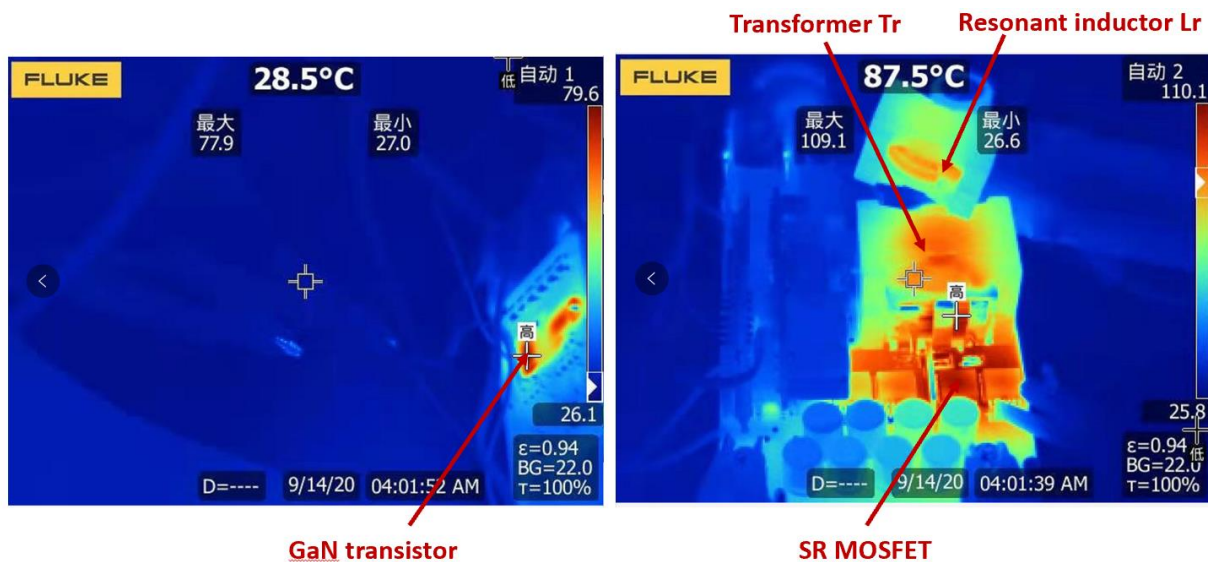


Figure 10. Thermal IR image at 400V input and 3KW

5.3 Electrical Waveforms

Figures 11 to 13 show the steady state waveforms at 400V, 380V, and 420V input. The switching frequency is variable from 220KHz to 280KHz with different input voltage.

Figure 14 is the load transient waveform from 10% load to 50% load and 50% load to 100% load. The peak-to-peak voltage is controlled within 3V during the load transient.

Figures 15 and 16 show the start-up waveform at no load and full load. During the start-up, the switching frequency starts from max 450KHz and gradually reduces to the regulated frequency.

Figure 17 shows the output current protection waveform. The output OCP is triggered at 60A output and the board is latched off. The main power must be cycled to restart the board.

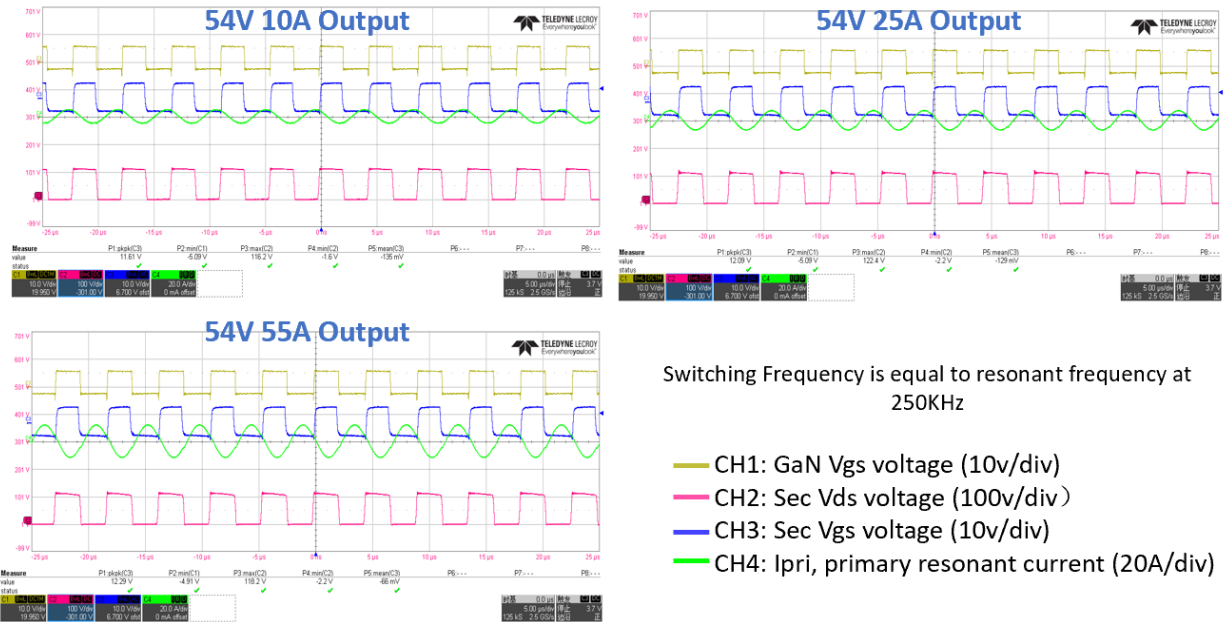


Figure 11. Steady state waveforms at 400V input and 10A, 25A, and 55A outputs

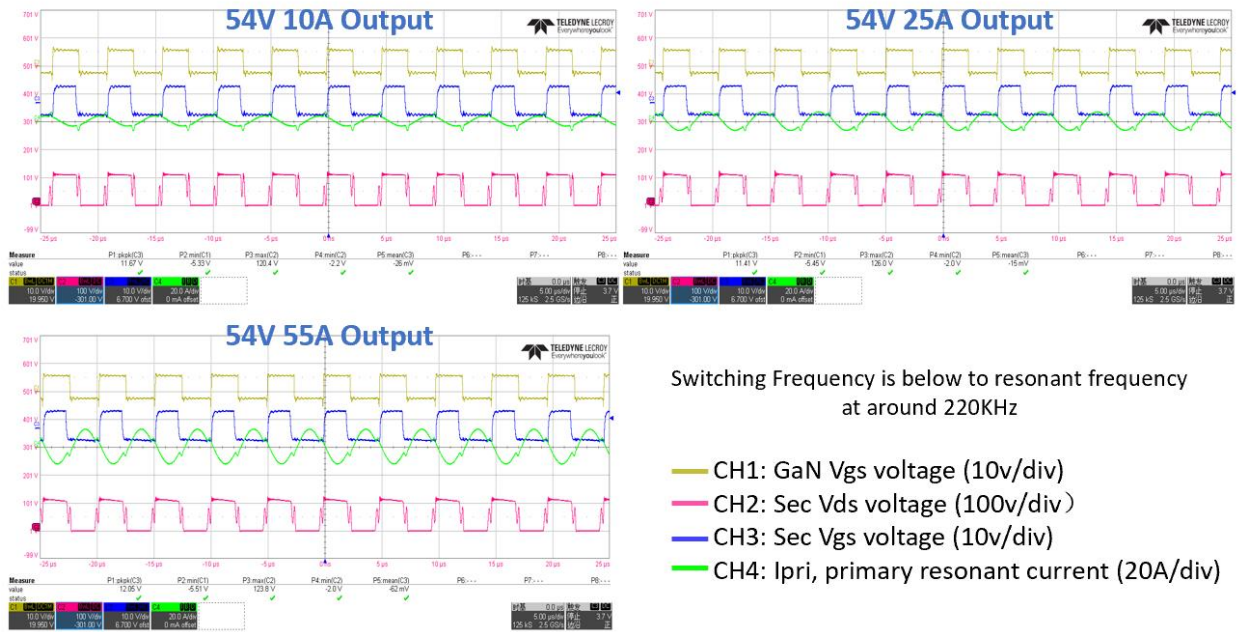
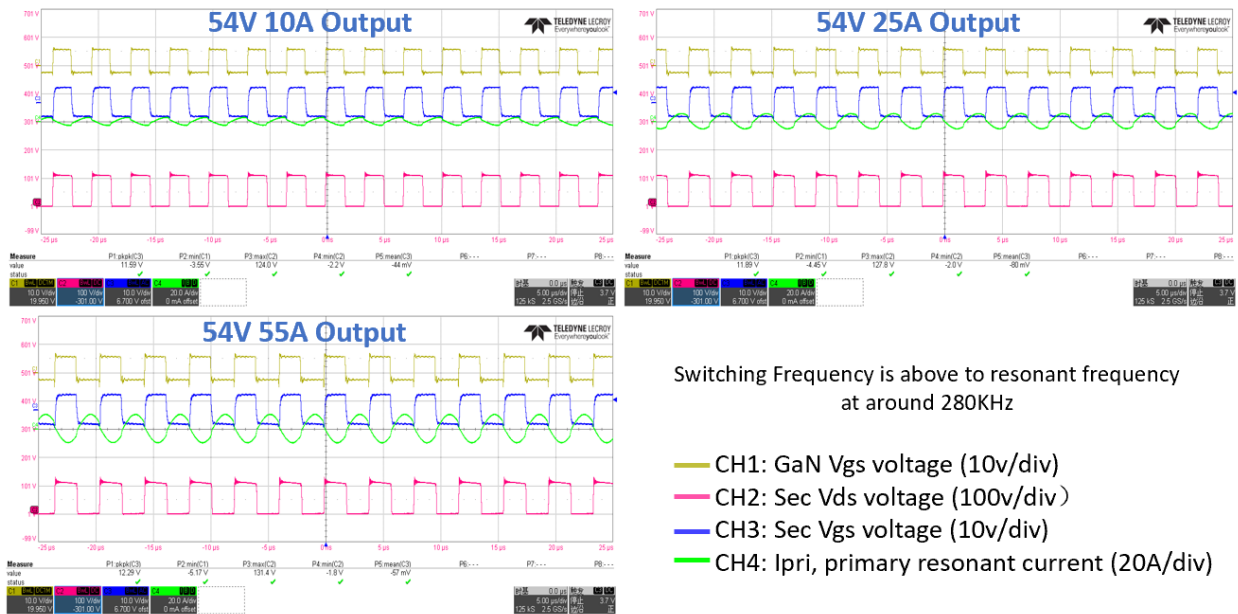


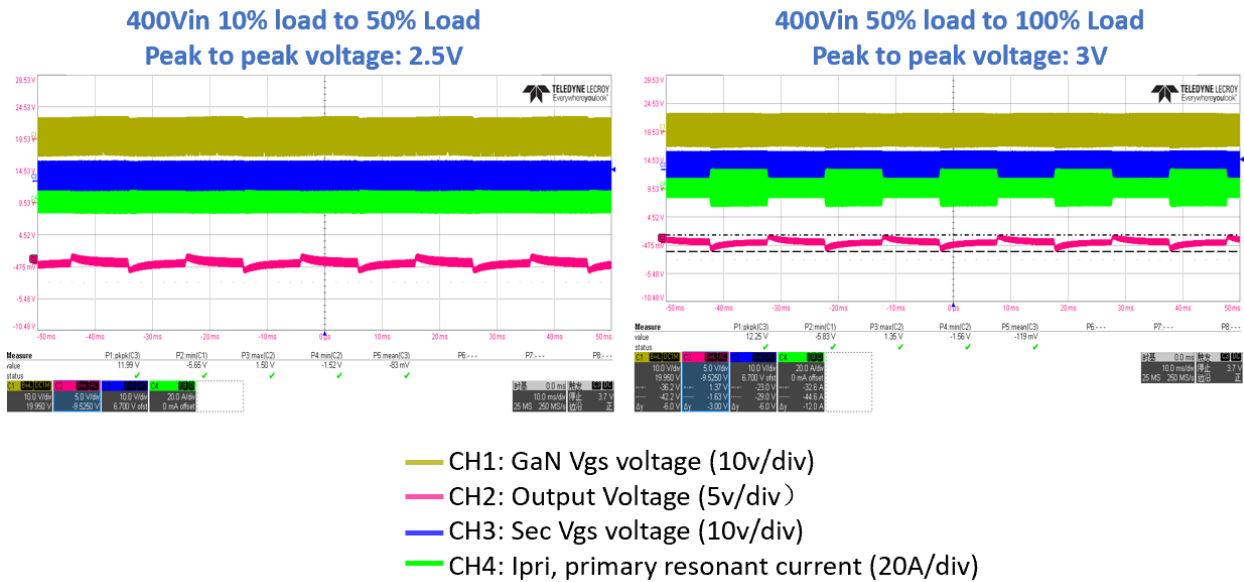
Figure 12. Steady state waveforms at 380V input and 10A, 25A, and 55A outputs



Switching Frequency is above to resonant frequency at around 280KHz

- CH1: GaN Vgs voltage (10v/div)
- CH2: Sec Vds voltage (100v/div)
- CH3: Sec Vgs voltage (10v/div)
- CH4: Ipri, primary resonant current (20A/div)

Figure 13. Steady state waveforms at 420V input and 10A, 25A, and 55A outputs



- CH1: GaN Vgs voltage (10v/div)
- CH2: Output Voltage (5v/div)
- CH3: Sec Vgs voltage (10v/div)
- CH4: Ipri, primary resonant current (20A/div)

Figure 14. Load transient waveforms at 400V input

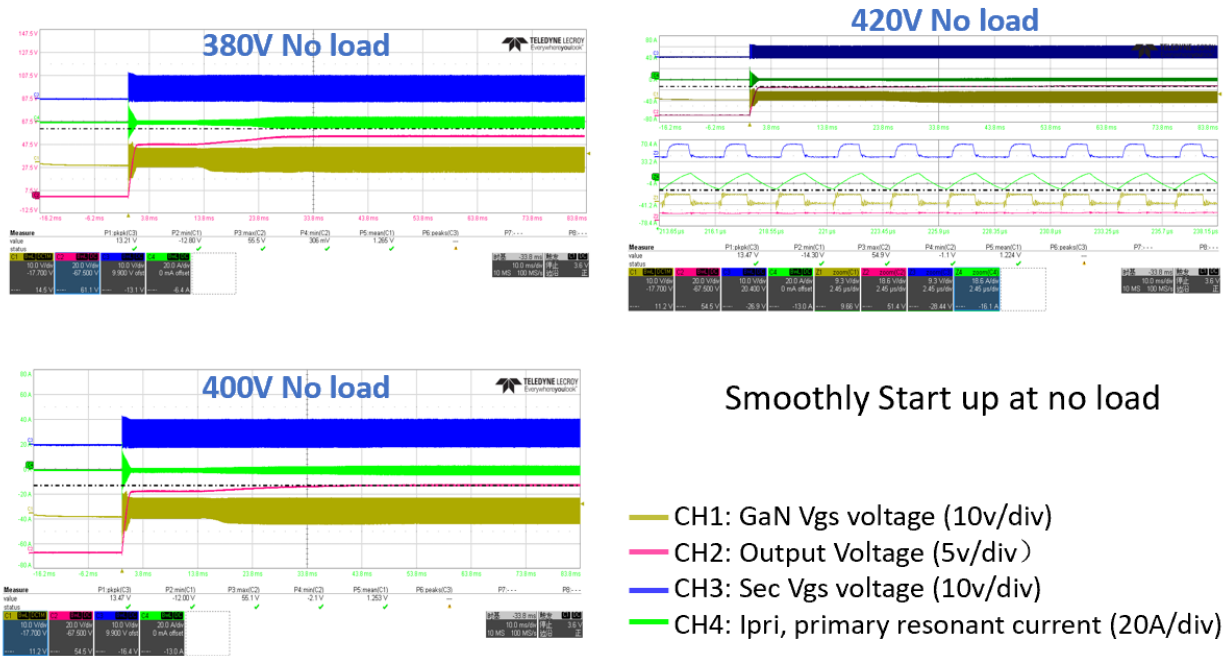


Figure 15. No load startup waveforms at 380V, 400V, and 420V inputs

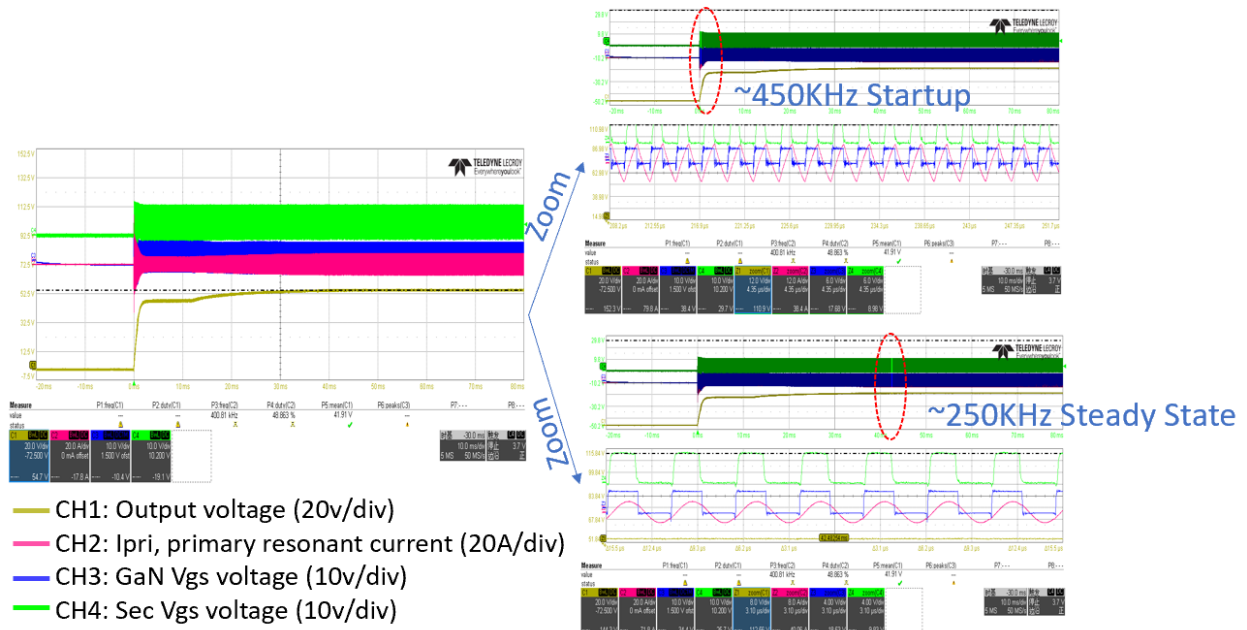
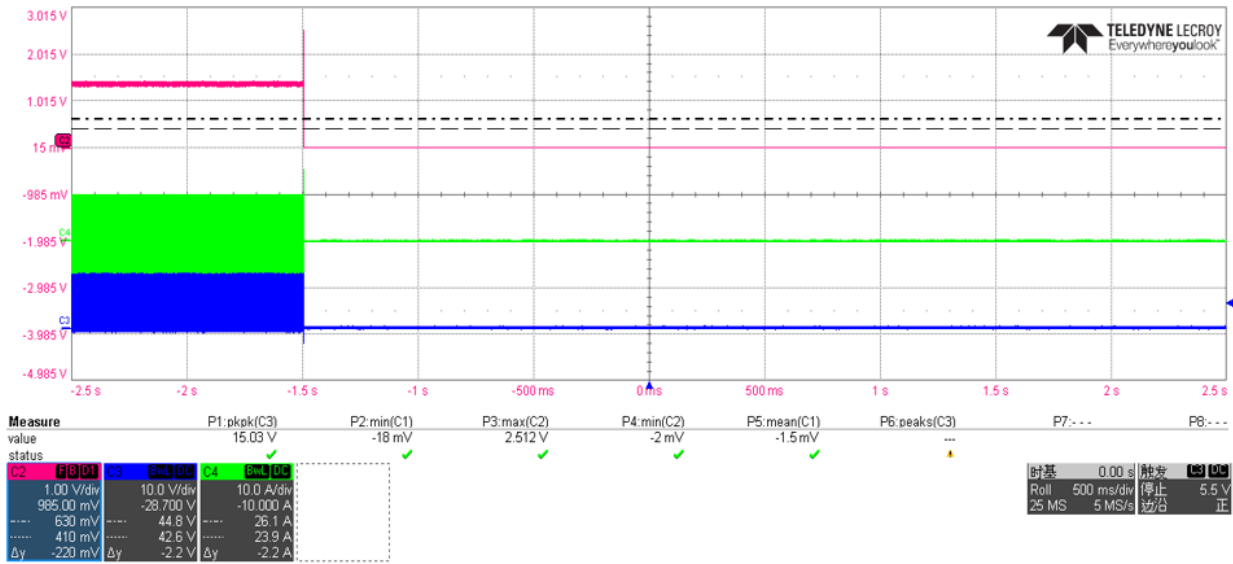


Figure 16. Full load startup waveforms at 380V, 400V, and 420V inputs



- CH2: Output current sense voltage (1V/div)
- CH3: Sec Vgs voltage (10v/div)
- CH4: Ipri, primary resonant current (20A/div)

Figure 17. Output OCP waveform at 60A

5. Conclusion

The 3KW LLC reference design uses GS-065-030-2-L for LLC main stage and GS-065-004-1-L for aux power stage. This GaN-based full bridge LLC resonant converter achieves the following best-in-class features and performance:

- Topology: Full Bridge LLC resonant converter with synchronous rectifier
- Power density: 146W/in³
- Height: <30mm
- Efficiency: >98%
- GaN Case Temp: 80°C

References

- [1] Design Considerations for a GaN-Based High Frequency LLC Resonant Converter, Jimmy Liu, [Online]. Available: [Design Considerations for a GaN-Based High Frequency LLC Resonant Converter - Technical Articles \(eepower.com\)](https://www.eepower.com/technical-articles/design-considerations-for-a-gan-based-high-frequency-llc-resonant-converter)
- [2] Investigation of High-density Integrated Solution for AC/DC Conversion of a Distributed Power System, Bing Lu, Virginia Polytechnic Institute and State University, PhD degree dissertation, May 2006

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